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Dedicated to:

Guillermo Trotti, for all of the love and thrills he has brought to my life and for all that is to come.

My family, the Newmans and Macks whom I love across the country.

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PREFACE

I have written *Interactive Aerospace Engineering and Design* for all students and learners who imagine flying a human-powered aircraft, being the first to step on the planet Mars, or have an insatiable curiosity about the governing physics underpinning the theory of flight. My inspiration began with the Apollo Program, the first human footsteps on the Moon, and with a desire to see peaceful human exploration of the solar system and beyond. My heartfelt thanks to Buzz Aldrin for contributing the Foreword. The purpose of this book is to provide a stimulating introduction to aerospace engineering and design. The two main themes I embrace for delivering my introduction to engineering thoughts are:

- hands-on design—where engineering becomes real, albeit challenging and thrilling.
- diversity in learning styles—where concepts and engineering laws can be understood through analytical, visual, and immersive techniques that are delivered through multimedia.

Chinese humanitarian Wei Jingsheng said, "To write, you must work methodically, forming your thoughts and prompting other people to think as they read. Writing requires work at both ends. That's what makes it special."

It has been a very special adventure for me, writing this book, reflecting on engineering education, and attempting to provide information and knowledge not only to assist the reader in thinking about the written words, but also to invite all readers to actively participate in their own education as well as to engage in a design process and build and fly their own lighter-than-air vehicle. I hope that you enjoy the material as much as I have enjoyed its creation.

Information technology (IT) is now revolutionizing the amount of knowledge disseminated worldwide. For the past few years, I have been contemplating how IT can best enhance engineering education, and I offer the following perspective: Multimedia and web-based tools provide students with an opportunity. The educational opportunity is for students to learn through analysis, visual animation, and interactive simulations at our own discretion. In other words, students are empowered to take charge of their own learning by using well-crafted IT tools that complement traditional knowledge dissemination via lectures and printed materials. This text describes the fundamentals of engineering and design in printed material enriched by a multimedia CD-ROM with animations, simulations, movie illustrations, and a web interface for electronic access and interactive demonstrations. Engineering students will find that this book augments their undergraduate core curriculum (i.e., physics, mathematics, and science). The hands-on lighter-than-air vehicle design project and accompanying design materials are intended for first- or second-year students to experience hands-on engineering.

For motivation during the wee hours while writing and editing, I kept these words of wisdom in mind:

> "Writing is humandkind's most far-reaching creation, its forms and designs endless."

> "Time is a luxury, thought a sanctity, and education a true gift. Respect them, honor them, and cherish them most of all."

Dava Newman

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Also, I am grateful to friends, not named, whose ideas I have implemented from conversations and sharing. Professor Thomas McMahon who taught me so much—how to truly teach and mentor based on creativity and sensitivity—I miss you. Finally, Guillermo Trotti has been my beacon from the first word to the closing image and last multimedia clip.

FOREWORD

Professor Dava Newman has written an exciting introductory book for students of aerospace engineering and design. We are all students in our universe, and her interactive illustrations take us from the earliest engineering feats to the Wright brothers' airborne flight to my spaceflight on Apollo 11 to future missions to Mars. Dr. Newman's *Interactive Aerospace Engineering and Design* makes engineering principles and the design process become intuitive components in our learning. Her landmark book offers the combination of text, animations, and simulations, utilizing information technology to motivate, illustrate, and demonstrate physical phenomena such as the principles behind flight, the fundamentals of the space environment, and artistic insight into creative design. The learning process culminates in *Interactive Aerospace Engineering and Design* with the lighter-than-air (LTA) vehicle design chapter. Through active, hands-on learning, blimps become operational and engineering principles are fully demonstrated in the team design.

This book is for those curious about engineering and design. I recommend it to college engineering students and teachers, advanced high school students, or members of the general public who want to think and be challenged to solve problems and learn technical fundamentals.

My Apollo 11 spaceflight to the Moon was the pinnacle of an engineering education, but my lifelong work is to continue answering technical problems for future aerospace endeavors, as seen in my collaboration with Professor Newman and colleagues to analyze novel Mars mission trajectories. In *Interactive Aerospace Engineering and Design,* Professor Newman invites us as a community of learners to take flight. This multidisciplinary, multimedia approach is how engineering should be taught.

Buzz Aldrin

FEATURED ICONS

The emphasis of this book is to inspire students new to the aerospace field to become actively challenged by this text, the CD-ROM, and the Internet resources. These various types of media will stimulate students with different learning styles to the excitement of aerospace engineering. While reading through the chapters, you will be exposed to animations, simulations, movies, and problems, all of which are easily identifiable by the following symbols:

Throughout the book, the image of the **thinker** in the margin is used to indicate that the problems presented are general thought-type questions. These problems do not require a quantitative answer, but require creative, qualitative contemplation.

$\int$

A **numeric** symbol alerts the reader to fundamental engineering problems that can only be solved through some mathematical computation. This type of problem requires a numerical solution.

When placed in the margin with a resource description, the **website** icon refers the reader to the author's website for up-to-date versions of URL addresses for these resources. A link to the author's website can be found through the McGraw-Hill website for this book at www.mhhe.com/engcs/aero/newman/.

A **CD-ROM** icon with a resource description is used to direct the reader to specific material on the accompanying *Interactive Aerospace Engineering and Design* CD-ROM. The CD-ROM contains animations, QuickTime™ movies, simulations, multimedia projects, design templates, and the complete e-text.

Interactive Aerospace Engineering and Design

Chapter 1

A Brief History of Flight

Amir R. Amir, Stanley I. Weiss, and Dava J. Newman

Humans have been fascinated with flight throughout history. The graceful fluidity of birds in flight motivated early inventors to mimic nature and propose vehicle designs that could carry humans above the confines of earth's surface. At first, people fashioned artificial wings and flapped them with their arms. As that proved unsuccessful and engineering advanced, mechanical mechanisms were used to flap the wings up and down, resulting in vehicles known as *ornithopters.* The great Italian artist, architect, scientist, and engineer Leonardo da Vinci (1452–1519) devoted much of his time to flight. His manuscripts contained some 160 pages of descriptions and sketches of flying machines. His work includes the world's first known designs for the parachute and helicopter, and it is believed that he made models of both and may have even flown them successfully. While da Vinci's work was brilliant, the concept of an ornithopter did not lead to sustained flight (see Figure 1.1).

It was only in the 18th century that humans achieved lighter-than-air flight. Then it took another 120 years to achieve heavier-than-air flight. This chapter provides a brief description of the history of flight.

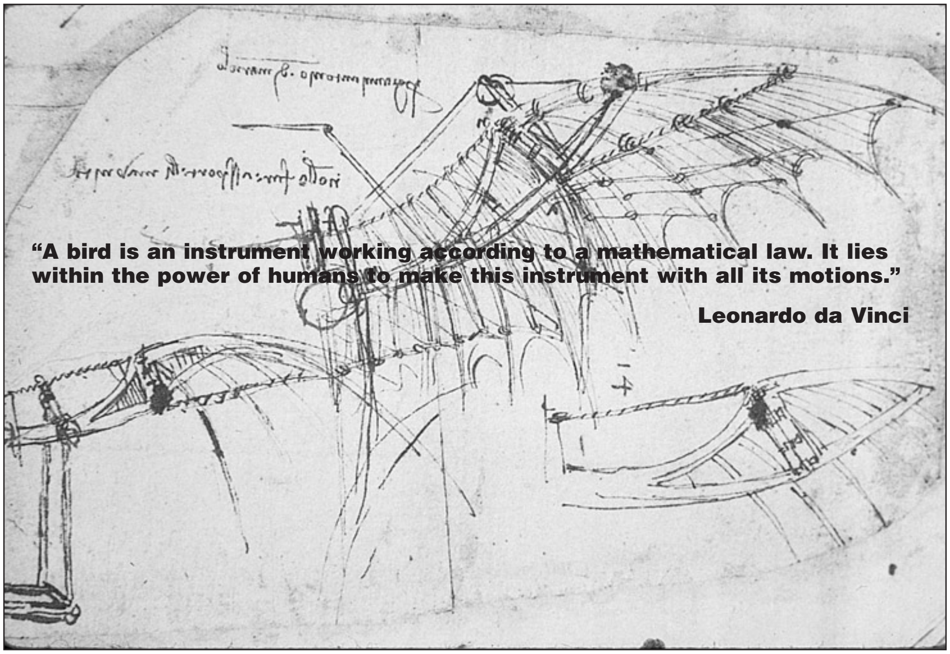
Online resource.

1.1 | BALLOONS AND DIRIGIBLES

Some 250 years later, two French brothers, Joseph Michael and Jacques Étienne Montgolfier, pioneered lighter-than-air flight with their innovative balloon designs. They conceived the idea of using the "lifting power" of hot air to achieve flight. On 25 April 1783, the Montgolfier brothers launched the first true hot-air balloon in Annonay, France. The balloon rose 305 m (1,000 ft) before the hot air cooled and it began its descent. On 19 September 1783, a command performance took place at the Court of Versailles when the Montgolfiers launched a sheep, duck, and rooster as the first passengers aboard their balloon. The first human to be carried aloft, François Filatre de Rozier, drifted 25.6 m (84 ft) in a

See the multimedia CD-ROM Ornithopter laboratory exercise. Ornithopter_Lab. PICT

Figure 1.1 | Leonardo da Vinci quotation and multimedia ornithopter tutorial on the accompanying CD-ROM.



tethered Montgolfier balloon on 15 October 1783. A month later Rozier, accompanied by Marquis d'Arlandes, made the first free flight in a balloon, remaining airborne for 25 min during which they traveled 8.5 km (5.5 mi).

Montgolfier lighter-than-air balloon.

The design of balloons matured rapidly. Hot air was replaced by hydrogen, which allowed the balloons to rise higher and did not depend on the temperature difference with the ambient air. Professor Jacques Alexandre César Charles was the first to successfully demonstrate a hydrogen balloon on 27 August 1783. Benjamin Franklin witnessed this event in Paris and was so impressed that he immediately wrote to scientists in the United States, stressing the military importance of this new invention. Charles and his assistant made a 43 km (27 mi) free flight from the garden of the Tuilleries, Paris, on 1 December 1783. Their ascent was witnessed by a crowd of 400,000 spectators. This balloon was so well designed that it is essentially the same as the gas-filled balloons used today. The Blanchards were other notable hydrogen balloonists. Jean-Pierre Blanchard was a barnstormer and experimenter. He was the first to attempt controlled flight with sails and rudders, first to cross the English Channel, and first to fly in the United States. Sophie Blanchard started flying in 1805 and was probably the first woman pilot. She made 59 ascents, flew at night, and put on fireworks displays from her hydrogen-filled balloon [1].

Balloons made way for blimps (or dirigibles), which were in essence elongated bags filled with gas, fitted with engines, propellers, and a rudder. First, steam engines and later electric and gasoline engines were used as power plants. The critical challenge was to maintain the shape of the gas bags. When they were fully filled, a slender, elongated aerodynamic shape could be maintained and steered; but when the bags were only partially filled, the vehicle sagged and was extremely difficult to steer.

By the 19th century, balloons were used for reconnaissance in warfare. France was still leading the way when Charles Renard and Arthur Krebs, officers in the French Corps of Engineers, flew the first fully controllable and powered dirigible on 9 August 1884. The vehicle, named *La France,* flew a circular course of 7.6 km (5 mi). It was powered by a 9 hp electric motor, which drove a 7 m (23 ft) diameter propeller. A maximum speed of 22.5 km/h (14 mph) was achieved during the 23 min flight.

The United States first used balloons for military purposes during the Civil War. After the war ended, many of the military balloonists became barnstormers. They traveled around the country, charging for rides, shooting off fireworks, dropping animals by parachutes, and performing aerial trapeze acts.

The German Count Ferdinand von Zeppelin (1838–1917) was the first to realize that maintaining a rigid shape was essential to making the vehicle steerable, and hence he designed a rigid but light frame containing the gas bags, which led to the development of dirigibles. The townspeople of Friedrichshafen, Germany, thought his ideas were ridiculous and nicknamed him "Crazy Count." On 2 July 1900, Count Zeppelin's dreams became reality when his Luftschiff Zeppelin (LZ-1) made its maiden voyage near Friedrichshafen. Dirigibles, which soon were called zeppelins, became a practical means of air transportation by 1908. In 1909, the German air transportation company Deutsche Luftschiffahrts AG (DELAG) was organized to develop and manufacture airships. Until the outbreak of World War I in 1914, more than 1,780 flights had safely carried more than 27,700 passengers. In 1922 the company built the *Los Angeles,* the U.S. Navy's premier airship. In the late 1920s and early 1930s, the LZ-127 *Graf Zeppelin* was the ultimate airship for passenger air travel. It was used for transatlantic passenger service and flew more than 1.5 million km in commercial service.

Another notable engineer, inventor, and flyer was the Brazilian-born Alberto Santos-Dumont. At an early age, his dreams were filled with airships and flying machines. In the years 1898 through 1905 he built and flew 11 dirigibles. Santos-Dumont's most noteworthy accomplishment took place in Paris on 19 October 1901 when he flew a dirigible from Park Saint Cloud to the Eiffel Tower and back, a distance of 3 km, in under 30 min. After his famous flight, his friend Louis Cartier was among those who celebrated his triumph. During the celebration, Santos-Dumont mentioned to Cartier his difficulty in checking his pocket watch to time his performance while keeping both hands on the controls. Cartier, in an effort to help his friend, developed a watch with a leather band and buckle to be worn on the wrist. Thus, Santos-Dumont's flight advanced aviation and initiated the wristwatch industry [2]!

Santos-Dumont's dirigible flying by the Eiffel Tower.

1.2 | HEAVIER-THAN-AIR FLIGHT

During the height of the zeppelin era, heavier-than-air flight was still in its infancy even though the groundwork had been laid at the end of the 18th century. An Englishman, Sir George Cayley (1773–1857), devised the basic configuration of modern airplanes. He separated the means of generating lift from the means of generating propulsion. In 1799, he designed an airplane that featured fixed wings for generating lift, paddles for propulsion, and a tail unit with horizontal and vertical stabilizers. Cayley had a great understanding of the basic concepts of flight—he not only identified the forces of lift, drag, and thrust, but also developed curved (so-called cambered) wings to increase lift and studied engines and propellers. Cayley's efforts culminated in 1853 with a full-size glider.

The aviation pioneer identified most strongly with gliding flights was the German engineer Otto Lilienthal (1848–1896). He built numerous single-wing and biwing gliders and flew them by running down a hill until he reached a speed high enough to fly. Before he died in a gliding accident, he had made more than 2,000 successful flights. In 1889, Lilienthal published his highly influential book *The Flight of Birds as the Basis of the Act of Flying.* Lilienthal laid the groundwork, and many aviation enthusiasts in Europe and the United States learned from his knowledge and used it as the basis for their work.

Online ballooning.

Among them were Orville Wright (1871–1948) and Wilbur Wright (1867–1912). The brothers eagerly followed Lilienthal's glider flights and corresponded frequently with him and other aviation researchers in Europe and the United States. The Wright brothers were the first to achieve controlled, powered, heavier-than-air flight because of their extensive research and excellent engineering approach. However, they were also fortunate that gasoline engine technology was advanced enough to permit the construction of a sufficiently lightweight powerplant.

> Isn't it astonishing that all these secrets have been preserved for so many years just so that we could discover them! (Orville Wright)

The brothers selected Kill Devil Hills near Kitty Hawk in North Carolina for their flying experiments because of the prevalent steady high winds in the area. In the fall of 1900 they conducted their first glider flights. They refined their design in the following years and added a 12 hp engine, which they had designed themselves since they could not find a suitable lightweight powerplant. On 17 December 1903, their aeroplane, named *Flyer I,* flew for the first time and covered a distance of 37 m (120 ft) in 12 s. Interestingly enough, this breakthrough of heavier-than-air flight remained largely unnoticed by the world for several years.

Many excellent aviation resources exist.

The Wright brothers built a second plane, and in the summer of 1904 they managed to fly on a circular course of 4.45 km (2.75 mi) in a sustained flight that lasted more than 5 min. Their breakthrough innovation was a slight warping (twisting) of the wings to provide attitude control and make turns.

In the following years, several other people began to build and fly aircraft. In the United States, Glenn H. Curtiss became a heralded pilot and maker of aircraft. In France, Alberto Santos-Dumont, Henri Farman, Louis Blériot, Gabriel and Charles Voisin, and Léon Levavasseur began to build and fly airplanes. In 1908, Wilbur Wright went to France to promote the brothers' aircraft and demonstrated that the Wrights were technologically far ahead of other airplane makers. However, they never managed to capitalize on their lead.

On 25 May 1909, Frenchman Louis Blériot became the first person to fly across the English Channel with his Blériot XI monoplane. The world was stunned by this achievement, and Britain's newspapers wrote that "Great Britain is no longer an island." Blériot's airplane had a design that is regarded as the classic configuration featuring a monoplane wing, a front-mounted propeller, and a tail at the rear. After the successful channel crossing, public enthusiasm for flying reached a new level. In August 1909 the French city of Rheims organized a week-long flight exhibition that was soon followed by similar events around Europe and in the United States. To promote the achievement of new aviation records, newspapers around the world offered substantial cash prizes.

Although the aircraft at the outbreak of World War I in August of 1914 were still quite fragile, they were used nonetheless in the conflict. At first their main use was for reconnaissance, but as the conflict continued and technology was quickly advanced, airplanes became more specialized and were used as fighters and bombers. The fighter pilots of the war were admired by the public, and none received as much acclaim as the German ace Manfred Freiherr von Richthofen. Having shot down 80 enemy aircraft, Richthofen, who became known as the Red Baron, was the most successful pilot of the war. The origin of his nickname was due to the red color of his Fokker D.VII plane. The Dutch airplane designer Anthony Fokker devised a mechanism by which the machine gun was synchronized with the engine so that the pilot could fire through the propeller. This system gave the Fokker planes an advantage over their British and French counterparts. Among these the most notable were the *Spad* and *Nieuport* from France and the S.E.5 and *Sopwith Camel* from Britain.

1.3 | SPECIAL SECTION: WOMEN IN AVIATION

Often overlooked in the history books are the amazing flying accomplishments of women. The first U.S. woman pilot was Blanch Scott, who attended Glen Curtiss' flying school. He did not approve of a woman pilot and blocked the throttle on her plane so that it would only taxi, but she outsmarted him and got her airplane 12.2 m (40 ft) into the air. A few weeks later, Bessica Raiche made her solo flight, but eventually gave up flying to become a doctor. Julia Clark and Harriet Quimby followed in these pioneering footsteps of flight. Quimby became the first U.S. woman licensed to fly in 1912 and a year later was the first woman to fly the English Channel [1].

Online resource.

Katherine Stinson first got her brother, Eddie Stinson, into the business of building airplanes. Then she trained Allied pilots at her own flying school and eventually went to France during the war and flew for the Red Cross [1]. Bessie Coleman, now a legend, was the first black U.S. woman to fly and the second black flyer (Eugene Bullard was the first, and he joined the French Foreign Legion and transferred to the French flying service). Coleman exemplifies the courage, determination, and ambition to fly, perhaps better than any other human. Against all odds, Bessie Coleman, the 13th child of a poverty-stricken Texas family, dreamt of flying rather than picking cotton in a very racist South. She was smart and had the determination to educate herself by reading every book she could obtain from the local library. She moved to Chicago and read about the heroes of flight in France. She desperately wanted to fly, but no U.S. flying school would admit her. She learned French in night school, saved her money, and sailed for France in 1921. In France, she attended the Coudron Brothers' School of Aviation. She flew *Nieuports* and graduated in 1922. Her love of life and flying continued with plans to set up her own flying school in the United States, which would be open to all. She raised money for the project by barnstorming in the United States and was entertained in Holland by Anthony Fokker and former German pilots in Berlin. In 1925, she flew in air shows in Houston and Dallas, but when she went back home to Waxahachie, Texas, for a show, the gates and bleachers were to be segregated. With her typical charisma, she proclaimed that there would be no show unless blacks and whites entered by the same gate. She fell to her death in 1926, at the age of 30, when the controls of her Curtiss Jenny aircraft locked and she spiraled uncontrollably to the ground [1]. African-American Bessie Coleman left behind a legacy as a magnanimous force for women's suffrage and equality for blacks.

On the other side of the earth, the Anglo-African woman Beryl Markham was one of the most prolific pilots from Europe to Africa. Born in England in 1902, she went with her father to Africa when she was four. She grew up on a farm in Kenya. Her adventurous spirit came through in her flying airmail in Africa, rescuing wounded miners and hunters in the bush, and flying to spot bull elephants for wealthy hunters. In 1936 she returned to England to make the first transatlantic crossing from east to west, and she survived a crash landing when her Percival Vega Gull airplane sputtered and went down a few kilometers short of the intended landfall. She wrote an unequaled book on flight, *West with the Night,* about her life in Africa and in the air [3]. Ernest Hemingway wrote to his colleague Maxwell Perkins

> . . . she has written so well, and marvelously well, that I was completely ashamed of myself as a writer. . . . But [she] can write rings around all of us who consider ourselves writers. The only parts of it that I know about personally, on account of having been there [in Africa] at the time and heard the other people's stories, are absolutely true. . . . I wish you would get it and read it because it is really a bloody wonderful book. (Ernest Hemingway)

The most famous woman pilot of this early era was Amelia Earhart. As fate would have it, she earned instant fame as the first woman to make a transatlantic flight, but she went as a passenger. Her job was to keep the flight log. Philadelphia socialite Amy Guest asked publisher George Putnam to organize the transatlantic flight in Guest's Fokker Trimotor aircraft. Putnam and Earhart manufactured much of her fame and rode the media wave. Earhart learned how to fly under the direction of Neta Snook, a California woman instructor. She was an experienced pilot at the time of the Atlantic crossing who was making her living as a social worker in Boston. Amelia Earhart flew the Atlantic solo in 1932 and capitalized on this grand accomplishment [1]. Her stardom helped her put forth important causes to which she was dedicated, specifically, women's rights, pacifism, and the art of flying. She remains famous since setting out to fly around the world and vanishing at sea in 1939, without a trace or any concrete explanation for her demise.

1.4 | COMMERCIAL AIR TRANSPORT

As previously mentioned, airships were commercially successful in the early decades of the 20th century. While zeppelins could fly not much more than 100 km/h, they could do so for thousands of kilometers without having to land. To demonstrate the technical ability of the Third Reich, the world's largest rigid airship, the LZ-129 *Hindenburg,* was built in 1936. The *Hindenburg* had a length of 245 m, a top speed of 135 km/h, and used some 200,000 m^3 of hydrogen. On 6 May 1937, while landing at Lakehurst, New Jersey, the *Hindenburg* was completely destroyed in a spectacular explosion attributed to a discharge of atmospheric electricity in the vicinity of a hydrogen gas leak from the airship. This disaster marked the end of the use of rigid airships in commercial air transportation.

The first scheduled flight of an airline using an aircraft occurred on 1 January 1915 from St. Petersburg, Florida, to Tampa, Florida. This effort to develop commercial aviation was premature since more advanced aircraft were needed. These became available following the Armistice in 1918 when excess military aircraft were adapted for passenger transport and mail service. The first regular commercial airline with passenger service was Germany's *Deutsche Luftreederei,* which began service from Berlin to Leipzig and Weimar in February 1919. In October of that year KLM (Royal Dutch Airlines) was founded in the Netherlands and is the world's oldest airline.

The aircraft of the period could carry between two and eight passengers and offered little in comfort. The passenger needed to wear warm leather clothes and gloves. Earplugs were "strongly recommended," and emergency landings were very frequent. But many refinements in aircraft design were introduced, and significant improvements in performance were achieved during the 1920s. Some of these were made by the National Advisory Committee for Aeronautics and Astronautics (NACA), the predecessor of NASA. The U.S. government created NACA in 1915 when it recognized how far it was behind Europe in aircraft production.

The most striking change was the conversion from biplanes to streamlined monoplanes as well as the use of all-metal airframes.

One of the most coveted prizes in aviation at the time was the Orteig Prize for the first nonstop flight between New York and Paris. Several men had lost their lives in pursuing this accomplishment, but this did not deter the young U.S. mail pilot Charles A. Lindbergh. With sponsors from St. Louis, Missouri, Lindbergh

Spirit of St. Louis.

ordered a customized aircraft, the *Spirit of Saint Louis,* from Ryan Aeronautical in San Diego, California. He left New York's Roosevelt Field on 20 May 1927 and flew solo along a northerly route to reach Paris' Le Bourget airport $33\frac{1}{2}$ h later. Winning the $25,000 prize, Lindbergh became virtually overnight a hero in the United States and Europe.

In 1916, William E. Boeing founded the Pacific Aero Products Company, which he renamed in the following year the Boeing Airplane Company. During World War I the company developed flying boats for the Navy. In 1933, the Boeing 247, an all-metal twin-engine low-wing monoplane, had its maiden flight. The Boeing 247 is nowadays regarded as the first "modern" airliner and was sought after by many airlines. However, Boeing restricted the sale of the aircraft until the order for its sister company United Airlines was fulfilled. This prompted competing carrier Trans World Airlines (TWA) to persuade Boeing's biggest rival, Douglas Aircraft Corporation, to launch its own commercial series of aircraft in 1933. The DC-1 was an improvement over the Boeing 247 with a better and more spacious cabin. It was refined to become the DC-2 and later evolved into the DC-3. Providing room for 21 passengers and featuring many small technical advancements, the DC-3 became the favorite aircraft among airlines and pilots. One of its many innovations was the introduction of an autopilot made by Sperry Gyroscope Company. By 1939, DC-3s were carrying 90 percent of all commercial traffic around the world.

During the 1930s and 1940s, seaplanes often exceeded the size and range of land planes. The reason was that airfields were fairly limited in size, but this was not so for lakes or coastal waters from which seaplanes could take off and land. Another factor was that the aircraft still lacked sufficient reliability, and airfields were scarce. A pioneer in the use of large seaplanes or "flying boats" was Pan American Airways ("Pan Am"), which had been founded in 1927 to fly airmail between Key West, Florida, and Havana, Cuba. In June of 1938, Pan Am inaugurated transatlantic passenger service with the "ultimate" flying boat, the Boeing 314, which carried up to 74 passengers.

1.5 | WORLD WAR II AND THE INTRODUCTION OF JET AIRCRAFT

WWW

The Boeing Clipper.

At the start of World War II, in September of 1939, Germany's aircraft industry was by far the most advanced in the world, which was reflected in the arsenal of Germany's air force—the Luftwaffe. Its aircraft included the Messerschmitt Bf 109, Focke Wulf FW-190 Junkers Ju 88, and the frightening dive bomber Junkers Ju 87 Stuka. Overall the role of aircraft was a minor one in World War I. This was not so in World War II—aircraft played a decisive role in the conflict since achieving air superiority became important to winning land and sea battles. Early in the war the tactically oriented Luftwaffe supported a rapid advance of ground forces and with its "blitzkrieg" (lightning war) tactics quickly crushed Poland, the Netherlands, Denmark, and even France. The most notable fighter aircraft by the Allies were the British Hawker *Hurricane* and the legendary Supermarine *Spitfire,* as well as the famous U.S. P-51 *Mustang* built by North American Aviation. In the Pacific the United States faced the Japanese Mitsubishi A6M *Rei-sen* ("Zero"), which in the beginning was superior to the U.S. aircraft.

Germany did not grasp the strategic aspect of air power and hence never produced a satisfactory heaver bomber. Strategic bombing—bombing selected targets vital to the war-making capacity of the enemy—became a key element in the victory of the Allies. The bombing of Germany and Japan was carried out chiefly with the Boeing B-17 *Flying Fortress* and the B-29 *Superfortress.*

During the course of the war, aircraft production reached enormous proportions. The Bf 109, the pillar of the Luftwaffe and most frequently built fighter aircraft, was produced some 33,000 times. But the aircraft production by the Allies—prerequisite for maintaining air superiority and the ability to conduct round-the-clock bombing operations—was overwhelming. The United States alone produced over 300,000 military aircraft in the period of 1940 through 1945.

Shortly before the end of the conflict, the first aircraft powered by jet engines were introduced. The jet engine was developed independently by Sir Frank Whittle in Britain and by Hans Joachim Pabst von Ohain in Germany. As the speed of propeller aircraft approaches 700 km/h, the efficiency of the propeller drops rapidly and so a different means of propulsion is necessary to fly much faster. A detailed description of how jet engine aircraft work is given in Chapter 6, "Aircraft Propulsion." Whittle had filed a patent in 1930 which became the basis for the British efforts to develop a jet engine, resulting in the first successful test of a turbojet engine in 1937.

However, the German *Heinkel He 178* became the first aircraft powered by a jet engine in August 1939. The first jet aircraft in service was the British *Gloster Meteor* followed by the German *Messerschmitt Me-262,* which was capable of a top speed of 870 km/h. While these jet fighters achieved a far greater maximum speed, rate of climb, and ceiling altitude than piston-engine planes, they had little military effect since they were introduced late in World War II.

Following the end of the war, the superiority of the jet engine made military aircraft with piston engines virtually obsolete, resulting in the introduction of the Lockheed P-80 *Shooting Star* and the swept-wing North American F-86 *Sabre* jet fighters by the United States.

The major challenge facing aviation was the so-called sound barrier (a speed of Mach 1). For years it was believed that crossing the sound barrier was impossible, and the numerous casualties among pilots seemed to corroborate that belief. The cause of the sudden breakup of the aircraft attempting to fly faster than the speed of sound was a rapid increase in drag as the aircraft approached the speed of sound and a phenomenon known as buffeting (a violent shaking of the aircraft). On 14 October 1947, a Bell *XS-1* rocket-powered research plane piloted by U.S. Air Force Major Charles "Chuck" Yeager became the first aircraft to fly at supersonic speeds. After being dropped from a Boeing B-29 mother ship, the XS-1 (later renamed *X-1*) reached a maximum speed of 1,126 km/h, or Mach 1.06. The X-1 was followed by several other experimental aircraft of which the X-15 became the most notable. The X-15, built by North American Aviation, attained a maximum altitude of 107,900 m and a top speed of Mach 6.7. Jointly the three X-15 aircraft conducted 199 flights, in all cases dropped from the B-52 mother ship. Among the test pilots flying the X-15 were several future astronauts, such as Neil Armstrong.

MiG-15 fighter of the Soviet Air Force.

In the United Kingdom, a committee chaired by Lord Brabazon determined which commercial aircraft should be built after the war. One of the suggested aircraft, the Brabazon IV, was especially far-sighted. Since the jet engine had been developed in Britain, the country understood the potential of the jet airliner. The Brabazon IV evolved into the de Havilland DH-106 *Comet I.* In 1952, the Comet I became the world's first jet airliner, able to carry 36 passengers over a range of 3,200 km at a speed of 720 km/h. The aircraft cut the travel time in half, and by flying at an altitude of 12,000 m, it passed above weather fronts and so passengers were less likely to need "paper bags." Once people had flown on the Comet, they had little desire to fly again with propeller-driven aircraft.

Due to a design error, the aircraft experienced catastrophic failures in flight from metal fatigue problems, which led to the grounding of the fleet and the cancellation of the program. U.S. manufacturers Boeing and Douglas learned from the design errors of the *Comet.* In 1966, Pan Am ordered 20 Boeing 707 and 25 of the similar Douglas DC-8 jet airliners, which initiated a worldwide jet-buying frenzy. In the 1960s, short-haul piston-engine airplanes also began to be replaced by turbine-driven propeller craft. In the commercial aviation sector, the fastest and largest commercial airliners to the present day had their maiden flights. The United States, the Soviet Union, and Britain with France worked on the development of a supersonic airliner. The U.S. effort, the Boeing 2707, did not even reach the prototype stage. The Soviet Tupolev Tu-144 was the first to fly faster than the speed of sound (Mach 1), but it remained in service only briefly. Only the British-French Concorde became a successful supersonic transport. The delta-wing Concorde was developed jointly by the British Aircraft Corporation (BAC) and France's Sud Aviation. It had its first flight on 1 March 1969 and entered revenue service in January 1976. The aircraft's cruise speed of about Mach 2 reduced the flight time between London and New York to about 3 h. Seventeen aircraft were manufactured for passenger service and remained in use with carriers British Airways and Air France until the summer of 2000, when a tragic crash in Paris took the lives of 113 people.

The Concorde supersonic airliner, the Boeing 747-100, the Airbus A320.

After Boeing lost a bid to build a large transporter for the U.S. Air Force, the company and its engine partner, Pratt & Whitney, decided to make good use of their design experience and embarked on an ambitious undertaking to develop a commercial aircraft capable of carrying up to 500 passengers. The end product was the first so-called wide-body or twin-aisle passenger jet, the four-engine Boeing 747—affectionately called the Jumbo Jet. Few aircraft are so widely recognized around the world as the 747 with its upper deck. The 747 had its maiden flight on 9 February 1969 and entered service in January 1970. The Jumbo Jet consists of some 6 million parts and with a height of 20 m is as tall as a six-story building. Since 1990 the aircraft of the U.S. President, Air Force One, is a Boeing 747 (with its military designation VC-25A).

The Boeing 747 exemplified the U.S. dominance in the airliner industry. By the 1960s, European countries realized that only a close cooperation between them could create a serious and lasting competition to U.S. manufacturers led by Boeing, McDonnell Douglas, and Lockheed. In December 1970, the Airbus Industrie consortium was set up to build a European high-capacity short-haul airliner. French and German companies had a dual role as both shareholders and industrial participants. They were joined by Spanish and British manufacturers in 1971 and 1979, respectively.

Airbus' premier model, which entered service in May 1974, was the A300B—the world's first twin-engine wide-body jetliner. The European consortium was less conservative than the well-established U.S. manufacturers. The Airbus 310 introduced a two-pilot cockpit and made considerable use of composite materials for the airframe. The short-haul aircraft A320, which entered service in 1988, was the first subsonic commercial aircraft to be designed with electric primary controls, called "fly by wire," and the first commercial aircraft to feature a "glass cockpit" in which mechanical displays and gages were replaced by electronic screens. Through these innovations and a growing family of aircraft offered, the European consortium achieved a market share of about 50 percent with the remainder held by Boeing, which became the sole manufacturer of large commercial aircraft in the United States.

In 1958, the McDonnell F-4 Phantom II had its maiden flight. Originally developed for the U.S. Navy, the F-4 was so impressive that the U.S. Air Force also ordered the aircraft. Its overall performance level was unmatched, and the aircraft set no less than 16 world records for speed, range, ceiling altitude, and other categories. It remained the premier fighter for several decades. In the Soviet Union, the famous airplane design bureau of Mikoyan and Gurevich developed the MiG-21, which had its maiden flight in 1955. More than 13,000 of this lightweight and compact fighter were built and sold to more than 50 countries. In Britain, Hawker Siddeley developed the *Harrier,* a fighter capable of a vertical or short takeoff and landing (V/STOL). In 1969, the *Harrier* became the world's first operational V/STOL fighter, and with the exception of the Soviet Yakovlev Yak-36, it remains the only aircraft capable of flying at near sonic speeds and VTOL.

In the 1970s, fighter technology was further advanced with the introduction of the F-14 Tomcat, F-15 Eagle, and F-16 Falcon. The F-14 was first deployed by the U.S. Navy in 1974 and was at the time the West's biggest, costliest, and most complex fighter aircraft. At the other end of the spectrum was the F-16, a lightweight fighter with electronic flight control. The first production aircraft were delivered to the U.S. Air Force in 1978. Due to generous coproduction contracts, the F-16 program became the largest multinational coproduction effort in history with some 4,000 F-16s delivered to 19 countries.

1.6 | HELICOPTERS

The German Focke-Wulf Fw 61 became the first practical helicopter when it flew in 1936 as the highlight of an indoor show in Berlin organized by the Nazis. However, the flight brought mostly trouble. The rotors blew sand from the circus ring in the eyes of the spectators, and the doors of the arena had to remain open despite the cold weather due to the large need of oxygen by the engine. The audience was more impressed by the famous female pilot Hanna Reitsch than by the helicopter. The Focke-Wulf Fw 61 had two rotors mounted on outriggers to the left and right sides of the fuselage and was quite a capable craft outdoors. It was able to reach an altitude of 2,439 m (8,000 ft).

In 1939, the Russian-born Igor Sikorsky designed, built, and flew the experimental helicopter Vought Sikorsky VS-300 in the United States. The VS-300 used a single main rotor for lift and a smaller vertical rotor mounted on the tail to counteract torque. With this rotor arrangement Sikorsky achieved the controllability that all predecessors lacked and set a pattern for helicopter designs and resulted in the first production helicopter, the R-4.

The R-4 and other early helicopters were devised for transportation, but it became quickly apparent that rotary aircraft could also be developed into a formidable weapons system. During the Vietnam war Bell Helicopter developed the Bell 209 Huey Cobra attack helicopter, which was the first helicopter designed for such a purpose.

1.7 | CONQUEST OF SPACE

Rocketry online.

The last sections of this chapter highlight the historical events of space travel. Chapter 11, "Human Space Exploration," presents a more detailed discussion on the engineering and scientific disciplines behind human space exploration.

In 1903 the Russian school teacher Konstantin Tsiolkovsky (1857–1935) published *Exploration of Cosmic Space by Means of Reaction Devices* in which he derived a fundamental equation for space travel, known as the rocket equation. In his later work, Tsiolkovsky put forth the idea of building liquid-fuel engines, recommended the use of liquid hydrogen and liquid oxygen as propellants, and suggested the use of gyroscopes for stabilization. In the Austro-Hungarian Empire, Hermann Oberth (1894–1989) was, like Tsiolkovsky, a school teacher and fascinated with space travel. In 1923, he published *The Rocket into Interplanetary Space.* The book became influential, but more important was the follow-up, *Ways to Space Travel,* which was published in 1929 and became a standard text on space technology. This book covered among other things the possibility of building rockets, a concept for spacecraft, a space station, and a space suit.

The center of rocket-related activities was the *Verein für Raumschiffahrt* or VfR ("Society for Space Travel") in Germany, which was formed in July 1927. The hope of the VfR was to popularize the idea of interplanetary flight and to perform serious experiments with rocket engines. The society grew immensely in its first years and by September 1929 had 870 members—among them was Wernher von Braun (1912–1977), who had just graduated from high school. Although the VfR was an amateur society, its achievements were impressive and of great value. By 1932, the rockets built by the society had a range of 5 km and could reach an altitude of 1,500 m.

Germany was not the only place where advanced rocket research was undertaken prior to World War II. The U.S. physics professor Robert H. Goddard

(1882–1945) performed numerous experiments with rockets. In 1919, Goddard published *A Method of Reaching Extreme Altitudes* in which he announced his ambition to fly to the moon, which caused him an unwanted wave of publicity. On 16 March 1926, Goddard launched the first liquid rocket using gasoline and liquid oxygen as propellants. The altitude reached was merely 12.5 m, but as with the Wright brothers' flight near Kitty Hawk, the event was a milestone.

The peace treaty of World War I imposed heavy restrictions on the German military, but since the treaty did not prohibit the development of rockets, the German army saw the opportunity for a new weapon. And so the best people of the VfR were hired by the army for its rocket program with Wernher von Braun serving as the top civilian specialist. In 1936, the German military provided funding for a rocket research center at the island of Usedom near Pennemünde. It grew to become a rocket development and test facility unmatched anywhere in the world. Heeresversuchsstelle Pennemünde, as the center was officially called, was a military installation, covering an area of more than 45 km^2 and employing as many as 18,000 people but organized and run as a private enterprise. At Pennemünde, researchers pioneered anti-aircraft missiles, submarine-launched solid-fuel missiles, and surface-to-surface missiles of which the V-2 with a top speed of 5,000 km/h and a range of 320 km was the greatest achievement.

In the United States, rocket development was undertaken at the Jet Propulsion Laboratory in California. The projects included rocket-assisted takeoff for aircraft and missiles, but the size of the undertaking was minuscule compared to that of Germany, involving fewer than 300 people.

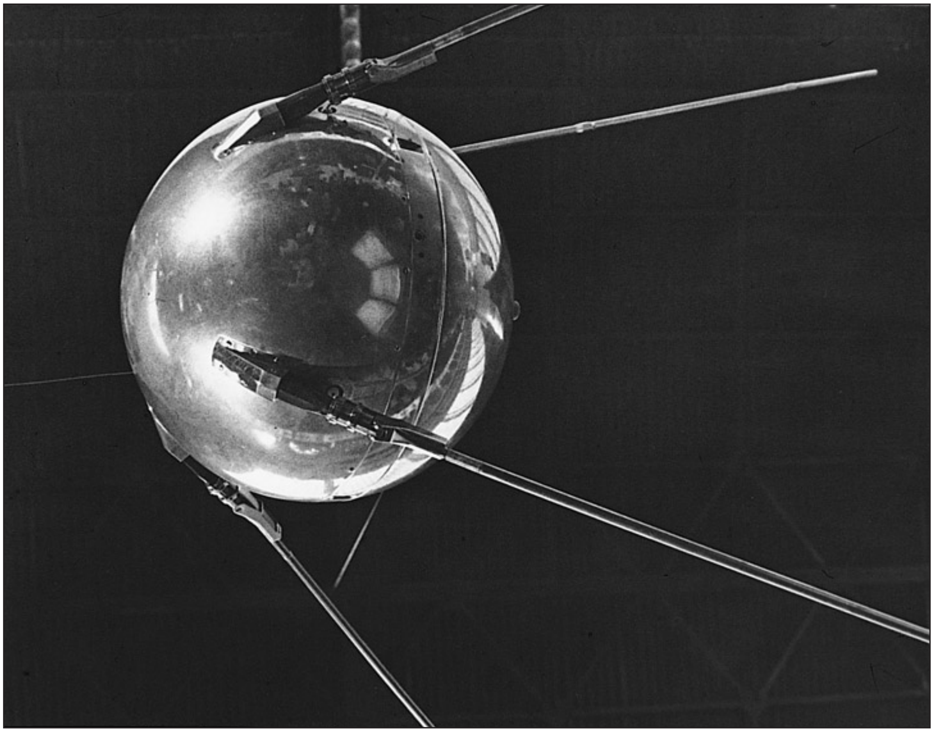
Both the United States and the Soviet Union acquired rockets, rocket facilities, and researchers after the defeat of Nazi Germany. However, the United States obtained the majority of the equipment and most of the top people, including Wernher von Braun. Military objectives dominated the further development of rockets since the United States and the Soviet Union quickly saw a great potential in combining the destructive capability of nuclear warheads with the "transportation" capability of rockets. However, the Soviet Union saw also the potential in using astronautics to demonstrate technical superiority, and so on 4 October 1957, the Soviet Union launched successfully *Sputnik 1,* the world's first artificial satellite, into orbit. Circling the earth every 96 min, the little sphere with four long antennas was viewed by the United States as a challenge and was the subject of much debate in the media and the public. Less than a month later, the Soviets launched the first living being, a dog named Laika, into space aboard *Sputnik 2.* Over the course of 7 days, the satellite sent measurements of the biological functions of the dog. The flight proved that humans could also survive in space.

Initial U.S. attempts to meet the Soviet challenge ended in failure. But by 31 January 1958 the United States successfully launched its first satellite, *Explorer 1.* The satellite stayed in orbit for 12 years and discovered the Van Allen radiation belt around earth. The "Sputnik shock" led to the creation of a new civilian agency on 29 July 1958. Named the National Aeronautics and Space Administration (NASA), the agency incorporated NACA as well as most existing military rocket facilities and initiated the Mercury human spaceflight program.

Online comprehensive Sputnik *resources.*

The Soviet Union continued to maintain its leadership and on 12 April 1961 Major Yuri Gagarin, aboard *Vostok I,* became the first human being in space. The

Figure 1.2 | The first artificial satellite in space, *Sputnik.*



27-year-old Gagarin completed one full orbit of the earth in his historic flight, which took 108 min and reached a maximum altitude of 200 km. Three weeks later, the United States countered by sending Alan Shepard into space but only on a ballistic trajectory lasting 15 min. The first U.S. orbital flight was made by John Glenn on 20 February 1962.

Wernher von Braun's Soviet counterpart was Sergei Korolev (1907–1966). He was the guiding genius behind the Soviet spaceflight program, directing the design, testing, construction, and launching of the *Vostok, Voskhod,* and *Soyuz* human-piloted spacecraft as well as many autonomous spacecraft.

The Soviet lead in astronautics was unacceptable to the United States, and so on 25 May 1961, having achieved so far only one ballistic flight, U.S. President John F. Kennedy announced the goal to land humans on the moon and return them safely to earth before the end of the decade. In preparation for the lunar landing the Gemini program, proving multiperson crew and docking capabilities, was undertaken. The first Apollo flight was delayed by a terrible accident. All three Apollo 1 astronauts perished as a fire broke out in the spacecraft during a launch rehearsal. Successive Apollo missions were all successful. Apollo 8 was the first with humans orbiting the moon, and Apollo 11 was the first to land humans on the moon. Apollo 11, with Neil Armstrong, Buzz Aldrin, Jr., and Michael Collins on board, was launched on 16 July 1969. Four days later, Armstrong and Aldrin landed on the surface of the moon, and Armstrong became the first human to walk on another planetary body with the now-famous words

> One small step for [a] man, one giant leap for mankind. (Neil Armstrong)

The astronauts spent about two hours gathering rock samples, taking photographs, and setting up scientific equipment. Later, Armstrong and Aldrin flew the Lunar Module to the Command Module with Collins on board in lunar orbit. The mission ended on July 24, with a splashdown in the Pacific Ocean. Five other missions landed on the moon, ending with Apollo 17 in December 1972. They carried out an extensive exploration of the lunar surface, collected large numbers of samples of moon rocks, and installed many instruments for scientific research. Apollo 13, launched in April 1970, suffered an accident caused by an explosion in an oxygen tank but returned safely to earth.

One of the three leftover Saturn rockets from Apollo was kept in flight-ready status, and its third stage was modified into the *Skylab* space station by converting the gigantic fuel tank to cabins. *Skylab* was launched into orbit on 14 May 1973 on top of a smaller Saturn rocket left over from the Apollo test program. The 75 ton station provided generous quarters for the astronauts and hosted three crews, each with three astronauts, for a total 171 days. The station had been abandoned for 5 years when it reentered the atmosphere uncontrolled in July 1979.

1.8 | THE COMMERCIAL USE OF SPACE

The first satellites were "passive" since they lacked on-board electronics and could therefore be used only as a relay station for communications, but many practical uses for more advanced satellites were evident. In 1958, the U.S. Air Force launched the first active communications satellite, Score, premiering the transmission of human voice from space. Tiros, launched in April 1960, was the first civilian satellite and the ancestor of today's weather observation satellites. The commercial satellite TELSTAR, launched in 1962, carried TV programs across the Atlantic Ocean for the first time. In 1963, SYNCOMM III became the world's first geostationary satellite. By being placed in an orbit 35,800 km above the earth's equator, satellites appear stationary from earth and are ideal for television broadcasts and communications over large regions of the world. The practicality of geostationary satellites was predicted by Arthur C. Clarke in a paper in a journal in October 1945. Chapter 10, "Satellite Systems Engineering," details satellite engineering and system design aspects of orbiting spacecraft.

Intrinsically associated with satellites are the rockets that launch them into space. The world's most successful commercial expendable launch vehicle is the European Ariane rocket. When the European Space Agency (ESA) was created in 1972, European nations also approved a program to develop a space launch vehicle. Led by France, the Ariane program launched its first rocket on 24 December 1979 from its space center Kourou in French Guayana. The Ariane series of rockets is responsible for placing more than one-half of all commercial satellites into space.

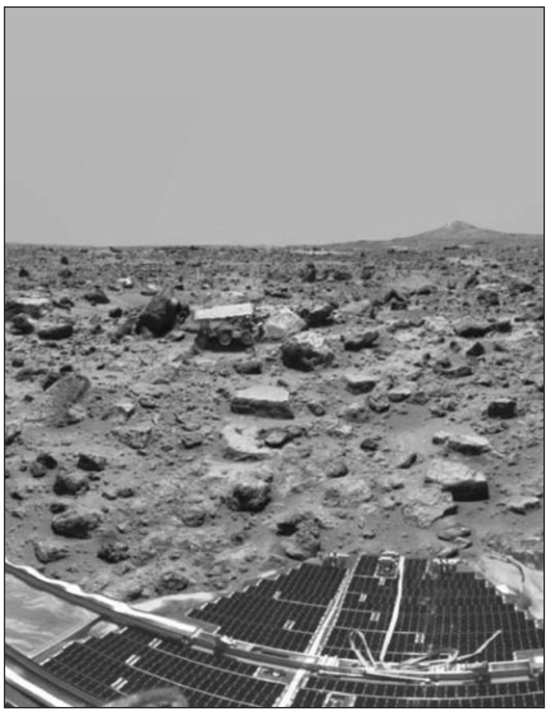
1.9 | EXPLORING THE SOLAR SYSTEM AND BEYOND

The exploration of the planets and moons of the solar system has been carried out by autonomous probes. In 1962, NASA launched two probes to Venus. The second one, Mariner 2, flew past the planet in December, marking the first successful mission to another planet. The Voyager autonomous interplanetary probes were launched by the United States to observe the outer planets of our solar system. Voyager 1, launched in September 1977, flew by Jupiter in 1979 and reached Saturn in 1980. It then took up a trajectory to lead it out of the solar system while Voyager 2, launched in August 1977, encountered Jupiter (1979), Saturn (1981), Uranus (1986), and Neptune (1989).

Few space missions captured as much of the public's attention as that of the Mars Pathfinder. On 4 July 1997, the Mars Pathfinder spacecraft landed on the Red Planet and released the 10.6 kg (23 lb) microrover Sojourner to explore the landing site. The mission validated various new technologies for planetary exploration and returned valuable scientific information.

The release of few satellites in recent history generated as much public interest as that of the Hubble Space Telescope (HST). Hubble was brought into orbit aboard a space shuttle in April 1990. To the great dismay of scientists and the

Figure 1.3 | The Mars rover *Sojourner* and the Mars *Pathfinder* spacecraft.



public, the optics of the telescope had a flaw, resulting in fuzzy pictures. The design of the gigantic telescope made it possible for it to be serviced in orbit, and so in December 1993, corrective optics were installed which made it possible for Hubble to produce spectacular images. Since Hubble was designed for observation in the visible portion of the electromagnetic spectrum, NASA launched in 1991 the Compton Gamma Ray Observatory (GRO) to capture gamma rays from far distant objects in space. The observation gap of the spectrum between Hubble and GRO was filled in 1999 with the launch of the Chandra X-ray Observatory. A few months later it was joined in orbit by the largest European satellite, the XMM (X-ray multimirror) telescope. Together the two X-ray telescopes are searching the universe for spectacular X-ray sources such as exploding stars.

1.10 | A PERMANENT HUMAN PRESENCE IN SPACE

Even before the Apollo 11 moon landing, NASA began thinking about a comprehensive space program plan to follow Apollo and the *Skylab* station. A space station with permanent human presence in low earth orbit, a reusable earth-to-orbit shuttle, and reusable chemical- and nuclear-powered space tugs were envisioned. Because of growing budget constraints only the Shuttle program survived. It was envisioned as an all-purpose launch vehicle with launch costs far lower than those of any expendable rocket. By 1972, the design was finalized. The resulting earth-to-orbit transport was a "stage-and-a-half" vehicle rather than the fully reusable, two-stage craft originally planned. The final design concept was selected to reduce high development costs while keeping the operational costs of human spaceflight acceptable. The collective shuttle program was officially named the Space Transportation System, or STS. On 12 April 1981, NASA launched the first Space Shuttle, *Columbia,* into orbit. It became the first human spacecraft designed for reuse. A fleet of four Space Shuttle orbiters has since served as both a transportation system bringing satellites and other payloads into orbit and a platform for short-duration microgravity experiments. In addition, the Shuttle has been used to retrieve or repair satellites already in orbit. It consists of an orbiter with wings, an external tank, and two solid rockets. The tank and the rockets are jettisoned after they are no longer needed during launch. At lift-off the complete Shuttle assembly stands 56 m high and weighs about 2 million kg. The program suffered a serious setback on 28 January 1986 when the Space Shuttle *Challenger* exploded 73 s after liftoff, killing the seven astronauts on board. Flights resumed 2 years later after corrective safety measures were completed, but the accident highlights the reality that even though the Shuttle is the most reliable space vehicle in existence (greater than 95 percent reliability), a completely (100 percent) reliable space vehicle cannot be attained. A replacement orbiter joined the fleet in 1991.

While the United States placed its emphasis on low-cost access to space through the development of the Space Shuttle, the Soviet Union favored the construction of space stations. The first generation of Soviet space stations allowed only a temporary human presence in space since they could not be resupplied or refueled. The world's first space station, *Salyut 1,* was launched into orbit on 19 April 1971. The crew of *Soyuz 11* lived aboard the station for three weeks but died upon return to earth as air leaked from their cabin. This was the first in a string of failures from which the Soviet Union recovered, and in the period from 1974 to 1977 the Soviet Union had three successful stations in orbit. *Salyut 6* (1977–1982) and *Salyut 7* (1982–1986) were the second generation of Soviet space stations. They allowed a long-duration stay through the existence of two docking ports, one used by the automated resupply vehicle *Progress.*

On 19 February 1986, the Soviet Union launched the *Mir* ("peace" and "world") space station. It became the world's first permanent space habitat and the first station designed to be expanded over time. At the time of launch, the station weighed some 20 tons and consisted of only one module (the core module). It provided basic services such as living quarters, life support, power, and some scientific research capabilities. Crews were brought to *Mir* with Soyuz-TM spacecraft and supplies with the *Progress-M* cargo transport. Six modules were added over the years so that *Mir* (with docked *Progress-M* and *Soyuz-TM* spacecraft) grew to a length of 32 m, a width of 27 m, and a total mass exceeding 91 tons.

In January 1984, U.S. President Ronald Reagan announced support for a permanent human-tended space station, which in 1988 was named *Space Station Freedom.* Due to large budget constraints, poor management, and the inability to meet schedules, the program was subject to heavy criticism. In 1992, a new, smaller design for the station was approved, and Russia joined the European and Japanese partners. In response, the name of the project was changed to International Space Station Alpha (ISSA) and later simply to the International Space Station (ISS), which is now a global partnership of 16 nations.

In preparation for ISS, the United States and Russia conducted the Shuttle-Mir Program from 1995 to 1998. The program included crew exchanges so that U.S. astronauts stayed on *Mir* and Russian cosmonauts flew aboard the Space Shuttle. The first element of the International Space Station, the Russian-built Functional Cargo Block named Zarya, was brought into orbit on 20 November 1998. It was joined the following month with the U.S.-built Unity Node[1]. It is hoped that by 2006 the assembly of the station will be completed.

PROBLEMS

1.1 In a few sentences describe the Montgolfiers' contribution to flight.

1.2 In a few sentences discuss the advent of dirigibles and the responsible inventors. Speculate on why we do not see blimps that carry hundreds of people flying today.

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1. The Zvezda module docked with the station in July 2000, with the first permanent crew living in orbit from November 2000 to March 2001. The United States' Destiny laboratory docked in February 2000 and the second ISS expedition crew arrived in March 2000.

1.3 What was the critical aerodynamic contribution that the Wright brothers implemented in order to achieve the first heavier-than-air flight?

1.4 List two women pioneers of aviation and their accomplishments.

1.5 When did aviation become an industry? How did for-profit organizations affect the science of flight?

1.6 Discuss a leading scientific advancement that contributed to the growth of the commercial airline industry.

1.7 Discuss the motivation for the United States to develop a space program.

(a) What was the role of the Soviet Union in the U.S. space program?

(b) What is the role of Russia in today's U.S. space program?

(c) List a major contribution of the European Space Agency (ESA).

1.8 List one scientific space probe. Perform a web search on the scientific mission, and provide a one-paragraph description of the science, accomplishments, and lessons learned.

2 Chapter

Introduction to Engineering

Dava J. Newman

2.1 | THE BIG PICTURE

What is engineering and what do engineers do? Before these questions are addressed, think about your personal professional goals and list at least two:

1.
2.

This can be a difficult exercise, but it is important to take the time to start fresh and try to list a few of your professional goals. As this chapter and Chapter 12, "Design: Lighter-Than-Air (LTA) Vehicle Module," unfold, you will be introduced to engineering and design, and it is important that you assess and reflect on how your goals align with these fields. By the end of this chapter, you will have a better understanding of what engineers do, and you should reflect to see if your own goals are best matched with the field of engineering. Engineering finds its basis in science, mathematics, and physics, and it is fortified with additional study in the humanities.

Engineering might be briefly defined as the following six statements:

- The adaptation of scientific discovery for useful purposes
- The creation of useful devices for the service of people
- The process of inventing solutions to meet our needs
- The solution of problems of a technical nature
- The conversion of forces of nature for our purposes
- The conversion of energy resources into useful work

Engineering design evolves from engineering and can include any of the items below (see Chapter 12 for comprehensive coverage):

- The act of creating a device, machine, or system that will fill a particular need
- The development of a mechanism to transform a given input to a particular output
- The process of devising a scheme to fulfill a particular requirement through the use of some bit of knowledge or an observation of nature
- The development of a solution to a particular problem
- The development of some sort of physical apparatus, some sort of hardware (no matter how complex or how simple)
- A problem-solving situation in which the design engineer is trying to satisfy a technological need
- Taking a need and breaking it down into a set of problems; devising solutions to those problems and developing ways to create a product to fill the need
- The business of inventing and creating ideas that will adapt a scientific discovery to the development of a useful product
- The recognition of a need, the planning for accomplishment, an application of ideas, the adaptation of natural laws to useful purposes, and a systematic synthesis of causes and effects
- The process of converting a specific input to a desired output while at the same time acknowledging all the environmental constraints that restrict the development of the solution
- A creative act of selecting, combining, converting, constraining, modifying, manipulating, and shaping ideas, scientific facts, and physical laws into a useful product or process
- Demand idea creation—creating for a purpose

The *Decavitator* Human-Powered Hydrofoil

EXAMPLE 2.1

A fantastic example of demand idea creation is the student-initiated, Massachusetts Institute of Technology (MIT) Human-Powered Hydrofoil project where a vehicle was conceived, designed, tested, redesigned countless times, and finally flown. The *Decavitator* is the name of the world-record-breaking hydrofoil. On 27 October 1991, Mark Drela pedaled the human-powered hydrofoil, the *Decavitator*, to a world-record speed of 9.53 m/s (18.5 kn) over a 100 m race course on the Charles River in Boston, Massachusetts. For this successful student-run design project, the *Decavitator* team was awarded the DuPont Prize for the fastest human-powered water craft. This prize was to be awarded to the first team to break 10.3 m/s (20 kn) over a 100 m course, or to the team with the fastest speed on record at the end of 1992. The project was an overwhelming success, but the 10.3 m/s (20 kn) barrier still exists, and is looming until a future design surpasses it (see Figures 2.1 and 2.2).

decavitator.mov

Figure 2.1 | *Decavitator* human-powered hydrofoil in action.

Figure 2.2 | *Decavitator* human-powered hydrofoil and the Boston skyline.

2.2 | IT ALL STARTED WHEN . . .

Engineering evolved as humans first learned to take advantage of natural phenomena for their own benefit (levers, wheels, water power, animal power, etc.).

2.2.1 It Was Not an Easy Process

Progress occurred through a trial-and-error process that was slowed due to a lack of understanding (science) and communication. Many of the "great early engineering" works were dictated by ambitious leaders (monuments and weapons) and were not for the *public good*, but it seems that exceptionally motivated engineers were able to leave their own creative mark on humankind as well.

2.2.2 Perfection by Accident?

Recent sophisticated stress analyses of ancient bows have shown that they were "optimally designed" (as uniformly stressed beams). The accomplishments of ancient civilizations are impressive and leave us wondering about their extensive engineering knowledge. The main lesson learned is that a deep working understanding of physical phenomena as well as effective communication is essential to further engineering innovations.

2.3 | THE AGES OF ENGINEERING

The great philosophers, Socrates and Plato to name two, are followed in time by a transcendence of philosophy into science; then the philosophy of science brings about the genesis of modern engineering. There was a time before the great philosophical era when survival was all that mattered. The Stone, Bronze, and Iron Ages embodied this existence, and creative means of survival arose. Humans had the luxury of thinking and contemplation throughout the Greek and Roman empires. Finally, the time period from the Renaissance through the Space Age realized fantastic creativity, discovery, and progress.

2.3.1 The Stone Age

Online resource.

The Stone Age covers the vast era of human history from 2 million years ago up to the first Egyptian dynasty, or everything except the last 5,000 years. The Stone Age is further divided into three periods: the Paleolithic, Mesolithic, and Neolithic eras. The Paleolithic era was the age of hunting and gathering, lasting until only 15,000 years ago. This was a rather static age with not much known technological progress, but artisans might have initiated cave painting in this era. The Mesolithic era shows technological progress in stone working with increased materials and techniques being displayed. Stone and bone figurines and tools start to appear in this era. The Neolithic ("age of new stone") era is referred to as the agricultural Stone Age from 8,000 years ago to the Bronze Age [4]. This was the first remarkable age of innovation and creativity. Neolithic artisans utilized stone, wood, and bone in such sophisticated manner, that they are not clearly understood today. Neolithic architects and engineers were largely responsible for designing and building the great pyramids, Stonehenge, and the Ahu statues of Easter Island. The pyramids were completed when bronze was still very new. The engineering techniques are impressive: drilling rock, sawing monoliths, understanding the mechanics of levers and pulleys to amplify human and animal force. Their instrumentation included the balance, the plumb bob, and the square.

> And so history humbles us. It limits our inflated ideas about human progress. The Neolithic engineers remind us how the human spirit will fill the room to its boundaries in every age. (J. Lienhardt [4])

2.3.2 The Bronze Age to the Iron Age

Online resource.

The construction of large structures continued from 4000 B.C. to the fall of the Roman Empire (about 475 A.D.). The Bronze Age never realized anything as grand as the pyramids. By 1000 B.C., the Dorians replaced bronze with iron, which led to a dark age. The first civil engineers may be from this age. There is a story that the first Suez Canal was started by the Persian conqueror of Egypt, Darius, along the same route as the modern Suez Canal, which Ferdinand de Lesseps is credited with finishing in 1869 [5]. Darius'and Napoleon's expert engineers gave them both the same bad advice (only 2,300 years apart) that the Red Sea was 9 m (30 ft) higher than the Mediterranean and that a canal connecting the two would lead to disaster. But in 250 B.C. a substantial canal did link the Red Sea and the Mediterranean, and credit is given to the Ptolemies who came after Darius. It is even hypothesized that the Queen of Egypt once rode down a much earlier version of the canal built around 1500 B.C. for shipping purposes. These feats laid the foundation for the civil/water engineers who shaped history, including the great Leonardo da Vinci.

2.3.3 Hellenistic Period

There was a booming age of invention around the time of Alexander the Great through the 1st century B.C. This Hellenistic period saw the great Greek civilization and gave us gears, screws, plumbing, and control valves. Euclid, Archimedes, and Ptolemy are the names you will recall from this era whose contributions to mathematics, geometry, and astronomy were astonishing. It was a time to think, postulate, and discover. At the same time, the great seafaring explorers of the world were traveling from Mesopotamia through the Persian Gulf to India. The Mediterranean and the west coasts of Europe and Africa were explored. Western knowledge of Asia was extended to the Indus River [6].

Online resource.

An aerospace engineering remnant from this period is a very old Egyptian bird model, circa 3rd century B.C. Could the modern concept of flight have its origins here? In the Cairo Museum you can view numerous ancient bird models, but one model does not quite fit. The legless, featherless, sycamore wood model with an 18 cm (7 in) wingspan and a vertical stabilizer is not a bird at all—it has to be an ancient model airplane [7]!

2.3.4 Vitruvius' Writings of Known Technology

The same year Christ was born, the chief architect and engineer under Julius Caesar was a man named Vitruvius. He is known as the Great Roman Architect and wrote a 10-volume manuscript of *known technology* that includes building technology and materials, city planning, acoustics, water clocks and sundials, and all kinds of pumps. The complete manuscript covers not only technology, but also the fields of astronomy, medicine, music, law, and the arts [8]. The manuscript is unprecedented in its comprehensive coverage of ancient technologies, but there is speculation that the great Roman Empire "*did not add much to what a freer people had created*" and in the end *"Rome gave way to new cultures that had the same inventive spirit she had forgotten."* The moral is that "*it's not enough to own knowledge. We have to continually create it as well"* [9].

2.3.5 The Middle Ages

Online resources.

We were taught that from the fall of the Roman Empire until the Renaissance was a time of desolate, uncivilized darkness, the Dark Ages or Middle Ages. Medieval Europe witnessed as a time of retreating to the forests typified by peasant and nomadic lifestyles with tales of Viking raiders terrorizing Europe. A rebirth of civilization was being manifested. Any technological progress is hard to point to in comparison to the Roman aqueducts, amphitheaters, and arches that still stand today. An encouraging picture arises at the level of humanity, though, where survival was the primary goal. A small 7th-century baptistry in Poitiers, France, illustrates an attempt to start a new life with dignity and grace [10]. The structure still stands as it should; it was meant for posterity. During the Dark Ages, the use of horses and control of water power were understood, setting the groundwork for future ages.

If we turn our attention to Mesoamerica, the label *Dark Age* does not apply. One of the world's largest societies was witnessed, numbering 9 to 14 million Mayans. Technological and cultural knowledge was widespread in Mesoamerica. The millennium failed to deliver foretold terrors of the end of the world; rather, Mesoamericans developed sophisticated astrological understanding. For instance, the Incas at Machu Picchu, Peru, constructed their sacred site situated in the Andes where the sun's passage forms cosmological maps [11]. Now, if we turn our attention East, the Mongols from central Asia began a century of domination over most of the Asian continent (1200–1300). Warfare and the use of horses were the signature of the Mongols' success. This is the era when central Asia was opened to overland traffic between the East and West. Coal was mined for the first time in Europe for fuel around 1250, but it is thought that the Chinese may have used coal as early as 1000 B.C. Back in Mesoamerica, the Aztec Empire raised its capital, Tenochtitlan, in 1325. The Chinese invention of gunpowder was used to expel the Mongol rulers by the mid-1300s. The end of the Middle Ages witnessed the bubonic plague that spread from the East to Europe, killing 25 million people.

2.3.6 The Renaissance

The Renaissance (~1300–1600) was a spectacular age of discovery that witnessed extraordinary artistic creations and the development of modern machinery. Gutenberg's movable-type press enabled mass printing in 1455, and the spread of knowledge through books in the following century was phenomenal [12]. Leonardo da Vinci (1452–1519), the Italian painter, engineer, musician, and scientist, was perhaps the most versatile genius of the Renaissance. His precocious artistic talent brought him to Florence to be with the masters. In his spare time he filled notebooks with engineering and scientific observations that were often centuries ahead of their time. Leonardo was a master at observing nature, learning from her, and making connections. His understanding of nature, anatomy, and birds led to advanced concepts of flight that would have been realized were it not for material limitations.

Nicholas Copernicus (1473–1543) laid the foundation of modern astronomy with his heliocentric theory, but this Polish physician who treated the poor, and many scientists to follow, would pay dearly for going against the misconception that the earth was the center of the universe (see Chapter 9, "Orbital Mechanics," for more details). A second *engineering handbook* [13], that of Ramelli in 1588, was published and included almost 200 illustrations of pumps, mills, looms, derricks, elevators, presses, sawmills, and war machines. These machines were constructed mostly of wood and demonstrated some of the most ingenious mechanisms ever seen.

Other great geniuses of this time included Francis Bacon (1561–1626), Galileo Galilei (1564–1642), René Descartes (1596–1650), and Isaac Newton (1642–1727). It is essential to mention their contributions to human discovery and understanding; thus, the era of modern science began. The life of Francis Bacon illustrates a recurring theme in history, namely, that creative ideas and genius are often ostracized by the establishment. Bacon was an English lawyer and held high government positions before attempting the colossal task of reorganizing the prevailing concepts of science. His masterpiece, *Novum Organum*, sought to establish a new methodology based on his conviction that the mind, freed from prejudices and generalizations, could attain the greatest knowledge—knowledge over nature [14]. He was barred to the Tower of London and stripped of his title, but fortunately he was pardoned and lived another 5 years, continuing to write his educational manuscripts. Galileo Galilei, the Italian astronomer and physicist, first used a telescope to study the stars in 1610 [15]. He was a vocal advocate of Copernicus' theory that the sun forms the center of the universe, which led to his persecution and imprisonment by the church. He was also the first to suggest that the accepted belief that objects fall to the ground at speeds proportionate to their body weights is *false*. He supposedly climbed to the top of Pisa's leaning tower and dropped cannonballs and bullets of various mass, ostensibly showing that except for fractional disparities caused by air resistance the objects all fall at the same rate of speed [12]. However, Isaac Newton formalized this discovery. Galileo published many notable works; in one he discussed the unevenness of the moon's surface as observed through his spyglass (*Siderius Nuncius*), and he continued to champion the Copernican system of astronomy [16]. His certitude was absolute, but the Inquisition broke him. René Descartes, a French mathematician who spent his adult years in Holland, is described as the father of modern science. A true scholar, his studies included mathematics, philosophy, physics, psychology, physiology, and cosmology. Like Bacon, he endeavored to create a new methodology, but Descartes' method was based on deduction rather than experience. He proclaimed that his theories encompassed all knowledge from the principles of science to the existence of God. He is best known for the statement "*Cogito, ergo sum*" (I think, therefore I am) [14]. He laid the foundation for Isaac Newton and was one of the giants that Newton so eloquently acknowledged:

> If I have seen further, it is by standing on the shoulders of giants [16].

Isaac Newton, the Englishman who was knighted, was a natural philosopher, mathematician, and scientist of enormous proportion who invented differential calculus and formulated the theories of universal gravitation and terrestrial mechanics. His discovery of differential calculus, when he was 23, is monumental in its impact on scientists and engineers alike. For the first time, rules are established for dealing with rates of change. Many problems that arise in engineering and natural phenomena involve constant change that makes accurate calculations impossible without calculus [12]. Newton invented modern physics, and some say that he was lucky. Why? *There is only one universe to discover, and he discovered it.* We continue from the enlightened age of the Renaissance to the age of progress for the masses, the Industrial Revolution.

For additional information on this most remarkable time period from the people who shaped the Renaissance to the inventions they discovered, see References 17 and 18.

2.3.7 The Industrial Revolution

The development of power gave rise to the Industrial Revolution in the late 1700s; it began in England, but rapidly spread and was fueled by the revolutionary spirit in the world. It is exemplified by the advances in metalworking and steam power, on one hand, and the parallel emergence of science as a discipline of new knowledge (not just philosophy) and the development of mathematics, on the other hand. This age continues today aided by continued scientific breakthroughs in chemistry, electronics, nuclear science, nanotechnology, etc. We are all witness to its 20th-century manifestation, namely, the Space Age. In the latter half of the 20th century, the Space Age witnessed travel, both human and robotic, to low earth orbit, the moon, and Mars. The next revolution is upon us—the technological information age ushers in the 21st century.

The evolution from science to engineering is epitomized by engineer James Watt. In 1901 Lord Kelvin, another eminent soul of Glasgow University, described Watt's contributions as such:

> Precisely that single-acting, high-pressure, syringe-engine, made and experimented on by James Watt one hundred and forty years ago in his Glasgow College workshop, now in 1901, with the addition of a surface-condenser cooled by air to receive the waste steam, and a pump to return the water thence to the boiler, constitutes the common-road motor, which, in the opinion of many good judges, is the most successful of all the different motors which have been made and tried within the last few years. Without a condenser, Watt's high-pressure, single-acting engine of 1761, only needs the cylinder-cover with piston-rod passing steam-tight through it (as introduced by Watt himself in subsequent developments), and the valves proper for admitting steam on both sides of the piston and for working expansively, to make it the very engine, which, during the whole of the past century, has done practically all the steam work of the world, and is doing it still, except on the sea or lakes or rivers, where there is plenty of condensing water. Even the double and triple and quadruple expansion engines, by which the highest modern economy for power and steam engines has been obtained, are splendid mechanical developments of the principle of expansion, discovered and published by Watt, and used, though to a comparatively limited extent, in his own engines.

Thus during the 5 years from 1761 to 1766 Watt had worked out all the principles and invented all that was essential in the details for realizing them in the most perfect steam engines of the present day. Watt stands as the discoverer and inventor of the "most powerful instrument in the hands of man to alter the face of the physical world." He takes his place "at the head of all inventors of all ages and all nations" [19, 20].

Albert Einstein (1879–1955), Nobel laureate, is my biggest hero from the past century. If you want creativity, humbleness, and unequaled genius, look no further. Einstein was a German-born U.S. physicist who transformed humankind's understanding of nature on every scale, from the smallest to that of the cosmos as a whole, and we begin the 21st century still trying to solve the remaining questions that he could not solve. Einstein created the special theory of relativity by demonstrating that measurements of time and distance vary systematically. Einstein's relativistic universe, which we inhabit, is quite different from Newton's universe, where space and time are absolute. Einstein created the quantum theory of light. He proved that atoms actually exist (a millennia-old debate). He completed special relativity by revealing light as a continuous field of waves. At age 26, he was just getting started. In an extension of special relativity, Einstein established the most famous relationship in physics, $E = mc^2$, where E is energy content, m is mass, and c is the speed of light. Albert Einstein spent numerous years trying to understand the evasive force of gravity. His principle of equivalence stated that gravity and acceleration are equivalent, and then he completed his general theory of relativity, showing that the *force* of gravity is a determiner of curved, four-dimensional space-time. His general relativity is a radical vision that interlaces space and time, matter and energy, and offers a new understanding of the universe. He also significantly contributed to the development of quantum mechanics.

Einstein's general theories of relativity supersede Newtonian physics and form the theoretical base for the exploitation of atomic energy [21]. In his autobiographical notes he apologized to Newton:

> Forgive me. You found the only way which, in your age, was just about possible for a man of highest thought and creative power. [22]

Finally, it is important to note that Einstein saw it as his duty not only to affect the world as a scientist, but also to be politically responsible and active. As an ardent pacifist, he often made his opinions known publicly. In a telegram he sent to prominent Americans on May 24, 1946, he wrote

> The unleashed power of the atom has changed everything save our modes of thinking and we thus drift toward unparalleled catastrophe (published in New York Times). [22]

A great example of a renaissance engineer is Dr. Charles "Doc" Stark Draper, who is often called the "father of inertial navigation." As an aerospace engineer, he formulated the theory, invented the technology, designed necessary systems, and led the effort that brought inertial navigation to operational use in vehicles (aircraft, space vehicles, and submarines) [23]. His formal education included arts and sciences, psychology, electrochemical engineering, and a doctorate in physics. Dr. Draper was among the pioneers of aircraft engineers. His genius is memorialized in such monumental efforts as the Apollo landing on the moon and development of guidance systems for all strategic missiles in the U.S. inventory, both land- and sea-based.

Online resource.

To replace celestial and radio navigation methods, Doc Draper's invention combined gyroscopes (rotating devices that react to changes in direction) and accelerometers (instruments that detect changes in velocity over time) to facilitate navigation and maintain a steady course. Inertial navigation systems can be completely automated, resulting in very precise navigation anywhere in the world. His creative spirit was contagious and fostered his outstanding engineering achievements. Doc Draper's legacy for future engineers is a belief that through outstanding engineering achievements the well-being and freedom of all humanity will be ensured.

Throughout history, great humans lead us full-circle from philosophy to science to engineering and back again. Embracing the future, these stories motivate us and stimulate our career choices to become engineers. Now, mentally transport yourself from the present to 4 years in the future—you have graduated with your Bachelor of Science degree in engineering. What will your boss expect of you in your first job? From what you know, let us continue to define *engineering*. If you would like to work for NASA or an industry, then you should consider how an aerospace engineer might be expected to perform.

2.4 | WHAT IS (AEROSPACE) ENGINEERING?

The following are some of the broad activities that engineering education strives to introduce:

- Traditional engineering fundamentals, creative idea generation and problem-solving skills, high-technology approaches to engineering complex systems, technical system integration and operation
- The technical areas of aerospace engineering including (often denoted by the disciplines shown in italic) mechanics and physics of *fluids*, *structures* and *materials*, instrumentation, *control* and estimation, *humans* and *automation*, *propulsion* and energy conversion, aeronautical and astronautical *systems*
- The methodology and experience of analysis, modeling, and synthesis
- Finally, an engineering goal of addressing sociohumanistic problems

2.4.1 What Do (Aerospace) Engineers Do?

An engineering education should produce engineers capable of the following:

- Conceive: conceptualize technical problems and solutions
- Design: study and comprehend processes that lead to solutions to a particular problem including verbal, written, and visual communications
- Development: extend the outputs of research
- Testing: determine performance of the output of research, development, or design
- Research: solve new problems and gain new knowledge
- Manufacturing: produce a safe, effective, economic final product
- Operation and maintenance: keep the products working effectively
- Marketing and sales: look for good ideas for new products or improving current products; *sell*!
- Administration (management): coordinate all the above

2.4.2 Where Do (Aerospace) Engineers Work?

They work just about anywhere that engineers are employed and in a multitude of other places:

- Commercial airline companies (i.e., Boeing, AirBus)
- Aerospace industry
- Academia
- Government (i.e., NASA, DOD, White House, Congress, DOE, EPA)
- Communications industry

- Electronics industry
- Automotive industry
- Power industry
- Manufacturing
- Computer companies (i.e., software and hardware jobs)
- Entrepreneurs
- Design companies
- Wall Street
- Medicine
- Law firms

2.4.3 Employer's Checklist

The desired attributes of a (Boeing) engineer are found in the following checklist (edited from [24]):

- A good grasp of these engineering science fundamentals:
  - Mathematics (including statistics)
  - Physical and life sciences
  - Information technology
- A good understanding of the design and manufacturing process (i.e., an understanding of engineering)
- A basic understanding of the context in which engineering is practiced, including
  - Economics and business practice
  - History
  - The environment
  - Customer and societal needs
- A multidisciplinary systems perspective
- Good communication skills:
  - Written
  - Verbal
  - Graphic/visual
  - Listening
  - Cultural appreciation and awareness
  - Group-team interactions
- High ethical standards
- An ability to think critically and creatively as well as independently and cooperatively

- Flexibility—an ability and the self-confidence to adapt to rapid, major change
- Curiosity and a lifelong desire to learn
- A profound understanding of the importance of teamwork

Online resource.

Boeing used this checklist and philosophy to hire the best overall engineers to develop the 777 aircraft. Keep this list handy, and make sure that you acquire all these necessary professional engineering skills. Be patient, our learning never ends—it is continuous, and through experience and desire you can attain proficiency in all the areas specified above.

2.5 | SUMMARY AND FINAL WORD

Now reflect on the two personal goals that you wrote down at the beginning of this chapter, and imagine achieving these goals. Do the incredible thinkers and engineering feats of the past resonate with you? And do you find yourself thinking, "I would love to accomplish some of the brilliance of Leonardo da Vinci" or "I am going to lead a student design team to build a human-powered aircraft"? The future promises to be exciting and to unfold things beyond our imaginations. We must carefully consider the impact of our engineering designs and technology. Finally, this section ends by reflecting on how to synthesize our ideas about engineering.

The engineering explosion of the last several generations is astounding. We have gone from the impressive to the extraordinary.

- From atmospheric flight to spaceflight to other planets
- From transmission over a wire to satellite transmission
- From lumps of coals to fossil-fuel revolution
- From quantum mechanics to atomic power, lasers, and solar cells
- From vacuum tubes to electronics
- From mechanical *adding machines* to electronic computers

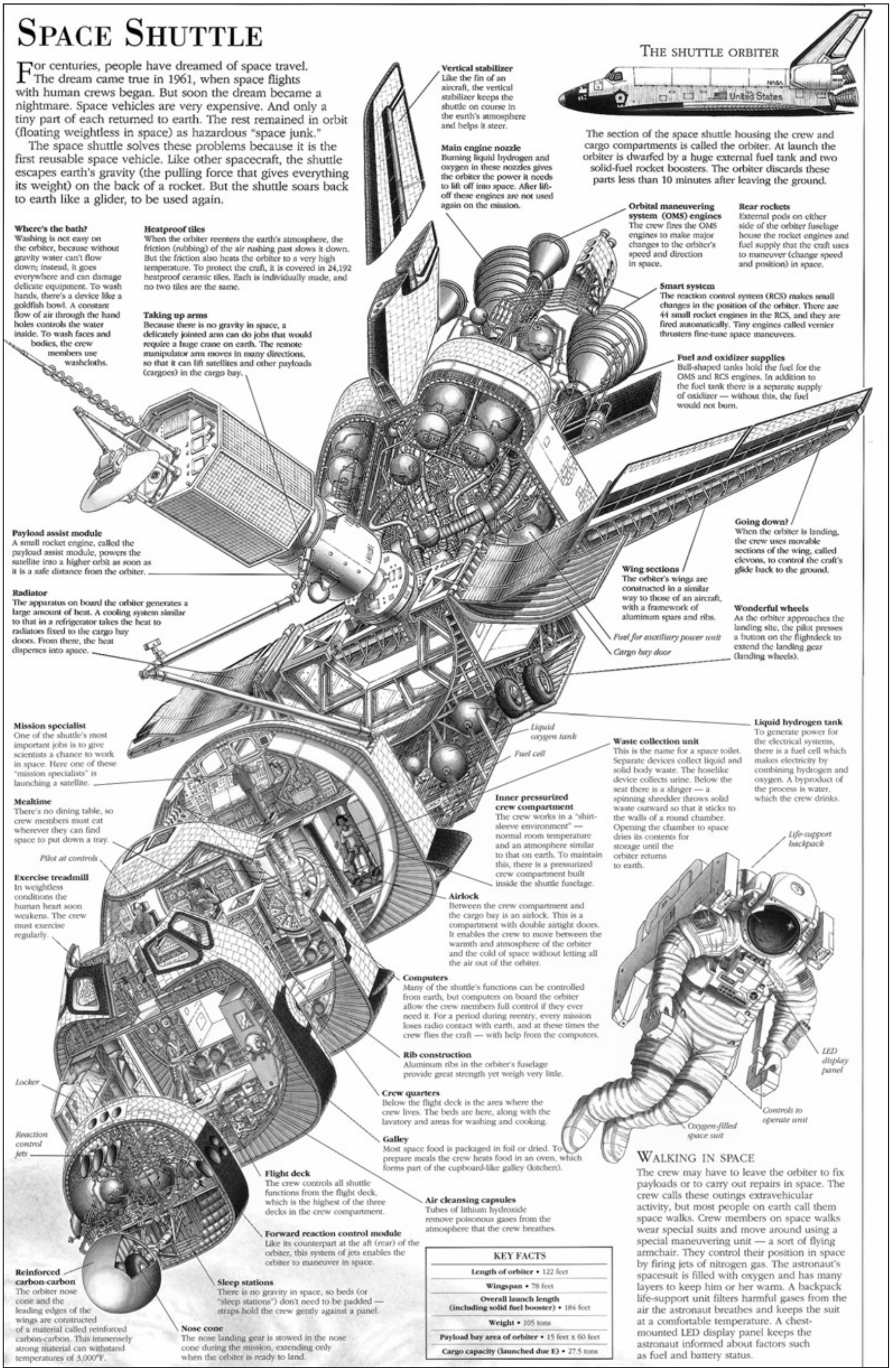
How would you like to be an aerospace engineer working for NASA on the design of the next space vehicle? Figure 2.3 provides an awesome cutaway drawing of a wonderful engineering feat, the development and design of the Space Shuttle.

2.5.1 Technological Impact

Taurus star-forming cloud.

I speculate that we are embarking upon another great age some 200 years after the Industrial Revolution, namely, the technological information age with daily scientific breakthroughs in the areas of aerospace, medicine, genetics, and nanotechnology. Images from the Hubble Space Telescope and other powerful telescopic instruments at the close of the 20th century have revealed almost 30 new planets orbiting nearby stars outside our solar system. Many of these planets orbit stars that are similar in size, age, and brightness to the sun and are at dis-

Figure 2.3 | Space Shuttle cut-away drawing.



tances ranging from 65 to 192 light-years from earth. The planets themselves range in size from slightly smaller to many times larger than the planet Jupiter. Their orbits tend to be very eccentric, tracing elliptical rather than circular paths (see Chapter 9, "Orbital Mechanics," for additional details). It is remarkable to contemplate the vastness of the universe. Genetic engineering has resulted in the cloning of Dolly the sheep and Cumulina the mouse [25]. There are many potential benefits as well as dangers associated with our technological achievements. Each individual must reflect upon his or her technological pursuits and their societal implications. For starters, consider the technological impact we are having as a human species on the earth through pollution, transportation, communications, consumerism, speed, and information overload. How are all these *technological advances* affecting your quality of life? In closing this chapter, I propose moving toward a systems perspective in which we think of designing, creating, and engineering in a synergistic manner to enhance human and global existence.

2.5.2 Fusing Our Thinking

Recall the story of one of the greatest engineers and thinkers of the past millennium, Descartes. René Descartes had a mechanistic view of the world, breaking everything into pieces, but not realizing that the whole is greater than the sum of the parts. Descartes wrote in Latin, and you might recognize his Latin name, *Cartesian*. A *systems* view, or perhaps *holistic thinking,* needs to be taken in order to consider complex problems and to eventually move closer to a solution. To view the world as a machine is extremely limited. It might have been particularly useful to view the world as a machine for 300 years, but that perception is inaccurate and is even harmful today; we need a new vision of the world. Systems thinking seems to make more sense of everything as we fuse our thoughts of philosophy, science, and engineering with our life's aesthetic and ethical experiences (i.e., systems thinking as opposed to mechanistic thinking). This provides knowledge, and through knowledge strength and power arise in a holistic manner. Descartes had a dream, and Newton actually made that dream come true by transforming it to scientific theory. Newton's great accomplishments (previously mentioned and expanded upon in Chapter 3, "Aerodynamics," and Chapter 9, "Orbital Mechanics") have set the tone of scientific discovery for nearly three centuries. But it is also important to heed the words of poet William Blake rather than to solely think in terms of a mechanistic, engineering frame of mind.

> If the doors of perception were cleansed, then everything would appear as it is, infinite. [14]

We have contemplated what engineering is and what engineers do in this chapter. You were asked to think about and list two of your personal professional goals. Hopefully, those personal goals align with a career in engineering. Your engineering future can realize the doctrine of Alfred Whitehead, who said that

> Neither physical nature nor life can be understood unless we fuse them together as essential factors in the composition of "really real" things whose interconnections and individual characters constitute the universe. (Quoted in [14], p. 338)

Finally, take time to think about the following three philosophical questions. Your answers will help you establish a framework from which you can judge your role as an engineer for societal good, or the global good. Can the planet survive our success as a species? How would you like to *engineer* your future? What really lies ahead, and what is the new evolving role of the engineer?

PROBLEMS

2.1 Write your own definition of engineering. Describe one accomplishment of your favorite engineer and how his or her achievement exemplifies your definition.

2.2 Find the following two web sites on the Decavitator human-powered hydrofoil and the product design process, which illustrate engineering design: the Decavitator, http://lancet.mit.edu/decavitator/Decavitator.html (courtesy of M. Wall); product design, http://me.mit.edu/2.744/ (courtesy of D. Wallace).

(a) Describe three examples of the iterative design process shown in the Decavitator project.

(b) Would you like to participate in a similar student project? Why or why not?

(c) Describe two new skills that you did not previously know but learned by reviewing the product design web site (e.g., how to make a sketch model, how to prototype).

2.3 You are at a career day for high school students. How would you describe the profession of engineering? (Remember to explain what an engineer does.) How would you encourage the students to pursue a career in engineering?

2.4 From the employer's desired attributes checklist, select and explain two categories for which you feel your education will best prepare you. Also select and explain two categories for which you feel your education will least prepare you and which might require some self-study.

2.5 Can the planet survive our success as a species? How would you like to engineer your future? What really lies ahead, and what is the new evolving role of the engineer?

2.6 Select your favorite aerospace-related cartoon. In a few sentences, describe any technological validity of the cartoon and/or any technical misconceptions. Describe the social implications for the aerospace field as well as aerospace engineers.

2.7 Extracurricular activity: Immerse yourself in the aerospace field. Take a trip to your local airport, air show, air club, or aircraft manufacturer. Talk to the people you meet there. Discuss aircraft as well as the aerospace industry.

OTHER ASSETS

3 Chapter

Aerodynamics

Dava J. Newman

3.1 | HISTORICAL PERSPECTIVE—AVIATION

Aeronautics is a relatively young engineering discipline, with most of its contributions being made during the past 100 years, which differs from philosophy, science, physics, and chemistry that have been developed over the centuries. As described in Chapter 1, “A Brief History of Flight,” the Wright brothers first flew on 17 December 1903. The technological developments necessary for heavier-than-air flight were unavailable until the early 1900s including engine development, proper understanding of aerodynamics and control, experimental wind tunnel testing, and pilots savvy in the understanding of aerodynamic flight. The two basic aerodynamic problems are lift and drag. The following had to be overcome before humans could fly:

- The resistance to motion
- Generation of lift
- Overcoming of drag
- Generation of an impulse (for space flight)

Lift and drag are the two major aerodynamic elements we will discuss in this chapter. Airplane designers must consider how to support the aircraft’s weight with air and how to overcome the resistance to motion. This is accomplished by generating lift and overcoming drag. The following sections specify how lift is generated and how drag is overcome.

The methods for generating lift are by static or dynamic means, namely, through buoyancy (i.e., static balloon) and fluid “air” motion (i.e., dynamic wing). For the case of ballistic spaceflight, lift around an airfoil or wing is not considered; rather, rocket propulsion provides the thrust or lift of the spacecraft, which is not considered further. The two primary sources of drag discussed in this chapter include profile drag and induced drag.

3.2 | GENERATING LIFT (IN NONBALLISTIC FLIGHT)

Rather than ask you to memorize all the governing equations of aerodynamics, which fill numerous textbooks, this chapter emphasizes general concepts and relations of aerodynamics. The goals of this chapter are to familiarize you with the nomenclature, provide an understanding of the concepts behind lift and drag, and introduce you to general aerodynamic principles, mostly through plots (rather than equations).

3.2.1 Buoyancy Lift

Balloon Flight Buoyancy is the easier method of generating lift. One of the first examples of lift through buoyancy is a hot-air balloon with a payload attached. Balloon flight came first technologically in 1852, some 51 years before the first airplane. The ancient Chinese are purported to have designed and flown balloons, or at least human-carrying kites, more than 1,400 years ago [26].

The governing principle of buoyancy lift is *Archimedes' principle*. This principle says that a difference in pressure on the surface of a body is equal to the volume displaced, and therefore, lift for balloon flight is governed by this principle. In other words, a difference in pressure on the surfaces of a body gives lift; or the weight of the fluid displaced equals the buoyant force.

Online resource.

$$\frac{\partial P}{\partial y} = -\rho g \quad [3.1]$$

$$F = -\frac{\partial P}{\partial y} \quad [3.2]$$

where the force is F, pressure is P, density is ρ, distance is y, and gravity is g. Force can be written in terms of the differential of pressure times volume.

EXAMPLE 3.1

Archimedes Takes a Dip

Let us think about a common example of Archimedes' principle applied to a fluid, namely, water. Consider the following thought problem: I grab two wood blocks of equal volume in my hands and submerge them in a bucket of water, with my left hand holding the first wood block 2 cm underneath the surface and the second wood block 20 cm underneath the surface of the water. What is the resulting *lift force* acting up on the blocks (taken from Reference 27)?

1. The lift force is stronger on block 1 than on block 2.
2. The lift force is stronger on block 2 than on block 1.
3. The lift force is equal on blocks 1 and 2.

Answer: 3. Each block displaces the same volume; therefore, the lift forces are equal.

The easiest way to apply Archimedes' principle to the subject of aerodynamics and flight is to model our balloon as a cylinder with diameter D and height D. Now we can calculate the pressure forces on the top and bottom surfaces.

$$F_{\text{top}} = P_0\left(\frac{\pi D^2}{4}\right) \tag{3.3}$$

$$F_{\text{bottom}} = (P_0 + \rho g D)\left(\frac{\pi D^2}{4}\right) \tag{3.4}$$

where P_0 is the pressure outside of the balloon and ρ is the density of air. By subtracting Equation (3.3) from Equation (3.4), the resulting net upward force is

$$F_{\text{net}} = \rho g D\left(\frac{\pi D^2}{4}\right) \tag{3.5}$$

The downward-acting forces are the weight of the gas inside the balloon and the weight of the payload (i.e., pilot, passengers, and basket for hot-air balloons). These forces are expressed by the following:

$$W_{\text{gas}} = \rho_{\text{int}} g D\left(\frac{\pi D^2}{4}\right) \tag{3.6}$$

$$W_{\text{payload}} = m_{\text{payload}} g \tag{3.7}$$

where weight is W, mass is m, ρ_{int} is the density of air inside the balloon, and $D(\pi D^2/4)$ is the volume of the balloon.

To find the static equilibrium state of the balloon, we sum the forces and set them equal to zero ($\Sigma F = 0$). Summing forces in the vertical direction, or y, results in

$$\sum F_y = \rho g V - \rho_{\text{int}} g V - m_{\text{payload}} g \tag{3.8}$$

which reduces to

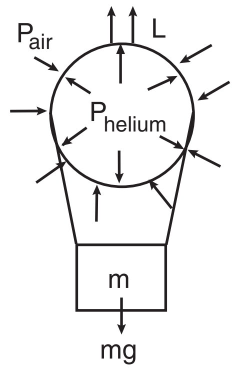
$$m_{\text{payload}} = (\rho - \rho_{\text{int}})V \tag{3.9}$$

Thus, the payload mass that will keep the balloon in the equilibrium is the difference in the inside and outside densities of the balloon, multiplied by the balloon volume.

Human-Carrying Balloon

EXAMPLE 3.2

Consider the diameter and volume necessary to lift a person via a helium balloon. Given are the densities of air and helium and the mass of a person.



$$\rho_{air} = 1.22 \text{ kg/m}^3 \qquad \rho_{helium} = 0.174 \text{ kg/m}^3 \qquad m_{payload} = 75 \text{ kg}$$

Using Eqn. (3.9) results in a diameter of 4.5 m and a volume of 71.7 m^3 to carry a 75 kg passenger. This seems rather large.

Buoyancy is typically more attractive in a dense medium; otherwise the design becomes very large. In sum, the lift provided and design needed appear rather bulky; balloon flight is not very fast, and the drag encountered is substantial.

Fluid Statics Let us consider one final example before we leave fluid statics and move on to fluid dynamics. This example is to make sure you understand the *concept* behind the quantity ρgh, or what you might commonly think of as potential energy, as well as to reinforce your knowledge of gravitational acceleration (taken from [27], p. 168).

Soda in Free Fall!

EXAMPLE 3.3

If I have a full, opened can of soda and tap a small hole into the side, fluid will start flowing out the hole onto the ground in a parabolic trajectory. (Recommendation: Carry out this example problem over a garbage can.) Of course, this assumes the fluid level is above the level of the hole. The question is: If I drop the can so that it is now in "free fall," what will the soda do?

1. The flow of soda from the side of the can will diminish.
2. The flow of soda from the side of the can will stop altogether.
3. The soda from the side of the can will now flow out in a straight line (horizontally).
4. The flow of soda from the side of the can will actually curve upward.

Answer: 2. At rest, the pressure on the walls of the can are due to the soda. Pressure depends on depth and is ρgh. *In free fall, both the soda and can have an acceleration of zero, not* g, *in the frame of reference of the can. In this frame, the pressure of the soda on the walls of the can is zero, so there is no outward flow [27].*

This concludes the section on lift created through buoyancy, but the concepts presented in this section are fundamental to the hands-on project of designing, building, and flying your own lighter-than-air (LTA) vehicle, presented in Chapter 12, "Design: Lighter-Than-Air (LTA) Vehicle Module." We continue with a discussion of lift and drag for vehicles moving through the air, typically aircraft, which is also critical information for your LTA vehicle design.

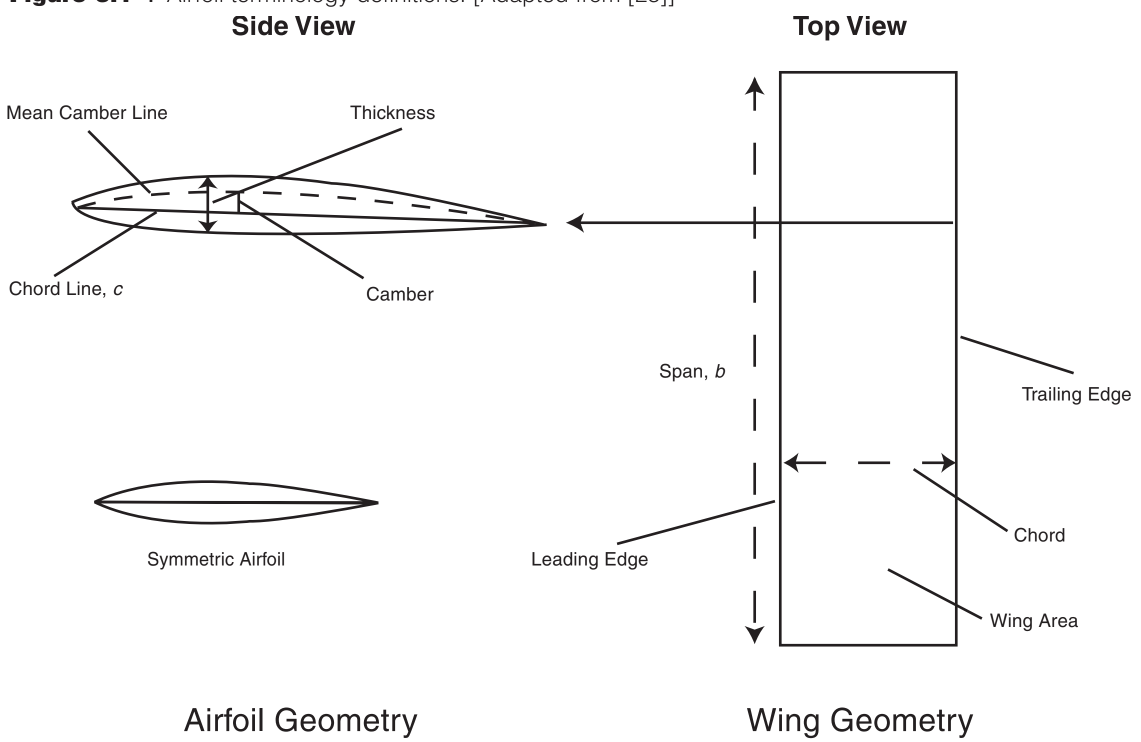
3.2.2 Lift from Fluid Air Motion

Airplane wing geometry is defined in this section since it is one of the chief factors affecting airplane lift and drag. This terminology is used throughout the aerospace industry and is also found in the NASA FoilSim software program, developed at NASA Glenn Research Center, from which much of this material is taken [28]. FoilSim is introduced in Section 3.4, "Simulation," and is provided on the CD-ROM. Airplane wings can be complex three-dimensional objects, but simple wing geometry is initially introduced.

Online resource.

Figure 3.1 shows a simple wing geometry, similar to that found on a light general aviation aircraft, as viewed from above (top view). The front of the wing, at the left, is called the leading edge; the back of the wing is called the trailing edge. The distance from the leading to trailing edges is called the chord *c*. The ends of the wing are called the wing tips, and the distance from one wing tip to the other is called the span *b*. The shape of the wing, when viewed from above looking down onto the wing, is called the planform. In this figure, the planform is a rectangle, and for a rectangular wing, the chord length at every location along the span is equal. For most other planforms, the chord length varies along the span. The wing area is the projected area of the planform and is bounded by the leading and trailing edges and the wing tips. The total surface area *S* includes both upper and lower surfaces; the wing area is a projected area and is almost one-half of the total surface area.

Figure 3.1 | Airfoil terminology definitions. [Adapted from [28]]



The aspect ratio (AR) of a wing is defined to be the square of the span divided by the wing surface area and is written as

$$AR = \frac{b^2}{S}$$

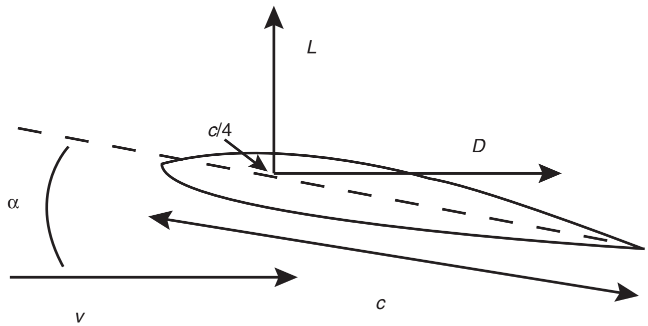
The aspect ratio is a measure of how long and slender a wing is from tip to tip. For a rectangular wing this reduces to the ratio of the span to the chord length. High-aspect-ratio wings have long spans (like high-performance gliders) while low-aspect-ratio wings have either short spans or thick chords (like the Space Shuttle). Gliders are designed with high aspect ratios because the drag of the aircraft depends on this parameter, and higher aspect ratios give lower drag and a better glide angle. The Space Shuttle has a low aspect ratio because of high-speed effects. Some airplanes can change their AR in flight by pivoting the wings (e.g., the F-14 and F-111), resulting in a large span for low speeds and a small span for high speeds.

A cut through the wing perpendicular to the leading and trailing edges shows the cross section of the wing. This cross section is called an airfoil, and it has some geometric definitions of its own, as shown to the left on the figure. The chord line has already been defined, and it cuts the airfoil into an upper surface and a lower surface. If we plot the points that lie halfway between the upper and lower surfaces, we obtain a curve called the mean camber line. For a symmetric airfoil that has an upper surface the same shape as the lower surface, the mean camber line is identical to the chord line. But for most airfoils, these are two separate lines. The maximum distance between the two lines is called the camber, which is a measure of the curvature of the airfoil (high camber means high curvature). The maximum distance between the upper and lower surfaces is called the thickness. Often you will see these values divided by the chord length to produce a nondimensional or "percent" type of number. Airfoils come with all kinds of combinations of camber and thickness distributions. The old NACA (National Advisory Committee for Aeronautics, which was the precursor of NASA) established a method of designating classes of airfoils and then tested the airfoils in a wind tunnel to provide lift coefficients and drag coefficients for designers. Airfoil data are available in the appendices of aerospace engineering texts and on the web from NASA and are included in this chapter via the FoilSim software program [28].

Aerodynamic Forces on a Wing Lift is the force that holds an aircraft in the air. How is lift generated? There are many explanations and a bit of controversy on this subject. Many of the common explanations given for how airplanes or birds attain lift are incorrect or misleading. There are two accepted descriptions, namely, the Bernoulli and Newton positions, which arise from the Bernoulli equation and Newton's second law. Both are discussed in this section, and you will see that both explanations have merit. The Bernoulli equation describes lift as generated by a pressure difference across the wing, and Newton's position states that lift is the reaction force on a body caused by deflecting a flow of gas. A body moving through a fluid generates a force by the pressure variation around the body. Turning a moving fluid also generates a force on a solid body, although you must be careful to consider the flow turning on both surfaces of an airfoil, for otherwise an incorrect theory results [28].

The dynamic wing is a lifting surface that generates lift as a reaction to the airflow passing over it. Lift L signifies aerodynamic forces perpendicular to velocity v, or freestream (often written as v_∞, while drag D represents aerodynamic forces parallel to the freestream. The angle at which the chord c of the airfoil moves in relation to the freestream is known as the angle of attack α. Lift and drag are seen to "act" through the quarter chord, or $c/4$, of an airfoil.

Figure 3.2 | Airfoil section with lift and drag forces depicted through the quarter chord.



The lift (and drag) of a given airfoil shape can be complex to calculate due to the multiple factors involved, such as airfoil geometry, flow speed, and flow type. Generally, all these parameters are lumped into an empirical nondimensional parameter to make the evaluation of the lift and drag more efficient. The nondimensional lift and drag terms are called the *coefficient* of lift and drag, respectively. [See Equation (3.10) and Equation (3.11).]

The lift coefficient is

$$C_L = \frac{L}{\frac{1}{2}\rho v^2 S} \tag{3.10}$$

And similarly, the drag coefficient is

$$C_D = \frac{D}{\frac{1}{2}\rho v^2 S} \tag{3.11}$$

Note that $\frac{1}{2}\rho v^2$ has units of pressure [(kg/m^3)(m^2/s^2)=N/m^2]. As in buoyancy, lift is still a pressure difference, but here it reveals the pressure above and below a lifting surface such as a wing. This pressure $\frac{1}{2}\rho v^2$ is called *dynamic pressure* and is represented by the symbol q. The dynamic pressure changes as you go along the airflow, so it is a measure of how much of the flow potential you have tapped. I like to think about it as kinetic energy per unit volume.

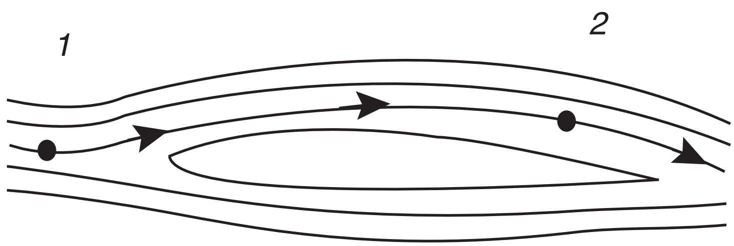
The Bernoulli method is essentially Newton's second law for fluid flow. We would like to calculate the pressure along a wing at a certain point in the flow (say, point 1 on Figure 3.3), given that we know the same information about another point in the flow along a streamline (say, point 2). A streamline is a path traced out by a massless particle as it moves with the flow. It is easiest to visualize a streamline if we move along with the body (as opposed to moving with the flow). The Swiss mathematician Leonard Euler first applied Newton's second law to the motion of a particle along a streamline. The sum of the forces in the streamwise direction (Fig. 3.3 from point 1 to 2) is equal to the mass of the fluid particle multiplied by the rate of change of its velocity, and can be written as

$$\sum F = m\frac{dv}{dt} = P\,dA - (P + dP)\,dA \qquad [3.12]$$

where the volume of the fluid particle is an infinitesimal streamwise distance *ds,* multiplied by the area of the perpendicular face *dA*. Therefore, the mass of the fluid particle (assuming a cubic geometric shape for the fluid particle) can be written as

$$m = \rho\,ds\,dA$$

Figure 3.3 | Flowfield, or streamlines, around an airfoil.



The velocity vector is defined to be everywhere tangent to the streamline, and the direction of *ds* is everywhere parallel to the local velocity, which yields

$$\frac{dv}{dt} = \frac{dv\,ds}{ds\,dt} = v\frac{dv}{ds}$$

and substituting into Equation (3.12) results in Euler's equation

$$-dP = \rho v\,dv \qquad [3.13]$$

Euler's equation is also known as the momentum equation because it relates the rate of change of a fluid's momentum to the forces acting on it. The integral form of Equation (3.13) is very useful. Assuming that the flow is *inviscid* (frictionless), which ignores viscous shear forces, and *incompressible,* which means that the density is constant throughout the flow field, we integrate along the streamline from point 1 to 2

$$\int_1^2 dP = -\rho \int_1^2 v\, dv$$

$$P_2 - P_1 = -\rho \frac{v^2}{2}\bigg|_1^2$$

This can be rewritten as Bernoulli's equation, after another 18th-century Swiss mathematician, Daniel Bernoulli:

$$P_1 + \frac{1}{2}\rho v_1^2 = P_2 + \frac{1}{2}\rho v_2^2 = \text{constant} \qquad \textbf{[3.14]}$$

The first pressure term on both sides of the equation is called static pressure, and the previously defined dynamic pressure is added to the static pressure. The static pressure plus the dynamic pressure equals the total pressure.

Fluid dynamics courses discuss the origin, uses, and limitations of the Bernoulli equation in greater detail. In its simplest and most used form, valid for a range of conditions useful in everyday engineering, the Bernoulli equation establishes a simple relationship between the *static pressure P,* the specific flow *kinetic energy* $\frac{1}{2}\rho v^2$, and *reference conditions* associated with where the flow came from. In this simple form, Equation (3.14) becomes

$$P + \frac{1}{2}\rho v^2 = P_0 \qquad \textbf{[3.15]}$$

where P_0 is a constant for the entire flow and is usually called the *stagnation pressure,* or sometimes the *total pressure.* In this relationship, v is the local flow speed, P is the local pressure in the fluid, and ρ (Greek lowercase rho) is the fluid mass per unit volume, or mass density (ρ is also identical to the inverse of the specific volume ν, which is an important thermodynamics parameter). According to Bernoulli, as the flow speed increases, the local pressure decreases, and vice versa. The constant P_0 is called the stagnation pressure because if the flow is brought to rest under controlled conditions (e.g., by a blunt body), the local pressure will increase until, in the stagnated region (or stagnation point), a maximum value is achieved, shown by the sum in Equation (3.15).

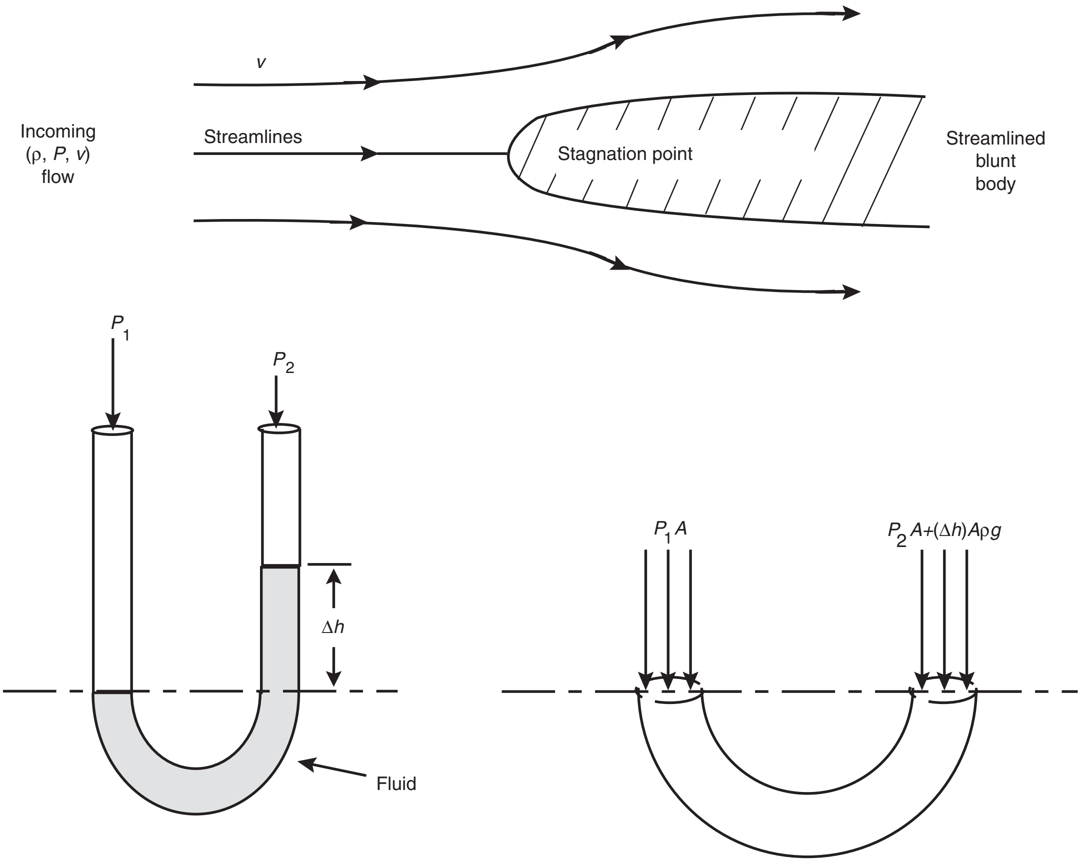
Long ago it was realized that this relationship provides a means of measuring flow speed, either in the laboratory or on an airplane, boat, etc. This eventually led to the invention of the *pitot static tube.* Formally, note that Equation (3.15) implies that the *flow speed* is given by

$$v = \sqrt{2\left(\frac{P_0 - P}{\rho}\right)} \qquad \textbf{[3.16]}$$

If you know the fluid density ρ and can measure both the local static pressure P and the stagnation pressure P_0, you can determine v.

A streamlined blunt body, illustrated in Figure 3.4, will bring the flow to rest smoothly enough to expect the pressure at the stagnation point to have the value P_0 (i.e., the stagnation pressure).

Figure 3.4 | Blunt body illustration showing stagnated flow and a U tube manometer schematic, which shows fluid forces.



If the shape of the blunt body is such that it allows the flow to return smoothly to a direction parallel to the incoming flow, the local pressure downstream on the body will reestablish itself (almost) at the original upstream local static value P. In fact, this is the motivation behind the design of streamline shapes.

The pitot static tube evolved as an instrument with two separate internal pressure chambers, attached to a differential manometer; one chamber achieves the stagnation pressure by having a small opening at the nose of the blunt body while the other chamber has one or more orifices open to the parallel flow being measured (see Figure 3.4).

Computed streamlines around an airfoil and around a baseball (cylinder) from a simulation using FoilSim resulted in the following parameters:

FoilSim streamline calculations around an airfoil and baseball. Foilsim.pct

For the airfoil:

- Airspeed = 160 km/h
- Altitude > 10,000 m
- Angle of attack = 5°
- Lift = 9.3×10^3 N

For the baseball:

- Left-handed pitcher
- Velocity of the fastball = 160 km/h

Since the streamline is traced out by a moving particle, at every point along the path the velocity is tangent to the path. Since there is no normal component of the velocity along the path, mass cannot cross a streamline. The mass contained between any two streamlines remains the same throughout the flow field. We use Bernoulli's equation to relate the pressure and velocity along the streamline.

Lift is caused by a pressure differential on the top and bottom surfaces of the wing. You can think about it as flow speeding up to get "over" the wing and flow slowing while going around the bottom of the wing, resulting in a greater pressure from the bottom side and lower pressure on the top side, which causes lift on the wing, or airfoil. From Bernoulli's equation we know that if $v_2 > v_1$, then $P_2 < P_1$.

Using Bernoulli's equation and the subscripts l and u for the lower and upper wing surfaces, respectively, we can rewrite Equation (3.14) as

$$P_l - P_u = \frac{1}{2}\rho(v_u^2 - v_l^2) \tag{3.17}$$

Rearranging yields an expression that shows that lift is solely dependent on the geometry and the angle of attack:

$$\frac{P_l - P_u}{\frac{1}{2}\rho v^2} = \left(\frac{v_u}{v}\right)^2 - \left(\frac{v_l}{v}\right)^2 = f(\text{geometry}, \alpha) \tag{3.18}$$

whereas lift is equal to the airflow pressure differential over the wing multiplied by the wing surface area *S:*

$$L = (P_l - P_u)S \tag{3.19}$$

Recalling Equation (3.10), we can write an expression for lift:

$$L = qSC_L \tag{3.20}$$

Looking at things a little more closely, you should be cautious when using the Bernoulli theory. True, the pressure can be determined from Bernoulli's equation as long as none of the assumptions are violated *and* the velocity variation is known. But how is the velocity variation determined? A simple one-dimensional flow relation could be used, but this gives the wrong answer since a wing section is truly three-dimensional. However, we often approximate it as a two-dimensional shape to simplify the calculations. A similar incorrect answer is obtained if the velocity is set to the velocity necessary for particles to separate, or detach, at the leading edge and meet at the trailing edge of the airfoil. The best way to understand the velocity variation is to use Newton's theory and determine the flow turning caused by a given shape. It is more difficult for complex geometries, but for some simple shapes the velocity variation can be determined. Once the velocity distribution is known, the Bernoulli equation can be used. Finally, an important aspect of airplane lift that is included in the Newton theory and does not appear in the Bernoulli theory is downwash. To generate lift, the flow must be turned in a direction opposite to the lift—downwash (see Section 3.3.2, "Induced Drag").

Lift is a force. From Newton's second law of motion, a force is produced when a mass is accelerated:

$$F = ma = \frac{d}{dt}(mv)$$

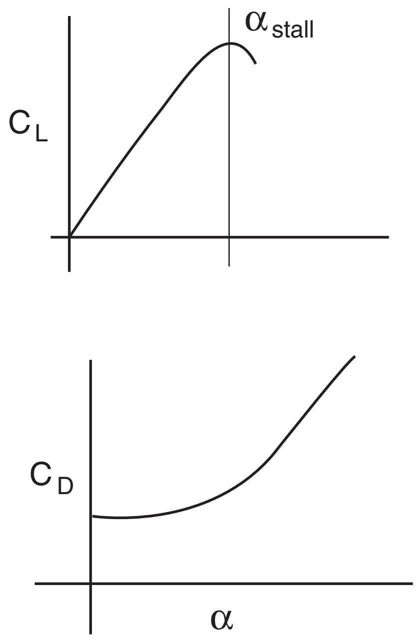
An acceleration is a change in velocity with a change in time. The important fact is that a force will cause a change in velocity; and likewise, a change in velocity will generate a force. Velocity is a vector and has both a magnitude (called the speed) and a direction associated with it. Vectors are reviewed in greater detail in Chapter 5, "Introduction to Structural Engineering." So, to change either the speed or the direction of a flow, you must impose a force. And if either the speed or the direction of a flow is changed, a force is generated.

Lift is a force generated by turning a flow. Since force is a vector quantity (like velocity), it has both magnitude and direction. The direction of the lift force is defined to be perpendicular to the initial flow direction. (The drag is defined to be along the flow direction.) The magnitude depends on several factors concerning the object and the flow. Lift can be generated by a wide variety of objects including airplane wings, rotating cylinders, and spinning balls.

In sum, lift and drag are mechanical forces generated on the surface of an object as it interacts with a fluid. The net fluid force is generated by the pressure acting over the entire surface of a closed body. The pressure varies around a body in a moving fluid because pressure is related to the fluid momentum (mass times velocity). The velocity varies around the body because of the flow deflection described above.

Relation between Lift and Angle of Attack Lift C_L, drag C_D, α, and velocity are critical parameters of airplane flight, and by looking at relations between these parameters we can understand how an airplane behaves in flight. We take a look at lift and drag as a function of the angle of attack of the wing to get an overall appreciation of aerodynamic performance. Lift of an airplane increases as α increases until a point called the *stall angle* (see Figure 3.5). Plots for L and C_L versus α have the same shape since the coefficient of lift is just a nondimensional representation of lift. Stall is defined as the point in dynamic flight when the wing is no longer attaining lift, and thus, the airplane starts falling under its weight. Stall is influenced by the smoothness of the surface of the wing and the viscosity of the fluid (i.e., air viscosity for airplane flight). You can see that C_L and α have a rather linear relation up until the stall angle of attack; therefore, we can state that C_L is approximately equal to $m\alpha$, where m is the slope of the C_L-versus-α plot.

Figure 3.5 | The plots show the relationship between the coefficient of lift and the coefficient of drag versus angle of attack.



When $\alpha < \alpha_{\text{stall}}$, the $C_L(\alpha)$ (pronounced "C_L of alpha") curve depends only on the wing geometry (shape). The wing size, airspeed, and air density are irrelevant. However, C_D is approximately the initial drag $C_{D,0}$ plus a constant k times α^2. This plot depends not only on wing geometry but also on surface smoothness and the air viscosity μ.

Specifically, the C_D-versus-α plot depends on another dimensionless parameter defined as the *Reynolds number* Re, which is defined here and discussed further in Section 3.3.1, "Profile Drag."

$$\text{Re} = \frac{\rho_\infty v_\infty x}{\mu_\infty} \qquad \textbf{[3.21]}$$

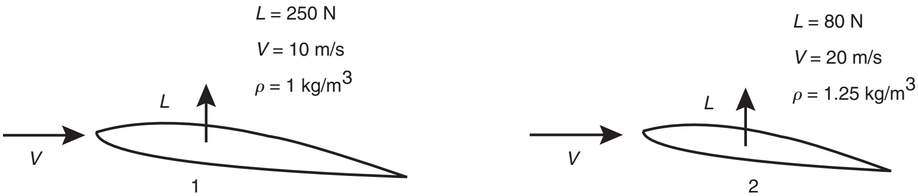
where ρ_∞ = density of air (for the freestream flow), v_∞ = freestream flow velocity, x is the distance from the leading edge of the airfoil, and μ_0 = viscosity of the flow.

Which Wing Is Providing More Lift?

EXAMPLE 3.4

Given two wings, one full size (S=5 m^2) and one a scale model (S=0.2 m^2), each with different airspeed and air density, compare the lift of each. See Figure 3.6.

Figure 3.6 | Full size wing airfoil (left) and scale model wing airfoil (right).



Question: Which wing is "lifting harder"? (That is, which wing has a greater angle of attack?)

Look at the dimensionless parameter C_L [Equation (3.10)] and make sure to include all units. For the full-size wing,

$$C_L = \frac{250\ \text{kg} \cdot \text{m/s}^2}{\frac{1}{2}(1.0\ \text{kg/m}^3)(10\ \text{m/s})^2(5\ \text{m}^2)} = 1.0$$

For the model wing,

$$C_L = \frac{80\ \text{kg} \cdot \text{m/s}^2}{\frac{1}{2}(1.25\ \text{kg/m}^3)(20\ \text{m/s})^2(0.2\ \text{m}^2)} = 1.6$$

The model airfoil has a larger C_L and therefore a higher relative lift. This shows that it is more efficient at the given conditions.

3.3 | SOURCES OF DRAG

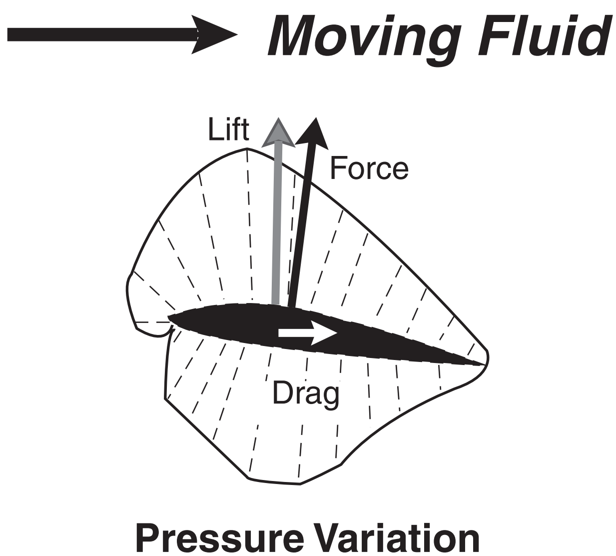
Drag is the aerodynamic force that opposes an aircraft's motion through the air. Drag is generated by every part of the airplane including the engines [28]. How is drag generated? Similar to lift, drag is a mechanical force. It is generated by the interaction and contact of a solid body with a fluid (liquid or gas). It is not generated by a force field, in the sense of a gravitational field or an electromagnetic field, where an object can affect another object without being in physical contact. For drag to be generated, the body (e.g., airplane wing, golf ball) must be in contact with the fluid. This is the reason that there is no aerodynamic drag once you reach space, or in a vacuum, because if there is no fluid, there is no drag (see Chapter 8, "The Space Environment: An Engineering Perspective," for an actual definition of where *space* begins). Drag is generated by the difference in velocity between the solid object and the fluid. There must be motion between the object and the fluid. If there is no motion, then there is no drag. It makes no difference whether the object moves through a static fluid or the fluid moves past a static solid object. Drag acts in a direction that opposes the motion. (Recall that lift acts perpendicular to the motion.)

While many of the factors that affect lift also affect drag, there are some additional sources of aircraft drag. We can think of drag as aerodynamic friction, and one of the sources of drag is the skin friction between the molecules of air hitting the solid surface of the aircraft. Because the skin friction is an interaction between a solid and a gas, the magnitude of the skin friction depends on the properties of both. For the solid, a smooth, waxed surface produces less skin friction than a rough surface. For the gas, the magnitude depends on the viscosity of the air and the relative magnitude of the viscous forces to the motion of the flow, expressed as the Reynolds number defined in Equation (3.21). Along the solid surface, a boundary layer of low energy flow is generated, and the magnitude of the skin friction depends on the state of this flow.

Online resource.

We can also think of drag as aerodynamic resistance to the motion of the object through the fluid. This source of drag depends on the shape of the aircraft and is called *profile,* or parasite, drag. As air flows around a body, the local velocity and pressure are changed. Since pressure is a measure of the momentum of the gas molecules and a change in momentum produces a force, a varying pressure distribution will produce a force on the body (see Figure 3.7). We can determine the magnitude of the force by integrating the local pressure times the surface area around the entire body. The component of the aerodynamic force that is opposed to the motion is the drag; the component perpendicular to the motion is the lift.

Figure 3.7 | Surface pressures on an airfoil.



There is an additional drag component caused by the generation of lift. Aerodynamicists call this component the *induced* drag. This drag occurs because of the three-dimensional effects of the wings where the flow near the wing tips is distorted spanwise because of the pressure difference from the top to the bottom of the wing. Swirling vortices are formed at the wing tips, and there is an energy associated with these vortices. The induced drag is an indication of the amount of energy lost to the tip vortices. The magnitude of this drag depends on the amount of lift being generated by the wing and on the wing geometry. Long, thin (chordwise) wings have low induced drag; short wings with a large chord have high induced drag.

Additional sources of drag include wave drag and ram drag. As an aircraft approaches the speed of sound, shock waves are generated along the surface. There is an additional drag penalty associated with the formation of the shock waves that is called wave drag. The magnitude of the wave drag depends on the Mach number of the flow. Ram drag is associated with slowing down the freestream air as air is brought inside the aircraft. Jet engines and cooling inlets on the aircraft are sources of ram drag.

In general, we can write the drag force as the dynamic pressure times the surface area times the coefficient of drag, similar to our definition of lift in Equation (3.20):

$$D = \frac{1}{2}\rho v^2 S C_D = qSC_D \qquad \textbf{[3.22]}$$

Compare the C_D for the Airfoils Given in Example 3.1

EXAMPLE 3.5

Does the full-size wind or scaled model have more drag?

Recall C_D [Equation (3.11)] and make sure to include all units. For the full-size wing,

$$C_D = \frac{5 \text{ kg} \cdot \text{m/s}^2}{1/2(1 \text{ kg/m}^3)(10^2 \text{ m}^2/\text{s}^2)(5 \text{ m}^2)} = 0.02$$

For the model wing,

$$C_D = \frac{2 \text{ kg} \cdot \text{m/s}^2}{1/2(1.25 \text{ kg/m}^3)(20^2 \text{ m}^2/\text{s}^2)(0.2 \text{ m}^2)} = 0.04$$

The model airfoil has a larger C_D and therefore a higher relative drag to accompany the higher lift produced.

For low-speed aerodynamics, the primary concerns are profile and induced drag, which are detailed in Section 3.3.1, “Profile Drag,” and Section 3.3.2, “Induced Drag.” Wave drag and ram drag are beyond the scope of this chapter.

3.3.1 Profile Drag

Profile drag is the drag force on an aircraft that is related not to lift, but to the viscous effects of the flow over the lifting surface. This drag is based on skin friction drag and pressure drag. In analyzing airfoils and two-dimensional representations of lifting surfaces, profile drag is the only drag that exists. Skin friction drag is caused by shear stress on the lifting surface. This shear stress can be written as a function of the Reynolds number [recall Equation (3.21)]:

$$\mathrm{Re} = \frac{\rho_\infty v_\infty x}{\mu_\infty}$$

The shear stress on the lifting surface τ is written as

$$\tau = \frac{0.664 q_\infty}{\sqrt{\mathrm{Re}}} \qquad \textbf{[3.23]}$$

as a function of the Reynolds number and dynamic pressure. The skin friction drag is then calculated by integrating τ along the lifting surface:

$$D_f = \int \tau \, dx \qquad \textbf{[3.24]}$$

$$D_f = \frac{1.328 q_\infty L}{\sqrt{\rho_\infty v_\infty L/\mu_\infty}} \qquad \textbf{[3.25]}$$

where x=the entire length of the lifting surface.

As we have previously mentioned, drag depends on the wing (object) shape and angle of attack, as well as the effects of air viscosity and compressibility. To correctly use the drag coefficient, one must be sure that the viscosity and compressibility effects are the same between measured experimental cases and predicted cases. Otherwise, the prediction will be inaccurate. For very low speeds [$<$ 89.4 m/s ($<$ 200 mph)] the compressibility effects of air are negligible. At higher speeds, it becomes important to match Mach numbers between experimental data and predicted performance. The Mach number M is the ratio of the velocity to the speed of sound, or

$$M = \frac{v}{c} \qquad \textbf{[3.26]}$$

At supersonic speeds, or $M > 1$, shock waves are present in the flow field, and wave drag must also be accounted for in the drag coefficient. The important point is this: It is completely incorrect to measure a drag coefficient at some low speed (say, 200 mph) and apply that drag coefficient at twice the speed of sound (approximately 1,400 mph, $M = 2.0$). It is even more important to match air viscosity effects. The important matching parameter for viscosity is the Reynolds number that expresses the ratio of inertial forces to viscous forces. Recall that skin friction drag depends directly on the viscous interaction of the object and the flow. If the Reynolds numbers of experimental and flight data are close, then we can properly model the effects of the viscous forces relative to the inertial forces. If the numbers are very different, we do not correctly model the physics of the real problem and will predict an incorrect drag [28].

Pressure drag is also sometimes called *form drag* due to separation of the boundary layer around the form of the object. This drag is generated by separation, or imbalance of pressure forces, of the flow from the lifting surface. The difference in pressures at the front and back of a body produces a net force in the drag direction, or pressure drag. Figure 3.8 shows the difference between attached and separated flow over an airfoil. Pressure drag can be reduced by delaying separation, as in the case of the design of dimpled golf balls (see Figure 3.9). Imagine a spherical golf ball with a smooth surface and without dimples. In this case, the streamlines hit the front face of the ball, and about halfway around the surface the flow separates and becomes turbulent. The dimpled surface design has greater skin friction drag, but the flow separates farther aft on the body, reducing pressure drag. Since golf balls are round, they inherently have higher drag than more aerodynamic, streamlined, tapered shapes.

Figure 3.8 | Attached and separated flow over an object.

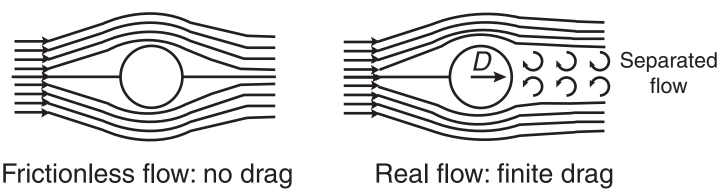
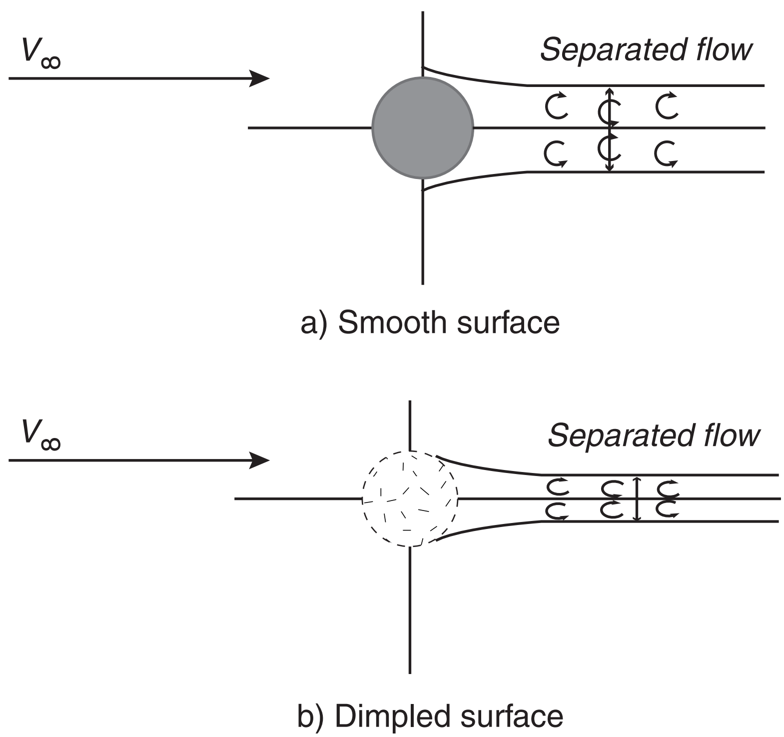
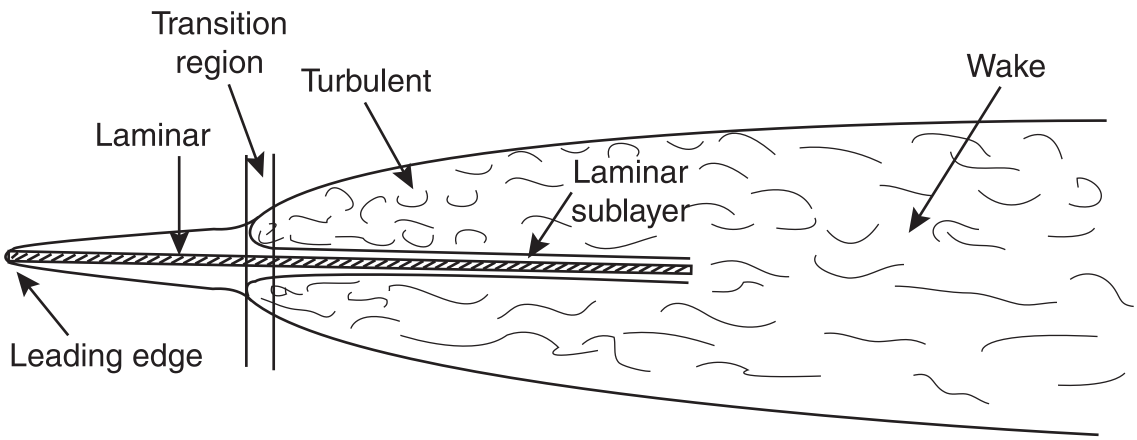


Figure 3.9 | The effect of smooth and dimpled surfaces on golf ball design.



Reynolds numbers identify the fluid flow regime and are illustrated in Figure 3.10.

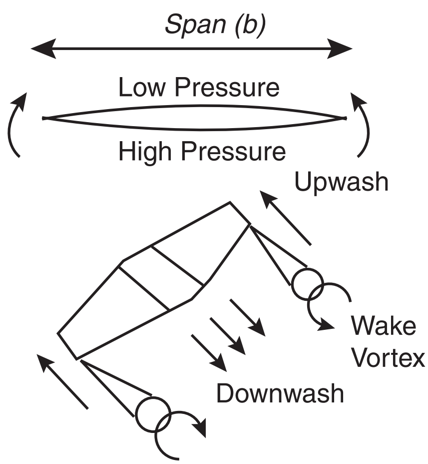
Figure 3.10 | Flow separation regimes over a flat plate as determined by Reynolds number showing laminar flow transitioning over to turbulent flow.



3.3.2 Induced Drag

Recall, induced drag is the form of drag on an aircraft that is related to lift. Specifically, induced drag arises from the three-dimensional effects of a wing caused by downwash velocity near the wing tip. The circulatory motion of the air at the trailing edge of the wing (called a vortex) tends to drag the surrounding air down with it, causing a downward velocity component at the wing (see Figure 3.11). This downward component is called the downwash velocity and is often visually apparent when an airplane emerges out of a cloud bank.

Figure 3.11 | Downwash and the creation of wake vortices.



The Cessna Citation depicted on the Web has just flown above a cloud deck shown in the background. The downwash from the wing has pushed a trough into the cloud deck. The swirling flow from the tip vortices is also evident.

Online resource.

When in flight, the wing is at a certain angle of attack α relative to the airflow over it. Downwash causes this angle of attack to be deflected downward by the angle α_I, the induced angle of attack. Induced drag can be written as

$$D_i = L \sin \alpha_I \qquad \textbf{[3.27]}$$

where L is the lift of the wing (or airfoil). However, for small angles, $\sin \alpha_I \approx \alpha_I$, yielding

$$D_i = L\alpha_I \qquad \textbf{[3.28]}$$

The value of α_I can be approximated by

$$\alpha_I = \frac{C_L}{\pi \text{AR}} \qquad \textbf{[3.29]}$$

where C_L is the coefficient of lift of the wing and AR is the aspect ratio of the wing.

(*Note:* This equation is only good for elliptical lift distribution in an incompressible flow, which produces uniform downwash distribution. Later we will show how we can still use this substitution to arrive at the formula for induced drag using an efficiency factor.)

Combining the equations and solving for D_I yield

$$D_i = \frac{LC_L}{\pi \text{AR}} \qquad \textbf{[3.30]}$$

Since $L = q_\infty S C_L$, substituting gives

$$\frac{D_i}{q_\infty S} = \frac{C_L^2}{\pi \text{AR}} \qquad \textbf{[3.31]}$$

The induced drag coefficient is then defined as

$$C_{D_I} = \frac{C_L^2}{\pi \text{AR}} = \frac{D_i}{q_\infty S} \qquad \textbf{[3.32]}$$

For all wings, a span efficiency factor e can be defined so that

$$C_{D_I} = \frac{C_L^2}{\pi e \text{AR}} \qquad \textbf{[3.33]}$$

Lifting line theory shows that the optimum (lowest) induced drag occurs for an elliptical distribution of lift from tip to tip. For elliptically loaded wings, $e = 1$. For all other loading cases $e < 1$, and a typical value is 0.7, thus allowing us to account for the substitution made above for α_I. The outstanding aerodynamic performance of the Spitfire of World War II is partially attributed to its elliptical wing, with elliptic lift distribution.

3.3.3 Effects on Drag

The total drag coefficient can now be defined as the drag due to profile and induced drag. Another way to think of profile drag is as the drag at zero lift, and we write the coefficient of drag as C_{D_0}. Finally, the total drag coefficient becomes

$$C_{D_{\text{TOTAL}}} = C_{D_0} + \frac{C_L^2}{\pi e \text{AR}} \qquad [3.34]$$

Figure 3.5 gave the overall shape of coefficient of lift and coefficient of drag curves as a function of airfoil angle of attack. The flow field around a cambered airfoil is that lift produced at a zero angle of attack. This is because the camber of the foil results in faster flow velocities and lower pressures above the top surface of the airfoil. The effect of a cambered airfoil compared to a symmetric airfoil is that the cambered airfoil's lift curve remains about that of the symmetric foil. The cambered airfoil has the unwanted effect of flow separation occurring sooner than that in the symmetric foil; therefore, cambered foils stall at a lower angle of attack than symmetric foils. A figure that plots coefficient of drag versus coefficient of lift (rather than angle of attack) is known as a drag polar. The drag polar helps show the relation of lift and drag. A cambered airfoil has minimum drag at a nonzero value of C_L (see Figure 3.12 and Figure 3.13). The effect of Reynolds number on the lift and drag curves is shown in Figure 3.14. Higher Reynolds numbers reveal that the transition from laminar to turbulent flow occurs closer to the leading edge of the airfoil. Higher Reynolds numbers have more skin friction drag, but less pressure drag since flow separation is delayed.

Figure 3.12 | Lift curve for symmetrical and cambered airfoils.

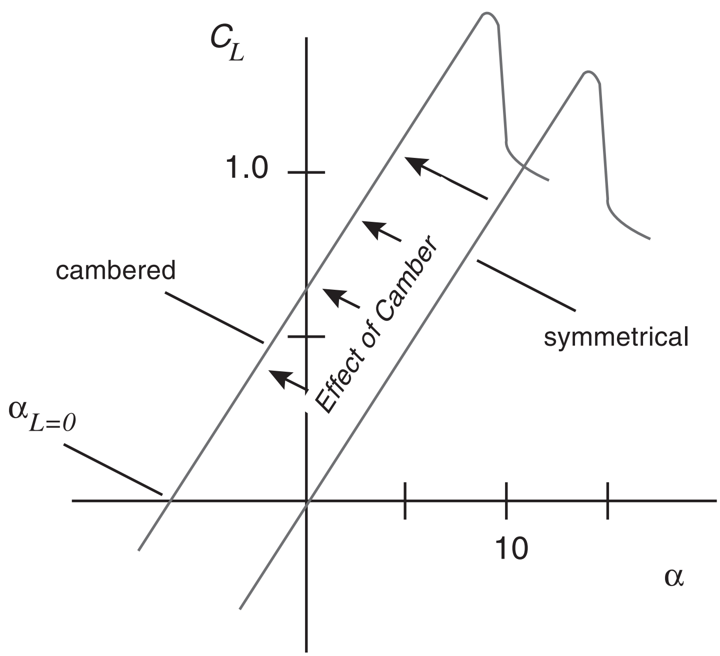


Figure 3.13 | Drag polar curve for symmetrical and cambered airfoils.

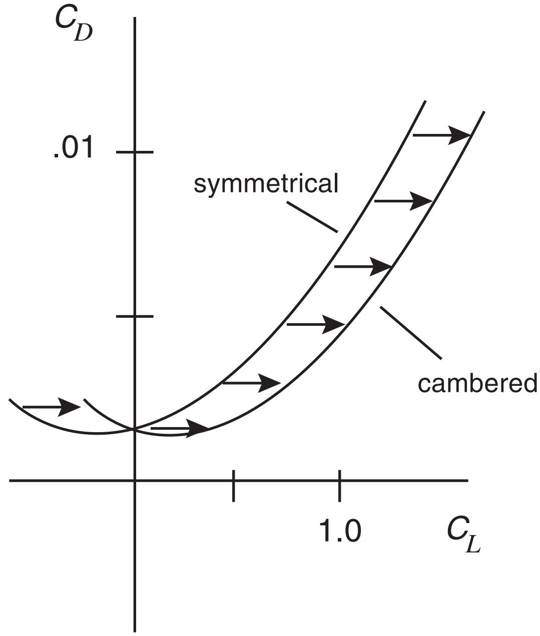
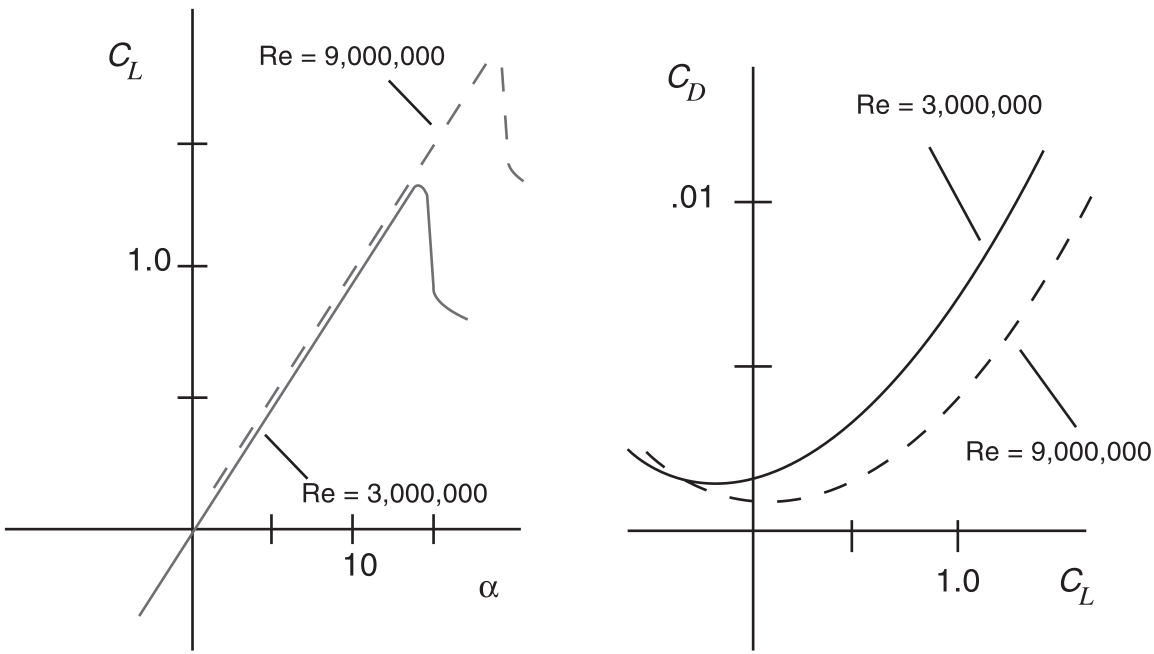


Figure 3.14 | The effect of Reynolds number on lift and drag curves.



However, the total drag can be either higher or lower depending on the relative magnitude of skin friction and pressure drag, which are also governed by the angle of attack. Once the angle of attack becomes high where separation and pressure drag dominate, the reduction in pressure drag due to delayed separation usually results in less total drag at higher Reynolds numbers.

Finally, a word on reading airfoil charts. Most introductory aerospace engineering and aerodynamics books contain appendices of airfoil data that were generated from wind tunnel tests. As an aerospace engineering student, you are often asked to read airfoil data charts. Figure 3.15 gives an example of airfoil data for an NACA 4412 airfoil. NACA performed most of these airfoil tests, and the four-digit codes identify the particular airfoil shape. The first digit represents the maximum camber in percent of the chord. The second digit represents where on the airfoil the maximum camber occurs, in tenths of the chord length aft of the leading edge. The third and fourth digits represent the maximum thickness in percent of the chord length (1 to 99 percent). The charts always show the lift curve as the left panel and the drag polar and moment polar (C_D and C_M versus C_L) as the right panel. A schematic of the airfoil is drawn in the top of the drag polar panel. The moment coefficient is about the aerodynamic center. Data points are plotted for various Reynolds numbers, and the key is given in the bottom of the drag polar panel. An NACA 0012 airfoil is a symmetric airfoil with a maximum thickness at 12 percent of its chord length. An NACA 4412 has 4 percent camber, its point of maximum camber located at its 40 percent chord point, and a maximum thickness at 12 percent of its chord length.

3.4 | SIMULATION

3.4.1 FoilSim

Online resource.

The FoilSim computer program developed by NASA provides an excellent demonstration of the principles covered in this chapter. It is a powerful tool to investigate the aerodynamics of flight, lift, and drag and how these relate to aircraft performance. FoilSim software is included on the CD-ROM and can be downloaded or run from www.lerc.nasa.gov/WWW/K-12/aerosim/

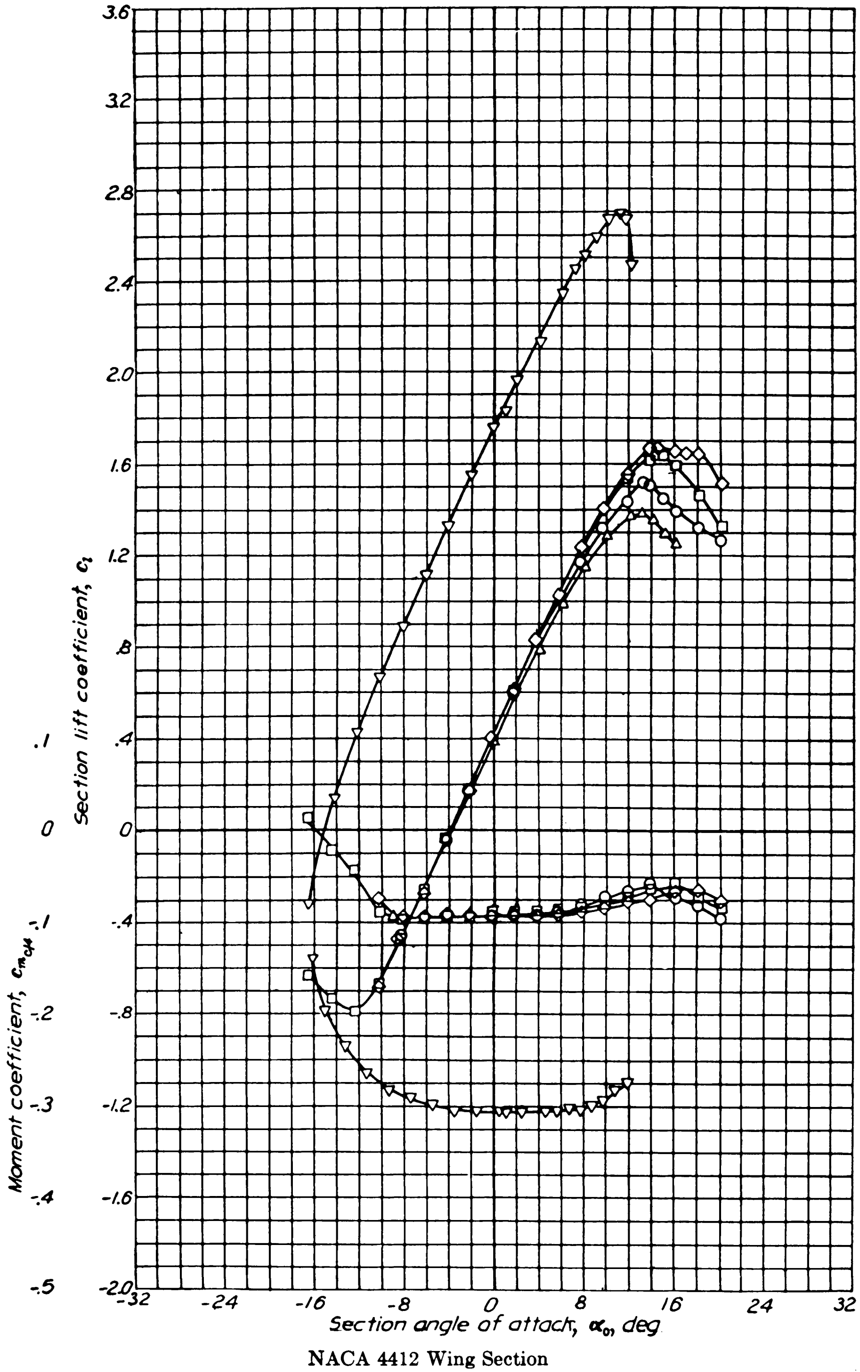
Problems at the end of this chapter provide an introduction to the use of FoilSim and postulate some interesting aerodynamics problems to solve by using the software.

PROBLEMS

3.1 Compare and contrast the aerodynamic design of the *Voyager* to the *Boeing 747.* Explain the advantages and disadvantages of each design.

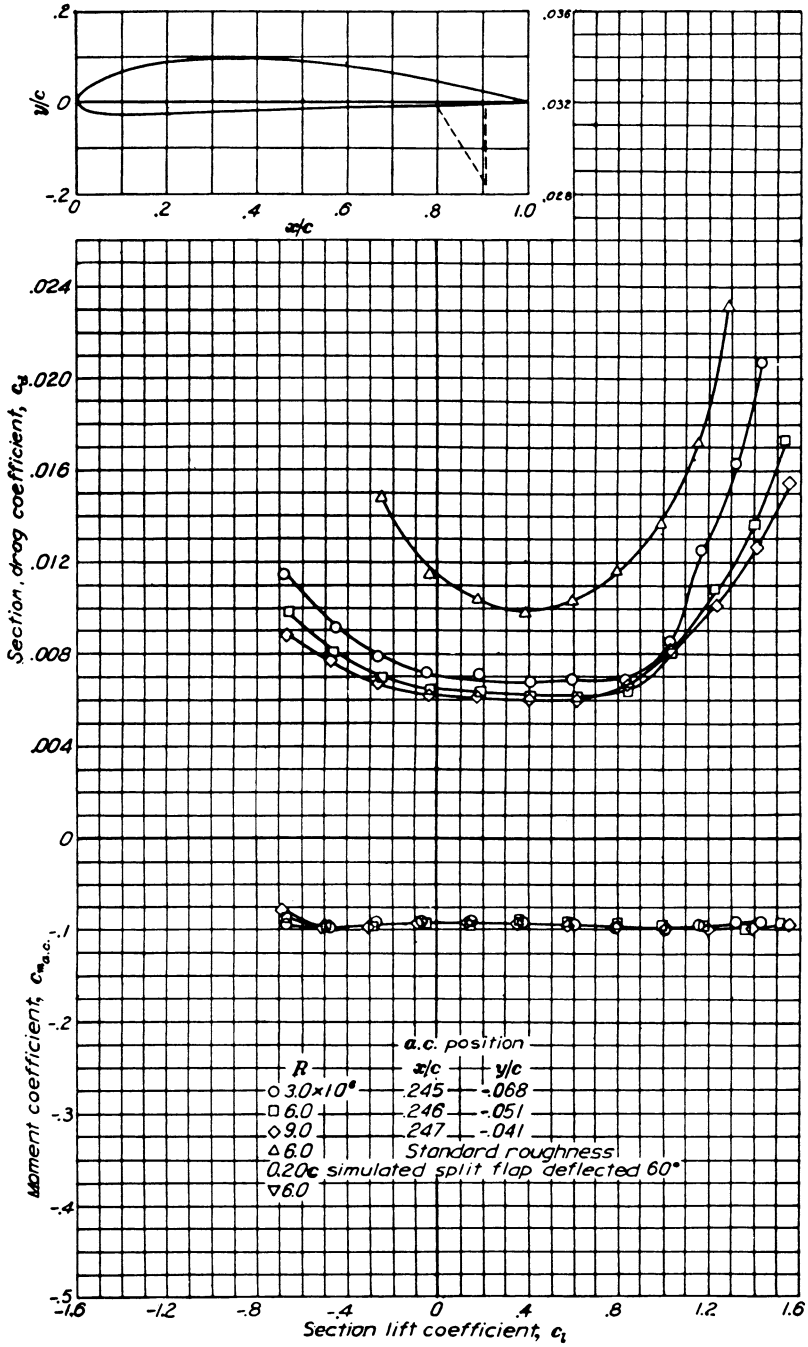
3.2 Some aircraft such as the French fighter Rafale do not have horizontal stabilizers on their tails, but rather have them in front of the wing, in which case they are called canards. The control surfaces on the wing are used for both pitching and rolling. Find the name of these control surfaces (you might be able to guess). Answer: The control surfaces are called *elevons.* The name is a contraction of *elevators* and *ailerons.*

Figure 3.15a | NACA 4412 airfoil data. Lift, drag, and moment coefficients are plotted. (from Anderson, pp. 742–3)



(continued)

Figure 3.15b | *(continued)*



NACA 4412 Wing Section (*Continued*)

3.3 Using the FoilSim program in the Play Ball mode, answer the following questions.

(a) The Colorado Rockies are hosting the Boston Red Sox. From what you can tell from the analysis and graphics, will a left-handed pitcher who throws a pure fastball at 99 mph throw a strike? What if the release angle changes to 1°?

(b) What is the altitude?

(c) The Red Sox right-handed pitcher throws a curve ball at 85 mph. The spin on the ball is −666 rpm. What is the side force of the pitch? Is it a strike?

(d) If he alters his release point to 1, what is the difference at the plate?

3.4 Quick-answer thought problems (taken from [29]).

(a) Does the rudder on an airplane allow the plane to pitch up and down?

(b) When an airplane is in steady flight (constant velocity), is the force of drag equal to the thrust produced by the plane?

(c) Do the dimples on a golf ball increase the range of the golf ball?

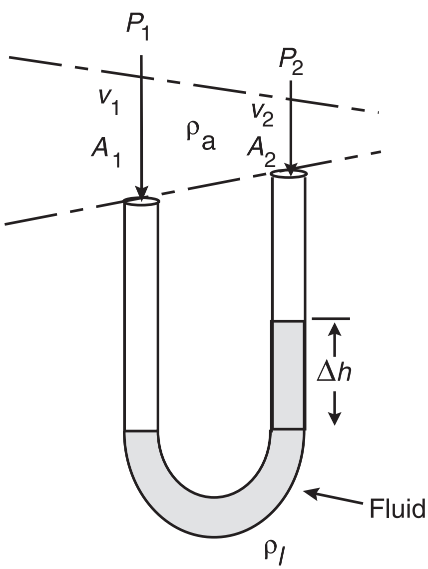
(d) In a world cup football match, can a player put back spin on the ball to increase its range?

(e) Does an airfoil create lift because there is circulation over the airfoil?

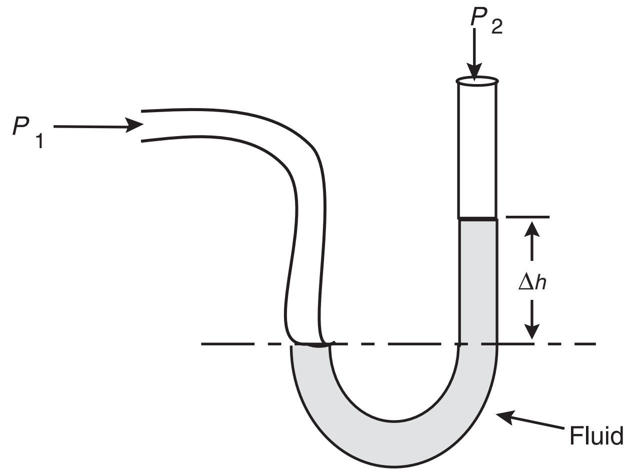
3.5 Explain lift on an airfoil in the context of Bernoulli's equation. State all assumptions.

3.6 See Figure 3.3b. Write an equation for Δh shown in the figure. What is the pressure difference $P_1 - P_2$?

3.7 A Venturi device is shown below. Suppose air flows over the U-tube manometer. Solve for v_2. The density of air and that of the liquid are ρ_a and ρ_l, respectively.



3.8 Now suppose the manometer looks like the figure below with air flowing past the opening from left to right. Solve for velocity *v*.



3.9 FoilSim for aerodynamic calculations (courtesy of NASA and R. Shea). Set the following on the FoilSim airfoil panel: airspeed, 200 mph; altitude, 5,000 ft.; camber, 0; angle, 2.5°; and surface area, 300 ft^2.

(a) Set the velocity to 50 mph and record the lift. Increase the airspeed slider to 100 mph. Record lift. Increase the velocity to 150 mph and record lift again. Finally increase the velocity to 200 mph and record lift. Describe the change that you observe in lift as velocity changes. Graph velocity versus lift by hand for these points.

(b) Set the angle at 2.5° and record lift. Repeat, setting the angle for 5.0°, 7.5°, and 10° and record the lift for each setting. Graph your results by hand. At what point will the airfoil not turn a flow? Complete your graph with a stall at an angle of 12°. Will lift be generated at an angle of 0°? Explain.

(c) Return the angle setting to 2.5° and set the surface area to 100 ft^3. Record the value for lift. Double the surface area. How is lift affected? Record lift. Double the surface area two additional times and record lift. Graph lift versus surface area from the data recorded. Explain how an airplane can slow its velocity for landing and still maintain sufficient lift to avoid a stall.

(d) Set the camber at 0. Record lift. Increase camber to 0.25, 0.30, 0.35, 0.40, 0.45, and 0.50, and record the changes in lift for each setting. Graph camber versus lift with the data recorded. Is it possible for camber adjustment to initiate a stall? Explain.

(e) Return the camber setting to 0. Adjust the altitude slider to 15,000 ft, 25,000 ft, 35,000 ft, and 45,000 ft; and record lift at each setting. Graph lift versus altitude with the data collected above, and predict the next two points on the graph. Is lift affected by an increase in altitude? List possible reasons for any changes observed.

(f) An airplane is beginning its descent at an altitude of 1,500 ft and a beginning velocity of 200 mph. Gradually decrease altitude and velocity, and note the change that occurs in lift. Record your observations. Explain how the lift force can be maintained while velocity and altitude are being decreased as the airplane approaches landing. Check your explanation using the FoilSim demonstrator. Summarize your results.

(g) An airplane travels 40,000 ft horizontally from the point where it began its descent at an altitude of 1,500 ft. Draw a diagram of the descent, showing the vertical and horizontal components, and calculate the angle of descent for the airplane.

3.10 You have been hired by Fly-for-Fun Associates (F^3A) as a consultant for the design of an airfoil section for a new, lightweight multipurpose general-aviation aircraft. The aircraft has the following characteristics: a cruise velocity of 120 mph, a landing velocity of 45 mph, a cruise altitude of 8,000 ft, $\alpha_{\text{landing}} = 15°$, $\alpha_{\text{cruise}} = 0°$, a wing area of 350 ft^2, and a gross takeoff weight of 1,500 lb. The total lift of the wing may not exceed 2,000 lb due to structural constraints.

Currently F^3A is considering using the NACA 3438 airfoil for the aircraft. Being a highly trained aerospace engineer, you decide to try the airfoil section out using FoilSim. Will it work? If yes, why; and if not, what should you do to fix it?

3.11 Before NASA, there was the National Advisory Committee on Aeronautics, or NACA. Their early aerodynamic research classified airfoils by a 4-digit code. The first integer indicates the maximum camber as a percentage of the chord. The second integer indicates the position of the maximum camber in terms of tenths of the chord length measured from the leading edge. The last two integers indicate the thickness of the airfoil as a percentage of the chord length. For instance, the NACA 2412 airfoil section has a maximum camber of 2 percent located at 0.4 (or 40 percent) of the chord length from the leading edge, and a maximum thickness of 12 percent of the chord length.

Due to their high speeds and wide, flat bodies, Formula 1 race cars often act as flat plates that produce lift. One race car design uses an inverted NACA 6321 airfoil with a C_L of 0.73, producing a downward lift force to remain on the track. The airfoil has two end plates, so the flow is assumed to be two-dimensional. On a straight run, if the car can be assumed to act as a flat plate with a C_L of 0.25 and an area of 32 ft^2 and the airfoil is 4 ft long and has a chord of 1 ft, how much can the car weigh and still remain on the track at a speed of 200 mph?

3.12 Paper airplane design using FoilSim. Design and build a paper airplane that has the longest time aloft and travels the greatest distance.

(a) Use unlined paper for your construction. Determine the wing area by breaking areas of the wings down into triangles and rectangles. Measure and calculate.

(b) Using the same launch angle and velocity, fly your airplane through five trials. Measure the wing surface area, distance traveled, and angle of inclination for the wings in each trial. Make a data table and record your results. Repeat the trial flights for time aloft. Again, record the wing surface area, time aloft, and angle of inclination for the wings in each trial. Graph the area/time or area/distance data for each set of trials. The trial flights must be completed indoors to eliminate wind effects. Write a summary of your results.

(c) Cut 1 in off the trailing edge of the wings. Place the cut-off pieces within the folds of the airplane so the mass remains constant. Repeat the trial flights, data collection, graphing, and written summary as above.

Chapter 4

Aircraft Performance

Dava J. Newman

4.1 | INTRODUCTION

In this chapter we discuss aircraft performance by deriving the operable range of speeds for aircraft as well as the range and endurance of flight vehicles. An introduction to the various components of an aircraft and their uses is given. A proposed two-dimensional model of an aircraft is derived, which leads to the equations of motion for an aircraft in steady, level flight. The final section of the chapter presents accelerated flight. The chapter is summarized through the use of a loading profile, called a V–n diagram (V for velocity and n for loading level in g's). The V–n diagram represents the aircraft flight envelope, thus providing an overall aircraft performance metric beyond which it is not feasible to operate.

4.2 | PERFORMANCE PARAMETERS

There are many possible measures for aircraft performance. While some apply for all aircraft, others are specific to a certain type. The most common performance parameters, applicable to all types of airplanes, include speed, range, and endurance.

- *Speed* What is the minimum and maximum speed of the aircraft?
- *Range* How far can the aircraft fly with a tank of fuel?
- *Endurance* How long can the aircraft stay in the air with a tank of fuel?

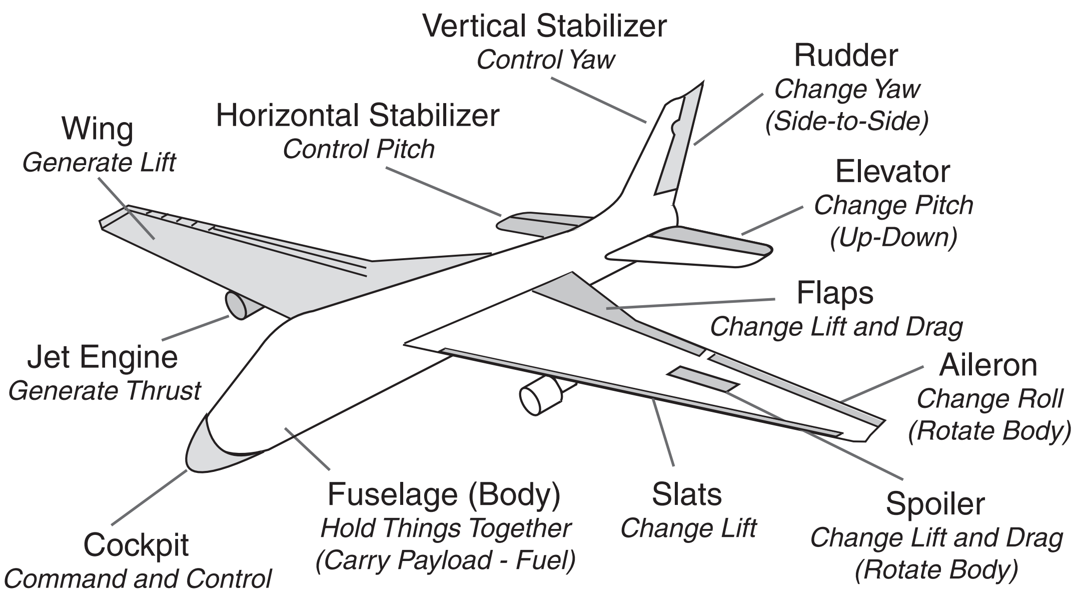
This chapter focuses on these three performance requirements, which can be computed by examining the *flight dynamics* of the vehicle. Additional performance measures found in aircraft performance texts include the aircraft climb rate, ground roll, safety, direct operating costs, passenger capacity, cargo capacity, maneuverability, and survivability.

4.2.1 Aircraft Components

In this section we introduce the key aircraft components. Although a wide variety of aircraft exist, almost all are made up of the same basic components that either are fixed or move. Generally, the fixed components include the wings, a fuselage, a tail, engines, a vertical stabilizer, and a horizontal stabilizer. For flight performance and maneuvers, aircraft employ moving surfaces (see Figure 4.1).

The fuselage is the "central body portion" of the aircraft designed to accommodate the crew, the passengers, and the cargo. All other main structural components such as the wings and the stabilizers are attached to the fuselage. As described in Chapter 3, "Aerodynamics," the main purpose of the wings is to generate lift. In the case of flying wing aircraft, such as the B-2 stealth bomber, there is no separate fuselage or tail, and the aircraft consists only of a wing that serves a dual purpose. Many recent aircraft are designed with protruding attachments at their wing tips called *winglets.* Their purpose is to decrease the drag on the aircraft by reducing the downwash (discussed in Section 3.3.2, "Induced Drag").

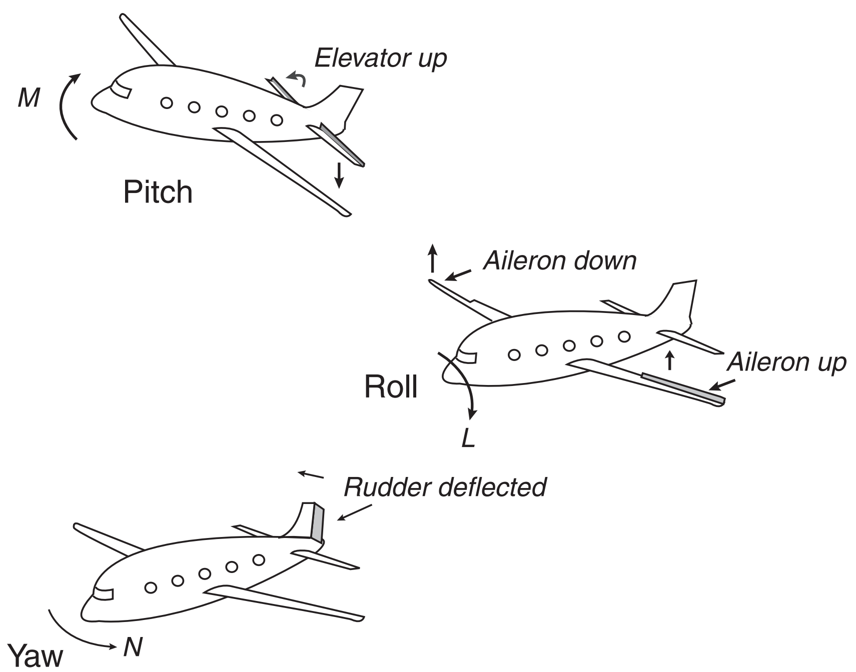
Figure 4.1 | Airplane parts and control surfaces [edited from [28]].



The engine or engines of an aircraft produce a force called thrust that propels the vehicle, as detailed in Chapter 6, "Aircraft Propulsion." Aircraft are equipped with two stabilizers at their tail whose task is to provide stability for the aircraft and to keep it flying straight. The fixed horizontal component is called the *horizontal stabilizer* or *tail*. Its purpose is to prevent an up-and-down motion of the nose (pitching). There is also a fixed vertical component, called the *vertical stabilizer* or *fin,* that keeps the nose of the plane from swinging from side to side (yawing).

Elevators, ailerons, and rudders are the three movable surfaces that change the control of aircraft pitch, roll, and yaw, respectively. These control surfaces on the wing and tail are responsible for changing the amount of force produced, providing a means to control and maneuver the aircraft. The outboard moving control surfaces of the wing are called the *ailerons.* Pilots deflect ailerons to cause the aircraft to roll about its longitudinal axis. Ailerons usually work in opposition—as the right aileron is deflected upward, the left is deflected downward, and vice versa. Aileron deflection changes the overall amount of lift generated by the wing airfoil. Aileron downward deflection causes the lift to increase in the upward direction. If the aileron on the right wing is deflected down and the aileron on the left wing is deflected up, then the lift on the right wing increases while the lift on the left wing decreases. Because the forces are not equal, there is a net torque in the direction of the larger force. The resulting motion rolls the aircraft counterclockwise. If the pilot reverses the aileron deflections (left aileron down, right aileron up), the aircraft rolls in the opposite, or clockwise, direction. Most aircraft can also be rolled from side to side by engaging the *spoilers,* which are small plates that are used to disrupt the flow over the wing. Spoilers are designed for use during landing to slow down the plane and to counteract the flaps when the aircraft is on the ground (see Figure 4.2).

Figure 4.2 | Depiction of aircraft pitch, roll, and yaw by moving control surfaces.



The moving control surfaces of the horizontal stabilizer are called the *elevators.* Elevators work in pairs—when the right elevator goes up, the left elevator goes up as well. Changing the angle of deflection at the rear of the tail airfoil changes the amount of lift generated by the surface. With greater upward deflection, the lift increases in the downward direction, or vice versa. The change in lift created by deflecting the elevator causes the airplane to rotate about its center of gravity in a pitching motion. Pilots can use elevators to make the airplane loop or, since many agile aircraft loop naturally, the deflection can be used to trim, or balance, the aircraft, preventing a loop. The moving control surface of the vertical stabilizer is called the *rudder.* Unlike the other two control elements (i.e., ailerons and elevators), a deflection of the rudder is made by the pilot not with his or her hands deflecting the control column but rather with his or her feet using the rudder pedals. With greater rudder deflection to the left, the force increases to the right, and vice versa, causing yawing motions counterclockwise and clockwise, respectively. Deflecting the rudder causes the airplane to rotate about its center of gravity.

Flaps are devices to create additional lift for the aircraft. Before takeoff and landing the flaps are extended from inside the wing and dramatically change the lift characteristics of the aircraft. It is remarkable how much the wing shape can be changed. Why flaps are needed will be shown in Section 4.4.2. The flaps at the trailing edge of a wing are called *simple flaps* if they consist of one single surface and *slotted flaps* if they are composed of several surfaces in a row. A 747-400, for example, has four slotted flaps. When the flaps are located at the leading edge of the wing, they are called *Krueger flaps.* Since their design is quite different from that of the trailing-edge flaps, some people prefer to refer to the high-lifting devices at the leading edge as *slats.*

The following sections present a planar two-dimensional (2-D) aircraft model and discuss performance about the longitudinal axis.

4.3 | A TWO-DIMENSIONAL AIRCRAFT MODEL

To compute the performance measures for an aircraft, we need to develop a simple two-dimensional model that captures the flight dynamics of the aircraft. Let us first discuss what a model is in a broad sense and then what our 2-D aircraft model in particular is, before we begin any derivations.

4.3.1 Understanding Engineering Models

In general, models in science and engineering are simplified (often mathematical) representations of real systems. Real systems of all kinds can contain thousands of different variables and depend on so many things that it would be impossible to analyze them if one attempted to incorporate all the system's characteristics. Meteorologists, for example, deal with one of the most complex systems that exists on earth—the weather. In the case of terrestrial weather, the system contains millions of variables ranging from the temperature of an ocean to the smoke output of a factory. Even if all system variables could be found and assigned values, it would be impossible to "compute" the weather with the existing supercomputers. These are just some of the reasons why we use models; there are many more that we can come up with.

For the purposes of this chapter we will restrict ourselves to a two-dimensional aircraft model and therefore assume that the motion is in a plane defined by the instantaneous velocity vector of the aircraft and the earth's gravitational acceleration vector. It is possible to capture several important characteristics of the vehicle without the complexity of higher-order models. The model is a mathematical one, meaning that it consists of equations. More precisely they are *equations of motion* which are ordinary differential equations (ODEs) that describe the motion (i.e., path) of the aircraft. The variables in these differential equations can be divided into two groups: *state variables* and *control variables.* The state variables such as velocity and altitude represent the *state* of the vehicle, whereas the control variables represent the *control* of the vehicle. The control variables are the physical quantities the pilot or autopilot can determine. An example of a control variable is the thrust of the aircraft. The other parameters in the equations are constants for a particular airplane (such as the mass of the aircraft) or constants for a particular environment (such as air density). Strictly speaking, neither the aircraft mass nor the air density is a constant since the total mass of the airplane is decreasing as fuel is burned and the air density varies with altitude. However, for now they are assumed to be constant.

Each of the four equations of motion will be a differential equation for a state variable, which will be a function of the other state variables, the control variables, and the constants. The solutions to the ODEs are not easily expressed in closed form (i.e., in terms of equations) because they are nonlinear. What can be done, though, is to integrate the state variables with computers starting from given initial values of the state variables, using some strategy for the pilots' choice of control. The equations can also be used in a real-time simulation where a human pilot decides on the control at each instant based on a display of the vehicle state. This means that these equations of motion are the basis for flight simulation programs. We could use our models to create an aircraft simulator on a home computer with very few lines of code. Another way to use the equations of motion is to linearize about an operating point, called a *trim condition,* so that solutions can be obtained in closed form.

This chapter will not become an exercise in solving nonlinear differential equations. We are more interested in obtaining simple and easy-to-use equations by making a few simplifying assumptions that will allow us to predict or analyze the aircraft's translational motion. These simplified equations are the flight performance equations mentioned in the introduction.

4.3.2 Equations of Motion

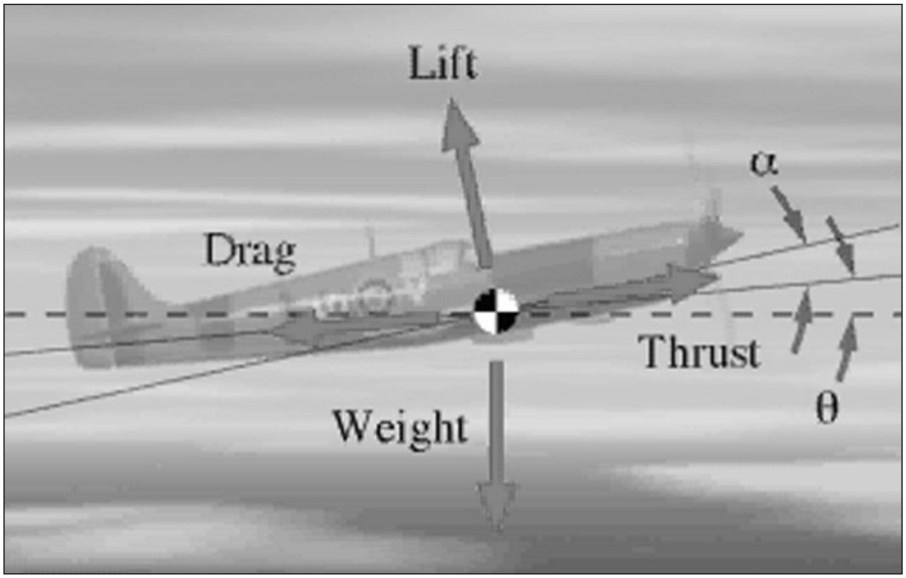
To derive the equations of motion, let us consider an aircraft in flight inclined at an angle with the horizon. The aircraft is considered a rigid body on which four forces are acting at the center of mass. These forces are:

- Lift L acting perpendicular to the flight path
- Drag D acting parallel to the forward velocity vector

- Weight $W = mg$ acting vertically downward
- Thrust T generally inclined at an angle α_T to the flight path (assumed to be zero in our case)

A sketch of the aircraft with all the forces acting on it is shown in Figure 4.3.

Figure 4.3 | Forces acting on an aircraft in a flight inclined at a flight path angle theta to the horizon.



The state variables are the velocity v, the flight path angle θ, the horizontal position x, and the altitude h. Only one of these four requires some explanation. The flight path angle (sometimes also called the pitch angle) θ is the angle that the velocity vector v makes with the horizon (or the x axis). It is *not* the angle between the body axis and the horizon. The control of the aircraft consists of the magnitude of the thrust vector $\mathbf{T}$ and the angle of attack α. In our model we will assume that $\mathbf{T}$ lies in the direction of flight, which in general depends on the location of the engine(s). The angle of attack is controlled by the elevators, which is the only one of the three control surfaces coming into play in a 2-D model. The weight of the aircraft is one of the constants.

Using the figure above and Newton's second law $F = ma$, we can derive the equations of motion. We begin by finding the acceleration $\dot{v}$ of the aircraft in the direction of flight. To get $\dot{v}$, we sum up the forces in the flight path (or tangential) direction

$$\sum F_{\text{tang}} = T - D - mg \sin\theta \qquad \textbf{[4.1]}$$

and since $F = ma = m\dot{v}$, we can write

$$m\dot{v} = T - D - mg \sin\theta \qquad \textbf{[4.2]}$$

Dividing by m, the mass of the aircraft, we get the equation of motion in the tangential direction:

$$\dot{v} = \frac{T}{m} - \frac{D}{m} - g \sin \theta \qquad \textbf{[4.3]}$$

The sum of the forces acting in the direction normal to v is given by

$$\sum F_{\perp} = L - mg \cos \theta \qquad \textbf{[4.4]}$$

But when we try to find the acceleration in the normal direction, we have to pay attention to the fact that the flight path angle θ will not be constant if there is an acceleration in the normal direction. The total force $\Sigma F_{\perp}$ can be viewed as a radial force in circular motion. From physics we recall the following equation

$$F_{\text{radial}} = \frac{m v_{\tan}^2}{r} = m v_{\tan} \dot{\theta} \qquad \textbf{[4.5]}$$

where $v_{\tan}$ is the tangential velocity and equal to v in our case. Setting Equation (4.4) and Equation (4.5) equal, we obtain

$$m v \dot{\theta} = L - mg \cos \theta \qquad \textbf{[4.6]}$$

Dividing both sides of the equation by the mass of the vehicle, we arrive at the equation of motion for the normal direction:

$$v \dot{\theta} = \frac{L}{m} - g \cos \theta \qquad \textbf{[4.7]}$$

After having arrived at the differential equation in the tangential and normal directions to the flight path, or in other words in the two directions of a coordinate system attached to the aircraft, we can write down differential equations for a coordinate system attached to "ground" (or the surface of the earth).

The velocity component of the flight velocity in the horizontal or x direction is given by

$$\dot{x} = v \cos \theta \qquad \textbf{[4.8]}$$

and correspondingly the velocity component in the vertical or h direction is

$$\dot{h} = v \sin \theta \qquad \textbf{[4.9]}$$

Now we can summarize the equations of motion for an aircraft in translational flight:

$$\begin{aligned} \dot{v} &= \frac{T}{m} - \frac{D}{m} - g \sin \theta \\ v \dot{\theta} &= \frac{L}{m} - g \cos \theta \\ \dot{x} &= v \cos \theta \\ \dot{h} &= v \sin \theta \end{aligned} \qquad \textbf{[4.10]}$$

These four equations of motion constitute our two-dimensional aircraft model, but we must discuss the limitations of the model before initiating aircraft performance analysis.

In the process of deriving the two-dimensional model, we have made several assumptions of which we need to be fully aware. Those assumptions limit our model to only specific applications. First, the assumption was made that the vehicle can be represented by a point mass. All the force vectors, such as the weight or thrust, are assumed to act at one point—the center of gravity. Another convenient simplification was to assume *no wind,* so that the relative wind v_∞ was equal in magnitude to the flight velocity v. All other effects of wind do not apply to our model since it is two-dimensional.

4.4 | STEADY FLIGHT

The equations we derived in the previous section describe the general 2-D translational motion of an aircraft for accelerated flight. For the performance parameters we are interested in, we make another simplifying assumption that the aircraft is in *steady, level flight.* This means that the aircraft is in unaccelerated flight; therefore, the flight path angle is zero. Hence, the generalized equations of motion reduce to

$$D = T \tag{4.11}$$

$$L = W \tag{4.12}$$

The thrust produced by the engine(s) exactly balances the drag, and the lift balances the weight. The performance of an airplane in steady, level flight is called the *static performance.*

EXAMPLE 4.1 Equations of Motion for an Aircraft in Steady Flight

Equations of motion. JPG

Using the animation from the CD-ROM or simulations menu on the web site entitled Equations of Motion Movie, restate the four forces acting on the aircraft. Then draw an aircraft in steady, level flight with the governing equations of motion. Remember to label all forces and angles. (All answers are given in the animation.)

4.4.1 Thrust–Velocity Curves

We continue to explore the equations of motion that govern aircraft performance. An initial performance metric relates to how much thrust is required for an aircraft to maintain level, unaccelerated flight. Expanding Equation (4.11) and Equation (4.12) with the definitions of lift and drag

$$T = D = q_\infty S C_D \tag{4.13}$$

$$W = L = q_\infty S C_L \tag{4.14}$$

and dividing Equation (4.13) by Equation (4.14) yield

$$\frac{T}{W} = \frac{C_D}{C_L} \qquad [4.15]$$

Initially, we do not need to distinguish between the thrust produced by the engines, the thrust required, and the thrust available. We assume that the thrust available exceeds the thrust required and that the thrust produced by the engines is exactly as much as is required. Hence, the thrust required for steady, level flight is

$$T = \frac{W}{C_L/C_D} = \frac{mg}{L/D} \qquad [4.16]$$

where mg has been used instead of W. Given an aircraft mass and an altitude, the thrust varies with velocity v. The relationship between the required thrust and the velocity can be calculated for any aircraft as follows:

1. Determine the air density ρ_∞ from the standard atmosphere for a given altitude h.
2. Calculate the lift coefficient C_L for a given velocity v, by recalling the definition of dynamic pressure $q = 1/2\rho_\infty v^2$:

$$C_L = \frac{2W}{\rho_\infty v^2 S} \qquad [4.17]$$

3. Calculate the drag coefficient from the drag polar for the aircraft.

$$C_D = C_{D,0} + \frac{C_L^2}{\pi e \mathrm{AR}}$$

4. Calculate the thrust required for steady, level flight, using Equation (4.16).

Given a specific aircraft, we can determine the thrust required for many different velocities to find the so-called thrust–velocity curves. This is a tedious task when done by hand, but when automated is quite useful in capturing this aspect of aircraft performance.

Aircraft Thrust–Velocity Simulation

EXAMPLE 4.2

A thrust–velocity (T–v) simulation tool is provided on the CD-ROM. Use the simulator to characterize a Boeing 727 in steady, level flight. (See Figure 4.4.)

Given: Thrust available, T_A = 186,825 N; weight W = 711,235 N; wing surface area S = 145 m^2; aspect ratio AR = 7.67; Oswald efficiency e = 0.8; $C_{D,0}$ = 0.017; $C_{L,\max}$ = 1.4; altitude h = 5,000 m.

What is the thrust required at a velocity v = 99 m/s?

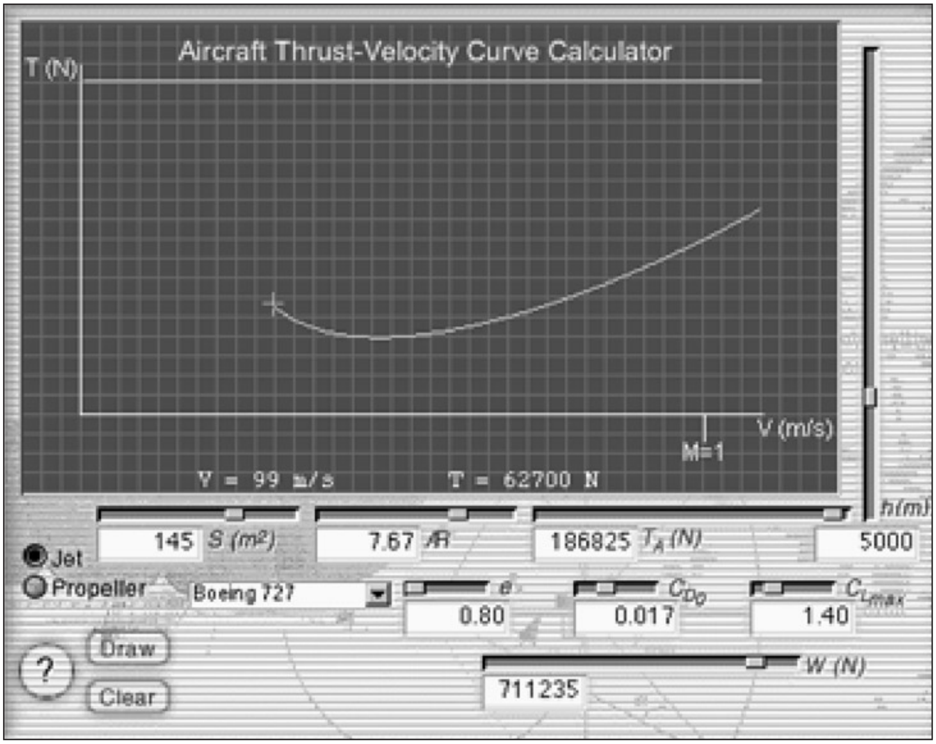
Answer: T = 62,700 N

What is the speed at the minimum thrust required?

Answer: v = 155 m/s when $T \approx$ 43,000 N.

Thrust–velocity simulation.

Figure 4.4 | Thrust–velocity simulation for a Boeing 727 aircraft.



For a propeller-driven aircraft, we assume that the thrust available decreases approximately linearly with increasing speed. For the jet engine example above, we assumed the engines put out thrust available over the entire operating range of aircraft velocities, which is reasonable for speeds less than Mach 1. However, thrust produced by propellers is significantly affected by the aircraft's operating velocity and altitude. There is a crossover velocity where diminishing thrust available and increasing thrust required intersect, as seen in Figure 4.5.

EXAMPLE 4.3 Thrust–Velocity Curve for a Propeller-Driven Aircraft

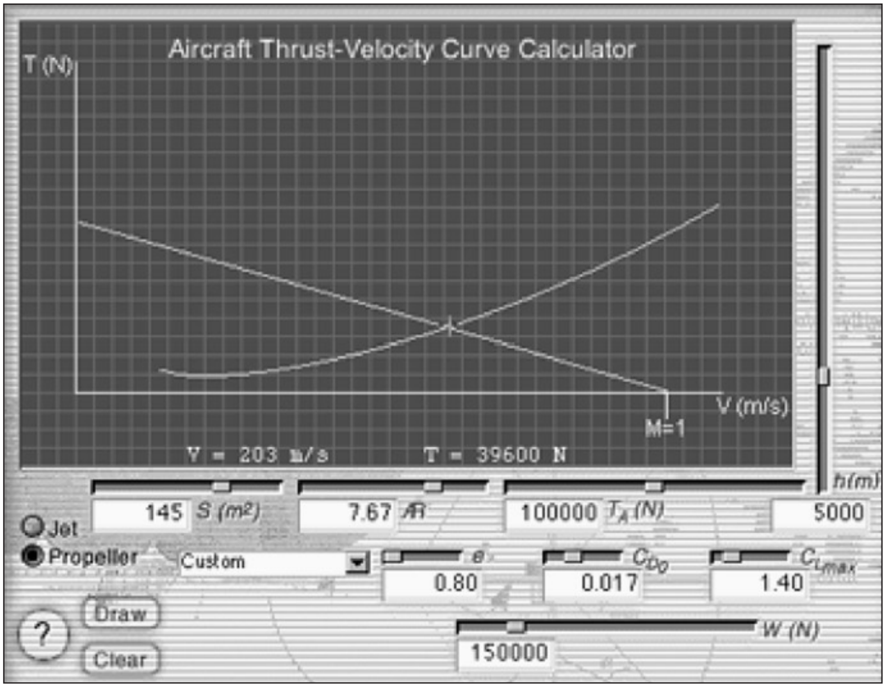
Using the thrust–velocity (T–v) simulation tool on the CD-ROM, find the crossover point for the following aircraft.

Given: Thrust available and thrust required $T_A = T_R = 39{,}600$ N; weight $W = 150{,}000$ N; wing surface area $S = 145$ m^2; aspect ratio AR = 7.67; Oswald efficiency $e = 0.8$; $C_{D,0} = 0.017$; $C_{L,\max} = 1.4$; altitude $h = 5{,}000$ m.

What is the velocity?

Answer: $v = 203$ m/s.

Figure 4.5 | Thrust–velocity curve for a propeller-driven aircraft.



4.4.2 The Stalling Speed of an Aircraft

The next important question to ask is, What is the slowest speed an airplane can fly in a straight and level flight? The derivation begins by writing down the definition of the lift coefficient.

$$C_L = \frac{L}{qS} \tag{4.18}$$

Multiplying both sides of the equation by qS and substituting for q the definition of dynamic pressure, we get

$$C_L\left[\frac{1}{2}\rho v^2\right]S = L \tag{4.19}$$

Since the aircraft is in a level flight, the lift L is equal in magnitude to the weight $W = mg$, so that the equation becomes

$$\frac{C_L \rho v^2 S}{2} = W \tag{4.20}$$

Rearranging the equation to obtain an expression for the minimum speed we get

$$v = \sqrt{\frac{2W}{\rho S C_L}} \tag{4.21}$$

If we examine Equation (4.21), we see that the minimum speed will occur when the lift coefficient reaches a maximum value. We saw that the maximum value of C_L is $C_{L,\,\max}$, the lift coefficient at stalling. The slowest speed at which an aircraft can fly in a straight and level flight is therefore called the *stalling speed* v_{stall}. It is given by the following equation:

$$v_{\text{stall}} = \sqrt{\frac{2W}{\rho S C_{L,\,\max}}} = \sqrt{\frac{2}{\rho C_{L,\,\max}}\left(\frac{W}{S}\right)} \tag{4.22}$$

For a given (real) aircraft all the parameters in Equation (4.22) seem to be constant. The wing area, mass, and maximum lift coefficient do not change. The problem with the minimum speed appears during takeoff or landing, where the airplane encounters its lowest speeds. To decrease the stalling speed, aircraft are equipped with high-lift devices such as flaps, as discussed earlier. The pilot can increase the wing area and the camber of the wing through the flaps, which in turn causes the denominator in Equation (4.22) to increase. The net result is that v_{stall} decreases significantly.

Notice that in the second formula for the stalling speed in Equation (4.22) the ratio W/S is explicitly written out. This is to highlight the ratio, known as the *wing loading,* which is a metric often quoted for aircraft performance.

EXAMPLE 4.4

An Aircraft in Stall

Returning to Example 4.1, for the same aircraft in steady, level flight, what is the stall speed?

$$v_{\text{stall}} = \sqrt{\frac{2W}{\rho S C_{L,\,\max}}} = \sqrt{\frac{2}{\rho C_{L,\,\max}}\left(\frac{W}{S}\right)} = \sqrt{\frac{2}{\rho(1.4)}\left(\frac{711{,}235\text{ N}}{145\text{ m}^2}\right)}$$

where density at 5,000 m is $\rho \approx 0.73762$ kg/m^3, which was obtained using the FoilSim program introduced in Chapter 3, “Aerodynamics.”

Answer: $v_{\text{stall}} = 99$ m/s

4.4.3 Maximum Lift-to-Drag Ratio

The maximum lift-to-drag ratio $(L/D)_{\max}$ has a great importance for many flight performance calculations. It is a measure of the overall aerodynamic efficiency of an aircraft.

Let us now find at which value of lift coefficient C_L the lift-to-drag ratio reaches a maximum. We start by noting that L/D is equal to C_L/C_D and use the constant k to represent the wing properties, $k = 1/(\mathrm{AR}\pi e)$. The lift-to-drag ratio can be written as

$$\frac{L}{D} = \frac{C_L}{C_D} = \frac{C_L}{C_{D,0} + kC_L^2} \quad \textbf{[4.23]}$$

Since we would like to maximize this expression, we differentiate it with respect to C_L and set it equal to zero. By the quotient rule, we obtain the following expression:

$$\frac{d(L/D)}{dC_L} = \frac{C_{D,0} + kC_L^2 - C_L(0 + 2kC_L)}{(C_{D,0} + kC_L^2)^2} = 0 \quad \textbf{[4.24]}$$

For Equation (4.24) to be zero, the numerator has to be equal to zero

$$C_{D,0} + kC_L^2 - C_L(0 + 2kC_L) = 0 \quad \textbf{[4.25]}$$

This occurs when

$$C_L = \sqrt{\frac{C_{D,0}}{k}} \quad \textbf{[4.26]}$$

We can rewrite the coefficient of lift at which the maximum lift-to-drag ratio occurs in terms of the wing aspect ratio and the airplane efficiency factor

$$C_{L,(L/D)_{\max}} = \sqrt{C_{D,0}\pi e \mathrm{AR}} \quad \textbf{[4.27]}$$

The above equation can also be understood as a *condition* for $(L/D)_{\max}$. By rearranging the equation, we get the condition that the parasite drag coefficient has to be equal to the induced drag coefficient, as shown in the following equation:

$$C_{D,0} = \frac{C_L^2}{\pi e \mathrm{AR}} = C_{D,i} \quad \textbf{[4.28]}$$

Knowing $C_{D,0}$, we can calculate $(L/D)_{\max}$ by writing

$$\left(\frac{L}{D}\right)_{\max} = \frac{C_L}{2C_L^2/(\pi e \mathrm{AR})} = \frac{\pi e \mathrm{AR}}{2C_{L,(L/D)_{\max}}} \quad \textbf{[4.29]}$$

Typical values of the maximum lift-to-drag ratio for some types of aircraft are shown in Table 4.1.

Table 4.1 | Typical values of the maximum lift-to-drag ratio

Type of aircraft	$(L/D)_{\max}$
Modern sailplanes	25–40
Civil jet airliners	12–20
Supersonic fighter aircraft	4–9

4.4.4 Endurance and Range of an Aircraft

In this section we derive equations that will allow us to calculate the *range* and endurance of an aircraft. The range is defined as the total distance an aircraft can traverse on a tank of fuel. Related to range is *endurance,* which is defined as the total time that an aircraft can stay aloft on a tank of fuel.

Both range and endurance depend not only on the aerodynamic characteristics of the aircraft but also on the characteristics of the engines. Hence, we need to make a distinction between piston-engine propeller-driven and jet-powered aircraft. We consider propeller aircraft first and then turn to jets.

Let us define a few important mass-related quantities:

- m_0 = mass of aircraft without fuel, kg
- m_f = mass of fuel, kg
- $\dot{m}_f$ = fuel mass flow rate, kg/s

The quantities m_0 and m_f are self-explanatory; the fuel mass flow rate is the amount of fuel (measured by mass) that the engines use per unit time. The gross mass of the aircraft is the sum of the mass of the aircraft and the mass of the fuel, so that we can write $m = m_0 + m_f$.

Endurance and Range of Propeller Aircraft A piston engine (or reciprocating engine) burns fuel in cylinders and uses the energy released to move pistons, which in turn deliver power to a rotating crankshaft on which a propeller is mounted. The power delivered to the propeller by the shaft is called *shaft brake power P.* The propeller uses the power delivered to it by the shaft to propel the aircraft. It does so with an efficiency η, which is always less than 1. Therefore the power required from the engine to overcome drag D and fly at a velocity v with a propeller having an efficiency η is given by

$$P = \frac{1}{\eta} D v \qquad \textbf{[4.30]}$$

The piston engine consumes fuel at a rate $\dot{m}_f$. The fuel mass the engine requires per unit energy it produces is denoted by c with units of kilograms per joule (kg/J).

We can replace P by $\dot{m}_f/c$ and multiply by W/L, which is equal to unity in steady, level flight, so that

$$\frac{\dot{m}_f}{c} = \frac{1}{\eta} D \frac{W}{L} v = \frac{1}{\eta} \frac{mg}{(L/D)} v \qquad \textbf{[4.31]}$$

The change in mass of the aircraft dm/dt is equal in magnitude to the fuel mass flow rate but opposite in sign, which we use to rewrite our expression as

$$-\frac{dm}{dt} = \frac{c}{\eta} \frac{mg}{L/D} \frac{ds}{dt} \qquad \textbf{[4.32]}$$

From Equation (4.32), we can derive both the range and endurance equations for propeller aircraft. Let us begin by finding the range. Rearranging the previous equation to

$$-\frac{dm}{m} = \frac{c}{\eta} \frac{g}{L/D} ds \qquad \textbf{[4.33]}$$

and assuming that $L/D = C_L/C_D$ is constant throughout the flight, we integrate both sides

$$\int_{m_0+m_f}^{m_0} -\frac{dm}{m} = \frac{c}{\eta}\frac{g}{L/D}\int_0^R ds \tag{4.34}$$

which produces

$$R = \frac{\eta}{c}\frac{L/D}{g}\ln\left(1 + \frac{m_f}{m_0}\right) \tag{4.35}$$

The above equation is the famous *Breguet range equation.* From the equation, we see that if we want to achieve the maximum possible range, we need to fly at the maximum lift-to-drag ratio.

Now let us find the endurance for a propeller-driven aircraft. Using Equation (4.32) and recalling Equation (4.21), we write

$$-\frac{dm}{m} = \frac{c}{\eta}\frac{g}{L/D}\sqrt{\frac{2mg}{\rho_\infty S C_L}}\,dt \tag{4.36}$$

Rearranging terms and replacing L/D by C_L/C_D yields

$$-\frac{dm}{m^{3/2}} = \frac{c}{\eta}g^{3/2}\left(\frac{C_D}{C_L^{3/2}}\right)\sqrt{\frac{2}{\rho_\infty S}}\,dt \tag{4.37}$$

Performing the integration

$$\int_{m_0+m_f}^{m_0} -\frac{dm}{m^{3/2}} = \frac{c}{\eta}g^{3/2}\left(\frac{C_D}{C_L^{3/2}}\right)\sqrt{\frac{2}{\rho_\infty S}}\int_0^E dt \tag{4.38}$$

results in the following expression for the endurance:

$$E = \frac{\eta}{cg^{3/2}}\sqrt{2\rho_\infty S}\left(\frac{C_L^{3/2}}{C_D}\right)\left(\sqrt{m_0} - \sqrt{m_0 + m_f}\right) \tag{4.39}$$

Equation (4.39) is the *Breguet endurance equation* or the maximum time a propeller-driven aircraft can stay in the air. To maximize its endurance, the aircraft needs to fly such that $C_L^{3/2}/C_D$ is a maximum.

Endurance and Range for a Jet Aircraft A jet engine produces thrust by combustion-heating an incoming airstream and ejecting it at a high velocity through a nozzle. The jet engine consumes fuel at a rate $\dot{m}_f$. The fuel weight the engine requires per unit thrust per unit time it produces is denoted by μ, with units of N/(N·s). Hence the thrust produced by the engines in terms of μ is simply

$$T = \frac{\dot{m}_f g}{\mu} \tag{4.40}$$

Equation (4.16) related the lift-to-drag ratio to the thrust. We can now rewrite the equation in terms of the fuel consumption

$$T = \frac{mg}{L/D} = \frac{\dot{m}_f g}{\mu} \tag{4.41}$$

The change in mass of the aircraft is identical to the fuel mass flow rate, so that we can write

$$-\frac{dm}{dt} = \mu \frac{m}{L/D} \tag{4.42}$$

Note that the minus sign reflects the fact that the total mass of the aircraft is decreasing due to a (positive) flow of fuel mass to the engines. The next step is to rearrange the equation and replace L/D by C_L/C_D, which we assume to be equal:

$$-\frac{dm}{m} = \frac{\mu}{C_L/C_D}\,dt \tag{4.43}$$

We can now integrate both sides of the equation

$$\int_{m_0+m_f}^{m_0} -\frac{dm}{m} = \frac{\mu}{C_L/C_D}\int_0^E dt \tag{4.44}$$

where E is the endurance, which yields

$$E = \frac{1}{\mu}\frac{C_L}{C_D}\ln\left(1 + \frac{m_f}{m_0}\right) \tag{4.45}$$

For a jet aircraft to stay aloft the maximum amount of time, it needs to fly at a maximum L/D.

To calculate the range of the aircraft, we go back to Equation (4.43) and replace dt by dl/v, where dl is the distance flown in time dt at a velocity v.

$$-\frac{dm}{m} = dl\,\frac{\mu}{(C_L/C_D)v} \tag{4.46}$$

From Equation (4.21) we know that

$$v = \sqrt{\frac{2mg}{\rho_\infty S C_L}} \tag{4.47}$$

which we plug into Equation (4.46):

$$-\frac{dm}{\sqrt{m}} = \frac{\mu}{\sqrt{C_L}/C_D}\sqrt{\frac{\rho_\infty S}{2g}}\,dl \tag{4.48}$$

Assuming that μ, C_L, C_D, and ρ_∞ are constant, we can now integrate both sides of Equation (4.48):

$$\int_{m_0+m_f}^{m_0} -\frac{dm}{\sqrt{m}} = \frac{\mu}{\sqrt{C_L}/C_D}\sqrt{\frac{\rho_\infty S}{2g}}\int_0^R dl \tag{4.49}$$

where R denotes the maximum distance the aircraft can fly on one tank of fuel—the range. Performing the forward integration, we obtain the following expression for the range of a jet aircraft:

$$R = \frac{2}{\mu}\sqrt{\frac{2g}{\rho_\infty S}}\frac{C_L^{1/2}}{C_D}\left(\sqrt{m_0 + m_f} - \sqrt{m_0}\right) \quad \textbf{[4.50]}$$

We see that the maximum range for a jet-powered aircraft is achieved when it flies such that $C_L^{1/2}/C_D$ is a maximum. This condition can be restated in terms of L/D by using Equation (4.21):

$$v\frac{L}{D} = \sqrt{\frac{2mg}{\rho_\infty S C_L}}\frac{C_L}{C_D} = \sqrt{\frac{2mg}{\rho_\infty S}}\frac{C_L^{1/2}}{C_D} \quad \textbf{[4.51]}$$

Hence we see that the maximum range of a jet aircraft is dictated by the product $v(L/D)$, while the endurance is determined by L/D.

To further understand aircraft range and the guiding performance parameters, let us compare the Boeing 747 four-engine jet aircraft and the Voyager around-the-world propeller aircraft. To attain the maximum range, four tradeoffs in Table 4.2 are highlighted.

Table 4.2 | Aircraft range comparison

Attaining maximum range	Boeing 747	Voyager
1. Large fuel mass/empty mass ratio	≈ 0.7	≈ 8
2. Large L/D	≈ 20	≈ 40
3. Large η	≈ 0.8	≈ 0.85
4. Low μ, low c	$\mu \approx 1.5 \times 10^{-4}\,\mathrm{s}^{-1}$	low c

Let us investigate the first two design parameters further, starting with the mass ratio. A large m_{fuel}/m_0 can be obtained through proper selection of aircraft structures, materials, and overall design, as shown in Table 4.3.

Table 4.3 | Designing for a large mass ratio

Mass ratio m_{fuel}/m_0	Boeing 747	Voyager
Efficient structure	Redundant for safety	Not redundant
Advanced materials	Aluminum	Graphite-epoxy (5× stronger and stiffer for given cut)
High aspect ratio	10	40
Smooth surface	Riveted aluminum	Molded
Fuselage, tail, etc.	Large	Small

A large L/D ratio is similarly obtained through the design parameters in Table 4.4.

Table 4.4 | Designing for a large L/D ratio

L/D design parameters	Boeing 747	Voyager
High aspect ratio	10	40
Smooth surface	Riveted aluminum	Molded
Fuselage, tail, etc.	Large	Small

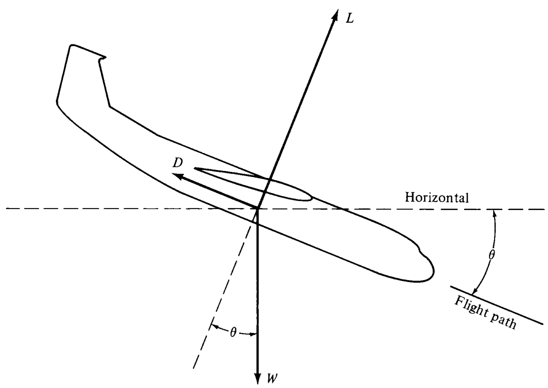
A high aspect ratio wing results in a mass penalty to attain the large L/D ratio, which reduces the m_{fuel}/m_0 ratio. Therefore, the design tradeoffs between attaining the optimal mass ratio and attaining the maximum lift-to-drag ratio are offsetting effects. Careful consideration and detailed analysis between the design trade space result in the optimal configuration depending on the aircraft mission (i.e., air passenger flight or around-the-world record-breaking flight).

The next performance metric to consider is how well a certain aircraft design glides.

4.4.5 Gliding Flight

Let us turn to a special case, gliding or unpowered flight. In this case the thrust is equal to zero; the flight path is steady, but it is not level. Figure 4.6 shows a free-body diagram of an aircraft in an equilibrium glide.

Figure 4.6 | Free Body Diagram of an aircraft in a gliding flight.



By examining Figure 4.6, it is easy to balance the forces. We write

$$L = mg \cos \theta \tag{4.52}$$

$$D = mg \sin \theta \tag{4.53}$$

To calculate the glide angle, we divide Equation (4.53) by Equation (4.52):

$$\frac{mg \sin \theta}{mg \cos \theta} = \frac{D}{L} \tag{4.54}$$

which can be rewritten as

$$\tan \theta = \frac{1}{L/D} \tag{4.55}$$

To achieve the maximum range, the glide angle has to be a minimum, which occurs when the lift-to-drag ratio is a maximum:

$$\tan \theta_{\min} = \frac{1}{L/D_{\max}} \tag{4.56}$$

Gliding flight is an excellent illustration of how the lift-to-drag ratio represents an overall aerodynamic efficiency criterion for an aircraft. We now move on to the final performance category of accelerated flight.

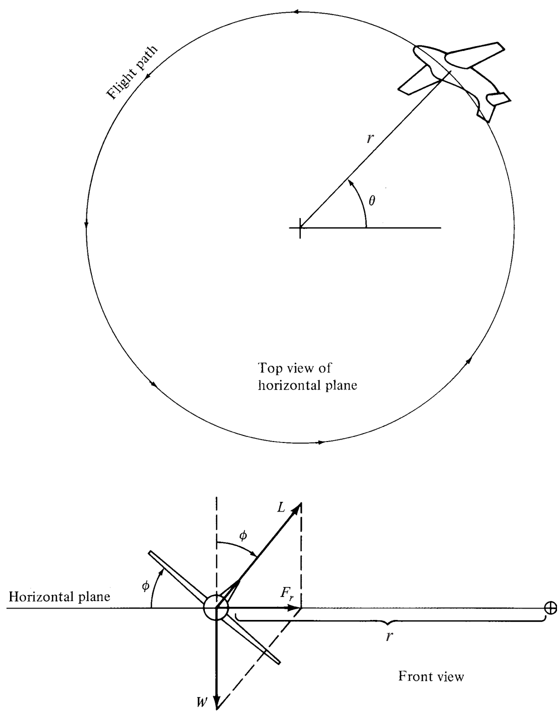
4.5 | ACCELERATED FLIGHT

In this section we examine the flight performance of an aircraft experiencing radial acceleration, which leads to a curved flight path. In particular, we consider three special cases: a level turn, a pull-up maneuver, and a pushdown maneuver. As part of the discussion, we introduce a quantity called the load factor, which allows us to determine the flight regime (i.e, an operational flight envelope) that an aircraft can fly as a function of velocity.

4.5.1 Turning Flight

Level Turn Consider an aircraft making a level (i.e., horizontal) turn. To make such a turn, the pilots needs to deflect the ailerons such that the lift vector on one wing is smaller than that on the other, which causes a net moment about the longitudinal axis of the aircraft and results in the wings making an angle, called the bank angle ϕ, with the vertical. A top view and side view of an aircraft making a level turn are shown in Figure 4.7. From Figure 4.7, it is easy to see that the

Figure 4.7 | The diagrams show a top view and a front view of an aircraft making a level turn.



weight of the aircraft is balanced by the vertical component of the lift vector, so that we can write

$$L \cos \phi = W = mg \tag{4.57}$$

The horizontal component of the lift vector acts as the centripetal force for the turn. It is in the radial direction, denoted by F_r, and written as

$$F_r = L \sin \phi = \sqrt{L^2 - W^2} \tag{4.58}$$

At this point it is useful to define the *load factor*

$$n \equiv \frac{L}{W} \tag{4.59}$$

It is fairly intuitive that an aircraft or any other mechanical device can tolerate only a limited amount of force (or acceleration) acting on it before a structural failure occurs. For aircraft, it is typical to specify this operating range in terms of the load factor n. Later, we will discuss the range of permissible load factors in greater detail. We can now write the bank angle ϕ in terms of the load factor

$$\phi = a \cos \frac{1}{n} \tag{4.60}$$

Let us now derive an expression for the turning radius of the aircraft in a level turn for a given load factor. We begin by rewriting Equation (4.58) in terms of the load factor

$$F_r = \sqrt{L^2 - W^2} = W\sqrt{n^2 - 1} \tag{4.61}$$

From physics, we recall that the centripetal force required for an object with mass m rotating is given by

$$F_r = m\frac{v^2}{r} = \frac{W}{g}\frac{v^2}{r} \tag{4.62}$$

where r is the radius and g is the gravitational acceleration. Setting Equation (4.61) and Equation (4.62) equal, we can solve for the turning radius

$$r = \frac{v^2}{g\sqrt{n^2 - 1}} \tag{4.63}$$

Alternatively, we can determine the load factor acting on an aircraft when it makes a level turn of a specified radius

$$n = \sqrt{\frac{v^4}{r^2 g^2} - 1} \tag{4.64}$$

The *turn rate* is the angular velocity of the aircraft $d\theta/dt$, which is simply

$$\frac{d\theta}{dt} = \omega = \frac{v}{r} \tag{4.65}$$

Substituting Equation (4.63) into Equation (4.65), we obtain the turn rate as a function of the load factor and the velocity of the aircraft

$$\omega = \frac{g\sqrt{n^2 - 1}}{v} \qquad \textbf{[4.66]}$$

The F-16 Turning Radius

EXAMPLE 4.5

For high-performance military aircraft, it is not the structure but the pilot who is the limiting factor for the maximum load factor. The load factor is typically specified in *g*'s, where 1 *g* means an acceleration of 9.81 m/s^2. The F-16 fighter is designed such that the aircraft and the pilot can withstand a load factor (i.e, an acceleration) of 9 *g* and more. The turning radius for an F-16 experiencing a load factor of 9 *g* and flying subsonically at, say, 800 km/h, is quite large:

$$r = \frac{v^2}{g\sqrt{n^2 - 1}} = \frac{(222\ \mathrm{m/s})^2}{(9.81\ \mathrm{m/s^2})\sqrt{9^2 - 1}} = 563\ \mathrm{m}$$

For large values of n, we can make the following approximation for r:

$$r = \frac{v^2}{g\sqrt{n^2 - 1}} \approx \frac{v^2}{gn} \qquad \text{for } n \gg 1$$

The lift in terms of the velocity is

$$L = \frac{1}{2}\rho_\infty v^2 S C_L$$

Rearranging the previous equation in terms of the velocity squared yields

$$v^2 = \frac{2L}{\rho_\infty S C_L}$$

We can substitute v^2 and n into the expression above for r, to yield

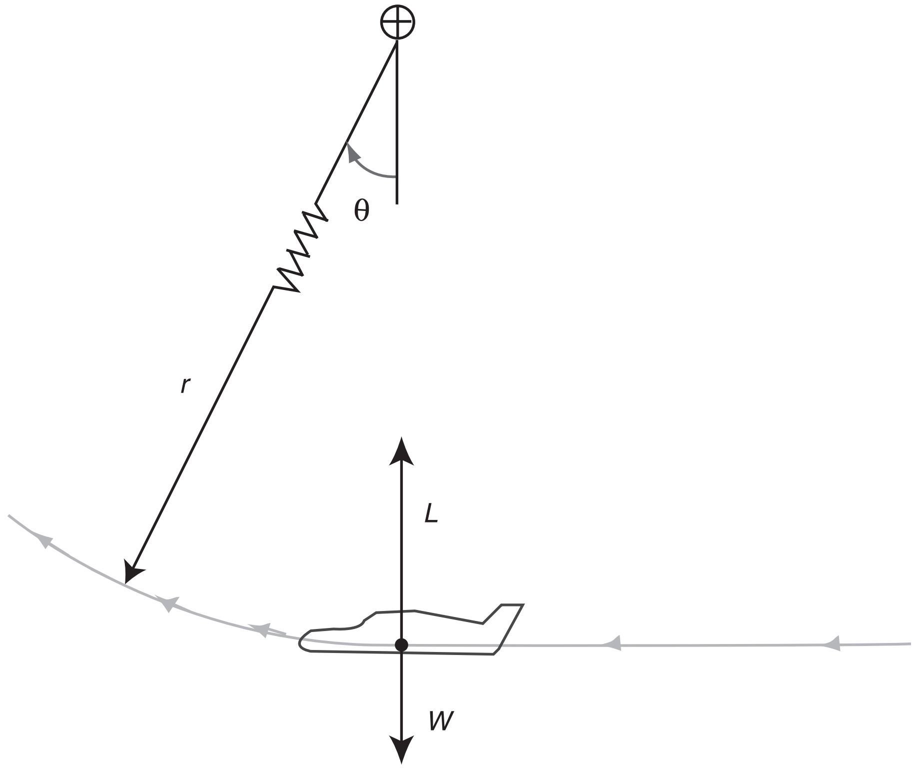
$$r = \frac{2}{\rho_\infty C_L g}\frac{W}{S} \qquad \text{for } n \gg 1$$

where we have expressed the turning radius r for large load factors in terms of the wing loading W/S.

The Pull-up Maneuver In the pull-up maneuver the aircraft is initially in straight and level flight, so that $L = W$. Then the pilot pulls on the control column (the yoke) to deflect both ailerons to create more lift. Due to the increase in lift, the aircraft will turn upward. The maneuver is shown schematically in Figure 4.8. As the figure shows, the flight path is curved in a plane perpendicular to the ground with a turn rate $\omega = d\theta/dt$. The net force F_r acting on the aircraft is given by

$$F_r = L - W = W(n - 1) \qquad \textbf{[4.67]}$$

Figure 4.8 | The diagram shows an aircraft in a pullup maneuver.



Thinking of this force as a centripetal force for a rotation, we write

$$F_r = m\frac{v^2}{r} = \frac{W}{g}\frac{v^2}{r} \tag{4.68}$$

as for the level turn. Equating Equation (4.67) with Equation (4.68) and solving for the turning radius r, we obtain

$$r = \frac{v^2}{g(n-1)} \tag{4.69}$$

Conversely, the load factor in terms of the turning radius and the velocity is given by

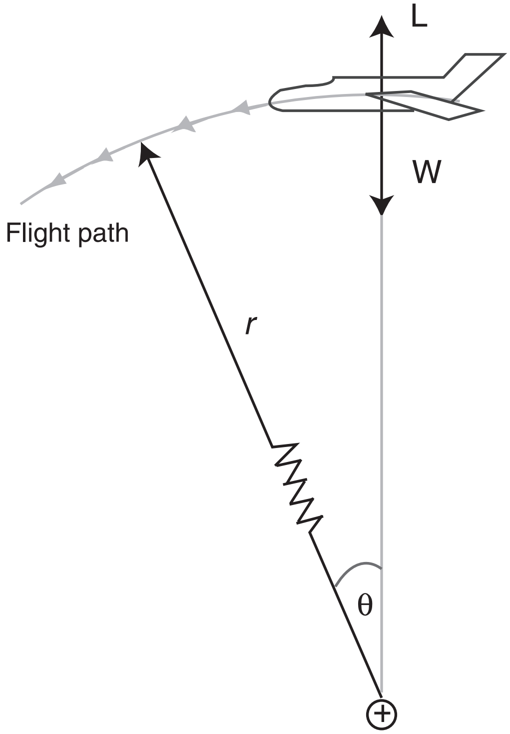
$$n = \frac{v^2}{rg} + 1 \tag{4.70}$$

The turning rate ω is calculated as for the level turn case, so that we obtain

$$\omega = \frac{v}{r} = \frac{g(n-1)}{v} \tag{4.71}$$

Pushdown Maneuver In the third and final case, the pushdown maneuver, the aircraft is initially in a straight and level flight. Then the pilot pushes on the control column (the yoke) to deflect both ailerons to create less lift. Since now $W > L$, the aircraft will turn downward. The maneuver is shown schematically in Figure 4.9.

Figure 4.9 | The diagram shows an aircraft in a "pushdown" maneuver.



A note of caution is necessary for this case. While an aircraft can make a complete level turn (i.e., a circle) or loop in a pull-up maneuver, aircraft cannot fly a loop downward. For this reason, the following calculation is only theoretical.

We follow the same procedure to determine the turn radius and the turn rate.

$$F_r = W - L = W(1 - n) = \frac{W}{g}\frac{v^2}{r} \quad \textbf{[4.72]}$$

Solving for r, we get the following expression:

$$r = \frac{v^2}{g(1 - n)} \quad \textbf{[4.73]}$$

Rearranging Equation (4.73) to produce the load factor in terms of the radius yields

$$n = 1 - \frac{v^2}{rg} \tag{4.74}$$

Since the radius, the velocity squared, and g are all positive quantities, the load factor n must be negative for this kind of maneuver. The turning rate is, as before, determined from v/r, which in this case turns out to be

$$\omega = \frac{g(1 - n)}{v} \tag{4.75}$$

4.5.2 The *V–n* Diagram

Let us now determine the *flight envelope* of an aircraft, in other words the region where the aircraft operates in terms of velocity and structural load. A diagram depicting the flight envelope is appropriately called the *V–n* diagram.

There are two kinds of sources for the operating boundary of the aircraft:

- Aerodynamic
- Structural

Recall the definition of the load factor, Equation (4.59), and substitute Equation (4.19) in for lift:

$$n = \frac{L}{W} = \frac{\frac{1}{2}\rho v^2 C_L S}{W} \tag{4.76}$$

Expressing n in terms of the wing loading, we have the following equation that relates flight velocity v to load factor:

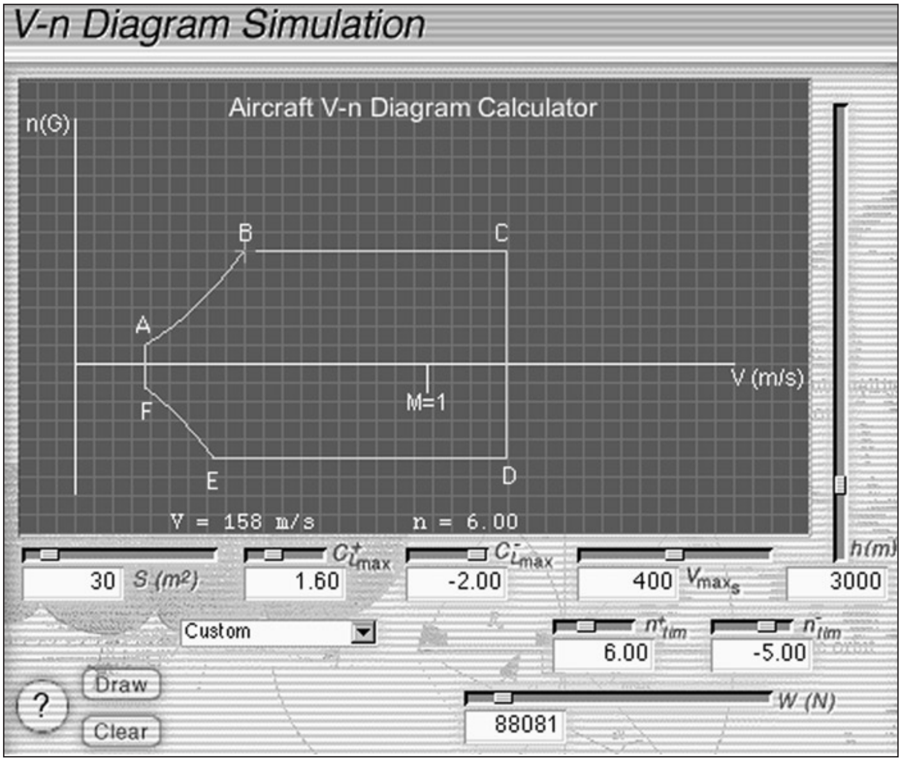
$$n_{\max} = \frac{1}{2}\frac{\rho C_{L,\max}}{W/S} v^2 \tag{4.77}$$

Notice that we used $C_{L,\max}$ instead of C_L since we wanted to determine the maximum value of n for a given velocity v.

As was alluded to earlier, an aircraft can operate only in a limited range of load factors due to structural considerations. A load factor larger than the *limit load factor* results in permanent deformation of the structure. If the load factor exceeds the *ultimate load factor,* the aircraft experiences a structural failure. In other words, it breaks apart. From an operational point of view, it is clear that we would like to operate below the limit load factor. Plotting Equation (4.77) and taking the limit load factor into account, we can draw a *V–n* diagram, which is shown in Figure 4.10.

Let us examine the boundaries of the flight envelope. Point A corresponds to a minimum velocity and positive load factor. The curve AB denotes the stall limit, which is an aerodynamic limit imposed on the load factor governed by $C_{L,\max}$. Flying outside of this region (i.e., to the left) marked by curve AB represents unobtainable flight because for a constant velocity along curve AB when

Figure 4.10 | *V–n* diagram, or flight envelope, for a Cessna *Citation*-like aircraft.



the angle of attack is increased, the wing stalls and the load factor decreases. As the velocity increases, so does the load factor to a maximum value $n_{\max}$, represented by point *B*. At point *B* both the lift coefficient and *n* are at their highest possible values that can be obtained within the allowable flight envelope. The velocity corresponding to point *B* is known as the *corner velocity* (marked by the cursor on the figure) or *maneuver point* denoted by v^* and calculated as follows:

$$v^* = \sqrt{\frac{2n_{\max}}{\rho C_{L,\max}} \frac{W}{S}} \qquad \textbf{[4.78]}$$

The maneuver point offers ideal performance because from Equation (4.73) and Equation (4.75) this point corresponds to the smallest possible turn radius simultaneously with the largest possible turn rate. The horizontal line *BC* marks the *positive limit load factor,* while the line *CD* is a high-speed structural limit. The velocity corresponding to line *CD* is the *terminal dive velocity.* The horizontal line *ED* is the *negative limit load factor.* By design, the magnitude of the positive limit load factor is typically larger than the magnitude of the negative limit load factor. The curve *AF* is the stall limit for negative angles of attack.

EXAMPLE 4.6 The *V–n* simulation

V–n *diagram simulation.*

Using the velocity–load (*V–n*) simulation tool on the CD-ROM, find the flight envelope for a Boeing 727 aircraft with the following characteristics.

Given: Flying at an altitude of 10,000 m; $S = 145\ \mathrm{m}^2$; $C_{L+\max} = 1.4$, $C_{L\text{-}\max} = -2.0$; $v_{\max} = 300$ m/s; the loading limits are $n = \pm 4$ *g*'s; and the aircraft weight is $W = 711{,}235$ N.

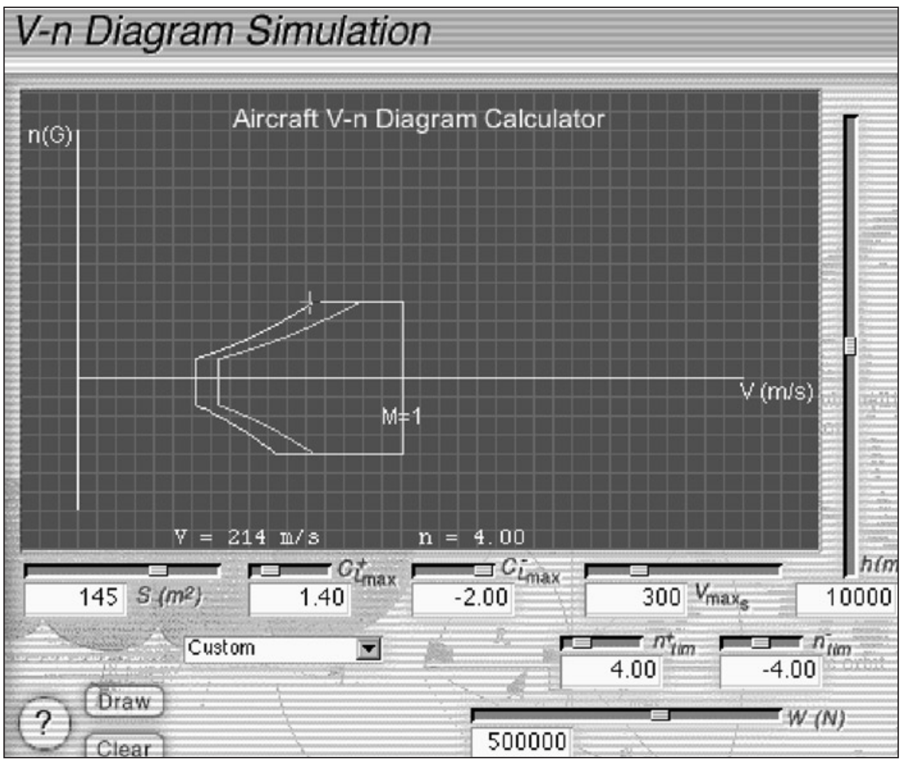
What is the velocity of load factor at the maneuver point?

Answer: $v = 261$ m/s.

If the aircraft weight were reduced to $W = 500{,}000$ N, describe in words how the flight envelope would change, and give the new corner velocity.

Answer: The flight envelope is expanded when the weight is reduced. Specifically, the regions corresponding to points *AB* and *EF* shift left. The maneuver speed, or corner velocity, is less than before at $v = 215$ m/s (see Figure 4.11).

Figure 4.11 | Expanding the *V–n* diagram flight envelope of an aircraft.



In this chapter we discussed aircraft performance, concentrating on aircraft speed, range, and endurance. A model was presented to investigate the flight dynamics by solving the equations of motion. We discussed steady flight where the relation between aircraft thrust and velocity was highlighted. The stall speed and maximum lift-to-drag ratios were shown to greatly affect flight performance calculations. Endurance and range were derived for both propeller-driven and jet-engine aircraft. Steady, nonlevel flight resulted in gliding flight. Accelerated flight led to derivations for turning flight and flight maneuvers. The chapter culminated in a determination of the aircraft flight envelope, or *V–n* diagram, where the boundaries of aircraft velocity and loading limits are coupled.

PROBLEMS

4.1 Using the "Equations of Motion" animation from the CD-ROM, the force and velocity vectors are given. Assume incompressible, inviscid flow. For a curvilinear path:

(a) Define, in words, lift, drag, thrust, and weight.

(b) What is the equation of motion along the direction of the flight path?

(c) What is the equation of motion normal to the flight path?

(d) What conditions must exist to be in stable, level flight?

4.2 Explain why it is important to know the amount and distribution of fuel and payload inside the aircraft before every flight.

4.3 Aircraft of the DC-9/Boeing 727 type have the engines attached to the tail. Hence the horizontal stabilizer cannot be mounted at its usual location on the tail and was placed on top of the vertical stabilizer. Does this arrangement affect the pitching moments acting on the aircraft (about the center of gravity)? Why or why not?

4.4 Imagine being the pilot of a multiengine aircraft, such as the Boeing 747 Jumbo Jet, whose rudder gets stuck in flight and can no longer be deflected. Can you think of a method to create a yawing moment without the help of the rudder?

$\int$ *Numeric*

4.5 The stall speed of wide-body airliner was determined to be 133 kn at sea level with flaps down and wheels up. Find $C_{L,\max}$ if the aircraft has a weight of 260 tons and a wing area of 360 m^2.

4.6 Calculate the thrust required for an aircraft, modeled after a Canadair Challenger Business Jet, to maintain steady level flight of 350 kn at an altitude of 6,500 m. Assume the following characteristics for the aircraft:

Weight = 16,350 kg

Wing area = 48.31 m^2

Wing span = 19.61 m

Parasitic drag = $C_{D,0}$ = 0.02

Oswald efficiency factor e = 0.8

4.7 For a given velocity and turning radius, does the level turn (LT) or the pull-up (PU) maneuver produce a higher load factor? Why?

4.8 Calculate the minimum landing speed that a short- to medium-range jetliner, modeled after the Boeing 737-300, can have when landing at the Denver, Colorado, International Airport when its landing weight is 40,000 kg. The wing surface area is 105 m^2, and the lift coefficient of the aircraft with flaps extended is 2.3. The elevation of the airport is approximately 1,600 m.

4.9 A sailplane is released at an altitude of 6,000 ft and flies at an L/D of 22. How far, in miles, does the plane glide in terms of distance on the ground?

4.10 An aircraft is in a steady, level flight with a velocity of 225 kn. It initiates a level turn with a bank angle of 30° to reverse its course. Assuming that the aircraft maintains its velocity, how long does it take for the plane to reverse its course (i.e., change its direction by 180°)? What is the turning radius of the aircraft?

4.11 Calculate the maximum lift-to-drag ratio for a business jet with the following characteristics:

Wing span = 19.61

Wing area = 48.31 m^2

Parasitic drag = $C_{D,0} = 0.02$

Oswald efficiency factor $e = 0.8$

4.12 Some aircraft such as the F-22 Raptor feature thrust vectoring. By changing the nozzle configuration in flight, the direction of the thrust can be modified about the pitch axis or the yaw axis. Derive the 2-D equations of motion for an aircraft with pitch thrust vectoring.

4.13 A U.S. Navy F-14D Tomcat uses 2 high-thrust turbo fan engines with the following characteristics: a gross takeoff weight of 72,900 lb. Each engine has an average thrust of 27,000 lb, a fuel capacity of 1,900 gal of JP-4 jet fuel, a wing area of 540 ft^2, a wing span of 50 ft, a parasitic drag coefficient of 0.032, and a wing efficiency factor of $e = 0.87$. Assume that JP-4 has a density of 6 lb/gal.

Assuming the total fuel consumption is 1 N of fuel per newton of thrust per hour of operation, find the range R in miles if the F-14 cruises at an altitude of 8 km at v_{max}.

4.14 Estimate the range and endurance of a four-engine long-haul jet airliner based on the Airbus A340-300. Assume that the aircraft flies at a cruise speed of Mach 0.82 at an altitude of 35,000 ft and that it carries the maximum allowable payload. Use a density of 6.7 lb/gal for the jet fuel.

The specifications of the aircraft are as follows:

Operating empty weight = 129,900 kg

Maximum takeoff weight = 260,000 kg

Maximum payload = 43,500 kg

Fuel tank capacity = 141,500 l

Wing area = 361.6 m^2

Wing span = 60.3 m

Parasitic drag coefficient = 0.015

Oswald efficiency factor = 0.81

Engines: Four CFM-56-5C4, each with a maximum thrust of 151.1 kN

Thrust specific fuel consumption: 0.567 h^{-1}

Hints: First determine the air density and temperature at an altitude of 35,000 ft from a standard atmosphere table. To find the cruise speed, first calculate the speed of sound, then calculate velocity. The aspect ratio of the aircraft, fuel mass, and aircraft mass can then be calculated. Finally, calculate range and endurance, using the coefficients of lift and drag.

5 Chapter

Introduction to Structural Engineering

Dava J. Newman and Amir R. Amir

Don't fight forces, use them.
Buckminister Fuller

5.1 | INTRODUCTION

This chapter describes the discipline of structural engineering. The entire engineering profession is concerned with structural design, especially aerospace, mechanical, civil, ocean, materials, environmental, and bioengineers. Improper structural engineering design can lead to catastrophes such as the disastrous Tacoma Narrows bridge, commonly known as "Galloping Gertie," collapse with which you might be familiar [31]. On the other hand, sound structural engineering has led to such wonders as the Golden Gate Bridge, "Big John" Hancock Tower in Chicago, and the Space Shuttle. This introduction provides essential definitions and relates the three great principles, which are important for any structural engineer to know [32]. Then a review of vector notation is provided that leads to a section on forces, moments, and static equilibrium. An introduction is given to the physics of forces exerted on solid materials (i.e., an aluminum airplane wing section). Equipped with this knowledge, you can embark on truss analysis to calculate how structures respond to applied forces. By the end of the chapter you will be able to perform a structural analysis and to design your own bridge, airplane wing, rocket truss structure, or lighter-than-air vehicle structure.

Tacoma Narrows bridge failure. (Narrows.mov)

5.1.1 Definitions and Objective

Structural engineering is the application of statics and solid mechanics to devise structures with sufficient strength, stiffness, and longevity to fulfill a mission without failure with a minimum amount of weight. Aerospace engineers pay particular attention to designing light structures because of the exorbitant launch costs, which depend on launch weight.

Here are some definitions of key terms used in structural engineering:

- *Structure* A structure holds things together, carries loads, and provides integrity.
- *Statics* The study of forces and moments in systems at rest (the acceleration in Newton's second law is $\mathbf{a} = 0$) is called statics.
- *Solid mechanics* Solid mechanics is the branch of Newtonian mechanics that describes the deformation and failure of solids.
- *Solid* A solid is a substance or body that undergoes a deformation and then stops when a force is applied.
- *Rigid body* A rigid body is an idealized body that does not undergo a deformation when external forces are applied.

5.1.2 Three Great Principles

You can think of structural engineering as being governed by three main principles [32], namely, equilibrium, compatibility, and constitutive relations.

1. *Equilibrium*—relationship among forces.
2. *Compatibility*—relationship among displacements.
3. *Constitutive relations*—relationships between forces and displacements.

Equilibrium is the principle expanded upon in this chapter. Compatibility and constitutive relations are left for a course focused on structures. In an advanced structural engineering course you will also learn about the theory of elasticity and how it is used to find 15 unknowns (6 strains, 6 stresses, and 3 displacements) using 15 equations of elasticity (3 equations of equilibrium, 6 strain-displacement relations or compatibility relations, and 6 stress-strain relations or constitutive relations), a task which is beyond the scope of this chapter. Before we put the first of the great principles, equilibrium, to work solving a truss problem, it is wise to review the mathematical construct of a vector.

5.2 | VECTORS

5.2.1 Definition, Types, and Notation

Vectors are mathematical symbols used for quantities that have both magnitude and direction. In contrast, a *scalar* quantity has only magnitude.

There are numerous ways to denote vectors. It is likely that you will encounter most, if not all, at some point or another. All the vector notations in Equation (5.1) are equivalent.

$$\underline{F} = \underset{\sim}{F} = \grave{F} = \vec{F} = \mathbf{F} \tag{5.1}$$

The magnitude of a vector is its length:

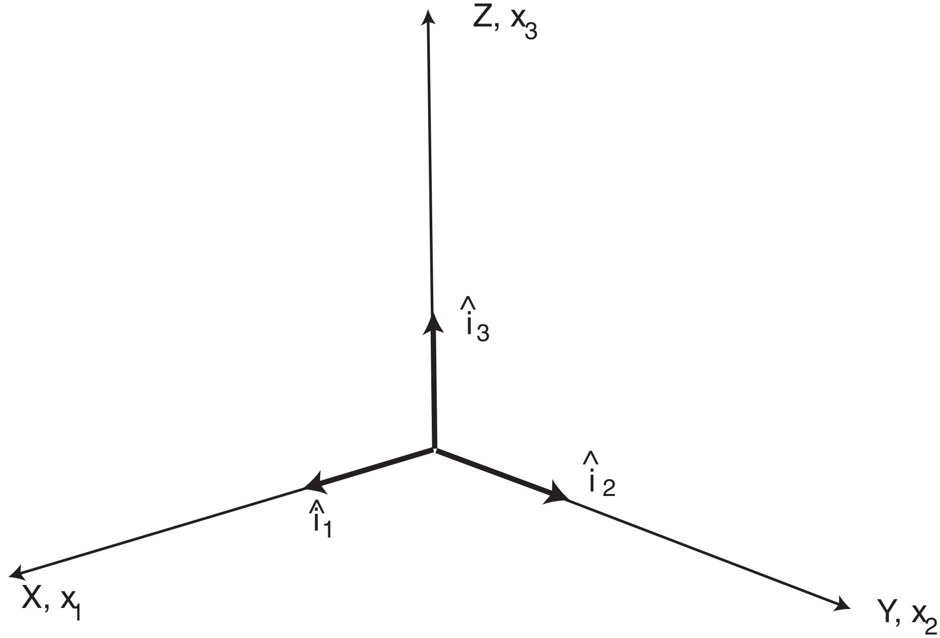
$$|\mathbf{F}| = F = \sqrt{F_1^2 + F_2^2 + F_3^2} \qquad \textbf{[5.2]}$$

There are several "special" vectors that we will use: (1) Position vectors are those whose tail is at the origin of a reference frame, (2) unit vectors are those vectors whose length is equal to 1, and (3) base vectors are vectors defining a coordinate system and have a length of unity. Sometimes a little "hat" is used to indicate base vectors. For example, the three base vectors for a rectangular right-handed coordinate system are often written as

$$\hat{i}_1, \hat{i}_2, \hat{i}_3 \quad \text{or} \quad \hat{i}, \hat{j}, \hat{k} \quad \text{or} \quad \mathbf{i, j, k} \qquad \textbf{[5.3]}$$

See Figure 5.1.

Figure 5.1 | A rectangular right-handed coordinate system with base vectors.



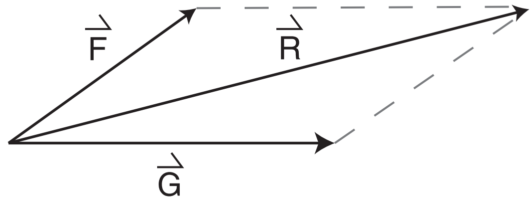
5.2.2 Summation of Vectors

The summation or addition of vector quantities such as forces is straightforward. The numerical procedure is as follows, given two vectors **F** and **G:**

$$\begin{aligned}\mathbf{R} = \mathbf{F} + \mathbf{G} &= F_1\hat{i}_1 + F_2\hat{i}_2 + F_3\hat{i}_3 \\ &= \sum_{m=1}^{3} (F_m + G_m)\hat{i}_m\end{aligned} \qquad \textbf{[5.4]}$$

See Figure 5.2.

Figure 5.2 | The resultant vector shown and the summation of two vectors.



5.2.3 Dot Product

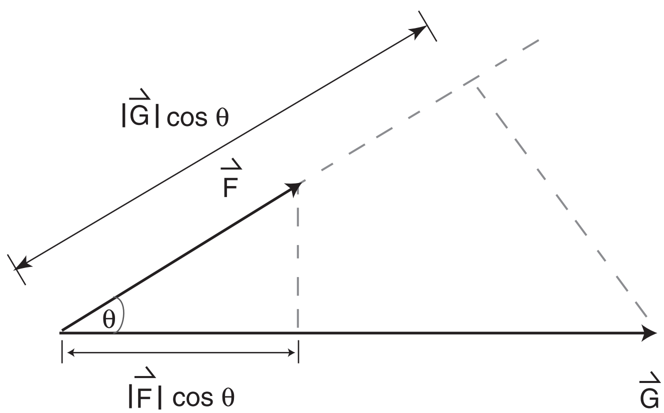
The *dot product* (or *scalar product*) of two vectors returns a scalar quantity. Physically the scalar product is the length of the projection of a vector onto another vector times the length of the vector on which the projection is made.

The dot product is calculated as follows:

$$\mathbf{F} \cdot \mathbf{G} = |\mathbf{F}| \cdot |\mathbf{G}| \cdot cos\theta = F_1G_1 + F_2G_2 + F_3G_3 = \sum_{m=1}^{3} F_mG_m \qquad \textbf{[5.5]}$$

See Figure 5.3.

Figure 5.3 | Geometric explanation of the dot product calculation.



If two vectors are normal to each other (i.e., perpendicular to each other), their scalar product is zero. For example, the dot product of two unit vectors is

$$\hat{i}_1 \cdot \hat{i}_2 = 0 \qquad \textbf{[5.6]}$$

This is a good point to introduce the *Kronecker delta* δ_{mn}, which is defined as

$$\begin{aligned} \delta_{mn} \equiv 1 \quad &\text{when } m = n \\ 0 \quad &\text{when } m \neq n \end{aligned} \qquad \textbf{[5.7]}$$

In matrix form the Kronecker delta is written

$$\delta_{mn} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = I \tag{5.8}$$

where I is the identity matrix.

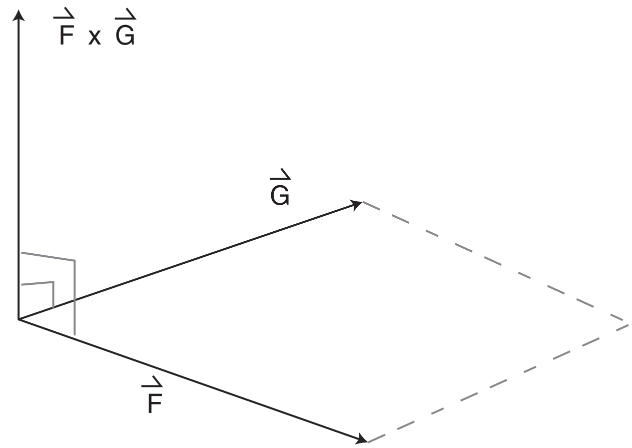
Hence, in general we can write the dot product of unit vectors as

$$\delta_{mn} = \hat{i}_m \cdot \hat{i}_n \tag{5.9}$$

5.2.4 Cross Product

The *cross product* (or *vector product*) of two vectors results in another vector. The resultant vector is perpendicular to a plane made up by the two vectors being multiplied. The direction of the new vector is given by the right-hand rule, and the magnitude (i.e., length) of the vector is equal to the area of the parallelogram made up by the two vectors being multiplied (see Figure 5.4).

Figure 5.4 | Geometric explanation of the cross product calculation.



The cross product is calculated as follows:

$$\mathbf{F} \times \mathbf{G} = \begin{vmatrix} \hat{i}_1 & \hat{i}_2 & \hat{i}_3 \\ F_1 & F_2 & F_3 \\ G_1 & G_2 & G_3 \end{vmatrix} \tag{5.10}$$

The magnitude of the resultant vector can be obtained by the following formula:

$$|\mathbf{F} \times \mathbf{G}| = |\mathbf{F}| \cdot |\mathbf{G}| \cdot \sin\theta \tag{5.11}$$

5.3 | FORCES, MOMENTS, AND STATIC EQUILIBRIUM

5.3.1 Forces and Moments

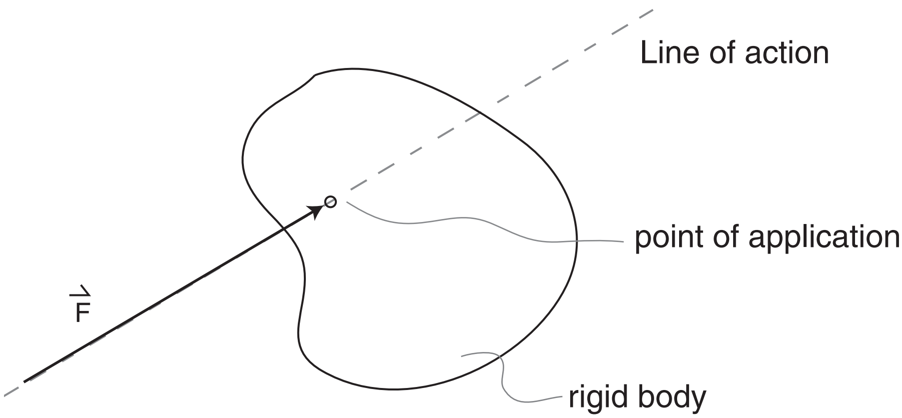
A force is a directed interaction. It has magnitude, direction, and a point of application. A very important property is that the superposition of forces satisfies the laws of vector addition.

There are two types of forces:

1. Surface forces (i.e., contact forces)
2. Body forces (i.e., field forces)

The concept of *transmissibility of forces* is that on a rigid body the force can be placed anywhere along the *line of action.*

Figure 5.5 | A schematic illustrating the concept of transmissibility of forces.



The moment, or torque, is defined as

$$\mathbf{M} = \mathbf{r} \times \mathbf{F} \tag{5.12}$$

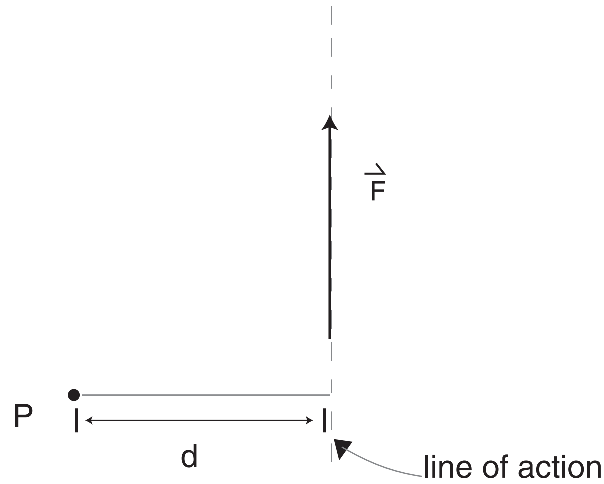
The direction of **M** is given by the right-hand rule, which is always true for a cross product. Note that the moment is taken about the point at which vector **r** originates. Hence, if the vector is a position vector, then the moment is about the origin.

For a moment about a point P we can write

$$|\mathbf{M}_P| = d \cdot |\mathbf{F}| \tag{5.13}$$

where d is the moment arm. See Figure 5.6.

Figure 5.6 | Schematic of vector and moment arm.



5.3.2 Supports and Reaction Forces

There are four types of supports in statics, namely, rollers, pins, clamps, and friction. Here you can see the reaction forces caused by each:

1. *Roller* produces one reaction force and is illustrated in Figure 5.7.
2. *Pin* produces two reaction forces and is illustrated in Figure 5.8.
3. *Clamp* produces two reaction forces and a reaction moment. See Figure 5.9.
4. *Friction* produces one reaction force. In this case, the reaction force is the force of friction, written as $\mathbf{F}_{\text{friction}} \leq \mu_s \mathbf{n}$, where μ_s is the coefficient of static friction and **n** is the normal force.

Figure 5.7 | Schematic representation of a roller reaction force.

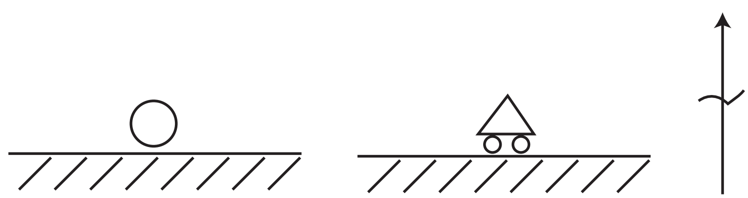


Figure 5.8 | Schematic representation of pin reaction forces.

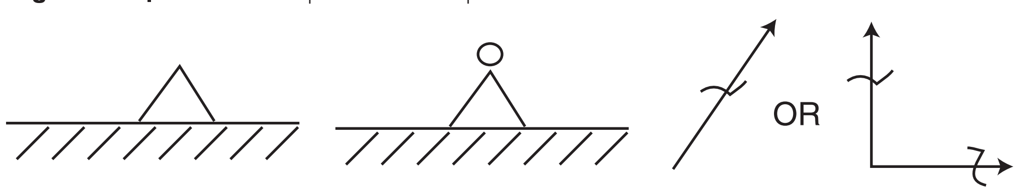
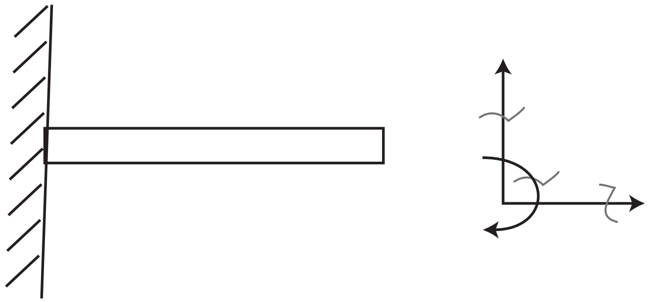


Figure 5.9 | Schematic representation of a clamp reaction forces and moment.



5.3.3 Static Equilibrium

Now that we have reviewed vectors and understand the possible reaction forces, we proceed to a discussion of equilibrium and finally truss analysis. Newton's second law can be written as

$$\sum_n \mathbf{F}_n = m\mathbf{a} \qquad \textbf{[5.14]}$$

As previously mentioned, a *static* system is at rest, and therefore $\mathbf{a} = 0$.

The three necessary and sufficient conditions for a rigid body to be in static equilibrium are that (1) the vector sum of the external forces must be zero, (2) the sum of the moments of all the external forces about an arbitrary point must be zero, and (3) the sum of all external applied moments must be zero.

Mathematically the condition for static equilibrium can be written as follows:

$$\sum_n \mathbf{F}_n = 0 \quad \text{and} \quad \sum_n \mathbf{M}_n = 0 \qquad \textbf{[5.15]}$$

An Aircraft in Static Equilibrium

EXAMPLE 5.1

Consider the following aircraft in straight and level flight. (See Figure 5.10.) Assuming a planar force system, determine the drag D, lift produced by the wing L_w, and the lift produced by the tail L_t in terms of the aircraft weight W and the thrust T.

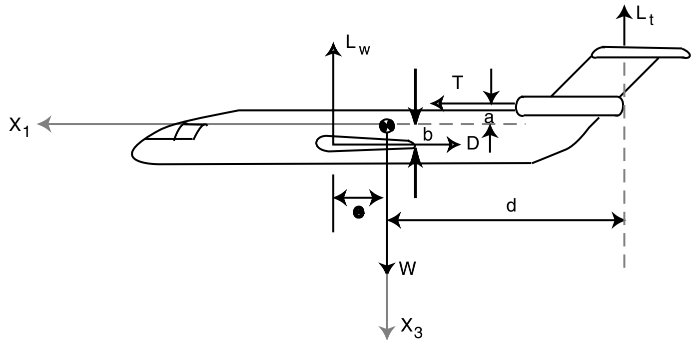
$$\sum F_1 = 0 \quad T - D = 0$$

$$\sum F_3 = 0 \quad W - L_w - L_t = 0$$

$$\sum M_2 = 0 \quad \text{(leading edge nose up is positive)}$$

$$-aT + eL_w - dL_t - bD = 0$$

Figure 5.10 | Schematic representation of an aircraft in static equilibrium.



We can solve these equations:

$$D = T \text{ (This makes sense since we assumed straight and level flight!)}$$

$$W = L_w + L_t$$

$$eL_w - dL_t = aT + bD$$

$$L_t = \frac{eW - (a+b)T}{e+d}$$

$$L_w = \frac{(a+b)T + dW}{e+d}$$

5.4 | PHYSICS OF SOLID MATERIALS

From an equilibrium state, we then consider structural design criteria, which depend on forces and solid materials to which the loads are applied. A solid material opposes an applied load through an internal force. The internal load is a result of the molecules of the solid material be slightly displaced by the external load. The strong intermolecular forces resist change to the overall shape of the solid. Collectively, the internal molecular forces reach equilibrium with the applied external load. The internal force is defined as *stress,* which is force per unit area and usually denoted by σ. The three types of stress forces are tension, compression, and shear. Stress is represented as

$$\sigma = \frac{F}{A} \tag{5.16}$$

where F is an imposed force and A is the cross-sectional area. In tension, an object has the external applied force acting to pull away from both ends of the object. The tensile stress acts perpendicular to the cross-sectional area of the object. For a compressive stress, an external force F acts into an object, thus compressing the object. For example, a uniform aluminum beam could have a compressive force acting equally on both ends over the cross-sectional area of the beam. Equation (5.16) governs both tensile and compressive stresses. Shear stress is defined as an external force acting parallel, or tangentially, to the cross-sectional area of the object. For the external force to remain in equilibrium, it might act in an upward direction over one-half of the object and in a downward direction over the other half of the object, which causes a shear stress within the object, denoted by τ and Equation (5.17):

$$\tau = \frac{F}{A} \qquad [5.17]$$

All three stress forces cause solid materials to change their shape and size. You can imagine a compressive stress acting along a beam and changing its length (i.e., shortening in the case of compression and lengthening in the case of tension). *Strain* ε is defined as the change in length of the object over the initial length of the object:

$$\varepsilon \equiv \frac{\Delta l}{l} \qquad [5.18]$$

5.4.1 Material Properties

There is often a proportionality that exists between stress and strain in solid materials. Up to a certain stress, denoted the yield stress σ_y, stress is directly proportional to and related to strain by a material property, namely, the modulus of elasticity. This property is known as Young's modulus, denoted by E.

$$\sigma = E\varepsilon \qquad [5.19]$$

This relation is also known as Hooke's law. Strain is a dimensionless parameter, thus, the units of E are the same as the units of stress.

The strength of the material is specified in terms of yield stress and ultimate stress σ_{ult}. The ultimate stress of a material is the limit beyond which additional force results in catastrophic failure, or irrecoverable damage, of the material. The yield stress, as the name implies, is a stress level where the material properties of the solid material change, and perhaps deform, but where the material does not break. Figure 5.11 shows a stress–strain diagram for deformable material structures.

Additional material specifications include stiffness, inertia, and toughness. The stiffness of a material determines the allowable elastic deflections that are permissible, or loads below the *buckling load.* A relevant geometric property is the moment of inertia I of the structural material. The toughness of a material is quantified so that strength is not lost from abuse or overuse. For aerospace structures, stess and stain govern airplane wing bending under the influence of lift, torque, and aircraft weight. By combining the definitions used in Section 5.3.2, "Supports and Reaction Forces," and Section 5.3.3, "Static Equilibrium," with these material property definitions, a preliminary aircraft structural analysis is achieved. Representative structural loading profiles are shown in Figure 5.12 where the structural form is depicted along with an aerospace design application. Beams and simple supports can be used to model the loading environment of an aircraft.

Structural members, such as beams, resist bending due to their geometric and material properties. The moment of inertia is a geometric property usually

Figure 5.11 | Material strain-stress diagram comparing the behavior of composites with metals [33].

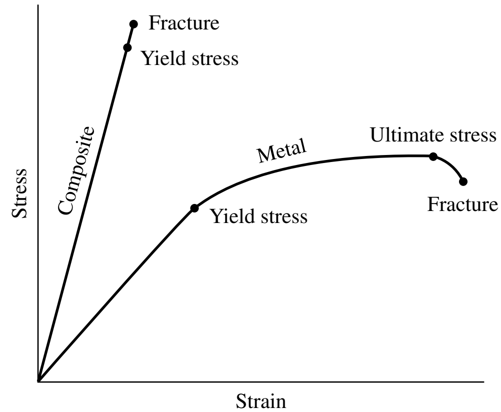
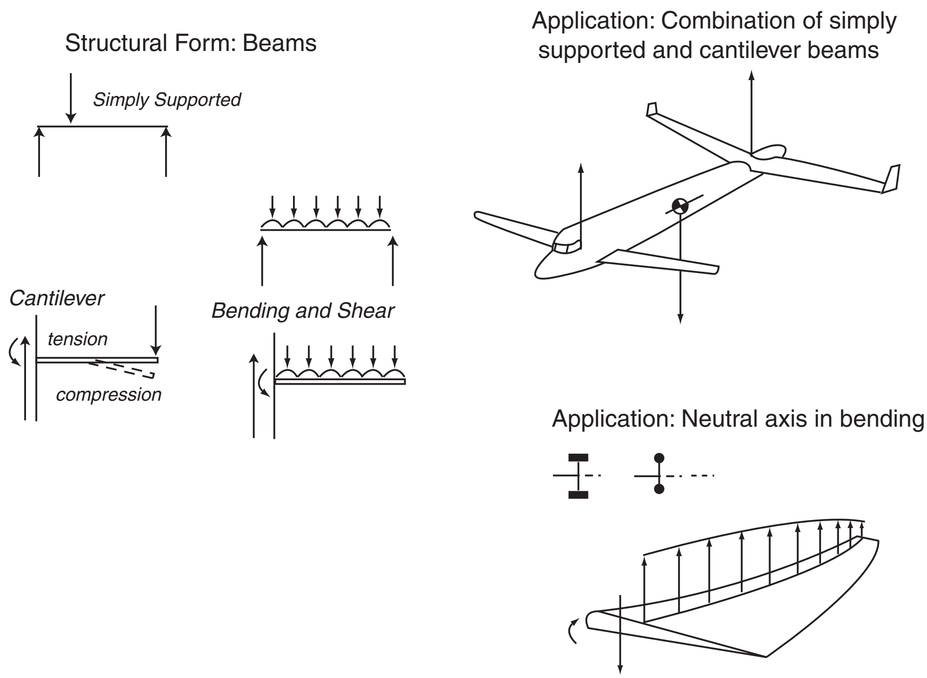


Figure 5.12 | Structural application of beam theory.



associated with the cross section of the beam. Typical values of Young's modulus E are given in Table 5.1. Aircraft structures continuously undergo dynamic loading profiles, which include torsional twisting throughout the airframe. The deformation of material due to shear tends to *kink* the material, and the measure of deformation is often denoted by the angle θ. The angle is termed the *shearing strain* and is analagous to the case of tension and compression where up to a cer-

Table 5.1 | Typical material properties (adapted from [34])

Material	Young's modulus E (N/m^2 $\times$ 10^9)	ρ (kg/m^3 $\times$ 10^3)
Aluminum	68–78	2.66–2.88
Carbon fiber	70–200	2.2
Glass	50–79	2.38–3.88
Spruce	100	0.4–0.6
Common wood	9–16	0.4–0.6

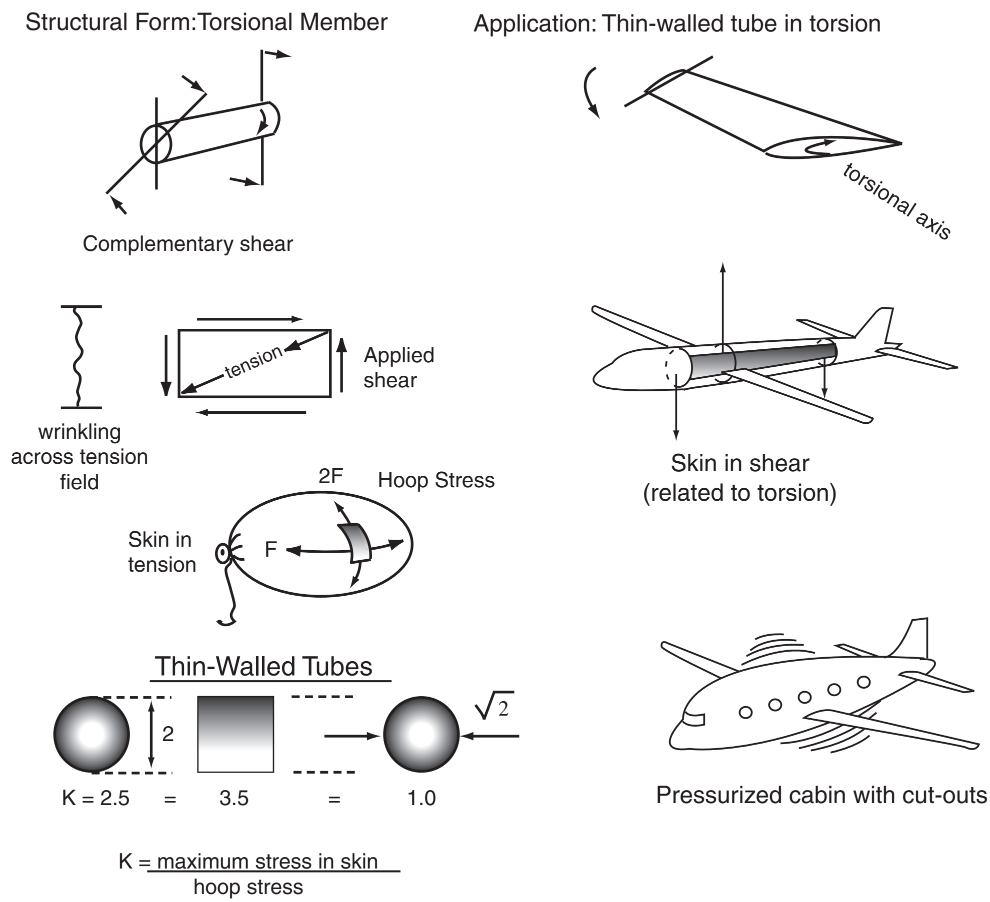
tain limit, the shear stress is proportional to the strain. Akin to Young's elastic modulus E, the shear modulus is represented by G and can be thought of as the *modulus of rigidity.* The proportional relation is

$$\tau = G\theta \qquad [5.20]$$

where τ is the shear stress, G is the shear modulus, and θ is the deformation angle.

Figure 5.13 represents the connections between torsional structural members and the actual aircraft component application. The most commonly used material

Figure 5.13 | Structural application of torsion.



in aircraft structures is aluminum, which has an ultimate stress about 1.5 times greater than its yield stress. With our increased understanding of structural materials, we recall the flight envelope (*V–n* diagram) previously discussed in Chapter 4, "Aircraft Performance," where the positive and negative load limits corresponded to the yield stress of the aircraft. The safety factor in an aluminum aircraft design is then 1.5. Aircraft designs have much lower safety factors than bridges, cars, and buildings because weight savings drive aircraft and spacecraft design tradeoffs.

5.5 | TRUSS ANALYSIS

Have you ever driven over a bridge and wondered how engineers calculate the forces in all the bridge truss members? What were the structural loads in the Tacoma Narrows bridge that caused it to collapse? As an aerospace engineer, you could be called on to perform truss analysis to determine forces in each member of a rocket interstage structure. Interstages are trusses, typically made of aluminum, that connect one rocket stage to another (i.e., the first and second stages). Numerous spacecraft also contain truss structures. An example is the solid rocket motor, which transfers its thrust to a mated spacecraft through a truss structure. Determining the forces and moments in each member of the truss is essential, and if the load is too high, the thrust will buckle the truss members, and you might be out of a job. On the other hand, with proper engineering truss analysis and design you can fashion an elegant space frame that ensures mission success.

Narrows.tif
narrowsfail.tif

5.5.1 Static Determinacy

In general there are 3 classes of structures:

1. *Statically determinate.* The structure is exactly restrained. The number of reactions is equal to the number of available equations.
2. *Not statically determinate.* The structure is not sufficiently restrained. There are fewer reactions than the number of available equations. The structure moves!
3. *Statically indeterminate.* The structure is over-restrained. There are more reactions than the number of available equations.

This section shows how to analyze planar two-dimensional trusses using the Method of Joints. Before we discuss the actual method, we need to make simplifying assumptions:

- The members, called bars, are straight and massless.
- The bars are assumed to be rigid.
- The bars are connected at their ends through joints.
- External loads are applied only at joints.
- Supports, such as pins and rollers, are frictionless.
- The loads in the bar have lines of action collinear with the bar axis. The force is uniaxial and can be either tensile or compressive.

Understanding the concept of a *free-body diagram* (FBD) is essential, and applying it results in the solution of structural engineering problems. FBDs isolate an object (or body, or a system of bodies) and identify the forces and moments acting on the body. Creating a free-body diagram is the first step to take in approaching a new problem. The following steps suggest a methodology to follow when constructing an FBD [35]:

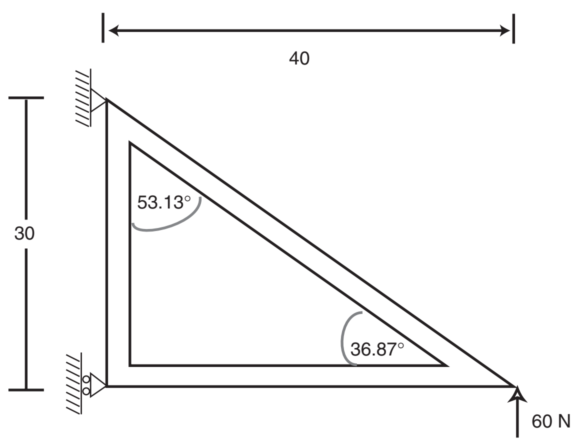
1. Identify the object that will be isolated.
2. Make an approximate sketch of the object removed from the surroundings, and include its relative dimensions and angles.
3. Draw vector approximations of the external forces and body forces, and label them.
4. Choose an appropriate coordinate system to simplify your calculations. The coordinate system is only relative to the point being analyzed. If there are multiple points experiencing forces within a system, each point can have a separate set of axes.
5. When you draw free-body diagrams, it is a good technique to visually check your sketches for equilibrium. This is done by verifying that each force can be counteracted by the components of one or multiple other forces acting in the opposite direction.

Assuming all objects act as single points and are not subject to rotation is a reasonable simplification when you construct an FBD. The force of gravity acts in the downward direction, and is considered when an object's mass is involved.

5.5.2 Method of Joints

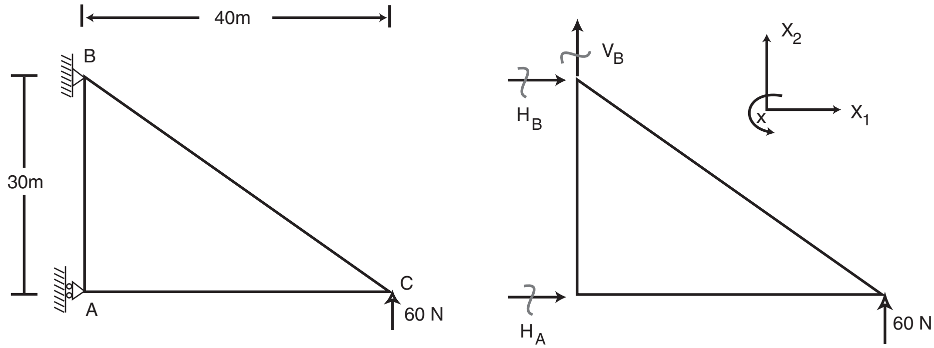
The best way to explain this method for performing truss analysis is by doing an example. Consider the truss in Figure 5.14.

Figure 5.14 | Sample truss structure.



1. Draw the FBD.
   a. Model the supports.
   b. Draw a neat sketch of the truss object to be analyzed with applied loads and supports. See Figure 5.15.
   c. Replace supports by reactions (through positive orthogonal components).

Figure 5.15 | Free-body diagram for the truss structure.



2. First write the generic form and the specific form of the equations of equilibrium

$$\sum F_{X_2} = 0 \Rightarrow V_B + 60 = 0$$

$$\sum F_{X_1} = 0 \Rightarrow H_A + H_B = 0$$

$$\sum M_A = 0 \Rightarrow 40(60) - H_B(30) = 0$$

   Count the unknowns and the equations, and find the determinacy of the system. There are three unknowns (H_A, H_B, V_B), and there are three equations. Therefore, the system is statically determinate.

3. Solve the equations of equilibrium, and redraw the sketch, labeling all quantities. See Figure 5.16.

$$V_B = -60 \text{ N}$$

$$H_B = 80 \text{ N}$$

$$H_A = -80 \text{ N}$$

4. Determine the internal loads. See Figure 5.17.
   a. Isolate a single joint.
   b. Show the (unknown) bar forces as tensile forces pulling away from the joint.

Figure 5.16 | FBD with solutions to the equations of equilibrium.

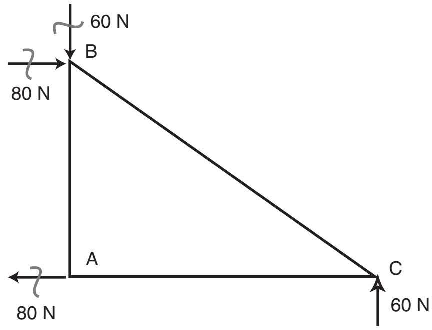
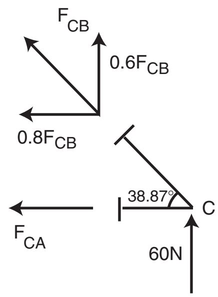


Figure 5.17 | Determining the internal loads at joint C.

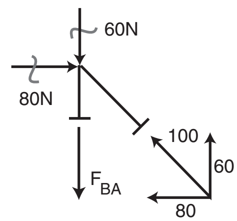


c. Calculate and show orthogonal components of forces at an angle.

d. Repeat the procedure until all internal loads are determined. The internal force in the bar between joint C and joint B is F_{CB}. The internal force in the bar between joint C and joint A is F_{CA}.

Show the bar forces as tensile forces (i.e., pulling away from the joint). Tension is indicated by $+$ and compression is indicated by $-$. See Figure 5.18.

Figure 5.18 | Forces shown as tensile and compressive.



$$\left.\begin{aligned} \sum F_{X_2} &= 0 \Rightarrow 60 + 0.6F_{CB} = 0 \\ \sum F_{X_1} &= 0 \Rightarrow -F_{CA} + (-0.8)F_{CB} = 0 \end{aligned}\right\} \Rightarrow \begin{aligned} F_{CB} &= -100\text{ N} \\ F_{CA} &= 80\text{ N} \end{aligned}$$

Force F_{CB} is known to be a compressive force and pushes toward the joint.

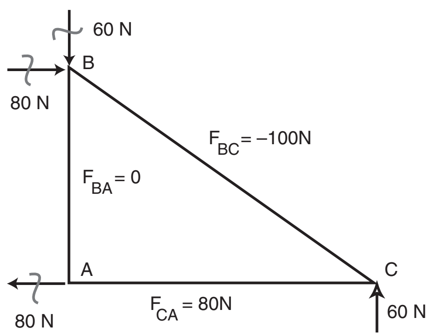
$$\sum F_{X_2} = 0 \Rightarrow -60 + 60 - F_{BA} = 0$$

$$\sum F_{X_1} = 0 \Rightarrow 80 - 80 = 0$$

Hence, $F_{BA} = 0$ N

See Figure 5.19.

Figure 5.19 | Solution using the method of joints for a truss structure.



5. Check the solution:

$$\sum F = 0$$

$$\sum M = 0$$

Note: $F_{BC} = F_{CB}$, $F_{AC} = F_{CA}$, etc. This is always true.

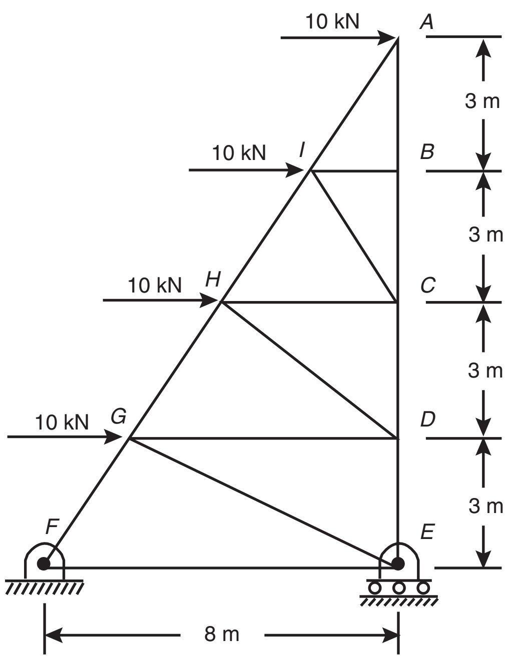
The method of joints can be used to solve planar as well as three-dimensional trusses as necessary for space frame trusses. The method of sections can also be used to solve for loads in truss structures.

5.5.3 Method of Sections

An equivalent alternative for truss analysis is the *method of sections,* where a truss is *cut* into two sections and the three equilibrium equations are applied to either section to calculate the load and moments on individual truss members. The method of sections is also best explained through an example. All truss analysis starts with a free-body diagram. *Note:* Since there are only 3 equilibrium equations, be careful to cut your truss where there are only three unknown member forces.

The truss shown in Figure 5.20 is used to demonstrate the method of sections technique.

Figure 5.20 | Sample truss section.



1. Draw a free-body diagram, and solve for the reactions.
2. Use the method of sections to solve for the loads in members *GF, GE,* and *DE*.
3. Draw a final sketch showing all forces, reactions, and internal loads.
4. Check the equilibrium of joints *E* and *F* with the method of joints.

The following three assumptions are made for planar truss structures:

- All members are in the same plane.
- All loading is at the joints.
- All joints are pinned (free rotation).

Similar to the method of joints, the following five steps are prescribed to find the solution using the method of sections.

1. Draw the FBD.
   a. Model the supports.
   b. Draw a neat sketch of the truss object to be analyzed with applied loads and supports.
   c. Replace supports by reactions (through positive orthogonal components).
2. Write the equations of equilibrium. Solve for the two support forces using the positive reference frame.

$$40 + H_F = 0 \Rightarrow H_F = -40\text{ kN}$$

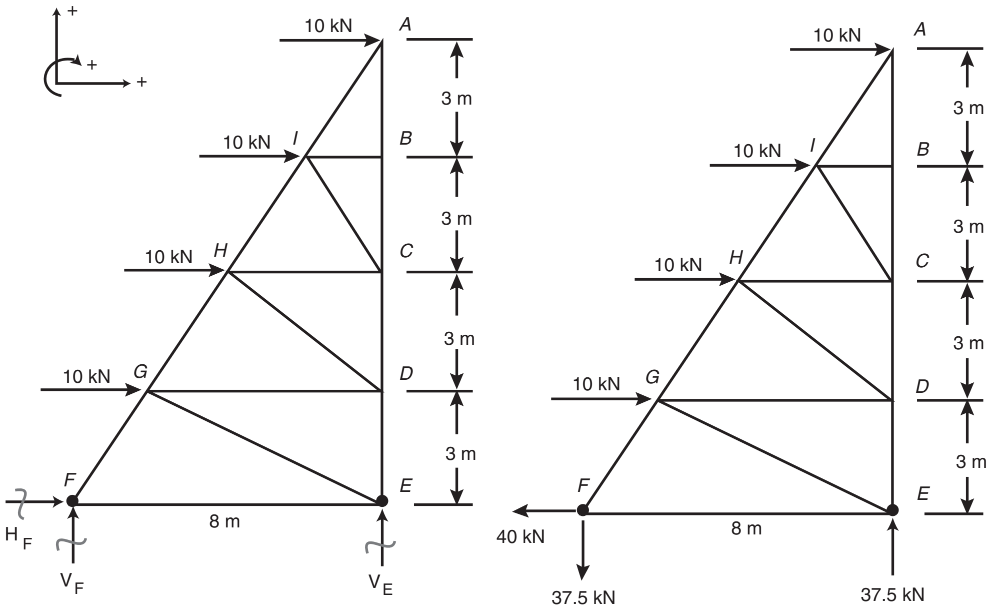
$$V_E + V_F = 0$$

$$\sum M = 0 \Rightarrow 10 \cdot 12 + 10 \cdot 9 + 10 \cdot 6 + 10 \cdot 3 + V_F \cdot 8 = 0$$

$$V_F = -37.5\text{ kN} \quad \therefore V_E = 37.5\text{ kN}$$

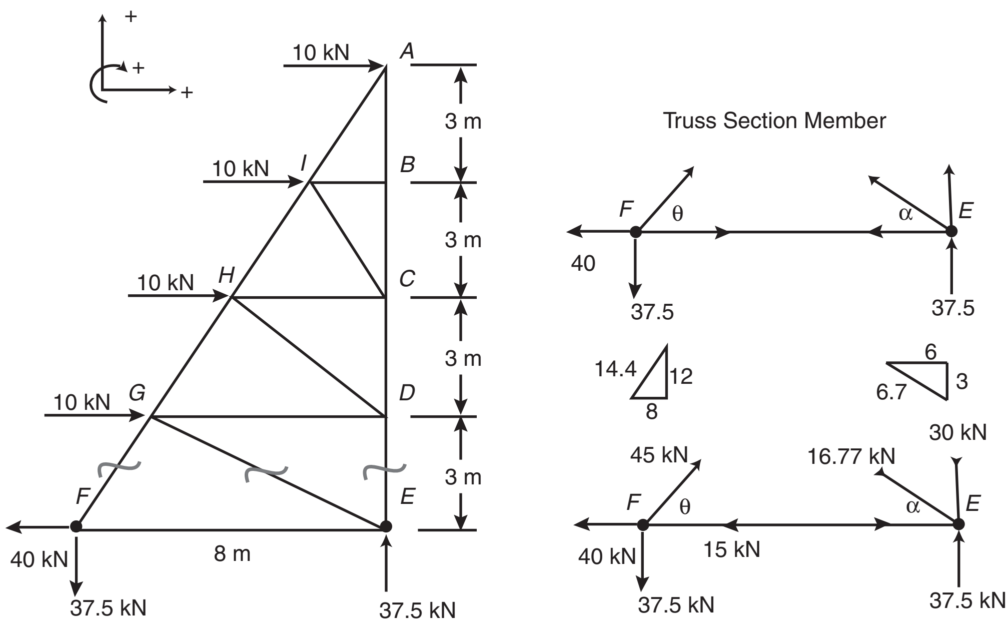
3. Count the unknowns and the equations, and find the determinacy of the system. The method of sections can be applied to any statically determinant truss. There are three unknowns (H_F,V_F, V_E) and three equations. Therefore, the system is statically determinate.
4. Solve the equations of equilibrium, and redraw the sketch, labeling all quantities. See Figure 5.21. Section off part of the truss, and apply the three equilibrium equations: the sum of forces and the sum of the moments equal zero.
5. Determine the internal loads.
   a. Isolate a section of the truss.
   b. Show the (unknown) bar forces as tensile forces pulling away from the joint.
   c. Calculate and show orthogonal components of forces at an angle.
   d. Repeat the procedure until all internal loads are determined.

Figure 5.21 | Free-body diagram with support reactions calculated.



A final assumption is that the loading occurs at a joint. Nonjoint loading (i.e., along the truss member) are beyond the scope of this example. Beam theory and bending are necessary for nonjoint loading. See Figure 5.22.

Figure 5.22 | The Method of Sections cut for the truss solution.



$$\tan\theta = \frac{12}{8} \Rightarrow \theta = 56°$$

$$F_{FE} - 40 + F_{FG}\cos\frac{8}{14.4} = 0$$

$$F_{FG}\sin\frac{12}{14.4} = 37.5$$

$$\therefore F_{FG} = 45\text{ kN} \quad F_{FE} = -15\text{ kN}$$

$$F_{EF} = F_{FE} = -15\text{ kN}$$

$$\tan\alpha = \frac{6}{3} \Rightarrow \alpha = 63.4°$$

$$-15 - F_{EG}\sin\alpha = 0 \Rightarrow F_{EG} = -16.77\text{ kN}$$

$$\sum M_F = 0 \Rightarrow -F_{ED}\cdot 8 - (37.5\cdot 8) - 8\cdot F_{EG}\cos\alpha = 0$$

$$F_{ED} = -37.5 + 7.5 = -30\text{ kN}$$

The loads in the members are as follows: member *FG* (or member *GF*) is a 45 kN tensile force, member *EG* (or *GE*) is a 16.77 kN compressive force, and member ED (or DE) is a 30 kN compressive force.

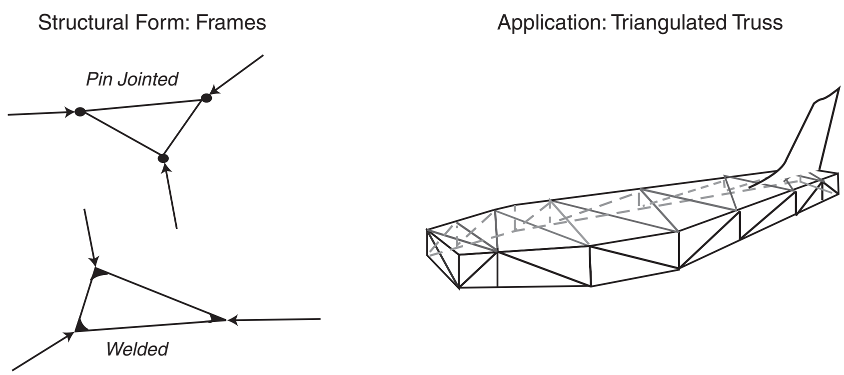
Keep in mind these hints when you perform truss analysis:

- Be neat.
- Label forces, moments, and dimensions.
- Clearly define your coordinate system and the direction of positive moments.
- Use solid lines for vectors and dashed lines for vector components.
- Remember the convention: + means tension and − means compression.

5.5.4 Structural Applications of Trusses

Figure 5.23 previews how structural analysis is used in aerospace applications. The detailed analysis is beyond the scope of this book, but the figure shows how real aerospace systems are analyzed using structural engineering principles.

Figure 5.23 | Structural application of truss analysis.



Representing aerospace systems by simple trusses leads to an initial analysis of structural loading. Your structural frame design for the aerospace vehicle project described in Chapter 12, "Design: Lighter-Than-Air (LTA) Vehicle Module," can be analyzed using the structural analyses described in this chapter.

PROBLEMS

5.1 Using the video clip on the accompanying CD-ROM of the Tacoma Narrows bridge, nicknamed "Galloping Gertie," answer the following:

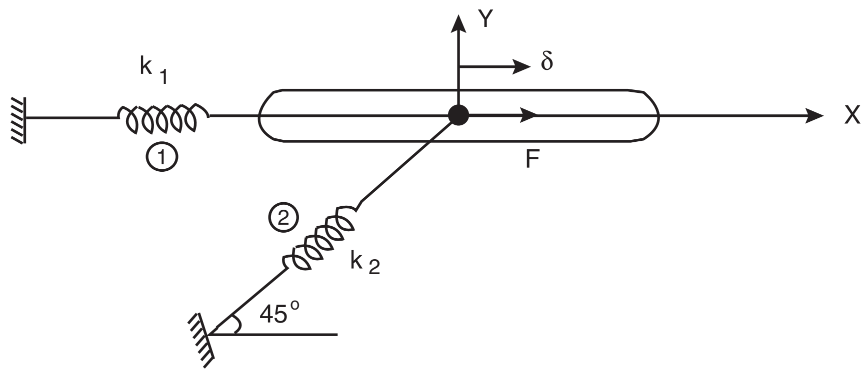
(a) Based on your knowledge of engineering, why did this event occur?

(b) If you were the engineer on the project, suggest how you would have constructed the bridge to prevent its collapse.

Narrows.mov

5.2 You are a structural engineer for NASA. Point out two strengths and two weaknesses of the current Space Shuttle's structure. Based on your knowledge of engineering, suggest improvements and revisions.

5.3 A peg slides in a slot which constrains its motion to the *X* direction. The peg has two springs attached to it, one along the *X* axis and one at an initial angle of 45°. In the undeformed position, there is no force in either spring.



(a) *Compatibility.* For a deflection δ, how much does spring 1 stretch? How much does spring 2 stretch? (*Hint:* Consider small and think of stretch along the original undeflected direction.) Note how the conditions enforce the compatibility that both springs stay attached to the peg.

(b) *Equilibrium.* Draw a free-body diagram of the peg, with the applied force *F* and the forces originating in the two springs. (*Hint:* You may need to represent one more force implicitly to represent the constraint imposed by the slot.)

(c) *Constitutive relations.* Write the constitutive equations for the two springs (i.e., the relationship between the force in the spring and its deflection).

(d) Find the solution by combining the equations to solve for δ in terms of F. Make neat sketches and label clearly all variables you define.

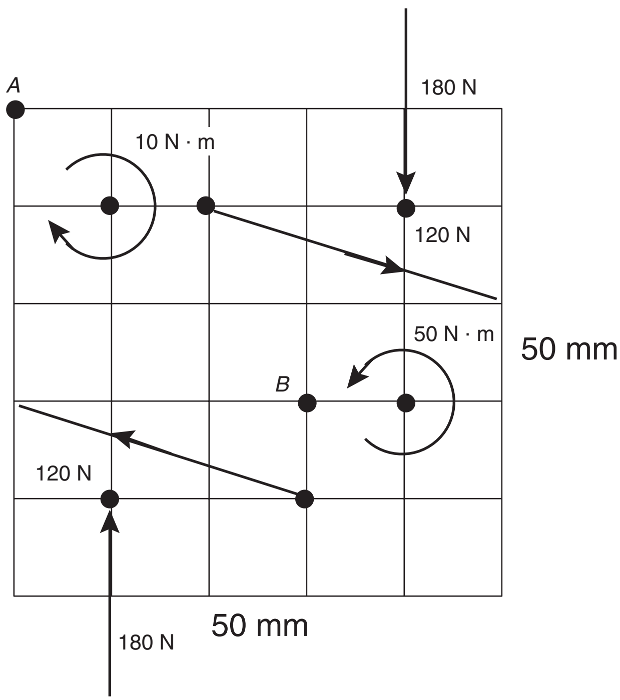
5.4 For the array of forces and moments shown in the figure, all of which act in the XY plane:

(a) Identify the moments.

(b) Find the moment about point A.

(c) Find the moment about point B.

(d) Generalize your answer to the extent appropriate.



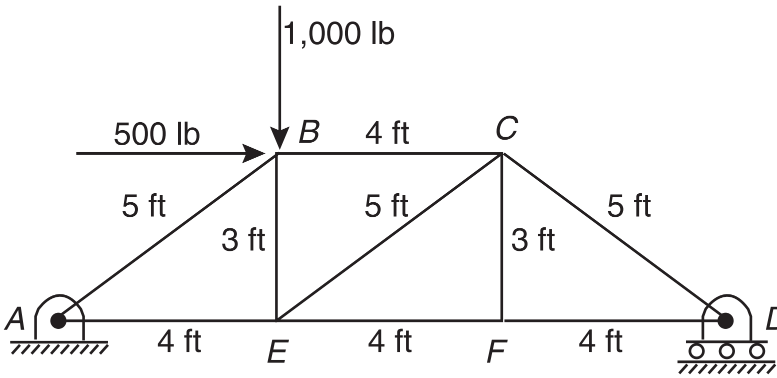
5.5 For the nine-member truss shown in the figure:

(a) Draw a free-body diagram, and solve for the reactions.

(b) Solve for the loads in all members, using the method of joints. Carefully sketch each joint, and be sure to indicate tension versus compression.

(c) Draw a final sketch with all external forces, reactions, and internal loads labeled.

(d) What checks are available to ensure that your answer is correct?

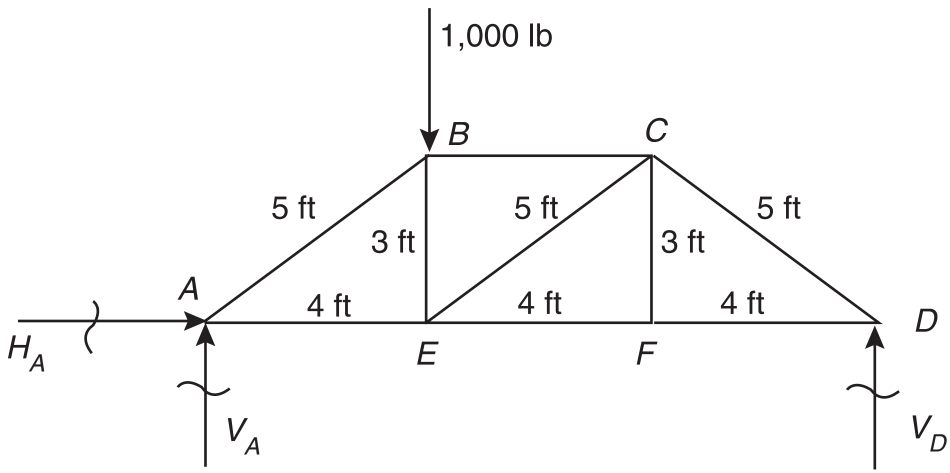


5.6 For a similar truss structure, but different reaction loads and only one external load, as shown in the figure:

(a) Draw a free-body diagram, and solve for the reactions.

(b) Solve for the loads in all members, using the method of joints.

(c) Draw a final sketch with all external forces, reactions, and internal loads labeled.



Chapter 6

Aircraft Propulsion

Dava J. Newman

6.1 | INTRODUCTION

Vehicles require a means by which to achieve motion, a way to thrust themselves to accelerate and then counteract frictional forces from motion. In this process, an engine converts potential energy to kinetic energy and also replenishes the kinetic energy that is lost to heat due to friction. For an aircraft, the most efficient way to move is to use the air around it. In this chapter, we look at the way aircraft engines work. All aircraft propulsion systems are based on the *principle of reaction* of airflow through an engine of some sort. It may also be thought of as the acceleration of air flowing through the aircraft engine.

Air-breathing propulsion systems require a source of power and the means for accelerating airflow. The three primary sources of power or energy for propulsion are

- Hydrocarbon fuels and a heat engine.
- Batteries and an electric motor.
- Solar cells and an electric motor.

A fourth type of power source for propulsion is human power (see the CD-ROM for world-record-breaking aircraft and hydrofoil designs that rely on human power plants). Human-powered aircraft are propeller-powered, but the "engine" is a human whose power output is transferred to the propeller using bicycle gearing.

Human powered flight.

The two means for accelerating an airflow presented in this chapter are through *propellers* and *jet expansion.* Rocket engines are beyond the scope of this chapter, but are mentioned briefly later.

The design of different types of engines satisfies various needs. Common goals of all propulsion systems are to provide sufficient thrust to balance the drag of the aircraft and to exceed the drag of the airplane for accelerated flight. Commercial transport aircraft and cargo planes place a premium on high engine

Pathfinder.jpg, NASA-jet.GIF, GE_YJ-93.jpg efficiency and low fuel usage, while fighter planes and experimental high-speed aircraft require high excess thrust to accelerate quickly. For these aircraft, engine efficiency is not as important as very high thrust.

6.2 | THE PROPELLER*

Thrust is the force that moves an aircraft through the air and is generated by the propulsion system. Different types of propulsion systems develop thrust in different ways, although it is usually generated through some application of Newton's third law of motion (see Section 9.3, "Newton's Laws of Motion and Gravitation," for more details). In his 1687 publication *The Mathematical Principles of Natural Philosophy,* commonly known as the *Principia,* Newton states

> To every action there is an equal and opposite reaction. In other words, if particle 1 acts on particle 2 with a force F_{12} in a direction along the line adjoining the particles; while particle 2 acts on particle 1 with a force F_{21}, then $F_{12} = F_{21}$.

For 40 years following the Wright brothers' first flight, airplanes used internal combustion engines to turn propellers to generate thrust. Most general aviation or private airplanes are powered by propellers and internal combustion engines similar to automobile engines. The engine takes air from the surroundings, mixes it with fuel, burns the fuel, thereby releasing the energy in the fuel, and uses the heated gas exhaust to move a piston that is attached to a crankshaft. In the automobile, the shaft is used to turn the wheels of the car whereas in an airplane, the shaft turns a propeller.

What is the difference between an engine and a motor? An engine produces work from heat (combustion), and a motor typically produces work from the conversion of electrical energy to mechanical energy. Combustion engines are further discussed in this chapter. Motors are highlighted in Chapter 12, "Design: Lighter-Than-Air (LTA) Vehicle Module," where batteries supply the electrical energy that is converted to the mechanical energy that turns the propellers to propel the lighter-than-air vehicles. State-of-the-art, solar-powered electric aircraft also use propellers.

6.2.1 Fundamental Equations Governing Propeller Propulsion

The details of propeller propulsion are complicated, but fundamental insights can be gleaned from physics, specifically, the principles of conservation of momentum and energy. The complexity stems from the fact that the propeller acts as a rotating wing, creating a lift force because of its motion through the air. For propeller-powered aircraft, the gas is accelerated as the surrounding air passes through the propeller. The actual process of combustion in the engine pro-

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*(edited from [36])

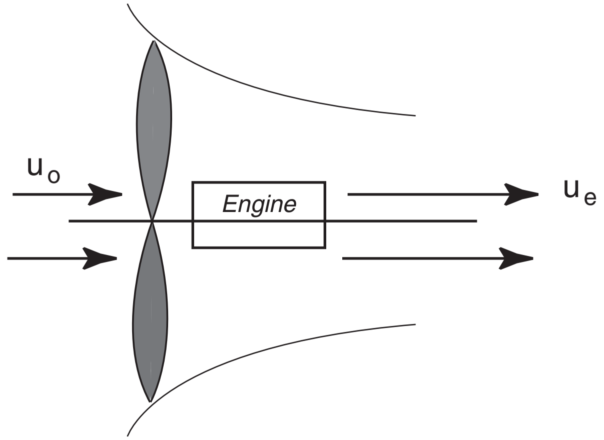
vides very little thrust. Rather, the thrust is produced by the propeller. Propellers have two, three, or four blades that are typically long and thin. A perpendicular cut through the blade reveals the propeller's airfoil shape. Because they are radial blades, the tip moves faster than the hub. Twisted blades offer a proven design for maximum propeller efficiency. The angle of attack of the propeller airfoils varies from the hub to the tip with lower angles at the tip, which makes precisely analyzing the airflow through the entire propeller challenging.

The engine turns the propeller and does work on the airflow, causing a significant change in pressure across the propeller disk. The propeller acts as a rotating wing, and in Chapter 3, "Aerodynamics," we learned that the pressure over the top of a lifting wing is lower than the pressure underneath the wing. The spinning propeller sets up a pressure lower than freestream in front of the propeller and higher than freestream behind the propeller.

A schematic of a propeller propulsion system is shown in Figure 6.1. The thrust force depends on the mass flow through the propeller and the corresponding change in velocity as the air moves across the propeller. The mass flow through the propulsion system is a constant. Therefore, the physics behind propeller-driven flight relies on Newton's equations of motion and the conservation of energy and momentum. Recall that Newton's second law, $F = ma$, is the time rate of change of momentum. As applied to our propeller, force (thrust in this case) = (mass/time)(momentum/mass). From the conservation of momentum, the force or thrust is equal to the mass flow times the difference between the exit and inlet velocities, written as

$$F = \dot{m}(u_e - u_0) \tag{6.1}$$

Figure 6.1 | Propeller schematic showing the envelope of a moving air mass where inlet velocity is u_0 and exit velocity is u_e.



where u_0 is the inlet velocity, u_e is the exit velocity, and $\dot{m}$ is the change in mass (the mass flow). The exit velocity is higher than the inlet velocity because the propeller accelerates the air. In reality, the thrust depends on the inlet velocity, but we assume that for our purposes the propeller is moving much faster (measured in revolutions per minute) than our propeller aircraft.

From conservation of energy, ideal propeller power output is equal to the kinetic energy flux across the propeller. This change in energy is the change in mass times the difference between the exit and inlet velocities

$$P = \dot{m}\left(\frac{u_e^2}{2} - \frac{u_0^2}{2}\right) = \frac{\dot{m}}{2}(u_e - u_0)(u_e + u_0) \tag{6.2}$$

where P denotes propeller power. We define *propeller efficiency* as a ratio of *useful work* to *input power,* or

$$\text{Propeller efficiency} = \frac{\text{useful work}}{\text{input power}} = \frac{Fu_0}{P}$$

where work is the force (thrust in this case) F times the inlet velocity u_0, and the power that goes into the engine is P. Efficiencies are often denoted by the Greek symbol eta (η):

$$\eta_{\text{prop}} = \frac{Fu_0}{P} \tag{6.3}$$

Substituting Equation (6.1) and Equation (6.2) into Equation (6.3) yields

$$\eta_{\text{prop}} = \frac{2u_0}{u_e + u_0} \tag{6.4}$$

More generally, we call this the propulsive efficiency, or η_p.

To attain a high efficiency ($\eta \sim 1$), we want to drive $u_e \rightarrow u_0$. However, from the momentum equation, at higher efficiencies we need a larger mass flow to achieve a desired thrust. Thus, there are certain real-world limits on how efficient an aircraft engine can be.

Rewriting Equation (6.1) as

$$\frac{F}{\dot{m}u_0} = \frac{u_e}{u_0} - 1 \tag{6.5}$$

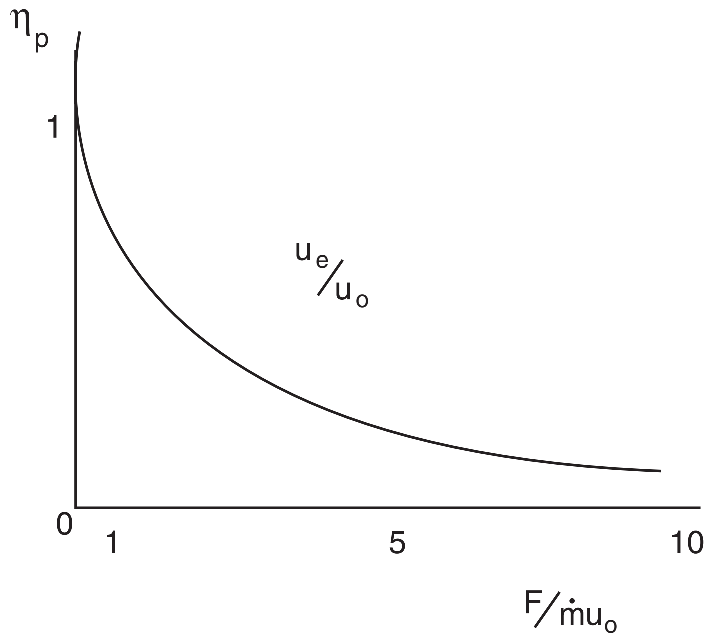
leads to the relation for propulsive efficiency, thrust, mass flow, and velocities shown in Figure 6.2.

Realizing that our engine is a combustion engine, which is often referred to as a heat engine, we need to include thermal effects as well as propeller efficiencies. We define *thermal efficiency* as

$$\eta_t = \frac{P}{\dot{m}_f Q} \tag{6.6}$$

where P is power, $\dot{m}_f$ is the mass flow of fuel, and Q is the heating value of the fuel.

Figure 6.2 | Propulsive efficiency relation.



A combustion engine's thermal efficiency is governed by thermodynamics. We can show that the thermal efficiency is less than the Carnot (ideal) efficiency.

$$\eta_t \le \eta_c = 1 - \frac{T_0}{T_{\text{source}}} \qquad \textbf{[6.7]}$$

For the atmosphere the mean temperature T_0 ranges between 200 and 300 K. For hydrocarbon fuels the source temperature is typically

$$T_{\text{source}} < 3{,}000 \text{ K}$$

Therefore,

$$\eta_c < 1 - \frac{200}{3{,}000} \approx 0.9$$

and the actual thermal efficiency is closer to

$$\eta_t = 0.5$$

Finally, we define the *overall efficiency* as thermal efficiency times propulsive efficiency, or the ratio of

$$\frac{\text{Power to push the aircraft}}{\text{Energy flow in the fuel}}$$

as Equation (6.8) shows.

$$\eta_{\text{overall}} = \eta_t \eta_p = \frac{F u_0}{\dot{m}_f Q} \qquad \textbf{[6.8]}$$

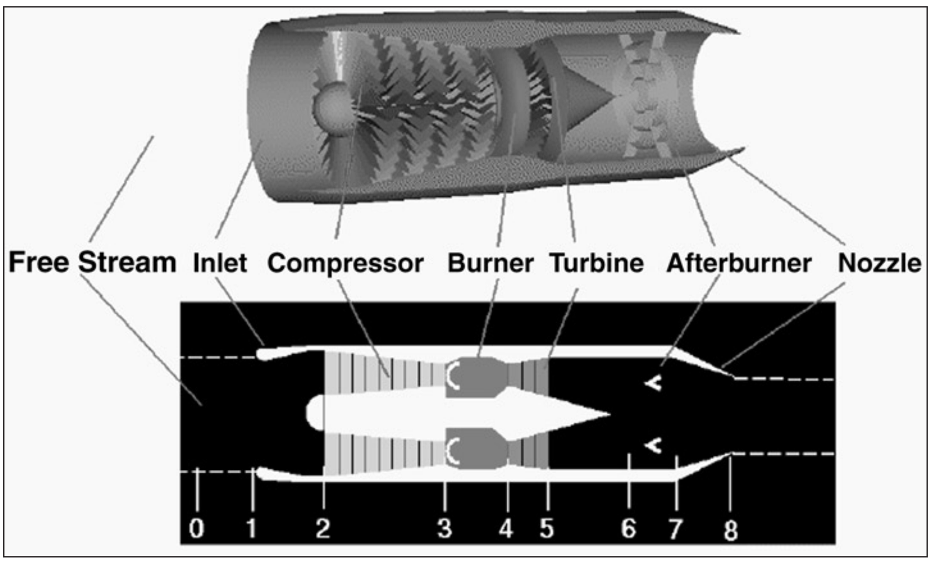
To attain higher flight velocities, we turn to jet engines. After World War II, jet engines gained popularity, and a transition between propellers and jets can be seen on some aircraft where jet engines are used to turn propellers. This propulsion system is called a turboprop, where the main thrust comes from the propellers, which are turned by turbine engines (see Section 6.4.3, "How Does a Turboprop Work?") [36].

6.3 | THE ILLUSTRATED JET ENGINE*

There are several different types of jet engines, often referred to as gas turbine engines, but all turbine engines share the same core elements: an inlet, compressor, burner, turbine, and nozzle. The *inlet* brings freestream air into the engine, which sits upstream of the *compressor*. The compressor increases the pressure of the incoming air before it enters the *burner* (sometimes called the combustor). Fuel is combined with high-pressure air and burned at this stage of the engine. The resulting high-temperature exhaust gas is used to turn the power *turbine* and to produce thrust when passed through a *nozzle*. The power turbine is located downstream of the burner and extracts energy from the hot flow, which is then used to turn the compressor. The nozzle is downstream of the power turbine.

Figure 6.3 shows a schematic of a jet engine with engine station numbers, which are useful in identifying the airflow through the various components. In

Figure 6.3 | Jet, or gas turbine, engine schematic with station numbers assigned to components [36].



*(edited from [36])

addition, the figure shows an *afterburner,* which most modern fighter aircraft incorporate into their engine design to fly faster than the speed of sound, or at supersonic speed. Details of the core components are given, followed by a description of six types of jet engines:

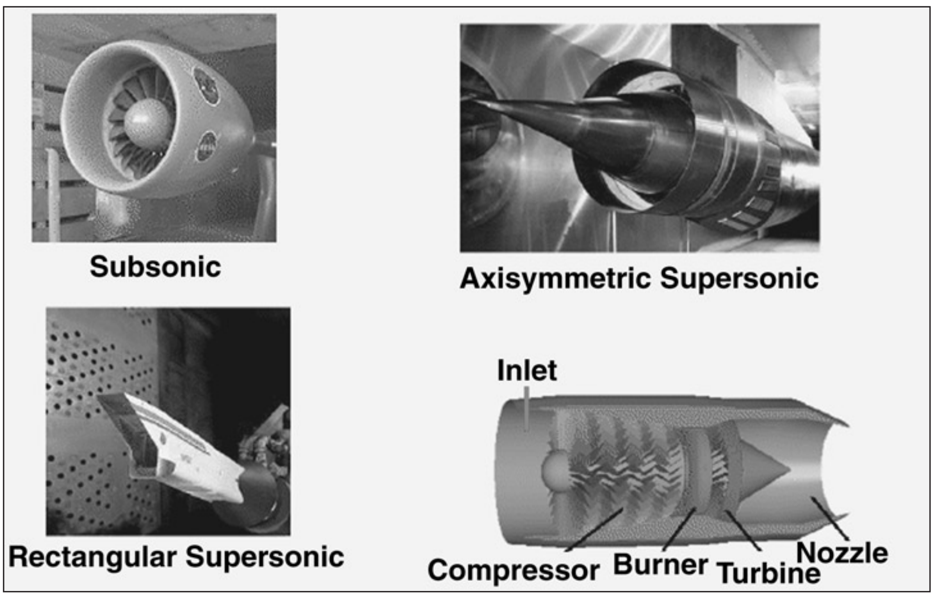
- Turbojets.
- Turbofans.
- Turboprops.
- Afterburning turbojets.
- Ramjets.
- Ultra high bypass engines.

6.3.1 Inlet or Intake

The freestream air enters the gas turbine engine at the inlet, also referred to as the intake. While the inlet does no work on the flow, there are important engineering design features to this component. Inlets come in a variety of shapes and sizes, usually dictated by the speed of the aircraft (see Figure 6.4). For aircraft that cannot go faster than the speed of sound, simple, straight, short inlet designs work well (e.g., for most commercial and cargo aircraft). The surface of the inlet is a continuous smooth curve where the very front (most upstream portion) is called the *highlight,* or the *inlet lip.* A subsonic aircraft has an inlet with a relatively thick lip. An inlet for a supersonic aircraft, on the other hand, has a relatively sharp

NASA Glenn animated turbine engines.

Figure 6.4 | Typical inlet designs for subsonic and supersonic jet engines [36].



lip. The design of a sharpened lip minimizes performance losses from shock waves that occur during supersonic flight. For a supersonic aircraft, the inlet must slow the flow down to subsonic speeds before the air reaches the compressor. Some supersonic inlets use an axisymmetric central cone to shock the flow down to subsonic speeds (Figure 6.4, top right), while other inlets use flat hinged plates to generate compression shocks with the resulting inlet geometry having a rectangular cross section (Figure 6.4, bottom left). This kind of inlet is seen on the F-14 and F-15 fighter aircraft. There are additional, more exotic inlet shapes used on some aircraft for a variety of reasons.

An inlet, or intake, must operate efficiently over the entire flight envelope of the aircraft. At very low aircraft speeds, or when it is stationary on the runway, freestream air is pulled into the engine by the compressor. At high speeds, a good inlet design allows the aircraft to maneuver to high angles of attack without disrupting flow to the compressor. Because the inlet is so important to overall aircraft operation, it is usually designed and tested by the airframe company as well as the engine manufacturer.

Because the inlet does no thermodynamic work, the total temperature through the inlet is constant. Referring to the station numbers on Figure 6.3, the temperature ratio between the freestream (denoted at stage 0) and the inlet boundary with the compressor is

$$\frac{T_2}{T_0} = 1 \tag{6.9}$$

However, the total pressure across the inlet can change due to aerodynamic flow effects, which are characterized by the inlet (total) pressure recovery (IPR). The IPR measures how much of the freestream flow conditions are "recovered," or the ratio in total pressure between stages 2 and 0 across the inlet lip at stage 1. The pressure recovery depends on a wide variety of factors, including the shape of the inlet, the speed of the aircraft, the airflow demands of the engine, and aircraft maneuvers. Analytically, the IPR is a function of inlet efficiency η_i, which is represented as

$$\eta_i = \frac{p_2}{p_1} \tag{6.10}$$

and Mach number M is the ratio of velocity to speed of sound [see Equation (3.26)]; therefore, IPR is given as

$$\text{IPR} = \frac{p_2}{p_0} = \eta_i 1 \qquad \text{for } M < 1 \tag{6.11}$$

$$\text{IPR} = \frac{p_2}{p_0} = \eta_i[1 - 0.075(M - 1)^{1.35}] \qquad \text{for } M > 1 \tag{6.12}$$

6.3.2 Compressor

In the turbine engine, air flows from the inlet to the compressor where the pressure of the incoming air is increased before it enters the combustor. Work is performed by the compressor to increase the air pressure. The two main types of compressors are axial and centrifugal. In an *axial compressor* the flow travels parallel to the axis of rotation (i.e., in the axial direction). In a *centrifugal compressor* the airflow is turned perpendicular to the axis of rotation. The very first jet engines used centrifugal compressors, and they are still used on small turbojets and turboshaft engines and as pumps on rocket engines. Modern large turbojet and turbofan engines usually employ axial compressors. An average, single-stage, centrifugal compressor increases the airflow pressure by a factor of 4. In the centrifugal compressor, the additional pressure increase results from turning the flow radially. A similar single-stage axial compressor increases the pressure by only a factor of 1.2, but several stages can be easily linked together, producing a multistage axial compressor. In the multistage compressor the pressure is multiplied from stage to stage (or row to row) (8 stages at 1.2 per stage gives a factor of 4.3). It is much more difficult to produce an efficient multistage centrifugal compressor because the flow must be ducted back to the axis at each stage. In the axial compressor, cascades of small airfoils are mounted on a shaft that turns at a high velocity. Because the flow is turned perpendicular to the axis, an engine with a centrifugal compressor tends to be wider (greater cross-sectional area) than a corresponding axial compressor. The greater cross section creates additional undesirable drag. For all these reasons, most high-compression jet engines incorporate multistage axial compressor designs. If only a moderate amount of compression is required, the best design choice is a centrifugal compressor.

The work that the pressure exerts on the flow is a function of pressure and temperature. The pressure increase metric is the *compressor pressure ratio,* or CPR, which is the ratio of the air pressure exiting the compressor to the air pressure entering the compressor (always > 1). Using the station numbers of Figure 6.3, the CPR is equal to the pressure at point 3 (p_3) divided by point 2 (p_2). The compressor pressure ratio is related to the temperature at the entrance and exit, and the temperature, in turn, is related to the total pressure for a compressible flow, given as

$$\text{CPR} = \frac{p_3}{p_2} = \frac{T_3^{\gamma/(\gamma-1)}}{T_2} \qquad \textbf{[6.13]}$$

where CPR is the compressor pressure ratio, p is pressure at stations 3 and 2, T is temperature at stations 3 and 2, and γ is a gas property, namely, the specific heat ratio ($\gamma \approx 1.4$ for air). The work of the compressor per mass flow can be quantified as

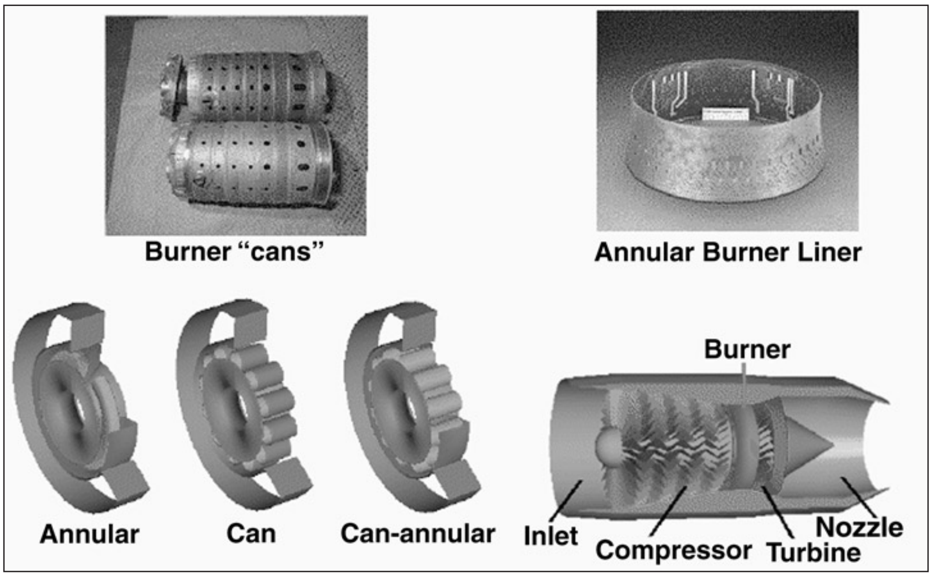
$$W_{\text{comp}} = \frac{cT_2}{\eta_c}(\text{CPR}^{(\gamma-1)/\gamma} - 1) \qquad \textbf{[6.14]}$$

where c is a constant and represents the specific heat of a gas, T_2 is the temperature at the compressor entrance, and η_c is the compressor efficiency. The efficiency factor is included to account for the actual performance of the compressor as opposed to the ideal performance. To achieve a desired design CPR, the compressor inefficiency must be overcome, and the necessary work is provided by the power turbine, which is connected to the compressor by the central shaft. The thermal effects in compressors are significant. In fact, on some engines, the temperature at the exit of the compressor becomes a design constraint (i.e., a factor limiting the engine performance) due to temperature limits on the compressor material, especially the last compressor stage.

6.3.3 Burner or Combustor

The burner is where combustion occurs, and it is often referred to as the combustor of the gas turbine engine. Fuel is combined with the high-pressure air coming out of the compressor, and combustion occurs. The resulting high-temperature exhaust gas is used to turn the power turbine and eventually to produce thrust after passing through the nozzle. The burner is located between the compressor and the power turbine (see Figure 6.5). The burner is arranged as an annulus (i.e., it is doughnut-shaped). The central engine shaft that connects the turbine and

Figure 6.5 | The components of the burner, or combustor, of a gas turbine engine [36].



compressor passes through the hole. Burners must be made from materials that can withstand the high temperatures of combustion. There is usually an outer casing and an inner liner. The liner is often perforated to enhance mixing of the fuel and air. The three main types of combustors are annular, with a liner inside the outer casing (peeled open in Figure 6.5); a can, which is a tubular design where each can has a liner and a casing; and a hybrid can-annular, where the casing is annular and the liner is can-shaped. Many modern burners incorporate annular designs, whereas the can design is older, but offers the flexibility of modular cans. The advantages of the can-annular burner design are that the individual cans are more easily designed and tested, and the casing is annular. All three designs are found in modern gas turbines.

The details of mixing and burning the fuel are complex. For our purposes, we consider the burner as simply the place where combustion occurs and where the working fluid (air) temperature is raised with a slight decrease in pressure. The burning occurs at a higher pressure than freestream because of the action of the compressor. The pressure in the burner remains nearly constant during burning, decreasing by only 1 to 2 percent. Using the station numbers from Figure 6.3, the *burner pressure ratio* (BPR) is equal to the pressure at point 4 (p_4) divided by that at point 3 (p_3), or

$$\text{BPR} = \frac{p_4}{p_3} \sim 1 \qquad \textbf{[6.15]}$$

The thermodynamics of the burner are different from those of the compressor and power turbine engine components because in the burner, heat is released in the combustion process. In the compressor and turbine, no heat enters; therefore, the pressure and temperature are related, and the energy equation determines the temperature change. The energy output of the burner stage is desired. Since fuel is added in the burner domain, we account for the added mass of the fuel by using a ratio f of fuel to air mass flow. The heat release Q depends on the particular fuel that is being burned and is determined experimentally. The burner has an efficiency factor η_b, just as the compressor stage does, to account for losses during burning. The fuel-to-air ratio of the burner is temperature- and gas-dependent and can be quantified as

$$f = \frac{\dot{m}_f}{\dot{m}} = \frac{(T_4/T_3) - 1}{\eta_b Q/(cT_3) - T_4/T_3} \qquad \textbf{[6.16]}$$

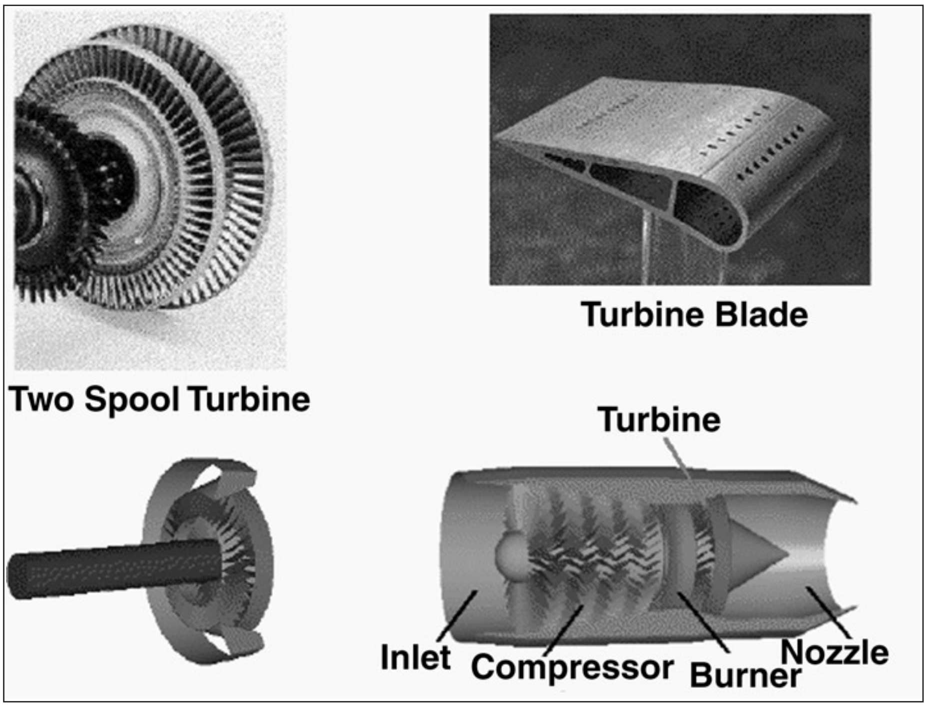
where $\dot{m}_f$ denotes the mass flow of fuel, Q is the heating constant, c represents the average specific heat, T_3 is the temperature at the burner entrance, T_4 is the temperature at the burner exit, and η_b is the burner efficiency. This ratio is very important for determining overall aircraft performance. Material selection and design constraints appear once again when we consider the maximum burner exit temperature (T_4). If the engine is run hotter than the maximum temperature design specification, damage can result to both the burner and the turbine. The burner entrance temperature (T_3) is determined by the compressor and the external flow conditions. The fuel heating value Q is known for the particular fuel being used, and the specific heat coefficient is a known property of air. We solve Equation (6.16) for the value of the fuel-to-air ratio, which allows us to precisely determine the engine's specific fuel consumption. As explained in Chapter 4, "Aircraft Performance," the specific fuel consumption factors into the maximum range over which an aircraft can fly.

How much thrust an engine generates is important, but how much fuel is used to generate that thrust is sometimes more important. Engineers use an efficiency factor, called *thrust specific fuel consumption* (TSFC), to characterize an engine's fuel efficiency. The fuel consumption or TSFC is "how much fuel the engine burns each hour." Propulsion engineers often refer to an engine's specific thrust, which is the thrust produced per mass of air. The *thrust* of TSFC is included to indicate that we are talking about gas turbine engines.

6.3.4 Power Turbine

All gas turbine engines have a power turbine located downstream of the burner to extract energy from the hot flow and to use that energy to turn the compressor. Work is done on the power turbine by the flow. The turbine is composed of two rows of small airfoil-shaped blades. The various parts of an axial turbine include the inner shaft that rotates at very high speeds—the *rotor*—and the other row that remains stationary—the *stator*. The turbine is linked to the compressor by the shaft, and the combination of the shaft, compressor, and turbine is called the *turbomachinery*. The stators keep the flow from spiraling around the axis by bringing the flow back parallel to the axis. Depending on the engine type, there may be multiple turbine stages present in the engine. *Turbofan* and *turboprop* engines usually employ a separate turbine and shaft to power the fan and gearbox, respectively, and are termed a two-spool engine. Three-spool configurations exist for some high-performance engines where an additional turbine and shaft power separate parts of the compressor. There are many interesting turbine design details (see Figure 6.6).

Figure 6.6 | Power turbine component of a jet engine [36].



The turbine extracts energy from the flow, causing a pressure drop across the turbine. The pressure gradient helps keep the flow attached to the turbine blades, and the pressure drop across a single turbine stage can be much greater than the pressure increase across a corresponding compressor stage. A single turbine stage can be used to drive multiple compressor stages. To keep flow from leaking around the edges of the turbine blades, because of the higher pressure gradient, the tips of the turbine blades may be banded together. The turbine blades exist in a much more hostile environment than compressor blades. Sitting just downstream of the burner, the blades experience flow temperatures of several hundred degrees Celsius ($>$ 1,000°F). Turbine blades must, therefore, be either made of special metals that can withstand the heat or actively cooled. A single, actively cooled turbine blade is shown in Figure 6.6. The blade is hollow, and cool air, which is bled off the compressor, is pumped through the blade and out through the small holes on the surface, to keep the surface cool.

The derivation of equations that govern how the turbine extracts energy from the heated flow exiting the burner is given below. As the flow passes through the turbine, the total pressure and temperature are decreased. Akin to the compressor pressure ratio, we measure the decrease in pressure through the turbine as the *turbine pressure ratio* (TPR), or the ratio of the air pressure exiting the turbine to the air pressure entering the turbine (always < 1.0). Using the station numbers of Figure 6.3, the TPR is equal to the pressure at point 5 (p_5) divided by the pressure at point 4 (p_4),

$$\text{TPR} = \frac{p_5}{p_4} = \frac{T_5^{\gamma/(\gamma-1)}}{T_4} \qquad \textbf{[6.17]}$$

Work is done by the flow to turn the turbine and the shaft. From thermodynamics, the turbine work per mass of airflow W_{turb} is related to the total temperature at stations 4 and 5, which is also related to the total pressure for a compressible flow.

$$W_{\text{turb}} = (\eta_t c T_4)(1 - \text{TPR}^{(\gamma-1)/\gamma}) \qquad \textbf{[6.18]}$$

where γ is the specific heat ratio (1.4 for air), c is the specific heat, and η_t is the turbine efficiency. The efficiency factor is necessary to account for the actual performance of the turbine.

6.3.5 Connecting the Compressor and Turbine

The compressor and turbine stages have both been described individually, but the overall jet engine system relies on the compressor and turbine working in concert. This section describes how that is accomplished through *compressor–turbine matching*. The compressor and turbine are matched to ensure proper engine operations. Analytically, we represent this relationship by setting the work done by the compressor equal to the work done by the turbine. Hence, we are ensuring the conservation of energy. Equating Equation (6.14) and Equation (6.16) yields

$$\frac{cT_2}{\eta_c}(\mathrm{CPR}^{(\gamma-1)/\gamma)} - 1) = (\eta_t c T_4)(1 - \mathrm{TPR}^{(\gamma-1)/\gamma}) \qquad [6.19]$$

The work of the compressor is between stages 2 and 3, and that of the turbine is between stages 4 and 5. Now, solving to get an expression for the turbine pressure ratio and a relation between stage 2 of the compressor and stage 4 of the turbine results in

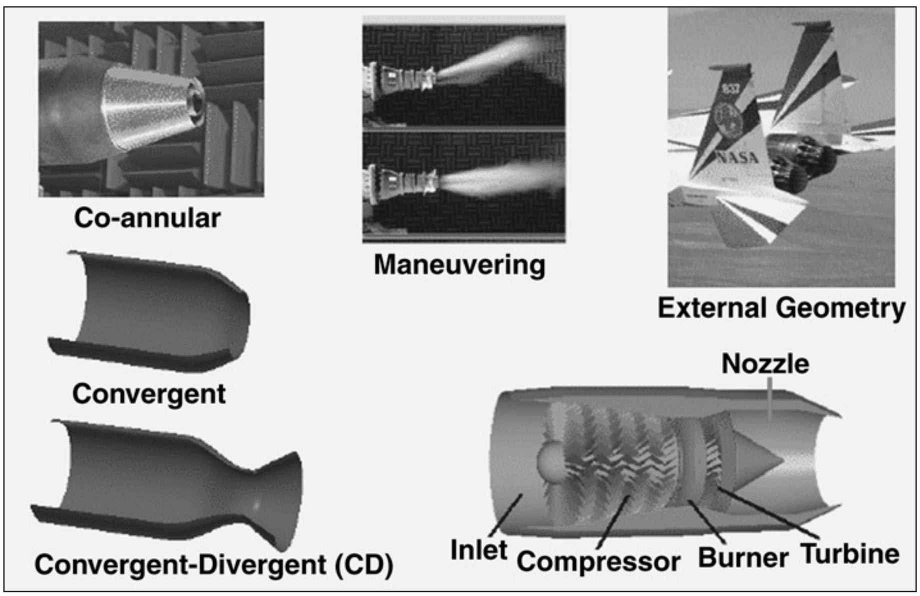
$$\mathrm{TPR}^{(\gamma-1)/\gamma} = 1 - \frac{T_2}{\eta_c \eta_t T_4}(\mathrm{CPR}^{(\gamma-1)/\gamma} - 1) \qquad [6.20]$$

The final stage of the gas turbine engine is the exhaust nozzle.

6.3.6 Nozzles

The gas turbine engine **nozzle** has three functions: to produce thrust, to conduct the exhaust gases back to the freestream, and to set the mass flow rate through the engine. See Figure 6.7. The nozzle sits downstream of the power turbine. A nozzle is a relatively simple device with a specific geometry through which hot gases flow. Nozzles come in a variety of shapes and sizes depending on the mission of the aircraft. Simple *turbojets,* and *turboprops,* often have fixed-geometry convergent nozzles. *Turbofan* engines sometimes employ a coannular nozzle where the core flow exits the center nozzle while the fan flow exits the annular nozzle. *Afterburning turbojets* and *turbofans* often incorporate variable-geometry convergent-

Figure 6.7 | Gas turbine nozzles [36].



divergent (CD) nozzle designs where the flow first converges down to the minimum area, or throat, and then is expanded through the divergent section to the exit.[1] The variable geometry causes these nozzles to be heavy, but provides efficient engine operation over a wider airflow range than do fixed nozzles. All the nozzles we have discussed thus far are round-tube designs. Recently, however, engineers have been experimenting with nozzles with rectangular exits, allowing the exhaust flow to be easily deflected. Changing the direction of the thrust with the nozzle makes the aircraft much more maneuverable.

The nozzle produces the thrust and also sets the total mass flow rate through the engine. The nozzle does no work on the flow; nonetheless, there are some important design features of the nozzle. Because the nozzle does no thermodynamic work, the total temperature through the nozzle is constant, and the total pressure is constant. Recalling the station numbers from Figure 6.3, we write

$$\frac{p_8}{p_5} = \frac{T_8^{\gamma/(\gamma-1)}}{T_5} = 1 \qquad \textbf{[6.21]}$$

where 5 is the turbine exit and 8 is the nozzle throat.

The static pressure at the exit of the nozzle is equal to the freestream static pressure, unless the exiting flow is expanded to supersonic conditions (a convergent-divergent nozzle). The *nozzle pressure ratio,* or NPR, is defined as the ratio of the nozzle *total* to *static* pressure and is written as

$$\text{NPR} = \frac{p_8}{p_{s8}} = \frac{p_8}{p_0} \qquad \textbf{[6.22]}$$

where p_8 is the total pressure and p_{s8} is the static nozzle pressure, or the freestream static pressure. The static pressure is known, but we need to solve for the value of the nozzle total pressure, which we determine from freestream conditions and the overall *engine pressure ratio* EPR. The EPR depends on the pressure ratio of all the other engine components. The EPR is defined to be the total pressure ratio across the engine, or simply the product of the pressure ratio across all the engine components, and is written as

$$\text{EPR} = \frac{p_8}{p_2} = \frac{p_3}{p_2} \cdot \frac{p_4}{p_3} \cdot \frac{p_5}{p_4} \cdot \frac{p_8}{p_5} \qquad \textbf{[6.23]}$$

where the compressor, burner, turbine, and nozzle stages are all represented. The EPR can be measured for an operating engine and is easily displayed to a pilot inside the craft, but the total pressure losses in the inlet are not contained in the EPR. Once the EPR is known, then the NPR, or static and total pressures at the nozzle, is known.

The ETR is similarly given as

$$\text{ETR} = \frac{T_8}{T_2} = \frac{T_3}{T_2} \cdot \frac{T_4}{T_3} \cdot \frac{T_5}{T_4} \cdot \frac{T_8}{T_5} \qquad \textbf{[6.24]}$$

---

1. An aside: Rocket engines usually incorporate a fixed-geometry CD nozzle with a much larger divergent section than is required for a gas turbine engine.

from which the nozzle total temperature (T_8) is calculated. Considering the energy equation and solving for the exit velocity, which depends on the NPR and the nozzle total temperature, yield

$$u_e = u_8 = \sqrt{2c\eta_n T_8[1 - (1/\text{NPR})^{(\gamma-1)/\gamma}]} \qquad \textbf{[6.25]}$$

where η_n is the nozzle efficiency, which is normally very close to 1.

The nozzle performance equations work just as well for rocket engines except that rocket nozzles always expand the flow to some supersonic exit velocity.

Because the nozzle conducts the hot exhaust back to the freestream, there can be serious interactions between the engine exhaust flow and the airflow around the aircraft. On fighter aircraft, in particular, large drag penalties can occur near nozzle exits. A typical nozzle-afterbody configuration is shown in Figure 6.7 for an F-15 with experimental maneuvering nozzles. As with the inlet design, the external nozzle configuration is often designed by the aircraft manufacturers whereas the internal nozzle design is usually the responsibility of the engine manufacturer.

We now know all the necessary relations between gas turbine engine components to solve for the thrust developed by the jet engine. Given that the EPR, the inlet losses, and the corresponding engine temperature ratio (ETR) are known, Section 6.4, "Fundamental Equations Governing Jet Engines," provides a summary of the analysis. The analytical section is followed by a description of six various engines: turbojets, turbofans, turboprops, afterburning turbojets, ramjets, and ultra high bypass engines.

6.4 | FUNDAMENTAL EQUATIONS GOVERNING JET ENGINES

We have described the gas turbine engine components and now want to solve for the thrust developed by the entire jet engine system. All the equations necessary to compute the thrust for a turbojet engine have been introduced and are synthesized in this section. The specific thrust depends only on the exit velocity from the nozzle, the freestream velocity, and the fuel-to-air mass flow ratio f [given in Equation (6.16)]. The equation for the exit velocity was developed in Section 6.3.6, "Nozzles," and depends on the thermodynamic properties of total temperature in the nozzle and the nozzle pressure ratio (NPR) [given in Equation (6.22)]. The total pressure and the total temperature in the nozzle depend on the overall engine pressure ratio and engine temperature ratio [given in Equation (6.23) and Equation (6.24)], which depend on the pressure and temperature ratios across each of the engine components. Recall that the thrust, Equation (6.1), is governed by conservation of momentum

$$F = \dot{m}(u_e - u_0)$$

The exit velocity derived from the nozzle performance is

$$u_e = u_8 = \sqrt{2c\eta_n T_8[1 - (1/\text{NPR})^{(\gamma-1)/\gamma}]}$$

and the nozzle pressure ratio is NPR $= p_8/p_{s8} = p_8/p_0$.

The engine core pressure and temperature are written as

$$p_8 = p_2(\mathrm{EPR}) \qquad \text{and} \qquad T_8 = T_2(\mathrm{ETR})$$

The engine pressure and temperature ratios are referenced to conditions at the compressor face, or stage 2.

$$p_2 = p_0(\mathrm{IPR}) \qquad \text{and} \qquad T_2 = T_0$$

where IPR was given by Equation (6.11) and Equation (6.12) for $M < 1$ and $M > 1$, respectively. The conditions at the compressor stage depend on inlet performance and freestream conditions. Temperature is given by

$$T_0 = T_{s_0}$$

where the total temperature at stage 0 is equivalent to the static, or freestream, temperature. The summary equations below are compressible forms for determining the total pressure and temperature conditions from the corresponding static conditions and the freestream velocity.

$$T_0 = T_{s_0}[1 + 0.5(\gamma - 1)u_0^2/a_0^2] \qquad \textbf{[6.26]}$$

$$p_0 = p_{s_0}(T_0/T_{s_0})^{\gamma/(\gamma-1)} \qquad \textbf{[6.27]}$$

$$a_0 = \sqrt{\gamma R T_0} \qquad \textbf{[6.28]}$$

where the variable a_0 is the freestream speed of sound and R is the gas constant (286 $m^2/s^2/K°$ (or 0.286 kJ/kg/K°) for air).

Calculate the Ratio of Thrust to Mass Flow Times Velocity — EXAMPLE 6.1

Given typical values for a jet engine

Inlet velocity $u_0 \approx 300$ m/s

Heating value of the fuel $Q = 4.8 \times 10^7$ J/kg

Mass flow ratio $\dfrac{\dot{m}_f}{\dot{m}} = 0.01$

Thermal and propulsive efficiencies $\eta_t = 0.5$ and $\eta_p = 0.5$

Determine the difference between the inlet and exit velocity.

$$u_e - u_0 = \frac{4.8 \times 10^7 \text{ J/kg}}{300 \text{ m/s}} \cdot 0.01 \cdot 0.5 \cdot 0.5 = 400 \text{ m/s}$$

Determine the thrust to mass flow times the velocity ratio.

$$\frac{F}{\dot{m}u_0} = \frac{u_e}{u_0} - 1 = \frac{700 \text{ m/s}}{300 \text{ m/s}} - 1 = \frac{4}{3}$$

Next, we would like to know how thrust varies with altitude. Using conservation of mass and assuming an isothermal atmosphere, we begin by writing

$$F = \dot{m}u_0\left(\frac{u_e}{u_0} - 1\right) \tag{6.29}$$

We assume that at stage 2, the compressor, the mass flow is density times velocity times area A, and we substitute into Equation (6.29) for $\dot{m}$:

$$F = \rho_2 u_2 A_2 u_0\left(\frac{u_e}{u_0} - 1\right) \tag{6.30}$$

The velocity at the compressor u_2 is fixed by the speed of the blades in the engine, resulting in a mass flow proportional to density $\dot{m} \propto \rho_2$.

$$\frac{\rho_2(\text{altitude})}{\rho_{\text{sl}}(\text{sea level})} \approx e^{-h/7{,}500} \tag{6.31}$$

where h is in meters. Therefore, the ratio of thrust at altitude to sea-level thrust is

$$\frac{F}{F_{\text{sl}}} = e^{-h/7{,}500} \tag{6.32}$$

Thus, we see that for a given velocity the thrust decreases exponentially. Section 6.7, "Aircraft Propulsion Simulator," provides numerous examples and applications of the jet engine aircraft derived in this section. Further discussion of how jet engines actually work and design enhancements to the standard configuration follows.

6.4.1 How Does a Turbojet Work?

The common components of the engine have been described, so now we concentrate on the entire engine system operation. The different types of engines will be discussed, specifically, the turbojet, turbofan, turboprop, afterburning turbojets, ramjets, and ultra high bypass engines. The turbojet is the basic engine of the jet age. Large amounts of air surrounding the engine are continuously brought into the engine through the inlet which then enter the compressor. The many rows of compressor squeeze the air to many times the freestream pressure. The compressor requires air and an energy supply to operate. At the exit of the compressor, the compressed air is forced into the burner. In the burner a small amount of fuel is sprayed into the compressed air, is ignited, and is burned continuously. A typical jet engine ratio has a 50 : 1 ratio of air mass flow to fuel mass flow. Leaving the burner, the hot, expanding exhaust is passed through the turbine. The turbine works as a windmill and extracts energy from the expanding gases while the blades rotate in the flow. In a jet engine the energy extracted by the turbine drives through a linked central shaft. The turbine depletes some energy from the hot exhaust, but there is sufficient energy left over to provide aircraft forward thrust by increasing the flow velocity through the nozzle—a demonstration of the action-and-reaction principle. For a jet engine, the exit mass flow is nearly equal to the freestream mass flow, since very little fuel is added to the stream.

The thrust equation given in Equation (6.1) contains two interesting terms. Aerospace engineers often refer to the first term (exit mass flow rate times exit velocity) as the *gross thrust* since this term is mostly associated with conditions in the nozzle. The second term (freestream mass flow rate times freestream velocity) is called the *ram drag*. For clarity, the engine thrust is then called the *net thrust*. Our thrust equation indicates that net thrust equals gross thrust minus ram drag.

6.4.2 How Does a Turbofan Work?

Most modern airliners use turbofan engines because of their high thrust and good fuel efficiency. A turbofan engine is a variation of the basic gas turbine engine, where the core engine is surrounded by a fan in the front and an additional fan turbine at the rear. The fan and fan turbine are composed of many blades, as are the core compressor and core turbine, and are connected to an additional shaft. As with the core compressor and turbine, some of the fan blades turn with the shaft and other blades remain stationary. The fan shaft typically passes through the core shaft for mechanical reasons. This type of arrangement is called a *two-spool engine* (one spool for the fan, one spool for the core). Some advanced engines have additional spools for even higher efficiency.

The incoming air is captured by the engine inlet. Some of the incoming air passes through the fan and continues on into the core compressor, then into the burner, where it is mixed with fuel and combustion occurs. The hot exhaust passes through the core and fan turbines and then out the nozzle, identical to the process in a basic turbojet. The fan causes additional air to flow around (bypass) the engine, just like the air through a propeller. This produces greater thrust and reduces specific fuel consumption. Therefore, a turbofan gets some of its thrust from the core and some from the fan. The ratio between the air mass that flows around the engine and the air mass that goes through the core is called the *bypass ratio***.**

Because the fuel flow rate for the core is changed only a small amount by the addition of the fan, a turbofan generates more thrust for nearly the same amount of fuel used by the core. A turbofan is very fuel-efficient—in fact, high bypass ratio turbofans are nearly as fuel-efficient as turboprops (discussed in Section 6.4.3). Because the fan is enclosed by the inlet and is composed of many blades, it operates more efficiently at higher speeds than a simple propeller. That is why turbofans are found on high-speed transports and propellers are used on low-speed transports. There are two types of turbofans: high bypass and low bypass (see Figure 6.8 and Figure 6.9). High bypass turbofans have large fans in

Figure 6.8 | High bypass turbofan engine schematic.

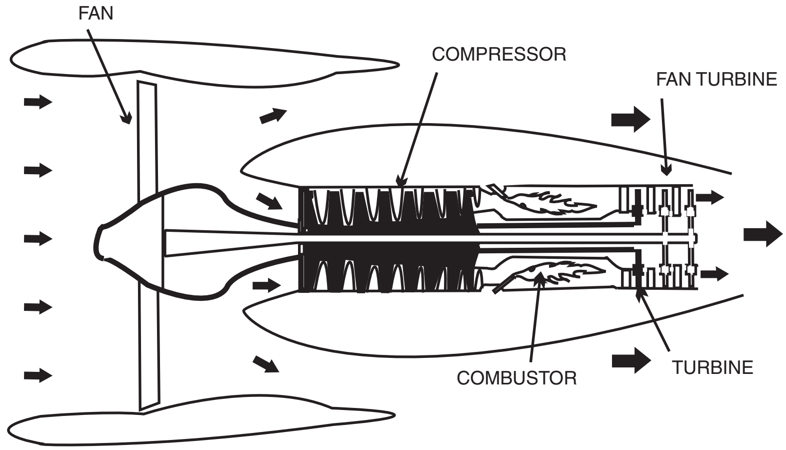
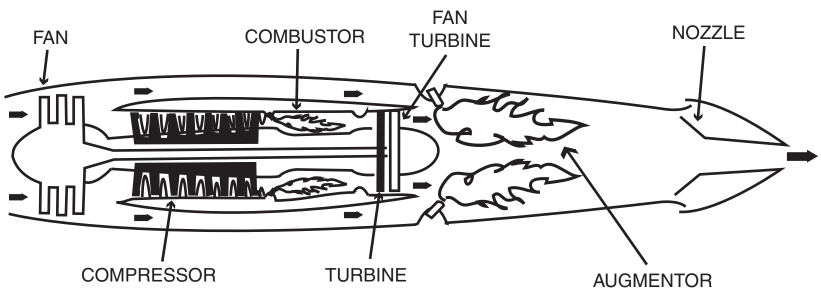


Figure 6.9 | Low bypass turbofan engine schematic.

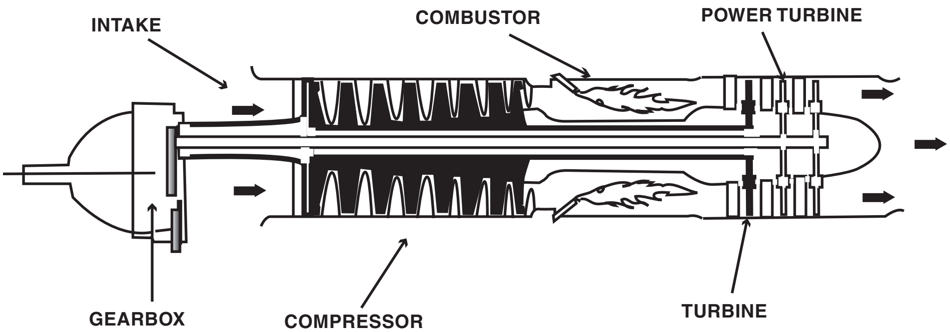


front of the engine and are driven by a fan turbine located behind the primary turbine that drives the main compressor. For supersonic flight, a low bypass fan is used that has a much smaller front fan, and often afterburners (discussed in Section 6.4.4) are added for additional thrust. Even low bypass ratio turbofans are more fuel-efficient than basic turbojets. They can then cruise efficiently but have sufficient thrust for dog-fighting and military maneuvers. Even though the fighter plane can fly much faster than the speed of sound, the air going into the engine must travel at less than the speed of sound for high efficiency. The airplane inlet slows the air down from supersonic speeds.

6.4.3 How Does a Turboprop Work?

Many small commuter aircraft use turboprop engines that have a gas turbine core to turn a propeller. As mentioned previously, propeller engines develop thrust by moving a large mass of air through a small change in velocity. Propellers are very efficient and can use nearly any kind of engine (including humans!) to turn the propeller. There are two main parts to a turboprop propulsion system: the core engine and the propeller. The core is very similar to a basic turbojet except that instead of expanding all the hot exhaust gases through the nozzle to produce thrust, most of the exhaust energy is used to turn the turbine. There may be an additional turbine stage present, which is connected to a driveshaft. The shaft drives the propeller through gear connections and produces most of the thrust. The exhaust velocity of a turboprop is low and contributes a small amount of thrust since most of the energy of the core exhaust has gone into turning the driveshaft (see Figure 6.10).

Figure 6.10 | Turboprop engine schematic.



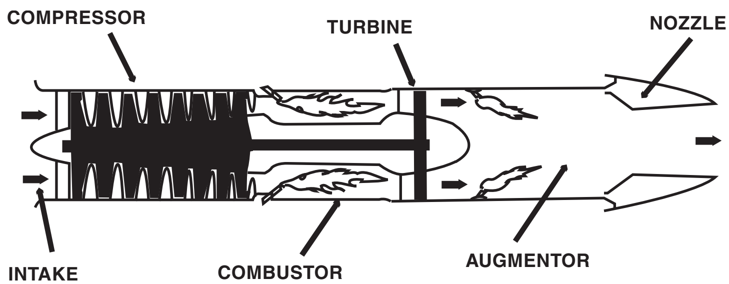
The thrust of a turboprop is the sum of the thrust of the propeller and the thrust of the core. We can use our basic thrust equation on the propeller and core to obtain the thrust equation for the turboprop. As we have noted above, the mass flow through the propeller is much greater than the mass flow through the core engine. And we have also noted that the exhaust velocity of the core is low and almost equal to the velocity into the core. The mass flow rate exiting the core is almost equal to the mass into the core. Comparing with the pure propeller theory, the thrust is equal to the mass flow through the propeller times the velocity change across the propeller plus a smaller amount of thrust from the core engine.

Because propellers become less efficient as the speed of the aircraft increases, turboprops are only used for low-speed aircraft. A variation of the turboprop engine is the turboshaft engine. In a turboshaft engine, the gearbox is not connected to a propeller but to some other drive device. Many helicopters use turboshaft engines, as well as tanks, boats, and even some old race cars.

6.4.4 How Do Afterburning Turbojets Work?

Most modern fighter aircraft employ an afterburner on either a low bypass turbofan or a turbojet. In order for planes to fly at supersonic speeds, they have to overcome a sharp rise in drag near the speed of sound. A simple way to get the necessary thrust is to add an afterburner to a core turbojet, often called an augmentor. In a basic turbojet, some of the energy of the exhaust from the burner is used to turn the turbine. The afterburner is essentially a long *tailpipe* into which additional fuel is sprayed *directly* into the hot exhaust and burned to provide extra thrust. Figure 6.11 shows that the nozzle of the basic turbojet has been extended, and there are now a couple of flame holders in the nozzle. In three dimensions, the afterburner is composed of a series of hoops placed in the exhaust stream. When the afterburner is turned on, additional fuel is injected through the hoops and into the hot exhaust stream of the turbojet. The fuel burns and produces additional thrust, but is less efficient than in the combustion section of the turbojet. The additional thrust comes at the cost of much more fuel. When the afterburner is turned off, the engine performs as a basic turbojet. The mathematics of an afterburning jet is the same as that for a nonafterburning jet as far as thrust is concerned. The exhaust velocity is increased compared to that of the nonafterburning jet because of the higher temperatures involved.

Figure 6.11 | Turbojet engine schematic with an augmentor, or afterburner.



Afterburners are only used on fighter planes and the supersonic *Concorde* airliner. (The *Concorde* turns the afterburners off once it gets into cruise. Otherwise, it would run out of fuel somewhere over the Atlantic.) Afterburners offer a mechanically simple way to augment thrust and are used on both turbojets and turbofans.

6.4.5 How Do Ramjets Work?

A ramjet is a very different engine design from a gas turbine engine since it has no moving parts. It achieves compression of intake air by the actual forward speed of the aircraft. Air entering the intake of a supersonic aircraft is slowed by aerodynamic diffusion created by the inlet and a diffuser to velocities comparable to those in a turbojet afterburner. The expansion of hot gases after fuel injection and combustion accelerates the exhaust air to a velocity higher than that at the inlet, thus creating positive forward thrust [37].

The name *scramjet* is an acronym for *s*upersonic *c*ombustion *ramjet.* The scramjet differs from the ramjet in that combustion takes place at supersonic air velocities through the engine. It is a simple, elegant physical design, but vastly more complicated aerodynamically than a jet engine. Hydrogen is usually the fuel used in the burner. Figures 6.12 and 6.13 show line drawings of a ramjet and scramjet [37].

Figure 6.12 | Ramjet engine schematic.

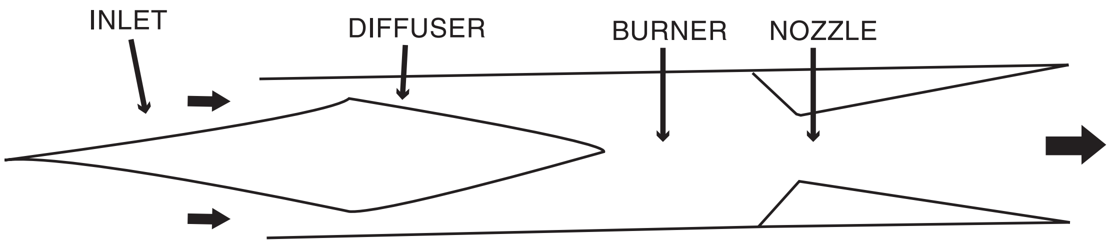
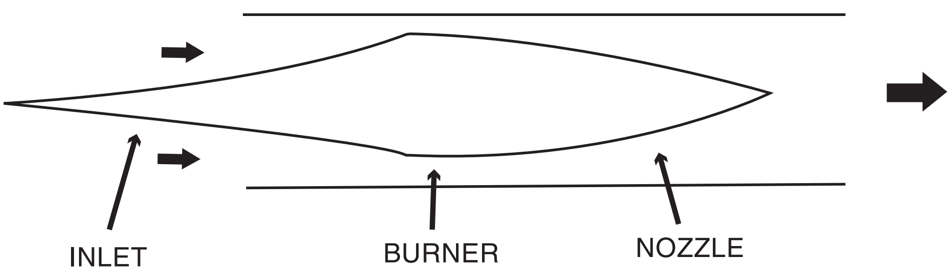


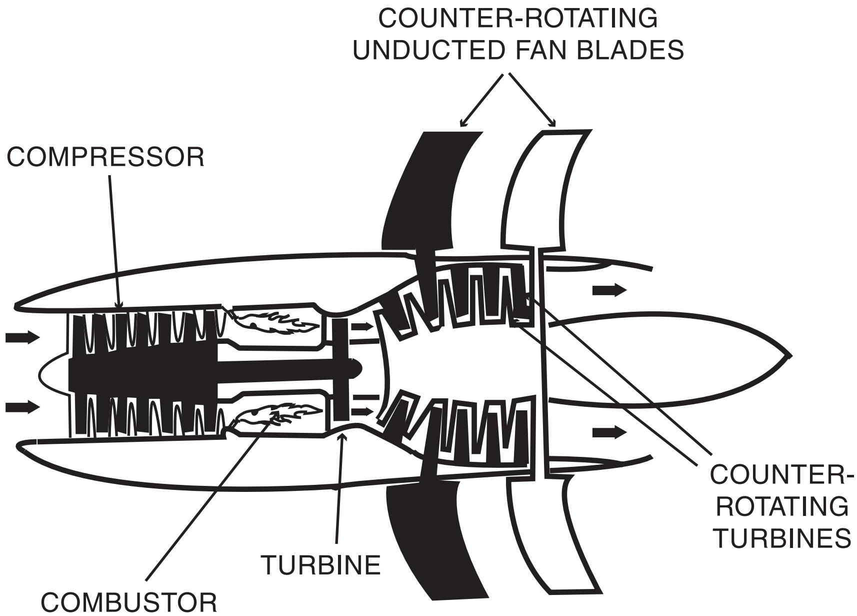
Figure 6.13 | Supersonic combustion ramjet (Scramjet) engine schematic.



6.4.6 How Do Ultra High Bypass Engines Work?

To improve fuel consumption, some ultra high bypass engines are on the drawing board. The physical layouts of components vary, but one example is the unducted fan (UDF) engine that eliminates the need for a gearbox to drive a large fan. The jet engine exhaust drives two counterrotating turbines that are directly coupled to the fan blades. The large-span fan blades are designed with variable pitch (blade angle of attack) to accommodate various aircraft speed and power requirements (see Figure 6.14). The advantage of a UDF engine is that 20 to 30 percent reductions in fuel consumption can be achieved over subsonic turbofans [37].

Figure 6.14 | Ultra high bypass engine schematic.



6.5 | ROCKET ENGINES IN BRIEF

A rocket in its simplest form is a chamber enclosing a gas under pressure. A small opening at one end of the chamber allows the gas to escape, and in doing so it provides a thrust that propels the rocket in the opposite direction. Think of the example of a balloon. Air inside a balloon is compressed by the balloon's rubber walls. The air pushes back so that the forces on each side are balanced. When the nozzle is released, air escapes through it and the balloon is propelled in the opposite direction. For spacecraft, the gas is produced by burning propellants that can be solid or liquid in form or a combination of the two.

All three of Newton's axioms of mechanics are applicable to rocket flight. The second and third laws have already been stated in this chapter, and the first law states that

> Every particle persists in a state of rest or of uniform motion in a straight line unless acted on by a force.

When a rocket is at rest, then the forces on it are balanced. It takes an external force to unbalance the forces and make the object move. If the object is already moving, it takes such a force to stop it, change its direction from a straight-line path, or alter its speed. In rocket flight, forces become balanced and unbalanced all the time. A rocket on the launch pad is balanced. The surface of the pad pushes the rocket up while the gravitational acceleration pulls it toward the center of Earth. As the engines are ignited, the thrust from the rocket unbalances the forces, and the rocket travels upward. Later, when the rocket runs out of fuel, it slows down, stops at the highest point of its flight, then falls back to Earth.

Applying Newton's second law to rocket flight highlights the pressure differential created by the controlled explosion inside the rocket's engines as extreme thrust propels the rocket skyward. That pressure accelerates the gas one way and the rocket the other. The thrust for the rocket continues as long as its engines are firing. Because propellant is burned, the mass of the rocket changes during flight.

Rocket components include engines, payload, control system, propellant tanks, and propellants. By far, the largest contributor to the rocket's mass is the propellant. Newton's second law of motion is especially useful for designing efficient rockets. For a rocket to climb into low Earth orbit, it must achieve a speed in excess of 28,000 km/h. A speed of over 40,250 km/h, called the escape velocity, enables a rocket to leave Earth and travel out into deep space. Attaining spaceflight speeds requires the rocket engine to achieve the greatest thrust possible in the shortest time. In other words, the engine must burn a large mass of fuel and push the resulting gas out of the engine as rapidly as possible.

Newton's second law of motion can be restated in the following way: The greater the mass of rocket fuel burned, and the faster the gas produced can escape the engine, the greater the upward thrust of the rocket.

Newton's third law of action–reaction also applies to rocket flight, as mentioned previously. A rocket can lift off from a launch pad only when it expels gas from its engine. The rocket pushes on the gas, and the gas in turn pushes on the rocket. With rockets, the action is the expulsion of gas from the engine. The reaction is the movement of the rocket in the opposite direction. To enable a rocket to lift off from the launch pad, the action, or thrust, from the engine must be greater than the mass of the rocket. In space, however, even tiny thrusts will cause the rocket to change direction.

An unbalanced force must be exerted for a rocket to lift off from a launch pad or for a craft in space to change speed or direction (first law). The amount of thrust (force) produced by a rocket engine will be determined by the mass of rocket fuel that is burned and how fast the gas escapes the rocket (second law). The reaction, or motion, of the rocket is equal to and in the opposite direction of the action, or thrust, from the engine (third law).

Rocket Engines and Their Propellants Most rockets operate with either solid or liquid propellants. The word *propellant* accounts for both the fuel and the oxidizer. The fuel is the chemical that rockets burn, but for burning to take place, an oxidizer (oxygen) must be present. Jet engines draw oxygen into their engines from the surrounding air, but rocket engines do not have this luxury; they must carry oxygen with them into space, where there is no air.

Solid rocket propellants, which are dry to the touch, contain both the fuel and the oxidizer combined together in the chemical itself. Usually the fuel is a mixture of hydrogen compounds and carbon, and the oxidizer is made up of oxygen compounds. Other rocket engines use liquid propellants. Liquid propellants, which are often gases that have been chilled until they condense into liquids, are kept in separate containers: one for the fuel and the other for the oxidizer. Then, when the engine fires, the fuel and oxidizer are mixed together in the engine. This is a much more complicated engine, requiring sophisticated valves and pumps to handle the flow of fuel. They also require special mixing chambers and propellant feed lines.

The fuel of a liquid-propellant rocket is usually kerosene or liquid hydrogen; the oxidizer is usually liquid oxygen. They are combined inside a cavity called the combustion chamber. Here the propellants burn and build up high temperatures and pressures, and the expanding gas escapes through the nozzle at the lower end. To get the maximum power from the propellants, they must be mixed as completely as possible. Small injectors (nozzles) embedded in the chamber spray and mix the propellants at the same time. Because the chamber operates under high pressures, the propellants are forced inside by powerful, lightweight turbine pumps between the propellant tanks and combustion chambers.

With any rocket, and especially with liquid-propellant rockets, weight is an important factor. In general, the heavier the rocket, the greater the thrust needed to get it off the ground. Due to the mass of the pumps and fuel lines, liquid engines are much heavier than solid engines.

Hybrid rockets combine elements from both types of rockets. In a hybrid rocket, a gaseous or liquid oxidizer is stored in a tank separate from a solid fuel grain. The major benefit of solid rockets over hybrid rockets (and liquid systems, too) is their simplicity. In hybrid systems, then, it seems that higher complexity is the price paid for better performance. However, note that the performance for these rockets rivals that of liquid systems. Furthermore, hybrid rocket systems require support for only one fluid system, including tanks, valves, regulators, etc. In sum, although hybrid rockets are more complex than solid systems, they offer comparable performance to liquid systems yet only half of the plumbing. This vastly reduces the overall system mass and cost, while increasing its reliability (fewer parts that can potentially fail). Hybrid rocket systems are also safer to produce and store and can be more ecologically safe with proper propellant choice; and the fuel grain, being inert, is stronger than manufactured solid propellant grains (for solid rockets), and is therefore more reliable.

The mass of a rocket can make the difference between a successful flight and just wallowing around on the launch pad. As a basic principle of rocket flight, it can be said that for a rocket to leave the ground, the engine must produce a thrust that is greater than the total mass of the vehicle. It is obvious that a rocket with a lot of unnecessary mass is not as efficient as one that is designed for minimum mass. For a typical rocket, the total mass of the vehicle might be distributed in the following way: Of the total mass, 90 percent is propellant, 6 percent is structure (tanks, engines, fins, etc.), and 4 percent is typically payload. Payloads may be satellites, astronauts, or spacecraft that will travel to the Moon or planets. In determining the effectiveness of a rocket design, engineers speak in terms of *mass fraction* (MF). The mass of the propellants of the rocket divided by the total mass of the rocket gives the mass fraction:

$$\text{MF} = \text{mass of propellants/total mass}$$

The mass fraction of the typical rocket given above is 0.80. From the mass fraction formula one might think that an MF of 1.0 is perfect, but then the entire rocket would be nothing more than a lump of propellants that would simply ignite into a fireball. The larger the MF number, the less payload the rocket can carry; the smaller the MF number, the less its range becomes. An MF number of 0.80 is a good balance between payload-carrying capability and range. The Space Shuttle has an MF of ~0.82. The MF varies between different orbiters in the Space Shuttle fleet and with various mission payload weights.

Goddard.gif, X33.jpg, Atlantis.jpg, Buran.jpg, X-31.mov

Rocket Demonstrations In 1926, Robert H. Goddard launched the first liquid-fueled rocket. The 20th century has seen continuous improvement in the design of rocket engines and their performance. Lockheed Martin has designed the X-33 reusable launch vehicle for use in the 21st century. The rocket engines of the Space Shuttle era include those that have propelled NASA's Shuttle and the Russian's Buran reusable space vehicles into orbit. The X-1 used a rocket engine to become the first aircraft to reach supersonic flight.

6.6 | CERTIFICATION OF JET ENGINES

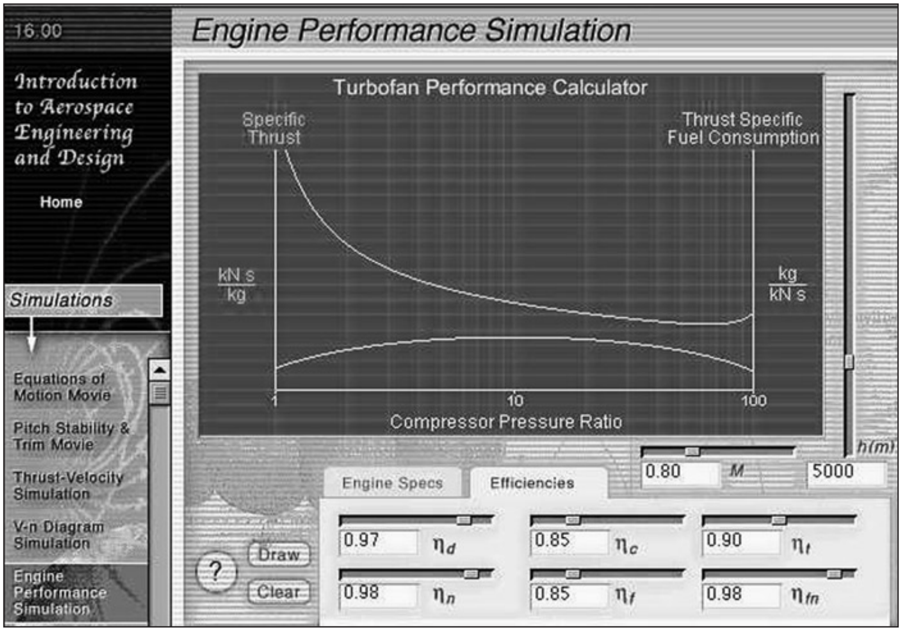
Returning to the topic of jet engines, this section introduces the certification testing that engines must undergo. Large turbofan jet engines for commercial transport aircraft undergo an exhaustive series of tests before they are certified, including bird, ice, and water ingestions as well as containment of broken blades. The bird ingestion test is a little messy, but is critical to prove that the engines will continue to work while flying through natural hazards. If a fan blade fails and is thrown from the hub at the incredibly high rate of rotation at which the engine is turning, passengers inside the aircraft (especially those sitting inside aligned with the engines) want to be absolutely sure that the engine fan case will contain the broken blade and that there is no chance that the turbine blade will penetrate the fuselage. Select from the movie clips on the CD-ROM of tests conducted on the Pratt & Whitney PW4084 engine for the Boeing 777.

Certification tests and propulsion simulator.

6.7 | AIRCRAFT PROPULSION SIMULATOR

The final section of this chapter introduces a turbofan engine simulator that brings together the theoretical concepts introduced throughout the chapter (see the accompanying CD-ROM). In thinking about engine performance, two important operational metrics emerge: What is the specific thrust of the engine and how much fuel does the engine require? The turbofan simulation shows these two metrics, specific thrust and thrust specific fuel consumption, as a function of engine compressor pressure ratio. Parameters such as efficiencies, velocity, altitude, and engine specifications can be varied while interacting with the simulation (see Figure 6.15). For a comprehensive propulsion reference, *Aircraft Engines and Gas Turbines* by J. L. Kerrebrock [38] is highly recommended.

Figure 6.15 | Screen of the turbofan engine performance simulator.



PROBLEMS

6.1 What is the fundamental physical principle behind propulsion? Why is this such a necessary characteristic?

6.2 What kind of propulsion system does the Space Shuttle use, as opposed to an airplane?

6.3 *Jet engine certification.* What is the first step in preparing a properly disposed of, 8 to 10 lb bird for an FAA-regulated, large bird ingestion test? (An engine manufacturer actually learned this the hard way).

$\int$ **6.4** You are on a team designing engines for a new NASA vehicle. The primary design requirement is that for a standard altitude of 50 km the engines produce a thrust of 150,000 N. One of your fellow design engineers approaches you, says that she has solved the problem, and presents you with the following data: mass flow, 25 kg/s; exit area, 2 m^2; exit velocity, 4,000 m/s; and exit pressure, 2×10 N/m^2. Has she solved the problem? Why or why not?

6.5 The work done by the compressor is written as:

$$W_{\text{comp}} = \frac{cT_2}{\eta_c}(\text{CPR}^{(\gamma-1)/\gamma} - 1)$$

For convenience, it may also be written as

$$W_{\text{comp}} = cT_2(\pi^{(\gamma-1)/\gamma} - 1)$$

where π represents the pressure ratio and the subscript represents the specific stage of the engine, in this case, c for compressor. Similarly, the work produced by the turbine is written

$$W_{\text{turb}} = (\eta_t cT_4)(1 - \text{TPR}^{(\gamma-1)/\gamma}) = cT_4(1 - \pi_t^{(\gamma-1)/\gamma})$$

$$\text{CPR} = \pi_c \qquad \text{and} \qquad \text{TPR} = \pi_t \qquad \text{and} \qquad \gamma = 1.4$$

(a) $C_p = 1{,}000$ J/(kg · K), $T_2 = 300$ K, and $\pi_c = 30$, what is T_3?
(b) Given $T_5 = 500$ K and $T_4 = 2{,}000$ K, find π_t.
(c) Compute the work of the engine, W_{comp} and W_{turb}.
(d) The two numbers should not be equal. Why? What was not considered?
(e) Assume an ideal turbine. What is η_c?

6.6 Select two of the following air/spacecraft:

(a) List a few examples of the primary requirements for engines on your selected craft.
(b) Consider your two choices and their primary flight function. How do they differ? What should an engineer be most concerned about when designing each engine?

6.7 Answer some advanced propulsion questions.

(a) Describe what you would go through if you sat on a volume of air as it traveled through an afterburning turbojet engine (aside from vertigo and severe burns).
(b) *Challenging.* What limits the altitude at which a jet engine may fly? What could happen if you flew too high? (I mentioned this in lecture a couple of times—it is very bad from a performance point of view.)
(c) *More challenging.* What are the advantages of having multiple spools in a turbofan engine? (It is related to the behavior of the fan. Think of it as comparable to a big propeller . . . and how the flow changes as it passes through the core.)

6.8 Using the Propulsion Simulator provided on the CD-ROM, answer the following for an engine with a 10 m^2 inlet area, $M = 0.8$, altitude $h =$

Propulsion simulator.

10,000 m, fan pressure ratio 1.5, burner pressure ratio 0.96, and a burner temperature of 1,500 K.

(a) Using the default values for engine efficiencies, for a compressor pressure ratio (CPR) of 10, what is the specific thrust? What is the thrust specific fuel consumption?

(b) What does increasing the compressor efficiency achieve?

(c) An increase in Mach number has what effect on thrust specific fuel consumption and specific thrust?

OTHER ASSETS

Chapter 7

Introduction to Aircraft Stability and Control

Dava J. Newman and Amir R. Amir

7.1 | BASIC NOMENCLATURE

Airplane *performance* is governed by *forces* along and perpendicular to the flight path. The translational motion of the airplane is a response to these forces. In contrast, airplane *stability and control* are governed by *moments* about the center of gravity, and the rotational motion of the plane is a response to these moments. Much of the information in this chapter is motivated by content in Anderson's *Introduction to Flight* [33], which is recommended for a more detailed discussion of stability and control. This chapter introduces basic nomenclature, defines airplane stability, derives the equations of motion for airplane stability, provides an interactive animation of stability and control where use of the CD-ROM is suggested, and concludes with an example to facilitate practice implementing the governing equations.

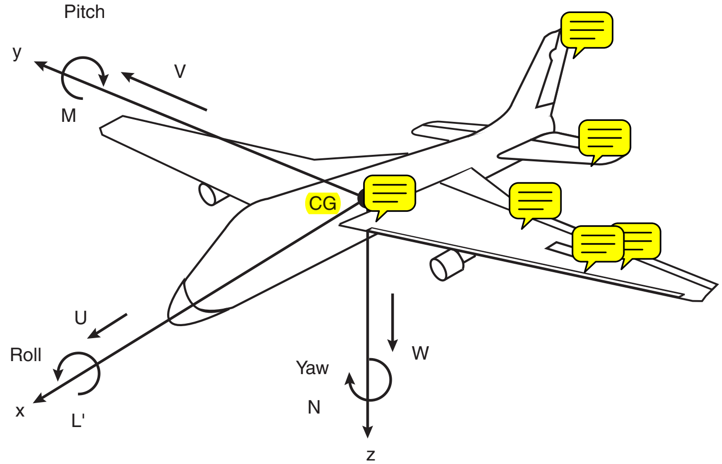
Figure 7.1 shows a rectangular right-handed coordinate system attached to the aircraft. The origin of the axes is at the aircraft's center of gravity. The x axis is along the fuselage, the y axis is along the wingspan, and the z axis points downward.

The aircraft's translational motion is given by the velocity components U, V, and W along the axes. Thus, the net velocity of the aircraft is the vector sum of these three velocity components. The rotational motion is given by the angular velocity components $(\dot{\phi}, \dot{\theta}, \dot{\psi})$ about the x, y, and z axes.

In summary, the nomenclature associated with rotational motion is as follows:

- x axis: roll axis, $L' =$ rolling moment, $\dot{\phi} =$ rolling velocity.
- y axis: pitch axis, $M =$ pitching moment, $\dot{\theta} =$ pitching velocity.
- z axis: yaw axis, $N =$ yawing moment, $\dot{\psi} =$ yawing velocity.

Figure 7.1 | Definition of the airplane's axis system.

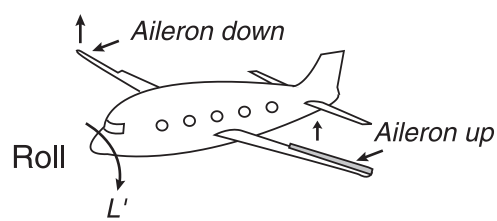


A classic airplane has three basic controls: *ailerons, elevator,* and *rudder.* They are designed to change and control the moments about the roll, pitch, and yaw axes. These control surfaces are flaplike surfaces that can be deflected back and forth at the command of the pilot.

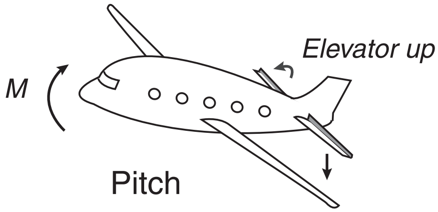
Figure 4.1 introduced and defined airplane control surfaces. The ailerons are located at the trailing edge of the wing. Similarly, the elevator is located at the trailing edge of the horizontal stabilizer, and the rudder is at the trailing edge of the vertical stabilizer.

A downward deflection of a control surface will increase the lift, since this makes the airfoil shape of the wing or tail "more bent downward" (in aeronautical jargon, it has a larger camber) and thus produces more lift. An increase or decrease of the deflection will change the moment and thus will result in a rotation about an axis.

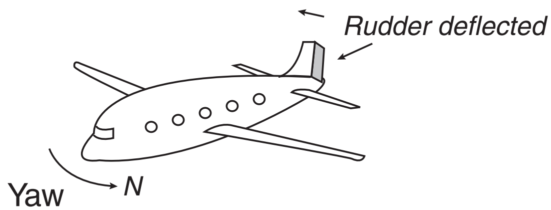
- *Rolling.* The ailerons control the roll or *lateral motion* and are therefore often called the lateral controls.



- *Pitching.* The elevator controls pitch or the *longitudinal motion* and thus is often called the longitudinal control.



- *Yawing.* The rudder controls yaw or the *directional motion* and thus is called the directional control.



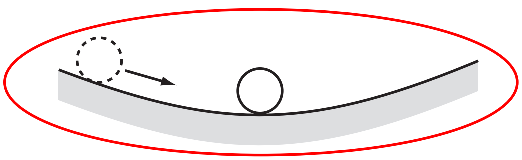
7.2 | AIRPLANE STABILITY

There are two types of stability: static stability and dynamic stability.

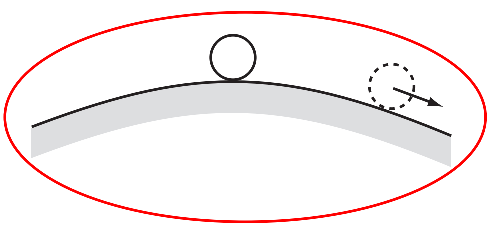
7.2.1 Static Stability

Static stability can be visualized by a ball (or any object) on a surface. Initially the ball is in equilibrium. The ball is then displaced from the equilibrium position, and its initial behavior is observed.

- *Statically stable.* If the forces and moments on the body caused by a disturbance tend initially to return the body toward its equilibrium position, the body is *statically stable.*



- *Statically unstable.* If the forces and moments are such that the body continues to move away from its equilibrium position after being disturbed, the body is *statically unstable.*



- *Neutrally stable.* If the body is disturbed but the moments remain zero, the body stays in equilibrium and is *neutrally stable.*

Of importance to us are only the first two cases; neutral stability occurs very rarely. A very important point is that static stability deals only with the *initial tendency* of a vehicle to return or diverge from equilibrium.

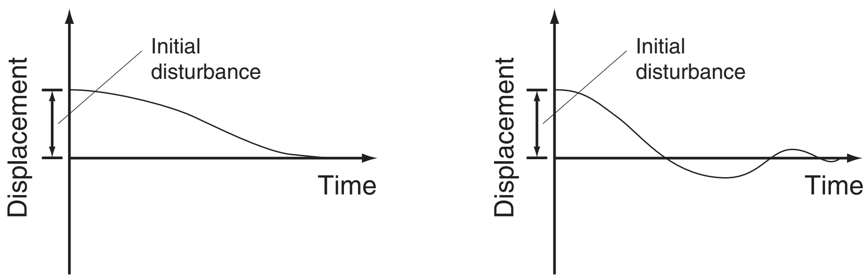
7.2.2 Dynamic Stability

Dynamic stability deals with the *time history* of the vehicle's motion after it initially responds to its static stability.

Consider an airplane flying at an angle of attack (AOA) α_e such that the moments about the center of gravity (cg) are zero. The aircraft is therefore in equilibrium at α_e and is said to be *trimmed,* and α_e is called the *trim angle of attack.*

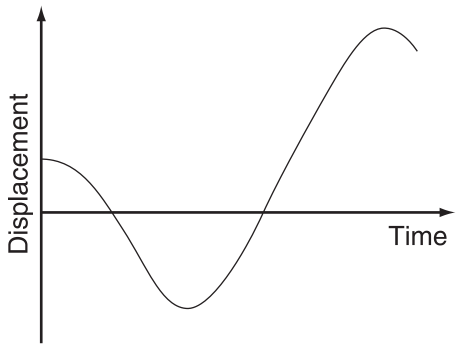
Now imagine that a wind gust disturbs the airplane and changes its angle of attack to some new value α. Hence, the plane was pitched through a displacement $\alpha - \alpha_e$. The plane's behavior could be as shown in Figure 7.2.

Figure 7.2 | Dynamically stable behavior.



In both situations the airplane eventually returns to its equilibrium position after some time interval. In the first case the vehicle approaches monotonically the equilibrium position (*aperiodic behavior*), while in the second case, it overshoots the equilibrium position (*damped oscillation*). A body is *dynamically stable* if, out of its own accord, it eventually returns to and remains at its equilibrium position over a period of time. It is important to note that static stability does not imply dynamic stability, as Figure 7.3 shows. The plane is dynamically unstable but still statically stable.

Figure 7.3 | Dynamically unstable behavior.



7.3 | STATIC FORCES AND MOMENTS ON AN AIRCRAFT

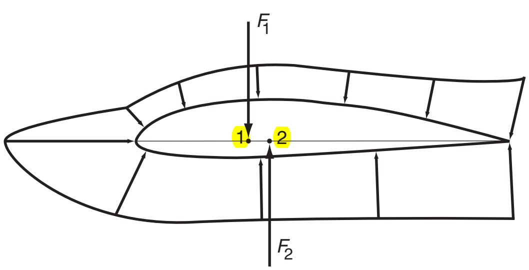
7.3.1 Resulting Force on a Wing

There is an aerodynamic force created by the pressure (and shear stress[1]) distribution over the wing surface. The resultant (net) force R can be resolved into two components: the lift L (perpendicular to the relative wind v_∞) and the drag D (in the direction of the relative wind v_∞).

7.3.2 Resulting Moment on a Wing

Consider just the pressure on the top surface of the wing. The net force due to that pressure distribution, called F_1, points downward and is acting through point 1 on the chord line. The pressure distribution on the bottom surface results in a net force F_2, pointing upward and acting through point 2 on the chord line. The total aerodynamic force on the wing is of course a summation of F_1 and F_2. If $F_2 > F_1$, there is lift. Since the two forces do not act through the same point, there will be a *net moment* on the wing. See Figure 7.4.

Figure 7.4 | The origin of the moment acting on an airfoil.



1. Pressure is the force perpendicular to the surface per unit area, while shear stress is the force along the surface per unit area. Both have units of pascals (or newtons per meter squared).

The magnitude of the moment depends upon the reference point about which the moment is taken. If the moment is taken with respect to the leading edge, it is denoted by M_{LE}. For subsonic wings it is often customary to take the moment about the *quarter-chord point* (i.e, the point that is a distance $c/4$ away from the leading edge). This moment is denoted by $M_{c/4}$.

Both M_{LE} and $M_{c/4}$ vary with the angle of attack. However, a special point exists about which the moment essentially does not vary with α. This point is called the *aerodynamic center* (ac). For that point,

$$M_{ac} = \text{constant (independent of angle of attack)} \qquad [7.1]$$

The moment coefficient about the aerodynamic center is defined as

$$C_{M,\,ac} \equiv \frac{M_{ac}}{q_\infty Sc} \qquad [7.2]$$

where q_∞ is the dynamic pressure, S the wing area, and c the chord length. (Recall the definition of the coefficient of lift and drag from Chapter 3, "Aerodynamics.")

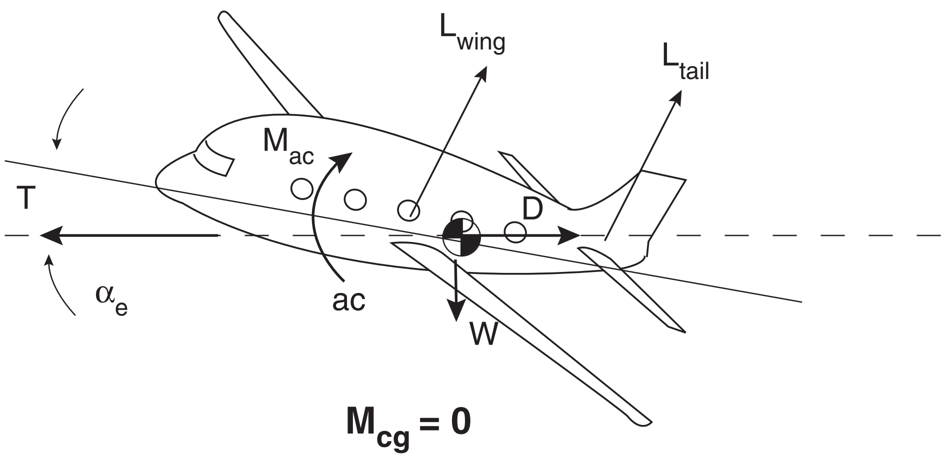
The value of $C_{M,\,ac}$ is zero for symmetric airfoils and varies from -0.02 to -0.3 or so for cambered airfoils.

7.3.3 Moment on an Aircraft

Having looked at a wing only, we can now consider a complete airplane, as shown in Figure 7.5. In examining a whole aircraft, the pitching moment about the center of gravity (center of mass) is of interest. The moment coefficient about cg is defined analogous to the moment coefficient about the ac:

$$C_{M,cg} \equiv \frac{M_{cg}}{q_\infty Sc} \qquad [7.3]$$

Figure 7.5 | Contributions to the moment acting about the center of gravity.



An airplane is in *pitch equilibrium* when the net moment about the center of gravity is zero.

$$M_{\text{cg}} = C_{M,\text{cg}} = 0 \qquad \text{airplane is } \textit{trimmed} \qquad [7.4]$$

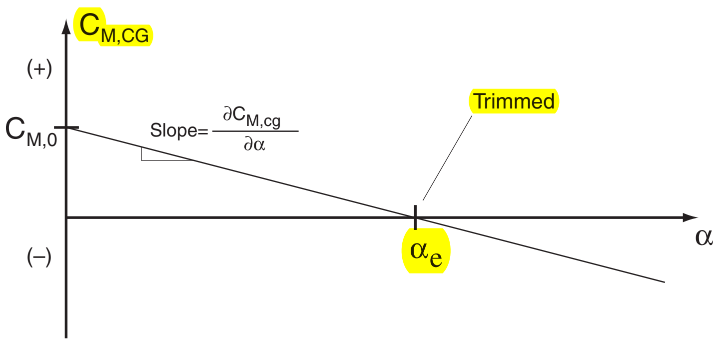
Note that while drag plays an essential part in performance determination, its role is small for stability and control. Its value is much less than that of the lift, and its acts not too far from the center of gravity, so its effects are often neglected.

7.4 | ATTAINING AIRCRAFT LONGITUDINAL STATIC STABILITY

Static stability and control about all three axes is necessary in the design of conventional airplanes. However, a complete description of lateral, longitudinal, and directional stability is difficult. We will focus on longitudinal motion (pitching motion about the y axis), which is the most important.

Consider an airplane with fixed control surfaces. Wind tunnel testing may reveal the following behavior (see Figure 7.6): The plot is almost linear and shows the value of the $C_{M,\text{ cg}}$ versus angle of attack α. The slope of the curve is $\partial C_{M,\text{ cg}}/\partial\alpha$, and is sometimes denoted with the letter "a." (A partial derivative rather than a total derivative is used since the coefficient does not depend on α alone.) The value of $C_{M,\text{ cg}}$ at an angle of attack equal to zero is denoted by $C_{M,\text{ 0}}$. The angle at which the moment coefficient is zero is, of course, the trim angle of attack.

Figure 7.6 | The moment coefficient about the center of gravity as a function of angle of attack for a longitudinally stable aircraft.

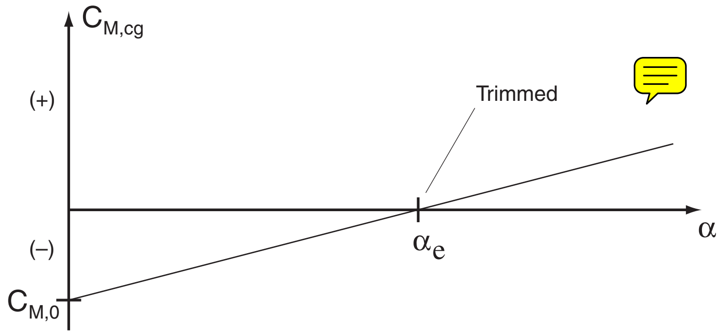


If the airplane is flying at its trim angle of attack α_e and suddenly encounters a disturbance that causes it to pitch up or down (e.g., due to a wind gust), the moment will be such that the plane will return to its equilibrium position. To see that, imagine a wind gust pitching the plane up from α_e to some larger α. By looking at the plot in Fig. 7.6, you can see that the moment coefficient (and hence the moment) will be negative, which makes the plane pitch *down* and return to equilibrium.

Suppose the curve of $C_{M,\,\mathrm{cg}}$ versus α is as shown in Figure 7.7. The plane would be unstable, as you can verify yourself. Thus, we can state the *necessary criteria* for longitudinal static stability and balance as

$$\boxed{\frac{\partial C_{M,\mathrm{cg}}}{\partial \alpha} < 0 \qquad \text{and} \qquad C_{M,0} > 0} \tag{7.5}$$

Figure 7.7 | The moment coefficient about the center of gravity as a function of angle of attack for a longitudinally unstable aircraft.



That is, the slope of the moment coefficient curve versus angle of attack has to be negative, and the moment coefficient at zero angle of attack has to be positive.

An airplane can fly trough a range of angles of attack, but α_e must be within this range, or else the plane cannot be trimmed. If the aircraft can be trimmed, it is said to be longitudinally balanced.

We can now answer the question, Why do airplanes have horizontal stabilizers? If you have a wing by itself, it will usually have a negative $C_{M,\,\mathrm{ac}}$ and thus a negative $C_{M,\,0}$ (this is characteristic of all airfoils with positive camber). Therefore a wing by itself is unbalanced. To correct the situation, a horizontal stabilizer is mounted behind the wing. If the wing is inclined downward to produce a negative lift, then a clockwise moment about the cg will be created. If this clockwise moment is large enough, it will overcome the negative $C_{M,\,0}$ for the wing-tail combination, making the aircraft as a whole longitudinally balanced.

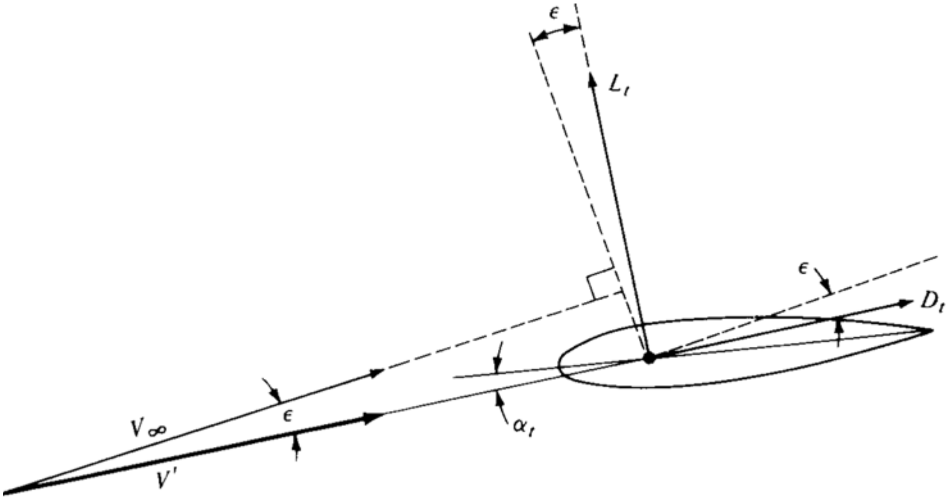
The horizontal stabilizer does not have to be placed behind the wing. If it is in front of the wing, it is called a *canard configuration.*

7.5 | USEFUL CALCULATIONS AND AN EXAMPLE

First consider the tail (horizontal stabilizer) by itself, as shown in Fig. 7.8. Since the tail is behind the wing, it feels *two interference effects:*

1. The airflow arriving at the tail does not have the same direction as that arriving at the wing, since the wing deflects the airflow downward due to

Figure 7.8 | Forces acting on the tail and relative wind seen by the tail [33].

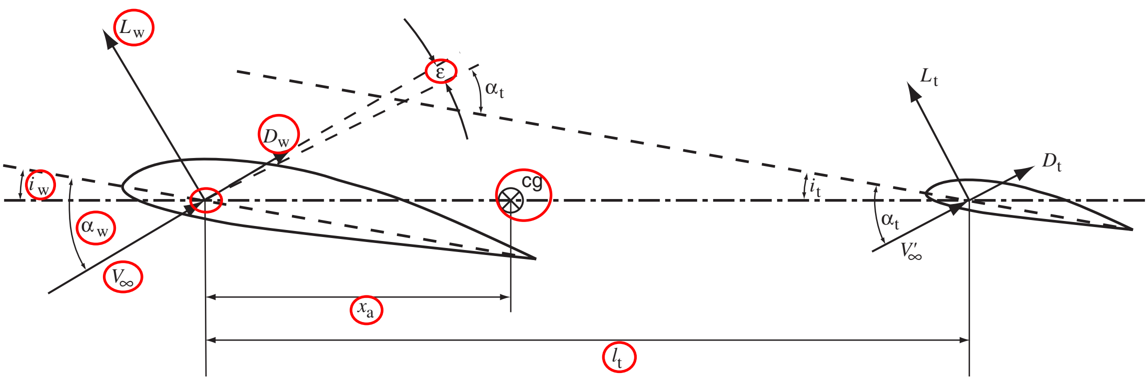


the *downwash* effect (an effect due to the finite length of the wings). Hence, the relative wind of the wing and tail makes up an angle ε.

2. Due to skin friction and pressure drag, the magnitude of the relative wind seen by the tail is smaller than the magnitude of the relative wind seen by the wing.

Now consider an idealized wing-tail configuration in steady, level flight such as shown in Figure 7.9. The wing and the tail are set at incidence angles i_w and i_t, respectively, with respect to the longitudinal aircraft axis. The relative wind V_∞ comes in at an angle α_w with respect to the wing. The relative wind V'_∞ comes in at an angle α_t with respect to the tail.

Figure 7.9 | Geometry of a wing-tail combination [39].



The tail angle of attack can be computed as follows:

$$\alpha_t = \alpha_w - \varepsilon + i_t - i_w \quad [7.6]$$

where ε is the downwash. Its value can be computed from the following equation:

$$\varepsilon = \varepsilon_\alpha \alpha_w \quad [7.7]$$

where $\varepsilon_\alpha \approx 0.3$ to 0.5. This allows us to rewrite the equation for α_t as

$$\alpha_t = (1 - \varepsilon_\alpha)\alpha_w + i_t - i_w \quad [7.8]$$

When the airplane is trimmed, the moments about the cg are zero. From this we can find the *trim condition*. The coefficients of lift for the wing and for the tail and the angle of attack can be defined as the product of the slope of the moment coefficient.

$$C_{L,w} = a_w \alpha_w \quad [7.9]$$

$$C_{L,t} = a_t[\alpha_w(1 - \varepsilon_\alpha) + i_t - i_w] \quad [7.10]$$

After several steps and a few simplifying assumptions, the trim condition can be

$$\boxed{\frac{C_{M,\text{cg}}}{a_w} = \left[\frac{x_a}{c} - \frac{A_t l_t a_t}{A_w c a_w}(1 - \varepsilon_\alpha)\right]\alpha_w + \left[\frac{C_{M,\text{ac}}}{a_w} + \frac{A_t l_t a_t}{A_w c a_w}(i_w - i_t)\right] = 0} \quad [7.11]$$

The first term in brackets is the sensitivity to the angle of attack. Consider again the situation where a wind gust disturbs a plane flying in trim and causes it to pitch up. For the plane to be stable, the moment coefficient $C_{M,\text{ cg}}$ (which was 0) has to be negative in order for the plane to pitch down. For stability we can then write

$$\boxed{\frac{\partial C_{M,\text{cg}}}{\partial \alpha} < 0 \qquad \text{or} \qquad \frac{x_a}{c} < \frac{A_t l_t a_t}{A_w c a_w}(1 - \varepsilon_\alpha)} \quad [7.12]$$

In designing your LTA vehicle, you can place the cg (and thus set the value of x_a) such that the vehicle is stable, using the above inequality. In the limiting case, when the cg is as far back as possible,

$$\boxed{\left(\frac{x_a}{c}\right)_{\text{max}} = \frac{\boxed{A_t} l_t a_t}{A_w c a_w}(1 - \varepsilon_\alpha)} \quad [7.13]$$

The cg is said to be at the *neutral point*.

The trim angle of attack can be written as

$$\boxed{(\alpha_w)_{\text{trim}} = \frac{C_{M,\text{ac}}/a_w + [A_t l_t a_t/(A_w c a_w)](i_w - i_t)}{(x_a/c)_{\text{max}} - x_a/c}} \quad [7.14]$$

For lift generation, $\alpha_w < 0$, $C_{M,\text{ ac}} < 0$, (usually), and $i_w - i_t > 0$. Also, L_t may have to be negative.

An animation was created to help you visualize airplane pitch stability and control. Run the animation to become familiar with the governing equations and to see the results of moments on the airplane resulting in stability and instability. Now that you have seen an airplane in motion, Example 7.1 provides additional practice in calculating airplane stability parameters.

Pitch Stability and Control Movie.

EXAMPLE 7.1

This numeric example illustrates the use of the equations presented. Consider a light aircraft with the following characteristics:

- $A_w = 15\ \text{m}^2$, $c = 1.6$ m.
- $A_t = 2.3\ \text{m}^2$, $l_t = 4.0$ m.
- $m = 1{,}050$ kg, $I_y = 1{,}600\ \text{kg}\cdot\text{m}^2$.
- $a_w = 5\ \text{rad}^{-1}$, $a_t = \text{rad}^{-1}$.
- $C_{M,\,\text{ac}} = -0.07$, $\varepsilon_\alpha = 0.45$.
- $V = 50$ m/s, $\rho = 1\ \text{kg/m}^3$ (approximately 1,500 m altitude).

Question 1. Where is the neutral point of the aircraft?

The implied lift coefficient for level flight (neglecting the tail contribution) is

$$C_{L,w} \cong \frac{mg}{\frac{1}{2}\rho V^2 A_w} = \frac{(1{,}050)(9.8)}{(0.5)(1)(50^2)(15)} = 0.549 \qquad [7.15]$$

The angle of attack of the wing is then

$$\alpha_w = \frac{C_{L,w}}{a_w} = \frac{0.546}{5} = 0.11 \text{ rad} \ = 6.3^\circ \qquad [7.16]$$

The neutral point can be calculated as follows:

$$\left(\frac{x_a}{c}\right)_{\max} = \frac{A_t l_t a_t}{A_w c a_w}(1-\varepsilon_\alpha) = \frac{(2.3)(4.0)(4)}{(15)(1.6)(5)}(1-0.45) = 0.264 \qquad [7.17]$$

$$(x_a)_{\max} = 0.42 \text{ m} \qquad [7.18]$$

Question 2. Suppose that the cg is placed halfway between the ac and the neutral point, that is, $x_a = 0.21$ m and $x_a/c = 0.132$. What is the angle of attack of the tail and the lift produced by the tail?

First the difference between the wing and tail incidence angles needs to be computed:

$$(\alpha_w)_{\text{trim}} = 0.11 = \frac{-0.07/5 + \{2.3(4)(4)/[(15)(1.6)(5)]\}(i_w - i_t)}{0.264 - 0.132} \qquad [7.19]$$

$$\Rightarrow i_w - i_t = 0.093 \text{ rad} = 5.3^\circ$$

The tail angle of attack is then

$$\begin{aligned}\alpha_t &= (1-\varepsilon_\alpha)\alpha_w + i_t - i_w \\ &= (1-0.45)(0.11) - 0.093 \\ &= -0.0325 \text{ rad} = -1.9^\circ\end{aligned} \qquad [7.20]$$

The lift generated by the tail is

$$\begin{aligned} L_t &= \frac{1}{2}\rho V^2 A_t a_t \alpha_t \\ &= \left(\frac{1}{2}\right)(1)(50^2)(2.3)(4)(-0.0325) = -374 \text{ N} \qquad \text{(negative lift!)} \end{aligned} \tag{7.21}$$

Note that since this lift is negative (i.e, a downward force), it adds to the weight of the vehicle as far as the required wing lift is concerned!

PROBLEMS

7.1 Design and make a paper airplane, focusing on performance and stability.

(a) Sketch a multiview drawing of your paper airplane. Necessary viewpoints are the side view, top view, and frontal view.

(b) Describe your design.

(c) Make five trial flights and discuss your results. Bring your design to the lecture ready to fly.

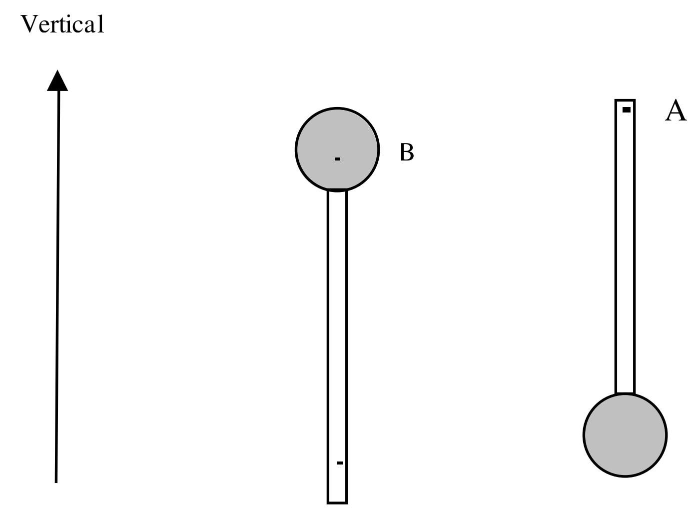
(d) Your in-class challenge will be to describe and then demonstrate your chosen aspect of performance or stability (you are to demonstrate only one stated objective). For example, use elevators to demonstrate pitch.

7.2 Sketch (in full scale) your rendition of an early Egyptian bird model (legless, featherless, sycamore wood) that is actually an ancient model airplane with an 18 cm wingspan and vertical stabilizer.

7.3 One definition of stability is the following:

Given a system in equilibrium [e.g., the position of a mechanical component is not changing, or the current in an electric circuit is constant, or the temperature in a furnace is constant, or the concentration of a species in a chemical reaction is constant] if the system is *subjected to a perturbation* and returns to its initial equilibrium position after the perturbation has disappeared, the system is said to be stable.

Consider the pendulum represented here; it is in equilibrium in both positions and can freely rotate around *A*.

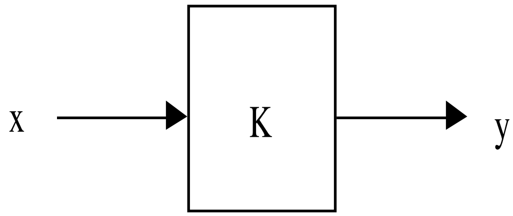


(a) Given the above definition of stability, which of the above systems is in a stable equilibrium?

(b) Sketch the evolution of the angle $\theta(t)$ between the segment AB and the vertical as a function of time following a brief perturbation for the two systems in the figures above. Justify your answer to part (a).

(c) Now consider the two pendulums immersed in a vat of honey! Sketch $\theta(t)$ for the two systems. How does it differ from your answer to part (b)? Suggest a physical explanation for this difference.

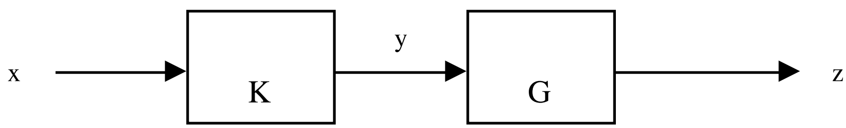
7.4 A block diagram is a graphical representation of a system (a model or an equation). The following conventions are used:



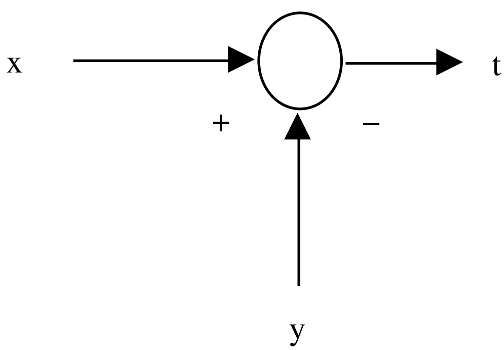
x is said to be the input, i.e., a quantity that is prescribed or imposed on the system, and y the output. The above graph represents the equation $y = Kx$ (the input multiplies what is in the box).

(a) Consider a mass M on a frictionless surface. Apply a force F to the mass (F is the input). Give a graphical representation of the fundamental equation of dynamics.

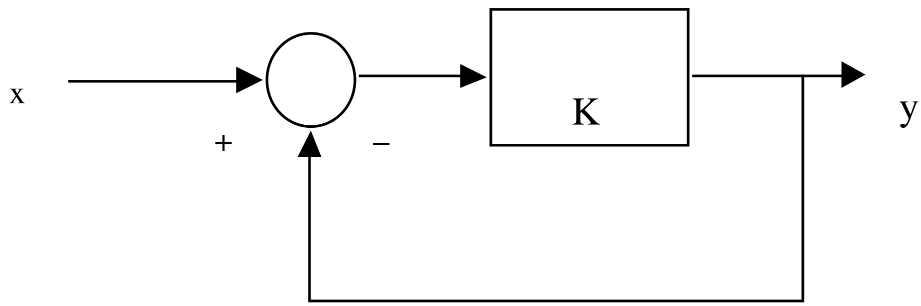
(b) The following blocks are said to be in series or in cascade. What is the relationship between x and z?



(c) The block here represents the equation $t = x - y$:



The following is the fundamental block diagram of a feedback control system. Find the equation that relates x to y (the input to the output).



Chapter 8

The Space Environment: An Engineering Perspective

Dava J. Newman and Joseph H. Saleh

In Shakespeare's play, Hamlet gazes at the sky, exclaiming

> *This most excellent canopy, the air, look you, this brave o'erhanging firmament, this majestical roof fretted with golden fire . . .*

8.1 | INTRODUCTION

The interests of scientists and engineers intersect in the space environment. While scientists focus primarily on making empirical observations of and studying space environment phenomena, aerospace engineers attempt to understand how these characteristics affect the design and operation of spacecraft and the humans inside them. Engineers and scientists both possess a passion to experience what William Shakespeare called "nature's [or the universe's] infinite book of secrecy" [40].

The greatest challenges to human spaceflight or high-performance airplane flight are not technological limitations. Rather, the greatest obstacle comes in the human body's ability to successfully tolerate and adapt to the challenges posed by extreme aerospace journeys. Human evolution in a 1 G (normal Earth gravity) environment under a protective oxygen-rich atmosphere has not prepared the human body for long-duration flight in the hostile environment of space. Due to many advances in spacecraft technology and design, we can transport the most critical portions of our environment with us into space, and it clearly makes sense to minimize the complexity and weight of these designs. Thus far, we have achieved successful spaceflight missions with the aid of life support systems, but we have not yet provided artificial gravity during flight. However, interesting concepts exist and are being considered for future exploration missions. The human response to reduced gravity is detailed in Chapter 11, "Human Space Exploration."

Our initial questions are, What constitutes the space environment and how will our space journeys be affected by the environment? This chapter starts by defining where space begins. As you will see, this is not as simple as it seems. The atmosphere and temperature extremes were the first topics of study of the space environment. Then, with the launch of the first satellites, people discovered that space was *radioactive* and that it could severely damage the operation of a spacecraft, not to mention the crew inside. A new field emerged to investigate the origins, distribution, and energy of radiation particles encountered in space, namely, space radiation. Obviously, the Sun is a key player in this field. The environment in low Earth orbit (LEO) is particularly interesting, and the Earth's magnetosphere in this region must be understood to plan successful space missions. As space is becoming more crowded, the study of the space environment has evolved to include artificial space debris, along with (micro) meteorites, and the probability of impacting and damaging an operational spacecraft. The final section of the chapter discusses planetary environments by emphasizing the Martian environment.

Some interesting and related space environment topics focus on the study of the *spacecraft* environment itself, including the acoustic, vibration, acceleration, and thermal constraints on the spacecraft. These issues are beyond the scope of this chapter and will not be addressed here, as they are more relevant to the study of space launch systems and mission analysis. An excellent reference on these topics is *Space Mission Analysis and Design* [41].

8.2 | WHAT IS SPACE?

To begin the discussion of space and spaceflight, we seek a working definition of what constitutes space. What characterizes space and where does space begin? How does the space environment differ from that of Earth? The question "Where does space begin" is complex; in fact, it depends not only on physical properties, but also on international politics.

8.2.1 Earth's Atmosphere

Our atmosphere, or Shakespeare's "excellent canopy of air," that surrounds Earth protects us from the hostile environment of space and provides our life support. The atmosphere is mainly composed of molecular nitrogen and oxygen with trace elements in the following proportions:

- Nitrogen, 78 percent.
- Oxygen, 21 percent.

- Argon, 1 percent.
- Carbon dioxide/water vapor, 0.03 percent.

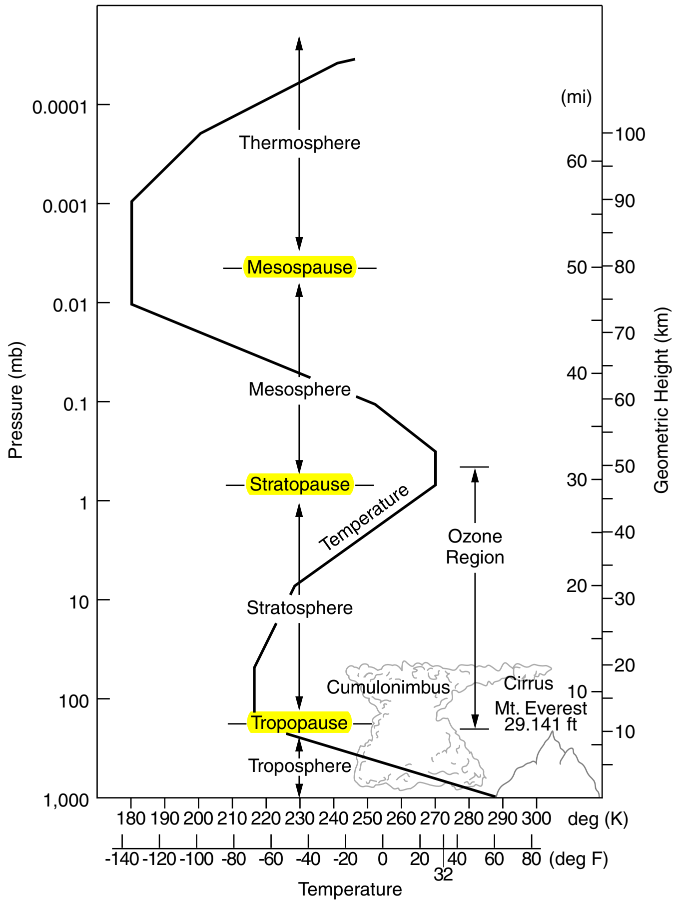
Our excellent canopy of air is impossibly fragile and small when we see it from space (see Figure 8.1). If breathable air were shown to scale on a basketball, it would be $^1/_4$ mm ($^1/_{100}$ in) thick. Yet, compare Earth with the Moon, whose surface has been pitted and hammered into dust by meteors. We have been less touched by all that falling iron. Our fragile canopy absorbs and burns the meteors before they reach us [42].

Figure 8.1 | The first impression one has looking back at Earth from Low Earth Orbit (LEO) is the realization that our atmosphere is a delicate, almost invisible, shield.

Breathable air, about *three human hairs* thick on our basketball model, is a powerful shield against more than meteors. It has a complex chemical structure. It is mostly *oxygen* and *nitrogen* at sea level, but it becomes richer in *carbon dioxide* (CO_2) and *ozone,* at altitude. Standard sea-level pressure and temperature are 101.3 kPa and 290 K (17°C), respectively. The density of air on Earth is equal to 10^{25} atoms per cubic meter (1.22 kg/m^3), which is considered to be a standard 1 atmosphere of pressure (atm, or 101.3 kPa).

The atmosphere itself is divided into five parts, namely, the troposphere, stratosphere, mesosphere, thermosphere, and exosphere. The thickness of these parts is determined largely by temperature gradients (see Figure 8.2). Each portion of the atmosphere is characterized by its temperature and plays a specific role in protecting humans from the harmful conditions in space.

Figure 8.2 | Variations in pressure and temperature as altitude increases. (from [50], courtesy of NASA.)



1. The *troposphere* begins at sea level and reaches a height of about 18 km. The temperature in this region varies with altitude from about 290 K (17°C) at sea level to 220 K (−53°C) at 11 km. Nearly all the weather effects we experience on the surface of Earth, such as rain and snow, occur within the troposphere. As is shown in the temperature gradient, the surface of Earth is the warmest part of the troposphere. Heat is transferred upward by means of infrared photon diffusion and gaseous convection. The *tropopause* is an extension of the troposphere where the temperature remains relatively constant, and it extends from 11 to 18 km.

2. The *stratosphere* begins at 18 km and continues to an altitude of 50 km. Here, the temperature gradient reverses, and the air actually gets warmer. At 18 km the temperature is about 220 K and rises to about 270 K (−3°C) at 50 km. This higher temperature results from heating via solar radiation. At an altitude of 22 km, aerospace vehicles can no longer, economically, compress air from the environment for cabin pressurization due to low atmospheric density and the threat of ozone poisoning. Human flight above this height requires a sealed environment with independent oxygen and pressure supplies. For humans, 22 km might be a good altitude to denote the beginning of the space environment. At approximately 45 km, aircraft propulsion requires an independent supply of fuel and oxidizer. So, essentially, for aircraft the space environment begins at 45 km. Astronauts who fly above the stratosphere receive "wings" for their achievements, so we might define the beginning of space here.

The stratosphere is also the sight of the *ozone* layer. Ozone is a molecule made of three oxygen atoms. It forms a gossamer-thin layer that screens out ultraviolet radiation. Without ozone, that radiation would kill off our nucleic acids and make life impossible. Visible light has only a slightly greater wavelength, but ozone lets it through. And life would also be impossible without that visible light and photosynthesis. High-altitude carbon dioxide caps off the atmosphere like a greenhouse window. Visible energy from the sun passes through, and Earth absorbs it. When Earth reradiates that energy as long-wavelength infrared energy, the CO_2 will not let it back out. The greenhouse effect is no theory. It is an absolute necessity. It keeps Earth warm enough to sustain life. The question is, Will we let the balance of carbon dioxide rise to the point where our atmosphere becomes a sauna bath? [42]

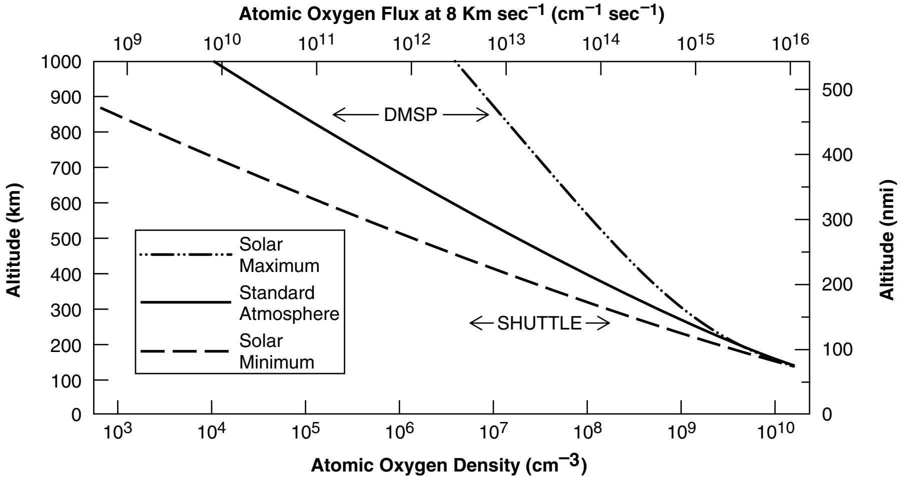
3. Extending even farther from the surface of Earth is the *mesosphere,* beginning at 50 km and extending to 85 km. As in the troposphere, the temperature in this region decreases with altitude from about 270 K at 50 km to 190 K (−83°C) at 85 km (this is the coldest region of the atmosphere). The mesosphere is essential for human survival on earth as it absorbs primary cosmic radiation and deadly solar ultraviolet and X-ray radiation, and vaporizes incoming meteorites entering from interplanetary space. At 60 km altitude no atmosphere is present to scatter sunlight, making the sky appear black and allowing the curvature of the earth to be discerned. This lack of atmosphere also prevents sound and shock waves from permeating, as it is too low for spacecraft and can only be reached by very large high-altitude balloons and NASA's record-setting solar-powered aircraft (Pathfinder, Pathfinder Plus, and Centurion), which have recorded flights up to 24,506 m (80,400 ft), setting altitude records for propeller-driven airplanes (6 August 1998). Previous altitude records were held by NASA's ER-2 aircraft, which is an outgrowth of the famous U-2 spy plane. The remotely piloted Pathfinder is a research vehicle developed to explore the feasibility of flight at very high altitudes and for extreme duration. Science flights are conducted for a variety of missions including environmental monitoring, atmospheric sampling for next-generation high-speed transports, hurricane surveillance, and telecommunications relays. The mesosphere is often thought of as a "no-person's land."

4. Beyond the mesosphere the temperature gradient rapidly reverses in the region known as the *thermosphere,* extending from 85 to 300 km. Here the temperature rises from 190 K (−83°C) to 1,000 K (773°C) at higher altitudes where ultraviolet (uv) radiation from the Sun is absorbed. If the solar cycle is at a maximum (many solar flares), the temperature can exceed 1,000 K due to the higher number of energetic particles in the region, which results in an *inflation* of the upper atmosphere and an increase in the density at a given altitude (see Section 8.4.1, "Solar Activity and Emissions," for details). The same effects—inflation and variation of density—are observed to a lesser extent in a day–night cycle. One way to think about it is to imagine the atmosphere breathing on a day–night basis, inflating during the day (or taking an extremely large breath in) during solar maximum (7 years) and exhaling during the night (or a large sigh during solar minimum) (4 years). Figure 8.3 shows the variation of atomic oxygen density with solar activity, which is the variable with the largest impact on the thermospheric composition. An index, the F10.7, shows the mean daily flux at 10.7 cm wavelength in units of 10-22 $w/m^2 \cdot Hz$. Within the thermosphere lies an imaginary line known as the *Von Karmen line.* Found at 100 km, the Von Karmen line denotes the altitude where aerodynamic forces (drag, viscosity, etc.) are minimal. An altitude of 100 km is the height that the U.S. Air Force Office of Aerospace Research defines as the beginning of space.

5. Finally, the *exosphere* begins at 300 km and merges with the ionized gases of the interplanetary medium. The temperature remains constant at 1,000 K with the exception of solar cycle variations. Here, atomic oxygen is more abundant than molecular oxygen or nitrogen. Atomic oxygen forms when solar ultraviolet radiation dissociates molecular oxygen. The nature of atomic oxygen is highly reactive due to its high chemical activity, particularly on satellite surfaces in specific orbits. Upper atmosphere aerodynamic drag affects spacecraft design and operations. This drag is created by the impact of atmospheric particles on the spacecraft surface. Although its magnitude is in no way comparable to aerodynamic drag encountered by aircraft, it is nevertheless present and below ~600 km should be considered. Atmospheric drag makes orbiting Earth below 200 km not viable; that is, a satellite at 200 km cannot remain there for more than several days (the orbit duration depends on the ratio of surface area to mass of the satellite, or more technically speaking, on the ballistic coefficient of the spacecraft). More than an order of magnitude of variation in atmospheric density is observed between solar minimum and solar maximum. This variation should be considered when designing a space system to be operated below 600 km.

Above the exosphere is the region known as *hard space.* While the idea of space is usually accompanied by a thought of emptiness, hard space is by no means empty. At 2,000 km altitude, we still see a density of 10^8 particles per cubic meter. While this number is significantly lower than the density of the surface of Earth, it does indeed show that space is not empty but, rather, is filled with electromagnetic radiation and particles [43].

Figure 8.3 | Atmospheric atomic oxygen density in low Earth orbit.



8.2.2 The Temperature Extremes of Space

There are limits to the temperature range that humans and equipment can endure. The extreme thermal conditions in space require not only shielding and insulation, but heat rejection capabilities as well. On Earth, heat transfer is carried out in three ways:

- Conduction—heat transfer through solids, liquids, and gases.
- Convection—transfer of heat due to fluid movement.
- Radiation—transfer of heat by a hot source (e.g., electromagnetic radiation).

In the vacuum of space an isolated body, such as a spacesuited astronaut during a spacewalk or a planet or a satellite, can transfer heat to or from another body solely by radiation, provided the body is in a state of thermal equilibrium. The term *satellite* is used to describe any vehicle or spacecraft in orbit in the space environment (see Chapter 10, "Satellite Systems Engineering"). The physical phenomenon of radiation is governed by Kirchhoff's law, which states that a body in thermal equilibrium will radiate an amount of energy equal to that absorbed from the outside universe. Energy exchange and balance determines the temperature of an astronaut, planet, or satellite in the space environment.

The extent to which a body absorbs solar radiation is determined by the *solar absorption coefficient* α. It is helpful to think of α, or the solar absorption coefficient, as affecting the amount of absorbed power similar to the way the coefficient of lift affects how much lifting force can be generated for a given aerodynamic surface. Likewise, the amount of power a body emits also depends on the emissivity ε. Kirchhoff's law is satisfied when the amount of power absorbed is equal to the amount of power emitted. From Kirchhoff's law, the equilibrium temperature of the body is determined as follows:

$$P_{\text{emitted}} = P_{\text{absorbed}} \tag{8.1}$$

By definition, the power absorbed from the Sun by a spherical body at a distance d from the Sun is given by

$$P_{\text{absorbed}} = (\alpha)\left(\frac{P_s}{4\pi d^2}\right)(\pi r^2) \tag{8.2}$$

where the total power emitted by the Sun is $P_s = 4.18 \times 10^{26}$ W, α is the absorption coefficient for solar radiation, and r is the radius of the body. For a perfectly diffuse sphere, the effective area of absorption is the frontal area of the body facing the Sun, expressed as πr^2, and the middle term in the equation is known as the solar irradiance or solar constant. For Earth, the solar constant is equal to 1,486.33 W/m^2. The power emitted from a body is proportional to the radius, equilibrium temperature T, and the emissivity of the body ε. The power emitted is given by

$$P_{\text{emitted}} = (\varepsilon\sigma T^4)(4\pi r^2) \tag{8.3}$$

where σ, the Stefan–Boltzmann constant, is equal to 5.67×10^{-19} W/(m$^2 \cdot$ K^4). Combining the above equations results in a solution for the equilibrium temperature for any body at a distance d from the Sun of

$$T = 0.707\, T_s\left(\frac{\alpha}{\varepsilon}\right)^{1/4}\left(\frac{R_s}{d}\right)^{1/2} \tag{8.4}$$

where T_s is the average temperature of the Sun and R_s is the radius of the Sun. Analyzing the equations for absorbed and emitted power, we find that the equilibrium temperature not only depends upon the distance of the body from the Sun, but also varies directly with the value of α/ε. Estimating the mean temperature of Earth, using $\alpha = 0.6$ and $\varepsilon = 0.9$, yields a value of 257 K. The mean temperatures of the outer planets, calculated in a similar manner, are found in Table 8.1.

Table 8.1 | Calculated mean temperatures of the outer planets

Planet	Temperature (K)	Temperature (°C)
Mars	217	−56
Jupiter	107	−166
Saturn	79	−194
Uranus	54	−219
Neptune	38	−235

EXAMPLE 8.1

Aluminum Satellite Considerations

You are the engineer in charge of designing a spherical satellite to be placed in high Earth orbit. Currently, you need to make a decision as to what finish to put on the outer surface, and you have a variety of materials that are feasible. If you choose an outer shell of polished aluminum, the values of α and ε are 0.19 and 0.042, respectively, giving an α/ϵ ratio of 4.5. From Equation (8.3) the temperature (neglecting the effect of Earth) is 414 K (141°C), which is very hot. Now you think about increasing the emissivity of the satellite shell for a better result. If you choose clear, anodized aluminum with $\alpha = 0.19$ and $\varepsilon = 0.7$, the temperature is considerably cooler, namely 205 K (−68°C). Values of α and ε for some common space materials are given in Table 8.2.

Table 8.2 | Solar Absorptivity and Infrared Emissivity of Selected Materials

Material	α	ε	α/ε
Metals: Solar absorbers	~0.04–0.60	~0.02–0.20	>>1.0
Aluminum 6061 (polished)	0.19	0.042	4.5
Gold (plated)	0.30	0.03	10.0
White paints: Solar reflectors	~0.15–0.25	~0.80–0.95	~0.20–0.30
Thermatrol, Dow Corning	0.19	0.82	0.23
VelvetWhite (3M Company)	0.24	0.85	0.28
Black Paints: Flat absorbers	~0.90–1.0	~0.85–0.95	~1.0
Black Velvet (3M)	0.95	0.88	1.08
Black Kemacryl (Sher.-Williams)	0.95	0.92	1.03
Transparent polymers (coated)	~0.10–0.40	~0.35–0.60	<1.0
Aluminized Mylar (1.0 mm)	0.14	0.36	0.39
Aluminized Teflon (1.0mm)	0.15	0.60	0.25

8.3 | MICROGRAVITY

When we hear astronauts describe the feeling of “weightlessness” while in orbit, what they are actually referring to is the effect of microgravity. Microgravity can be simulated either by placing an object in an environment where the force of gravity is naturally small (i.e., placing an object between two gravitationally equal massive bodies) or by placing an object in free fall, such as in low Earth orbit (see Figure 8.4).

Figure 8.4 | Mir21/NASA2—Mission photo taken of the Russian Mir space station. The first impression one has looking back at Earth from Low Earth Orbit (LEO) is the realization that our atmosphere is a delicate, almost invisible, shield.

8.3.1 What Is Microgravity?

Contrary to what many believe, astronauts on the Space Shuttle do *not* experience a zero gravity (0 G) environment that lacks the gravitational pull of Earth. Rather, in a low Earth orbit, a spacecraft (and the astronauts inside) experiences a radial gravity effect that is only one-tenth less than the standard 9.8 m/s^2 (1 G) environment. While orbiting Earth, the spacecraft and astronauts experience a constant state of free fall; and thus, they are considered to be in a microgravity environment where the centripetal acceleration of the spacecraft (acting tangentially) is responsible for the resulting microgravity environment (10^{-6} G) onboard. The term *microgravity* (or μG) is used to describe this very low-acceleration environment. To clarify this point, Section 8.3.2, “Law of Gravitation,” and Section 8.3.3, “Low Earth Orbit,” define the important details of the microgravity environment.

8.3.2 Law of Gravitation

Two of the most colorful personalities in the field of astronautics were Johannes Kepler and Sir Isaac Newton, who defined the laws of orbital motion and the law of gravitation, respectively. A full historical account and a derivation of their contributions are topics covered in Chapter 9, “Orbital Mechanics,” but need mention in this chapter to introduce Newton’s sweeping generalization about bodies in motion. Specifically, Newton based his law of gravitation on his axioms of mechanics (often referred to as Newton’s three laws, detailed in Section 9.3, “Newton’s Laws of Motion and Gravitation”) and Kepler’s law of equal areas of an orbit being covered in equal time intervals (again, detailed in Section 9.2 “Kepler’s Laws”) to state that

> Every particle in the universe attracts every other particle with the force that is directly proportional to the product of their masses and inversely proportional to the distance between their centers.

The law of gravitation can be expressed mathematically as

$$F_g = -\frac{GMm}{\mathbf{r}^2} \tag{8.5}$$

where F_g is the force on mass m due to mass M and $\mathbf{r}$ is the vector from M to m. The universal gravitational constant G has the value 6.67×10^{-8} dyn(cm^2/g^2).

Newton’s first law (or axiom) from his 1687 publication *The Mathematical Principles of Natural Philosophy,* commonly known as the *Principia,* states that

> Every particle persists in a state of rest or of uniform motion in a straight line unless acted on by a force.

Mathematically, the gravitational force between two objects can be very small [Equation (8.5)], but never becomes exactly zero for bodies with mass at a finite distance from one another. So, the practical question for us is, How small does the gravitational force need to be to carry out meaningful spaceflight studies, or *microgravity* experiments? To scientists and engineers, a microgravity environment is one in which the gravitational acceleration force is one-millionth that on Earth's surface. That is 0.000001 times less than that on Earth, or 1×10^{-6} Gs—nearly, but not quite, weightless.

Microgravity Calculation

EXAMPLE 8.2

Let us calculate how far away we would need to be from Earth to achieve this microgravity, or near-weightless, condition [45]. Recall that force is proportional to $1/r^2$ and that the distance r is measured as the distance between the centers of the two objects. Therefore, for a laboratory on the surface of Earth, r is Earth's radius, or 6,370 km. Assuming equal masses in both cases, our space laboratory must be at a distance

$$F_g = -\frac{GMm}{r^2} \approx \frac{1}{r^2}$$

$$F_\mu \approx F_g \cdot 10^{-6}$$

$$F_\mu \approx \frac{1}{r_\mu^2} \approx \frac{10^{-6}}{r^2}$$

$$r_\mu^2 = 10^6 \cdot r^2$$

$$r_\mu = \sqrt{1{,}000{,}000} \cdot r = 1{,}000 \cdot r = 6{,}370{,}000 \text{ km}$$

where the radius of Earth is r, the force at the surface of Earth is F_g, the force in microgravity is $F\mu$, and the distance from the center of Earth to the microgravity environment is $r\mu$.

In other words, to achieve one-millionth the force of gravity on the surface of Earth, we would have to move our laboratory a distance equal to the square root of 1 million (1 thousand) units farther away from the center of Earth. That is 1,000 Earth radii (or 6,370,000 km)! The moon is only about 60 Earth radii away, or 384,401 km, so this deep space laboratory to attain true microgravity does not appear very practical. Example 8.2 illustrates the point that spacecraft in orbit around Earth (like the International Space Station) are nowhere near far enough away to avoid Earth's gravitational field—they are only about 300 km above the surface of Earth (less than one-tenth of one Earth radius) [45]. Armed with this understanding of a true microgravity environment, we now discus the weightless environment experienced by astronauts and craft in low Earth orbit.

8.3.3 Low Earth Orbit

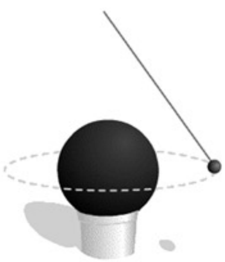
Scientists and engineers often refer to the environment within an orbiting spacecraft as *microgravity,* because of the similar effects experienced if the spacecraft were a thousand Earth radii away. In practice, however, there are still a multitude of accelerations affecting the spacecraft and everything in it—motions due to orbital thrusters, vibrations, aerodynamic drag, and astronaut motions. The manner in which satellites orbit Earth is often explained as *a balance achieved when the outward-pulling centrifugal force of a revolving object is equal to the inward pull of Earth's gravitational acceleration.* However, we find this explanation to be incomplete by examining Newton's first law, or axiom of mechanics, that states

> Every particle persists in a state of rest or of uniform motion in a straight line unless acted on by a force.

Earth-orbiting satellites follow elliptical paths rather than straight lines. Force is a vector quantity that has both direction and magnitude. It is a push or a pull in a particular direction. At any moment, the force of gravity on a satellite is exerted in the direction of a line connecting the center of mass of Earth to the center of mass of the satellite. Because the satellite is not stationary, the direction of this line, and consequently the direction of the force, is constantly changing. This is the force which acts on the satellite to curve its path.

A second issue with the satellite orbit explanation above is that centrifugal force is not an actual force; rather, it is an effect with which we all have firsthand knowledge. The difference between a force and an effect is illustrated in Example 8.3. Imagine that you are a passenger riding in a car that makes a sharp turn to the left. You feel yourself pushed against the right side door, which is interpreted as an outward-directed force. But is it really an outward-directed force? What would happen to you if the door were to open suddenly? We can answer the posed automobile questions through a simple demonstration relevant to low Earth orbit.

EXAMPLE 8.3 Low-Earth-Orbit Demonstration Using a Ball on a String [45]



Attach a ball to a string, and twirl the ball in a circle as you hold the other end of the string. The ball travels on a path similar to that of a satellite orbit. Feel the outward-pulling force as you twirl the ball. Next, release the ball and observe where it goes. If that force you experienced were really outward, the ball would fly straight away from you. Instead, the ball travels on a tangent to the circle.

Next, a simple model of a satellite orbiting Earth is created from a large stationary ball and a smaller ball at the end of a string. The ball and string become a pendulum that tries to swing toward the middle of the globe. However, the ball travels in an orbit around the globe when it is given a horizontal velocity in the correct direction. Although the small ball attempts to fall to the center of the larger ball, its falling path becomes circular because of its horizontal velocity.

The ball is attempting to travel in a straight line due to its inertia. The string provides the force that changes the ball's uniform straight-line motion to circular motion. The outward pull you feel is really the ball's resistance to a change in direction. In the case of the automobile example, if the door were to unexpectedly open during a turn, you would fall out of the car and continue moving in the same direction as the car was moving at the moment the door opened. While you perceive your motion as outward, the automobile is actually turning away from you as you go in a straight line.

Low Earth orbit, or LEO, is the term used to define orbits used for human spaceflight and some satellites, which are rather close to Earth (~300 to 1,000s km altitude). By flying in an orbit close to Earth, astronauts avoid strong doses of radiation that result from flying in high-altitude orbits. Even in LEO, satellites pass through the Van Allen belts, which are a source of heavy radiation and a major concern for human spacecraft missions (detailed in Section 8.4.3). LEO space travel does place some limitations on the mission and the functions of the satellite in orbit. To maintain a typical Space Shuttle LEO altitude (~300 km) where the satellite makes one Earth revolution approximately every 90 min, speeds close to 29,000 km/h must be maintained. If the Shuttle were to reduce its velocity, external forces, such as aerodynamic drag, would slow the spacecraft down until it reentered Earth's atmosphere. In fact, the Shuttle uses the atmosphere to slow down for reentry at the end of a mission. As orbital altitude increases, the speed necessary to sustain an orbit decreases, not surprisingly, because drag forces diminish as we venture farther from the atmosphere. The function of the spacecraft, therefore, changes as well. As detailed in Chapter 9, "Orbital Mechanics," the period of an orbit, the time it takes to complete one trip around Earth, increases with altitude until, at about 36,000 km, the orbital period is nearly 24 h long. At this point, satellites are considered to be in a geostationary earth orbit, or GEO, and remain "fixed" above one point on Earth. Typically, satellites in GEO have commercial communications applications where it is critical to maintain contact between Earth and the satellite at all times or military applications of monitoring a specific geographic region. Satellites are further discussed in Chapter 10, "Satellite Systems Engineering," which provides a systems perspective of satellite design for near Earth orbits.

8.3.4 Benefits of Microgravity

Working in a microgravity environment allows researchers to investigate essential questions of fundamental physics, life science, materials science, space science, earth observation, medicine, gravitational biology, and engineering technology. Microgravity allows scientists to observe phenomena usually overshadowed by the effect of gravity on the surface of Earth. Engineers explore new technologies and develop devices specifically designed to function in microgravity, but the big payoff might be back down on Earth. Research efforts in both aeronautics and space contribute immensely to the benefit of everyone on Earth. Many disciplines have benefited from studies conducted in microgravity by investigators all over the world. Medical professionals today use medicines developed in orbit; materials scientists and engineers have a better understanding of how substances interact to form various materials; and countless other areas of research have been developed from our ventures into the microgravity environment [46].

Looking forward to the next century, the NASA Strategic Plan carries this vision statement [47]:

> NASA is an investment in America's future. As explorers, pioneers, and innovators, we boldly expand frontiers in air and space to inspire and serve America and to benefit the quality of life on Earth.

There are four areas that are targeted for future exploration and microgravity investigations:

- The Space Science Enterprise is to solve mysteries of the universe, explore the solar system, discover planets around other stars, search for life beyond Earth; from origins to destiny, chart the evolution of the universe and understand its galaxies, stars, planets, and life.
- The Earth Science Enterprise is to expand scientific knowledge of the Earth system, using NASA's unique vantage points of space, aircraft, and in situ platforms, creating an international capability to forecast and assess the health of the Earth system; disseminate information about the Earth system; and enable the productive use of Mission to Planet Earth science and technology in the public and private sectors.
- The Human Exploration and Development of Space (HEDS) Enterprise is to prepare for the conduct of human missions of exploration to planetary and other bodies in the solar system; use the environment of space to expand scientific knowledge; provide safe and affordable human access to space, establish a human presence in space, and share the human experience of being in space; and to enable the commercial development of space and share HEDS knowledge, technologies, and assets that promise to enhance the quality of life on Earth.
- The Aeronautics and Space Transportation Technology Enterprise has three major technology goals supported by a set of enabling technology objectives. One technology goal is to enable the full commercial potential of space, and expansion of space research and exploration.

With the turn of the century, the International Space Station (ISS) is slated to begin operations. Assembly of this huge space facility is an undertaking that involves 15 countries, led by the United States, Russia, Europe, Japan, and Canada. This complex can serve as a world-class research laboratory. It promises to provide a permanent presence in space and bolsters the prospect that human space travel back to the Moon, onward to Mars and other destinations, may occur in the 21st century.

A major purpose of ISS is to provide a laboratory for long-duration microgravity experiments in the life and physical sciences. ISS offers major capability in the following areas:

- Biomedical research and countermeasures development.
- Gravitational biology and ecology (under variable gravity).
- Materials science.

- Biotechnology.
- Fluids and combustion.
- Human-machine interfaces and advanced life support.
- Low-temperature physics.
- Earth observation and space science.

The important microgravity questions to be investigated and answered by the next generation of aerospace engineers, scientists, and astronauts on ISS include these [46]–[49].

> What is the role of gravity in the evolution, development, structure, and function of lifeforms, and as a result of gravity, what are the lifeforms' interactions with their environment? What is required to ensure the health, safety, and productivity for humans living and working in space? How did the universe, galaxies, stars, and planets form and evolve?
>
> What technologies are best suited for long-duration missions of human space exploration? What is the optimum relationship between the process used to form a material and its resultant properties, and how can we achieve this in space and on the ground?
>
> How can the space environment help us obtain fundamental physical measurements of the highest accuracy? How does the Earth environment change over time, and what are the causes of these changes?

Long-duration spaceflight provides a new environment for space operations where we can live and work in microgravity for many months to maximize the scientific return. Space research efforts have already contributed major scientific and technical achievements about understanding the origin and development of the universe, and humanity's place in it. In addition, space technologies and spinoffs with Earth applications have been a boon to research in education, transportation, pollution control, rain forest protection, health care, and a host of other practical applications of benefit to all the world.

The microgravity environment has been well described, and now we discuss our eminent Sun and the space radiation effects that might be potentially deleterious to orbiting satellites. This expanded vision of the space environment makes us realize what our ancestors knew—that their lives depended upon the Sun. They held the Sun in reverent awe and sought, as we do, to understand how it works, why it changes, and how these changes influence life here on planet Earth [50].

Earth model (Earth.vrml).

Explore Earth from the vantage point of low Earth orbit and the International Space Station on the accompanying CD-ROM.

8.4 | THE NEAR EARTH RADIATIVE ENVIRONMENT

Seen from space, the near Earth environment looks like a cavity in the interplanetary milieu under which the Earth surface is more or less protected from the "hostile" space environment. Indeed, the blue planet offers to its inhabitants a fragile shield that consists of both its atmosphere and its magnetic field. Without it, life on Earth would be impossible. Outside this double protection, various types of radiation are encountered. Their nature, energy, origin, and distribution are highly variable. These issues are discussed in the following sections.

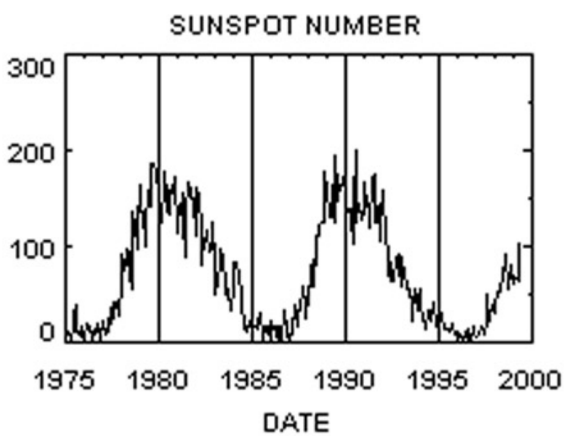
8.4.1 Solar Activity and Emissions

The Sun is a modest star by stellar standards, and it is one out of more than 100 billion stars that form our galaxy. However, it provides all the heat input to the solar system and dominates the gravitational field. The Sun contains 99.85 percent of the solar system mass. The gravity of the Sun creates extreme pressures and temperatures within itself, which makes it fundamentally a giant thermonuclear fusion reactor, fusing hydrogen nuclei and producing helium. And hence it produces a tremendous amount of energy. The Sun has no distinct surface or discrete physical boundary (the apparent surface is merely optical).

Observations of the Sun have clearly identified two basic features of our star. First is its variable rotation with latitude; for instance, a full rotation for a Sun day takes 24 days at the equator, but more than 30 days near the poles; and second is its cyclic evolution of activity. The source of this *differential rotation* is an area of current research in solar astronomy. The Sun's rotation axis is tilted by about 7.25º from the axis of Earth's orbit, so we see more of the Sun's north pole in September of each year and more of its south pole in March. Also the activity of the Sun is measured by the number of visible sunspots (organized in groups). This activity presents a periodicity of approximately 11 years, with essentially 7 years of maximums (i.e., high solar activity levels related to an increase in the number of sunspots, and associated with *violent* emissions of particles), and 4 years of minimums. Figure 8.5 shows recent variations of solar activity with time.

The radius of the Sun is 6.96×10^5 km, or about 109 times the radius of Earth. The distance from Earth to the Sun is referred to as an *astronomical unit,* or au. One au is about 1.5×10^6 km. Temperature, pressure, and density are highest at

Figure 8.5 | Eleven-year solar cycle. [51].



the core, or center, of the Sun. At the core, temperatures can reach as high as 16 million. This high-temperature zone is where fusion reactions occur to produce the energy that the Sun releases through solar activity. The temperature decreases farther away from the sun to about 10^6 K at the highest point of the atmosphere.

Because the gases in the atmosphere of the Sun become opaque close to the surface, we can only observe the Sun by peering into its atmosphere. The atmosphere is composed of three regions. The *photosphere* is the visible surface of the Sun with which we are most familiar. It begins at the surface of the Sun and extends only a short distance to about 330 km. Here, small structures known as *granules* are observed. Granules are zones of bright and dark gases that demonstrate the transient nature of the Sun. These granules transport hot gases upward while the cooler gases sink down, creating a stirring or bubbling effect when observed from Earth. Beyond the photosphere lies the *chromosphere,* where small jets of gas shoot upward as high as 10,000 km at velocities of 20 to 30 m/s. These streams, or *spicules,* exist in regions of stronger magnetic fields and play a role in balancing mass between the chromosphere and higher levels of the atmosphere. *Prominences* are also found in the chromosphere and are dense clouds of material suspended above the surface of the Sun by loops of magnetic field. Extending above the chromosphere is the *corona.* Observable during solar eclipses, the corona appears as a halo extending above the visible surface of the sun.

Spicules.jpg [51], Prominence.jpg [52], Corona.jpg [53]

Solar Wind The external gaseous envelope of the Sun, the corona, has an extremely high temperature, and thus it continuously ejects particles, mainly electrons and protons. This continuous flux of charged particles constitutes the solar wind. The solar wind streams off the Sun in all directions at speeds of about 400 km/s (about 1 million mph). The temperature of the corona is so high that the Sun's gravity cannot hold onto it. The solar wind–charged particles, under the influence of the solar magnetic field, diffuse in the entire interplanetary space (with a very nice structure resembling that of a ballerina squirt when spinning). The average speed of charged particles ranges from 400 to 1,000 km/s. These particles originate from two regions, the Sun's equatorial and polar regions. The equatorial area where the Sun's magnetic field is weak emits ions at ~400 km/s, which continuously affect the near-Earth environment. The Sun's polar region spits particles out at 1,000 km/s, but these only occasionally affect our neighborhood (when these regions extend to lower latitudes). One question you might ask is, What happens when these particles hit Earth's magnetic field (or shield)? This question is addressed in Section 8.5, "The Magnetosphere."

While the Sun itself is small in comparison to the size of the solar system, its effects are still noted beyond the orbits of Neptune and Pluto. The *heliosphere* is a magnetized bubble of hot plasma that envelops the solar system. Somewhere between 110 and 160 au this sphere comes to an end at a point known as the *heliopause,* where the charged particles and magnetic fields of interstellar space intersect with the remnants of the solar wind.

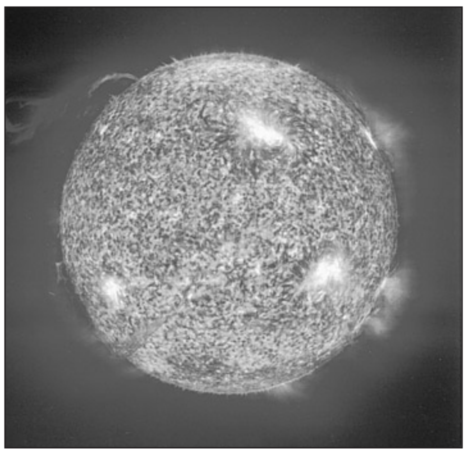
Sunspots and Solar Flares The main features of our active star are best understood through the Sun's magnetism. The Sun's magnetism, or magnetic field, is produced by the flow of electrically charged ions and electrons. *Sunspots* are places where very intense magnetic lines of force break through the Sun's surface. The sunspot cycle results from the recycling of magnetic fields by the flow of material in the interior. The prominences seen floating above the surface of the Sun are supported, and threaded through, with magnetic fields. Magnetic fields are at the root of virtually all the features we see on and above the Sun. Without magnetic fields the Sun would be a rather boring star [51].

Solarwind.jpg [54]

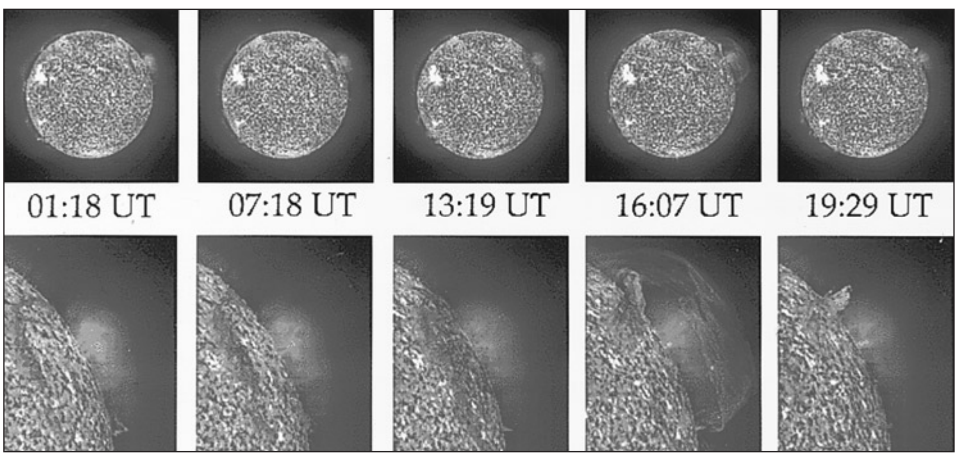
Sunspots are the most obvious dynamic phenomenon on the Sun. Large ones can be seen from Earth with the unaided eye, and they may look like dark objects passing in front of the Sun. Galileo was the first to show that sunspots are actually on the Sun's surface. In 1851, a German amateur astronomer, Heinrich Schwabe, published a paper in which he concluded that the number of sunspots was not constant, but went from a minimum to a maximum about every 10 years (he was not too far off the actual 11-year cycle).

Figure 8.6 | Solar activity. a) solar flares and b) time series.

(a)



(b)



Sunspots are found on the photosphere and are *colder* areas (by as much as 1,500 K) where an intense magnetic field blocks the thermal transport in the Sun. The magnetic field of the Sun forms vertical bands from the north magnetic pole to the south magnetic pole. Sunspots occur when the differential rotation of the Sun causes the magnetic field lines to overlap on themselves and to form regions of concentrated polarity. Intense magnetic fields are detected in the center of sunspots and are thought to be the reason for the decreased temperature. They often appear in complementary pairs, known as a bipolar spot group. From these active regions stem the *solar flares* that are associated with a violent release of energy for a short time, from an hour to a few days (see Figure 8.6). This burst of energy produces various types of radiation, mainly X-rays and gamma rays, and ejects particles that can have extremely high energy into the interplanetary environment. In a period of solar maximum, solar flares are often observed, and an active zone can be responsible for several consecutive solar flares. Sunspots tend to reside at high solar latitudes and remain at that latitude for the duration of their life.

One last remark is necessary. In the literature, solar flares are often referred to as solar proton events; this is not accurate, for a solar flare can be associated with protons or heavy ion ejections or, more plausibly, with various combinations of both. The solar phenomena described above, solar wind and flare activity, are often termed *solar cosmic rays* (SCRs). Two additional types of ionizing radiation are discussed below, namely, galactic cosmic rays and the Van Allen belts. Section 8.5, "The Magnetosphere," follows the discussion of ionizing radiation and details the Earth's magnetic field and implications for space travel.

8.4.2 Galactic Cosmic Rays

Galactic cosmic rays are mainly protons, heavy ions, and α particles with extremely high energies. As their name indicates, they are of galactic and/or extragalactic origin. Emitted by distant stars and even more distant galaxies, GCRs diffuse through space and arrive at Earth from all directions. It has been shown that outside the Earth magnetosphere, the GCR fluxes are isotropic. Moreover, during solar maximums, the GCR fluxes are lower than during solar minimums. One way to imagine this effect is to think about solar maximum periods as a strengthening of the heliosphere, the Sun equivalent of the Earth magnetosphere, that is, the magnetic shield of the Sun that extends throughout the entire solar system, and hence protects the planets from these particles.

Sun Magnetogram. Magnetogram.mpg

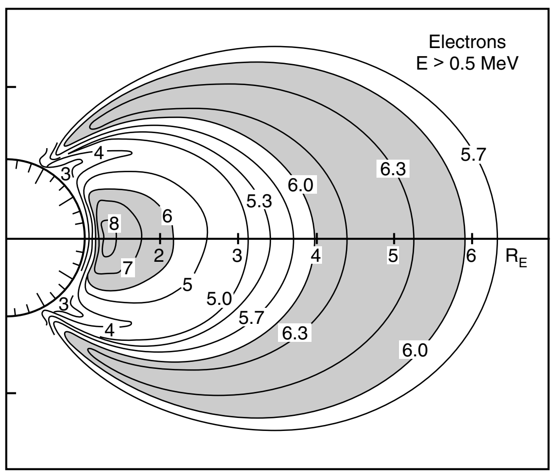
Magnetic features on the sun.

GCRs are a serious danger to spacecraft, and the humans inside, because a single particle, since it is highly energetic, can damage any common electronic component onboard. When a single particle causes such a malfunction, its effect is called a *single event effect,* or SEE, which is described in greater detail in Section 8.6.2, "Single Event Effects." The 11-year solar cycle produces a factor-of-2 variation in the cosmic ray dose at a geosynchronous orbit. Low-altitude, low-inclination orbits experience almost no dose variations due to the strong shielding produced by the combined effects of the atmosphere and geomagnetic field.

8.4.3 The Van Allen Belts

In addition to solar cosmic rays and galactic cosmic rays, there is a radiation effect closer to home. The third type of ionizing radiation is contained in the Van Allen belts, which are doughnut-shaped (toroid) regions of trapped particles, mainly protons and electrons, around Earth (see Figure 8.7) discovered on the Explorer 1 satellite mission on January 31, 1958. Where do these charged particles come from and how do they get trapped? The sources of these high-energy particles are basically the same as those previously described. As the particles hit Earth's magnetosphere, they undergo a velocity modification (charged particle moving in a magnetic field). Under certain conditions of incident angles and energy, the velocity modification results in a relatively stable trajectory of the particle around Earth, hence the particle gets trapped. As observations have shown, after detonation of nuclear weapons in space (i.e., the Starfish program in 1962), particles may reside in the Van Allen belts for periods of weeks to several years. It might seem that a trapped particle remains in a fixed position, but this is not the case. A trapped particle undergoes an interesting movement of three components: an oscillation between two mirror points in a North-South plane, a rotation around this path, and a slow drift of this plane to the East for the electrons and to the West for the ions (mostly protons). Naturally, the particles'energy, the structure, and the temporal dimensions of the Van Allen belts and radiative environment are functions of the solar activity.

Figure 8.7 | Van Allen inner and outer belts. [41]



Two concentric regions of trapped electrons have been identified: The first extends to about 2.4 Earth radii, and its radiation particle population is rather stable; the second is an outer belt from 4 to 6 Earth radii whose electron density is highly variable and very sensitive to solar activity. The doughnut-shaped Van Allen belts are distributed nonuniformly within the magnetosphere, and extended stays in either could be fatal to humans [55]–[57].

While the Van Allen belts are a severe environment for spacecraft and humans traveling through them, they do protect the low Earth orbits (below 1,400 km) from highly energetic particles, such as GCRs or ions associated with solar flares.

Van Allen belts mirror points (VAB Mirror.PICT).

8.5 | THE MAGNETOSPHERE

The magnetosphere is defined by the interaction of Earth's magnetic field and the solar wind. It is in the magnetosphere that Earth's space environment meets head on the effects of the Sun.

8.5.1 Magnetosphere Structure

Up to 4 or 5 Earth radii, the Earth's magnetic field resembles that of a simple magnetic dipole (a bar magnet), with field lines originating from the magnetic North pole, curving around in a symmetric arc, and entering at the magnetic South pole. A clarification of the North–South axis is needed because what is referred to as the North–South direction is the axis of the magnetic dipole that is tilted ~11° relative to the axis of rotation of Earth. Moreover, this dipole is offset 500 km toward the west Pacific (it is not at the exact center of Earth), and hence is not truly symmetrical around Earth, even below 4 Earth radii.

One noticeable effect of this offset is a weaker magnetic field over the south Atlantic, which is called the south Atlantic anomaly (SAA). In the SAA, radiation particles interfere with satellite, aircraft, and spacecraft communications. Usually, trapped particles are repelled by the strong magnetic field of Earth. However, within the SAA the weaker field strength allows more particles to reach lower altitudes, causing potential damage to spacecraft or communications blackouts (i.e., no radio signals are received from a spacecraft) when passing through the SAA because of the high concentration of charged particles in the region. These blackouts last about 15 to 30 min per orbit, and typical spacecraft pass through the SAA approximately 9 to 15 times per day. The SAA is also responsible for exposing astronauts to high doses of radiation in space. The SAA traps high-energy radiation from solar flares, solar wind, and GCRs. To avoid unnecessary exposure to this radiation, extravehicular activity (EVA), or spacewalks, is planned, as much as possible, for orbits that do not pass though the SAA. At an altitude of 500 km above Earth the SAA ranges from −90° to +40° in geographic longitude and −50° to 0° in geographic latitude.

South Atlantic Anomaly.PCT

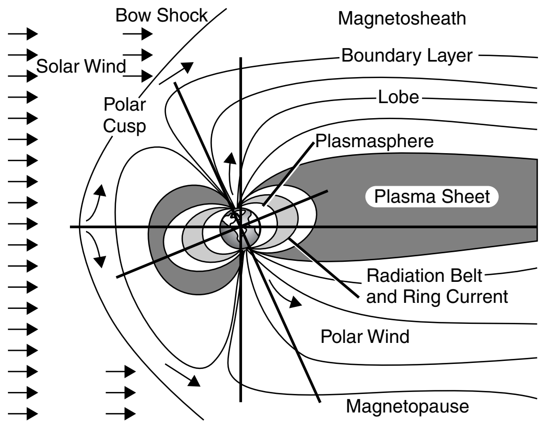
What are the characteristics of the magnetosphere above 4 Earth radii? The field lines deviate substantially from those of a simple dipole. As the solar wind hits Earth's magnetosphere, the magnetic field is compressed on the day side of the Earth. The region where the solar wind is *stopped* (but not exactly) is called the *magnetopause.* The magnetopause is situated around 10 Earth radii on the day side in the equatorial plane. However, during violent solar flares, this boundary could be as low as 6 Earth radii [i.e., approximately geostationary earth orbit

(GEO)], exposing satellites in GEO to harsh nonattenuated GCRs and solar particles. This situation is extremely damaging, if not lethal, to satellites.

Trapper particle radiation (VAB_Trapped.gif).

On the dark side (opposite direction of the Earth–Sun), the solar wind interaction with the magnetosphere results in its huge elongation. This stretched structure parallel to the flow of solar wind is known as the *magnetotail* (see Figure 8.8).

Figure 8.8 | Earth's magnetosphere illustrating key energetic particles that respond to variations in solar wind parameters. [41]



8.5.2 Magnetospheric Filtering

Charged particles of solar or cosmic origin are deviated by Earth's magnetic field when they are not trapped in the Van Allen belts. Therefore, in order for a charged particle to reach a given depth in the magnetosphere, it needs to have a certain energy. This energy is attenuated; hence so is its damaging potential, as it passes through the magnetosphere. This effect is called magnetosphere filtering, and it implies the shielding function of the magnetosphere.

One implication of shielding is that an orbiting spacecraft in LEO has an extremely small exposure to solar flares and GCRs, if its orbital inclination is below 50°. This is below the polar regions, which are areas that offer little resistance to radiation since this is where magnetic field lines converge (see Figure 8.8). The following section further expands on the consequences of designing spacecraft for the harsh environment of space.

8.6 | ENVIRONMENTAL IMPACT ON SPACECRAFT DESIGN

Energetic radiation can severely degrade the optical, mechanical, and electrical properties of a spacecraft. Specifically, satellite degradation results from ionization of atoms encountered, the breakup of chemical liaison, and displacement of atoms from crystal lattice sites. The important parameters that aerospace engineers design for include *cumulative* dose of radiation, *transient* effects that depend on the instantaneous flux of radiation, and *electrostatic arcing* due to the accumulation of electric charges encountered.

8.6.1 Cumulative Dose Effects

The absorbed dose is defined as the ratio of the average energy transferred to a given volume of a material by the radiation, per mass of this volume. The SI unit for the absorbed dose is the *Gray* (Gy), defined as 1 joule absorbed in 1 kilogram of matter. An older unit that is still often used is the *rad,* where 100 rad = 1 Gy. Note that the absorbed dose is a *macroscopic* cumulative parameter, and therefore it cannot pretend to capture the entire range of radiation effects on a spacecraft or material. The phenomena mentioned in Section 8.6.2, "Single Event Effects," complement this description.

The cumulative dose effect is mainly considered in spacecraft design because of its impact on the onboard electronics. Semiconductor components and bipolar structures undergo a severe degradation of their key parameters with increasing dose, resulting in functional failures, drift of threshold tension levels, timing skews, drops in transistor gains, and increases in leakage current with the immediate consequence of higher power consumption. These degradations can result in a loss of functionality of the components. Specifically, in solar cells, an increasing absorbed dose results in reduced efficiency in converting sunlight to electric power. That is why the upper exposed surfaces of solar panels are protected to some extent by the use of coverglass. Nevertheless, solar panels degrade on orbit, and satellite manufacturers give the *beginning of life* (BOL) and *end of life* (EOL) power available onboard, taking into account the degradation of solar cells. Other electronic components are simply *hardened* enough to survive the expected dose during the operational lifetime of the spacecraft. The expected dose depends primarily on the solar activity and the altitude and inclination of the orbit. Recall that passing through the Van Allen belts can be extremely damaging to the spacecraft (see Section 8.4.3, "The Van Allen Belts").

8.6.2 Single Event Effects

SEEs are radiation events caused by a single energetic particle (galactic cosmic rays, solar protons, trapped particles in the Van Allen belts), which are most damaging to electronic components. As the particle *plows* through a chip, it creates along its path a localized ionization. This ionization in turn can result in the following:

- If the electronic component is a memory device, local ionization can result in a change of the data point or state of the device (a change of 0 to 1 or vice versa). This phenomenon is called a *single event upset* (SEU) and is often nondestructive.
- Some electronic components undergo a *single event latch-up* (SEL). In this case, a conduction path is created between the power input and a substrate of the component. The component then draws excessive current from the

power source, which can drag down the satellite bus voltage. If the device is not being monitored (by a *watchdog*) and is not disconnected when a latch-up is detected, the excessive current may lead to the destruction of the component, or *burnout* (single event burnout, SEB). SELs and SEBs tend to be quite destructive SEEs. The SEE severity depends on the specific type of event and the system criticality of the component. Shielding the satellite and components has little effect against SEEs.

8.6.3 Spacecraft Surface Electrostatic Charging

Electrostatic charging of a spacecraft on orbit always occurs. Some materials behave differently on the day side of the orbit than during eclipse; to put it simply, they accumulate charges during eclipse and discharge elsewhere, maintaining a relatively low tension (i.e., ~1,000 V for kapton or 3,000 V for quartz), depending on the durations of eclipses and Sun visibility. Other materials such as Teflon continuously accumulate charges, regardless of the position of the spacecraft on orbit. Hence high voltage, 6,000 to more than 20,000 V, can be measured on Teflon. These materials should not be used on the surface of a satellite.

However, the danger associated with electrostatic charging is not the high voltage encountered on a satellite surface, but rather the differential charging; that is, if a surface material is at 6,000 V and the one next to it is at 1,000 V, arc discharges might occur. Arcing induces severe perturbations to the onboard electronics, ranging from clock resets and mode changes in instruments to complete loss of the payload. The simplest way to prevent this is to use conductive surfaces (same potential everywhere) whenever possible on the spacecraft. Highly energetic particles can induce internal charging in a spacecraft as well as external, and internal arcing is potentially more dangerous, but it is less probable.

We have discussed the Earth–Sun interaction, and in the following section we discuss natural and unnatural orbiting objects, namely, meteoroids and space debris, which clutter the space environment.

8.7 | METEOROIDS AND MICROMETEOROIDS

The background interplanetary meteoroids are solid objects whose size and mass vary over many orders of magnitude from very small to extremely large (10^{-15} to 10^{13} kg). They are most likely of cometry or asteroidal origin. *Micrometeoroids* are usually solid particles with a mass range from 10^{-15} to 10^{-1} kg.

To the aerospace engineer, the primary concern with meteoroids is their probability of collision with the spacecraft. Micrometeoroids near Earth often have sufficient energy to penetrate protective satellite coatings and to degrade surface thermal properties. Technical solutions exist to *harden* the satellite (e.g., through coatings, thermal conditioning, extra outside material layers). Regardless, a meteoroid can be fatal to a spacecraft, and nothing can be done to prevent it except to spot the object prior to impact and maneuver the satellite out of its orbital path.

The specifications of the Apollo and Skylab spacecraft were designed to withstand impacts from micrometeoroids no larger than 3 mm. Practically speaking as an engineer, it is difficult to incorporate all the potential dangers posed by meteoroids and micrometeoroids for space mission design. Perhaps the small probability of catastrophe is considered an unavoidable risk in human exploration of space.

Meteorites are the meteoroids that fall from space to Earth, which provide invaluable information about the formation of the solar system. They are pieces of very old material. Most result from asteroid collisions in the asteroid belt between Mars and Jupiter, but more recently meteorites from both the Moon and Mars have also been identified. The three main types of meteorites are the most common stone, and rarer iron, and hybrid stony iron. Stony-iron meteorites are the rarest. Antarctica is the best place to find meteorites because the Antarctic ice and aridity preserve them, sometimes for as long as a million years [59].

The connection between a large meteorite hit in Yucatan, Mexico, and the extinction of the dinosaurs is now certain. The dinosaurs were killed 65 million years ago after a huge meteorite hit Earth. The explosion caused great storms and waves, and the sky was dark for months with dust and ash. The dinosaurs, along with many other animals and plants, were probably killed by the climate changes that followed the explosion. However, this unfortunate incident permitted other animals to flourish and spread, including primitive mammals. "We may owe our very existence as a human species to a long-ago meteorite" [60].

An impact was finally witnessed by scientists and engineers when comet Shoemaker-Levy 9 was discovered heading for Jupiter. Jupiter's immense gravitational field tore the comet into more than 20 fragments, which were lined up and heading for Jupiter at over 60 km/s. In the summer of 1994 one fragment after another smashed into Jupiter, producing huge explosions. With this comet impact, the world witnessed the kind of massive impacts that have scarred all the planets, including Earth.

The famous Allan Hills 84001, or ALH84001, meteorite from Mars was found in Antarctica and has led to the speculation that life could have existed on Mars.

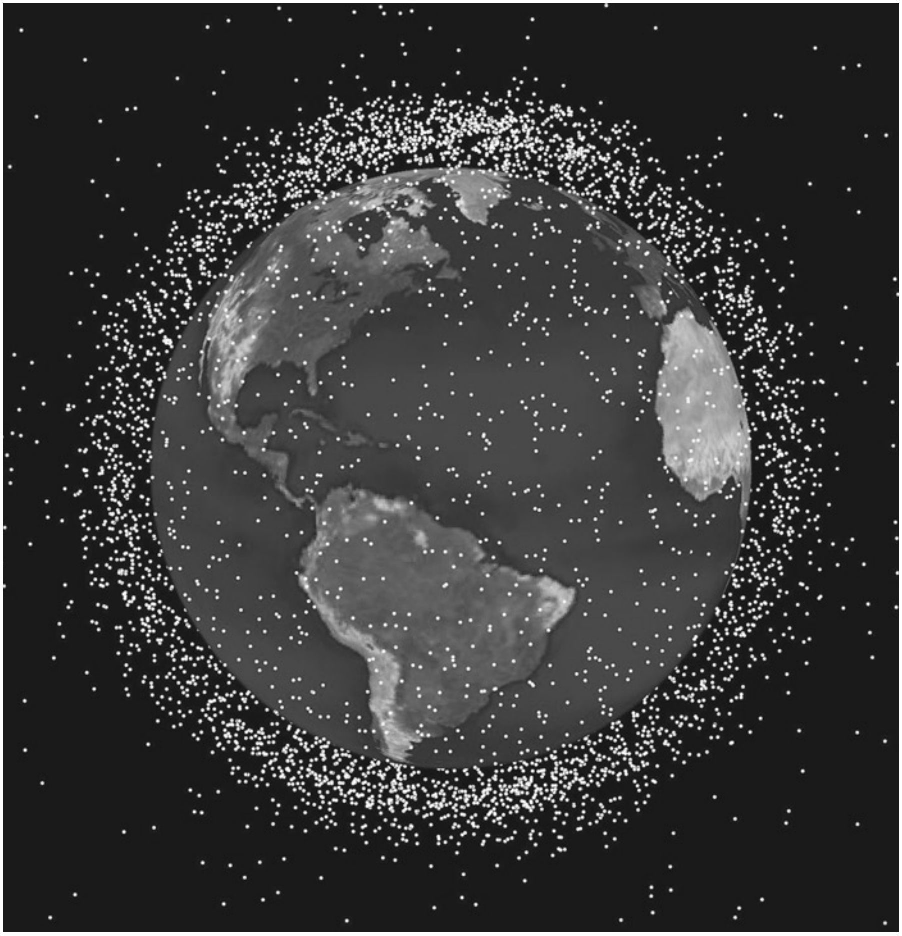
> The presence of oxidized iron in the chromite (Fe, Cr, Mg spinel) led to the reclassification of ALH84001 as a Martian meteorite. This was confirmed by oxygen isotope analyses. ALH84001 is by far the oldest martian meteorite, with a crystallization age of 4.5 billion years. It is a sample of the early Martian crust. The cosmic ray exposure age of 16 million years dates when the meteorite was ejected from Mars by impact, while the termination of that exposure gives ALH84001 a terrestrial age of 13 thousand years. The small amount of carbonate in ALH84001 is the center of attention concerning the possibility of life on Mars. These small grains that are barely visible to the naked eye, range up to 200 microns in size. They appear to have formed in fractures inside this igneous rock in the presence of liquid water or other fluid. [61]

There is considerable debate about the origin of these carbonates. The debate focuses on the temperature of formation. These grains are the sites of the three types of evidence that McKay et al. [1996] suggest represent ancient fossil life on Mars: polycyclic aromatic hydrocarbons (PAHs), or organic molecules; oxide and sulfide biominerals; and nannofossil-like structures. [61]

8.8 | SPACE DEBRIS

What does the near-Earth space environment look like to an external observer with regard to artificial objects in orbit? Figure 8.9 illustrates a partial answer.

Figure 8.9 | Orbital debris population distribution.



Online resource.

The aesthetic feature of this space debris picture raises our concern and consciousness of the problem, and the dangers posed by these human-made debris to operational spacecraft (pilotless or piloted) are a growing concern. A dramatic illustration of this fact is the recent impact of the mini satellite Cerise with an Ariane 4 third stage. Ground controllers lost contact with Cerise, a small British-built satellite, only to discover weeks later that the satellite was struck by a fragment from an Ariane rocket which had exploded several years previous. The collision broke off part of the satellite that helped maintain its stability. During a recent Hubble Space Telescope repair mission, astronauts found a small hole in the dish of one of the telescope's antennas. The likely cause? Space junk. To make matters worse, during the same repair mission while Hubble was docked to the Shuttle payload bay, a fragment from a Pegasus rocket that exploded several years ago came dangerously close, causing an immediate action to fire the Shuttle maneuvering jets to avoid this close encounter [62]. The Shuttle and Mir space station have both been impacted numerous times, but without jeopardizing crew safety. Most of the damage sustained by the Shuttle and Mir resulted in chipped windows, tiles, and, in some instances, solar panel penetration. Given the large size and planned duration of the International Space Station in LEO, it will certainly be hit by space debris particles.

Are these examples just unfortunate coincidence, or is there a really a space debris problem? If so, what exactly is the problem and how can we quantify it and deal with it?

8.8.1 The Future

Of all the artificial satellites currently orbiting Earth, less than 5 percent are operational spacecraft. The rest constitute an orbiting junkyard of dead satellites, rocket stages, discarded equipment, and fragments from satellite breakups [63]. Orbital debris is becoming a major concern for those planning spacecraft missions in Earth orbit, either in low Earth orbit (LEO) or in geosynchronous Earth orbit (GEO). It is a growing concern as constellations of dozens and hundreds of communications satellites are launched into LEO. Many NASA and national committees have studied the growing space debris situation [64, 65].

The problem with counting all the orbital space debris is that even tiny pieces of junk can cause significant damage. At orbital velocities of more than 28,000 km/h (17,500 mph), an object as small as 1 cm in diameter has enough kinetic energy to disable an average-size spacecraft. Objects as small as 1 mm can damage sensitive portions of spacecraft, but these particles are not tracked. The U.S. Space Command continuously tracks 6,000 objects in LEO of which more than one-half are fragments from on-orbit explosions, like the Ariane explosion that created the debris that disabled Cerise. However, there are estimates of 150,000 fragments of 1 cm or larger and more than a million objects greater than 1 mm [64]. On the other hand, there is some good news about orbital debris. Recent updated NASA models for estimating the amount of orbital debris in LEO found that the population of objects 1 cm or larger in orbit might be just one-half the number previously estimated. Even if there are only 75,000 objects 1 cm or larger in LEO, it is cause for concern for spacecraft planners.

A more subtle problem of debris tracking lies in the fact that the hazards are nondeterministic. That is, space junk often moves from its initial orbit, so the threat of danger is not clearly localized. This is due to the fact that space debris is more the result of fragmentation or breakup of satellites than deterioration and out-phasing of satellites. Typically a single breakup can result in as many as 500 or more observed pieces. Each piece is free to settle in a new unpredictable orbit, creating a nonlocalized potential danger for operational satellites (i.e., an impact can come from anywhere). Thus, the probability of collision increases and can be seen as triggering a chain reaction of potential collisions. Of course, the situation in the space environment is not that apocalyptic. However, some symptoms of this problem are burgeoning. The study of orbital debris is only a few decades old, but the future promises to provide numerous engineering jobs to those who come up with creative solutions to these emerging problems.

8.8.2 The Crowding of Specific Orbits

The situation at some specific orbits can be described as a crowding problem. At altitudes between 700 and 1,000 km, around 1,400 km, and in geostationary orbit, this is the case. These altitudes correspond to appropriate orbits for specific missions: Remote-sensing sun-synchronous missions are primarily between 700 and 1,000 km, communication satellites (and some of the main constellations) in low Earth orbits are typically above 700 and below 1,500 km, and geostationary orbit is around 36,000 km. The clustering of orbital debris in low Earth orbit is often referred to as the *beehive.*

Let us further consider the dangers associated with the crowding of the geostationary ring. If GEO satellites remain at this orbit after their operational lifetime, orbital mechanics tells us that they will slowly drift toward two stable longitudes at 105 E and 75 W. These two locations will therefore become an orbiting space museum of defunct spacecraft, implying a concentration of objects in a single location. Hence, a tremendous increase of the probability of collision, if not a certainty of collision, exists in the near future (~10 to 50 years). Some collisions will lead to breakups and will sow fragments all over the geosynchronous area, making it simply uninhabitable.

Orbital debris distribution in LEO and GEO (GEO_OrbDebrisA.jpg, GEO_OrbDebrisB.jpg).

So what is being done about it? Recently, concerns about removing a satellite from GEO after its operational lifetime have led to the idea to vacate desired longitudes by boosting satellites to higher altitudes (~100 km higher than GEO) at the end of their lifetime with onboard fuel. Another idea is to boost old satellites toward Earth so that they burn up and disintegrate when entering Earth's atmosphere. Both notions necessitate that satellites be equipped with sufficient onboard propulsion for the end-of-lifetime boost. Are these sufficient to *save* GEO? Probably not, but they are encouraging initial design implementations.

8.8.3 Reflection

What have we done to the space environment? It is certainly instructive to reflect on the past. Previously, planned experiments created considerable space debris. One example is the Westford Needles experiments in 1961 and 1963. The idea was to release a large quantity of small copper dipoles at around 3,900 km altitude. Over 300 million dipoles about 2 cm were to be released from a spinning canister. A belt of dipoles 8 km wide and 40 km thick was expected. Luckily, the first attempt was completely unsuccessful, and the second, in May 1963, encountered payload separation problems, resulting in clumps of dipoles. The decay of these objects was considered; however, of the 100 clumps cataloged by the U.S.–Canadian North American Aerospace Defense Command (NORAD), 60 are still in orbit.

Clearly, intentions to purposefully create space debris by destroying satellites in orbit pose a significant risk. Why would such logic be followed? Four reasons have been offered: for structural testing, destroying sensitive equipment, performing antisatellite tests (ASATs), and self-defense. An example is the Soviet anti-ASAT test program that accounts for approximately 20 percent of all space debris currently tracked. The theory behind such programs is that a missile, or interceptor, breaks up as it fires a conventional warhead when closing in on the ASAT target satellite; thus, the fragments of the interceptor supposedly destroy the target. A moral emerges:

> The impact on the Earth, humanity, and the space environment of all space endeavors must be considered.

Be critical of all proposed space endeavors, both past and future. History shows that some past exploration and early uses of near-Earth space were irresponsible, and perhaps unethical (nuclear explosions at high altitude, deliberate satellite fragmentation, etc.). Anecdotally, there exists celebrated space debris such as Ed White's spacesuit glove that drifted out of Gemini during the first U.S. spacewalk in 1965, and the loss of a powered screwdriver during the repair of the Solar Max in 1984.

8.9 | PLANETARY ENVIRONMENTS

The environments of the planets within our solar system vary greatly. In addition, the gravitational forces on the planets depend on their mass; therefore, the 1 G environment in which we humans have evolved is unique within our solar system.

8.9.1 Planetary Atmospheres

All the larger planets have atmospheres. The atmospheres of planets are held in place only by the force of gravity and do not have distinct boundaries in space. Therefore, a spacecraft operating in the vicinity of a planet with an atmosphere must be designed to tolerate the effects of that atmosphere, particularly if humans are aboard the vehicle.

The chemical composition of a planetary atmosphere varies greatly among planets depending on the distance from the Sun, its size, and its unique large-scale chemical reactions. The inner Earth-like planets (Mercury to Mars) are believed to have formed without extensive atmospheres. One theory as to how atmospheres came about is that gases once chemically combined in the crust have since escaped, and that additional gases from comet impacts became trapped under the gravity of the planet. In the case of Earth, research has shown that the presence of uncombined oxygen in noticeably large quantities is a direct result of the presence of life and suggests that the current atmosphere has evolved significantly over time (the past 4 billion years). Conversely, studies of the outer planets (Jupiter to Pluto) suggest that the atmospheres present today are nearly identical to those present when the planets formed.

Evolution of an atmosphere is greatly determined by the *selective* loss of gases by evaporation. For a given atmospheric temperature, lighter gas molecules will travel faster than heavier molecules. If the speed of a molecule exceeds the escape velocity of the planet, it will eventually be lost to space. This escape velocity is determined by the mass of the planet. Atmospheric temperature is determined by the planet's proximity to the Sun. Thus, as we move closer to the Sun and examine planets that are progressively less massive, we expect to see a greater loss of atmospheric gas until, finally, we see a loss of atmosphere all together.

Martian Environment The Martian atmosphere has a typical surface pressure of about 0.01 of Earth's atmosphere (i.e., Earth's atmospheric pressure at an altitude of 30,000 km). The Martian day, the Sol, is 24 h, 37 min, 23 s long. Composed mainly of carbon dioxide (95.3 percent), the atmosphere also has trace amounts of other gases, including nitrogen (2.7 percent) and argon (1.6 percent). Oxygen makes up only 0.13 percent of the Martian atmosphere. Clouds are rarely seen in Mars' sky, as the amount of water vapor is 25 percent that of Earth. It is thought that this amount, however, is enough to result in water ice beneath the surface. Finding (and utilizing) this ice is a future goal for exploration missions [66]. As shown by the Pathfinder spacecraft, the Mars surface is diverse.

WWW

Martian surface as viewed from the Pathfinder spacecraft.

Mars sees winds blowing from all directions within a single Sol, with the highest turbulence in the morning. The greatest wind speeds are seen in the early morning and around mid-day. Numerous dust devils have been recorded on a daily basis. The Martian regolith, or soil, ranges from particles of 40 μm to large boulders several meters in diameter. The regolith is harder than aluminum, but softer than nickel. A design consideration from the constantly blowing regolith is abrasion to equipment, solar panels, and spacesuits. The dust is magnetic and sticks to most surfaces. It also has the potential to charge equipment and produce electrical discharge, which could greatly interfere with mission operations. Finally, new measurements show dust adhering to solar panels at a rate of 0.28 percent per Sol, which means that in less than 20 Sols dust coverage could amount to 5 percent coverage. At this rate, the decrease in efficiency of solar panels is dramatic.

Temperatures vary from −133°C during the winter to 25°C at the equator during the summer. In comparison to an average Earth temperature of 15°C, Mars is −55°C. Interesting new data from the Mars Observer mission shows that the variation in vertical temperature from the Martian surface varies greatly over only a few meters. There are significant implications for spacesuit design. The average temperature of a suited astronaut on Mars might include a temperature differential of 10°C between the knee and the shoulders (over 0.75 m in height). The design solution is a spacesuit with automatic thermal control to account for the temperature variation in altitude as well as the extreme temperature changes from day to night. The Martian temperature variations will subject materials to continuous expansion and contraction, resulting in great stresses that must be accounted for in equipment designs.

The latest images from the Mars Observer high-resolution camera help identify interesting places for future exploration missions. The South polar cap looks like a promising place that might have preserved organic material. Through the ongoing robotic missions to Mars and current space science missions, the planetary and solar system databases are being continually updated and expanded.

Explore Mars, the Mars Surveyor Orbiter, the Mars Surveyor Lander, and how future space travelers could use artificial gravity on their 4 year mission to Mars on the accompanying CD-ROM.

Mars.vrml, Orbiter.vrml, and Lander.vrml

This chapter started by considering where space begins. The atmosphere and temperature extremes helped introduce the space environment. Then microgravity, radiation, and the Sun's effect on space missions were introduced. Understanding the environment in LEO and the Earth's magnetosphere is essential to planning successful space missions. The realization that space is continuously becoming more crowded highlighted the problem of orbital debris. The final section of the chapter touched on planetary environments. Previous chapters focused on aeronautics, but this chapter on the space environment completes a transition to the study of astronautics. One of the most fascinating space topics is covered in the next chapter, namely, "Orbital Mechanics."

PROBLEMS

8.1 We have seen that the space environment is commonly characterized in terms of four components: the neutral environment, the plasma environment, the radiation environment, and the particulate environment. Briefly describe those components of the space environment (a couple of lines per component), and give an example of how each can affect the operation of a spacecraft.

8.2 Why is the spacesuit thermal micrometeorite garment white? What do you think the design considerations were in choosing this material as an outer garment? The Space Shuttle or an astronaut during EVA (extravehicular activity) acts as a ___________ with absorption-to-emissivity ratio ____________.

8.3 Discuss two environmental constraints that spacecraft designers consider during vehicle design and development. What current methods are used to overcome these environmental effects?

8.4 What are the trapped radiation belts or the Van Allen belts (altitudes, structure, type of trapped particles, etc.)? Two identical satellites are launched on different orbits: The first one remains on a circular orbit below 1,400 km; and the second one is injected on a geo transfer orbit, i.e., an elliptical orbit that goes from 600 to 36,000 km then back to 600 km, etc. Which satellite is more likely to experience more failures and why? What types of failures do you think it will experience?

8.5 Briefly describe the effect of the solar wind on Earth's magnetosphere.

8.6 Space debris is becoming an ever-increasing problem.

(a) Discuss two current solutions.

(b) Develop your own creative solution and discuss.

8.7 Compare and contrast the atmosphere of Mars to that of Jupiter. How has each evolved over time? What are the contributing factors to this evolutionary process?

8.8 The following is an extract from an article by the Aerospace Corporation, Center for Orbital and Reentry Debris Studies (CORDS), on orbital debris and the risks encountered by satellites of colliding with such objects. Provide a short summary (less than a page) of the article.[1]

(a) What Is Orbital Debris?

Orbital debris generally refers to material that is on orbit as the result of space initiatives, but no longer serves any function. There are many sources of debris. One source is discarded hardware. For example, many upper stages from launch vehicles have been left on orbit after they are spent. Many satellites are also abandoned after end of useful life.

Another source of debris is spacecraft and mission operations, such as deployments and separations. These have typically involved the release of items such as separation bolts, lens caps, momentum flywheels, nuclear reactor cores, clamp bands, auxiliary motors, launch vehicle fairings, and adapter shrouds.

A major contributor to the orbital debris background has been object breakup. More than 124 breakups have been verified, and more are believed to have occurred. Breakups generally are caused by explosions and collisions.

The majority of breakups have been due to explosions. Explosions can occur when propellant and oxidizer inadvertently mix, residual propellant becomes over-pressurized due to heating, or batteries become over-pressurized. Some satellites have been deliberately detonated. Explosions can also be indirectly triggered by collisions with debris.

Three collisions are known to have occurred since the beginning of the space age. In addition, the debris research community has concluded that at least one additional breakup was caused by collision. The cause of approximately 22% of observed breakups is unknown.

(b) What Are the Risks Posed by Orbital Debris?

Orbital debris generally moves at very high speeds relative to operational satellites. In low Earth orbit, i.e., at altitudes less than 2,000 km, the average relative velocity at impact is 10 kilometers per second = 36,000 kilometers per hour = 21,600 mph. At this velocity, even small particles contain significant amounts of kinetic energy and momentum. For example, NASA frequently replaces Space Shuttle windows because they are significantly damaged by objects as small as a flake of paint. An aluminum sphere which is 1.3 mm in diameter has damage potential similar to that of a 0.22-caliber long rifle bullet. An aluminum sphere which is 1 cm in diameter is comparable to a 400-pound safe traveling at 60 mph. A fragment which is 10 cm in its long dimension is roughly comparable to 25 sticks of dynamite.

Debris particulates less than 1 mm in size do not generally pose a hazard to spacecraft functionality. However, they can erode sensitive surfaces such as

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1. The article can be found at the following website, along with related infromation and links: www.aero.org/cords/.

payload optics. Hence, while the spacecraft may survive, payload degradation can still result in mission loss.

Debris fragments from 1 mm to 1 cm in size may or may not penetrate a spacecraft, depending on material selection and whether shielding is used. Penetration through a critical component, such as the flight computer or propellant tank, can result in loss of the spacecraft.

Debris fragments from 1 to 10 cm in size will penetrate and damage most spacecraft. If the spacecraft bus is impacted, the satellite function will be terminated, and at the same time a significant amount of small debris will be created. In large satellite constellations, this can lead to amplification of the local smaller debris population and its associated erosional effect.

If a 10 cm debris fragment weighing 1 kg collides with a typical 1,200-kg spacecraft bus, over one million fragments 1 mm in size and larger can be created. This results in the formation of a debris cloud which poses a magnified impact risk to any other spacecraft in the orbital vicinity, such as other constellation members.

At geosynchronous altitude, average relative velocity at impact is much lower than in low Earth orbit, about 200 meters per second = 720 kilometers per hour = 432 mph. This is because most objects in the geosynchronous ring move along similar orbits. Nevertheless, fragments at this velocity can still cause considerable damage upon impact. A 10-cm fragment in geosynchronous orbit has roughly the same damage potential as a 1-cm fragment in low Earth orbit. A 1-cm geosynchronous fragment is about equivalent to a 1-mm low Earth orbit fragment.

(c) What Are Debris Clouds?

Any concentration of debris particles or fragments in a well-defined region of space is referred to as a debris cloud. Debris clouds are formed whenever debris is being created by a single source. For example, discarded upper stages generally are surrounded by a cloud of particulates which is released over time by degradation of various materials such as paint and multilayer insulation.

Whenever an orbital breakup occurs, a debris cloud is instantly formed. Such debris clouds first take on the form of an expanding three dimensional ellipsoid. The center of the debris cloud moves along a well-defined orbit, which for explosions is identical to the orbit of the original object. The debris cloud gradually spreads around this orbit. As time passes, the debris cloud eventually envelopes the entire orbit and any other satellites in the nearby vicinity.

Due to the laws of orbital motion and to physical processes involved in an explosion or collision, fragments are not spread uniformly throughout a debris cloud. At some locations, spatial density of fragments is much greater than at others. When spatial fragment density is high, the collision risk posed to satellites that fly through the cloud is greatly enhanced.

(d) How Can Risk Be Controlled?

Risk is best controlled by limiting the creation of debris through mitigation. Unfortunately, debris mitigation usually increases mission cost. Some debris mitigation procedures have only small impact on mission cost if they are specified early in the development phase. For example, deployment procedures can be designed to prevent ejection of objects. Tethered lens caps and bolt catchers for explosive bolts are examples.

To prevent explosions, satellite components that store energy can be made passive after end of useful life. For example, propellant in upper stages and satellites can be eliminated by either venting or burning to depletion. Batteries can be designed to reduce risk of explosion. These activities may entail moderate cost during the nonrecurring phase of the mission. Cost during operation should be small.

To prevent debris accumulation in preferred mission orbits due to collisions, satellites and other objects must be removed from the mission orbit after end of life before collisions are likely to occur. NASA's guidelines for limiting orbital debris recommend that an object not remain in its mission orbit for more than 25 years.

Satellites, upper stages, and deployed objects in low Earth orbit can take advantage of the Earth's atmosphere to reduce time spent on orbit. At sufficiently low altitudes, atmospheric drag on the object will cause the object's orbit to decay and result in reentry within 25 years. Vehicles at higher altitudes can perform post mission maneuvers to drop the perigee (orbital point closest to Earth) further down into the atmosphere. Propellant must be reserved for this maneuver. Hence, the cost to satellites is reduced mission life, and to upper stages it is reduced performance. If atmospheric decay is exploited to remove an object from orbit, then the risk posed to the ground by re-entry of the object must be considered.

At altitudes above 2,000 km, it is not feasible to force reentry within 25 years using currently developed space technology. At this time, it is generally recommended to place vehicles in disposal (often called "graveyard") orbits. Many spacecraft in geosynchronous orbit are already boosted into a higher disposal orbit at end of mission life.

Some missions may find it necessary to perform collision avoidance. The Space Shuttle has maneuvered to avoid collisions with other objects on several occasions. Regarding satellite constellations, if a potential collision will lead to the creation of a debris cloud that may result in damage to other constellation members, it may be worthwhile to perform a collision avoidance maneuver.

In the more distant future, it may be necessary to completely remove all satellites and upper stages from orbit. This will not be possible until new technology is developed to make this feasible.

Chapter 9

Orbital Mechanics

Dava J. Newman

9.1 | INTRODUCTION TO TWO-BODY ORBITAL MECHANICS

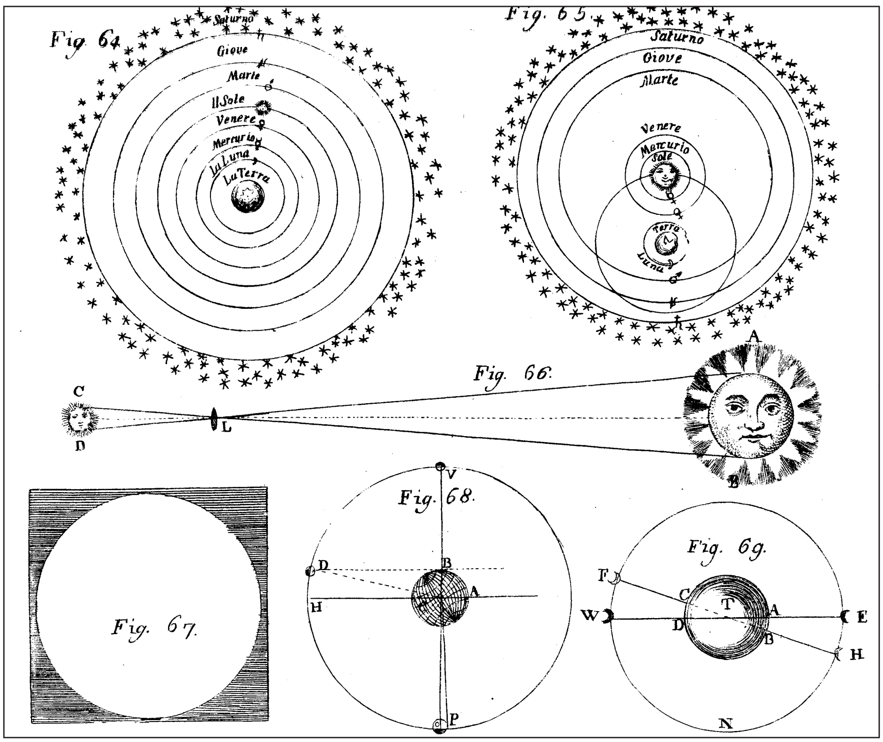
9.1.1 Historical Perspective

Humanity's interest in the universe seems to date back to approximately 1650 B.C. in Babylon and Egypt (i.e., the Ahmes Papyrus). It is a well-known fact that both of these ancient civilizations established elaborate systems of numeration in which positional or place-value notation was used. For instance, clay tablets exist from the ancient Babylonian civilization that possess cuneiform writing, illustrating the sexagesimal (base-60) system of notation that was used. This system of numeration remained in use through the time of Copernicus, and it forms the basis for modern timekeeping (i.e., 60 s in 1 min).

A heliocentric universe was first postulated in 300 B.C. by Aristarchus; the Sun and stars were fixed in position, and Earth revolved in a circular orbit about the Sun. This theory was summarily dismissed by the leading minds of the era, as the geocentric universe was firmly fixed in the annals of antiquity. Epicyclical motion of the planets was introduced by Hipparchus in the second century B.C. This powerful creation of Greek science, mathematical astronomy, was given final form by Ptolemy in the second century A.D. and became the principal theory for predicting the motions of the planets. While no physical principles were postulated on which to base this motion, the results obtained by this epicyclical theory, such as the rise and set of the planets, were very accurate. The Ptolemaic model of the universe, with Earth fixed at the center and the other planets moving in epicycles, remained virtually unchanged throughout the Middle Ages. It is interesting to note that the early Greeks were more accurate in speculating about the true nature of Earth; both Pythagoras and Aristotle supported the notion of a spherical Earth, a notion that somehow became lost in the Middle Ages. In the 13th and 14th centuries, a number of Arabic and Persian astronomical works were translated into Greek by scholars who traveled to Persia under the Ilkhanid Empire. Nasir ad-Din at-Tusi was among the first Arabic astronomers of the late 13th century at the observatory of Maragha in Persia who modified Ptolemy's models based on mechanical principles, in order to preserve the uniform rotation of spheres. His principal work on the subject was *Tadhkira fi ilm al-Haya* (Memoir on Astronomy).

Early in the 16th century, Copernicus (1467–1543) put forward a scheme that placed the Sun at the center of the universe. (See Figure 9.1.) In his model, the planets were seen as moving in epicycles about the Sun, with the Moon moving similarly about Earth. Copernicus also hypothesized that the stars lay on a sphere of very large radius, thus rendering them almost infinitely far from Earth. Needless to say, his theory was not well received among scientists or ecclesiastics alike. Conventional wisdom dictated to scientists that if Earth were a rapidly spinning body, all the people would be thrown off into space by centrifugal force. Clergy were of the opinion that God's favored creatures would necessarily occupy the center of the universe.

Figure 9.1 | Geocentric universe is replaced by the Copernican theory of a heliocentric universe.



Quantitatively, at least, the architecture for the universe devised by Copernicus accounted for several of the mechanisms observed in the sky: It explains the rising and setting of the Sun, Moon, and stars; and the aggregate motion of those celestial bodies is caused by the rotation of Earth around its polar axis. As well, the waxing and waning of the four seasons are seen to be due to the spin axis of the Earth being inclined 23.5° with respect to the ecliptic plane, that is, the plane which contains both Earth and Sun. As well, Copernicus managed to estimate the size of the solar system by predicting the relative distance between the planets in terms of astronomical units (au), that is, the distance between Earth and the Sun. Today, the astronomical unit is known to be approximately 149.7 million km (93 million mi).

Hence, the Copernican theory of heliocentric motion opened the way for more exact and proper theories, which would have to be based on accurate observations of celestial bodies. Tycho Brahe (1546–1601), a Danish astronomer, provided these data by meticulously recording the motion of various celestial bodies over a period of 13 years. In 1576, Brahe constructed an astronomical observatory on an island off the coast of Denmark to house the gigantic but precise instruments he used in making his celestial observations. Since there were no contoured mirrors or lenses to provide magnification of the planets and stars, Brahe was forced to fashion enormous protractors in order to measure angular separations with superb precision. Hence, Brahe was able to measure and record the angular position of the five visible planets, along with the locations of the more distant background stars, with unprecedented precision. When necessary, corrections for atmospheric refraction were made by noting that when the distant stars were near the horizon, their observed positions were shifted slightly. On his deathbed, Brahe released his tabulated measurements to his young assistant, Johannes Kepler (1571–1630), who went on to develop the first general empirical laws of planetary motion. Kepler's genius lay in the patience and mathematical insight necessary to unlock the hidden secrets of Brahe's measurements.

9.2 | KEPLER'S LAWS

9.2.1 Kepler's Three Laws

If not for Kepler, the destiny of the heliocentric theory of Nicholas Copernicus would have been considerably in doubt. Kepler was fascinated by the Copernican system of the world and devoted his life to uncover any additional geometric properties inherent in this heliocentric universe. Kepler's initial efforts to use the five regular geometric solids to account for the placement of the planets were both extensive and unproductive. It was not until he became an assistant to astronomer Tycho Brahe, in the observatory at Prague, that his research began to coalesce. Brahe's observations of the planet Mars, whose orbital eccentricity was pronounced, provided Kepler with the means of testing his theories of planetary motion.

The fundamental difficulty encountered by Johannes Kepler was that Brahe's observations were not made from an inertial reference frame deep in the outer reaches of space; instead they were made from a rapidly rotating platform that orbited the Sun. Consequently, Kepler faced two separate but inextricably intertwined problems: first, calculating the Earth's motion about the Sun, then decoupling this motion from that of the other planets' motion about the Sun.

Kepler's most important work, *Astronomia Nova de Motibus Stellae Martis,* was published in 1609 and contained the first valid approximations to the kinematic relations of the solar system; Kepler's first two laws arise from this work. Not until 10 years later was he able to quantify his third law, which he published in 1619 in the work *Harmonices Mundi,* which succeeded in uniting the field of celestial mechanics in a heretofore unheard of fashion.

While attempting to calculate the motion of the planet Mars using a very precise, complex mathematical algorithm, Kepler observed that no matter how many adjustments were made, circular orbits could not be made to match the planetary positions that Brahe had observed. Finally, he attempted to fit the orbit of Mars by using a little-known geometric shape that had principally been studied by Greek mathematicians. Immediately it was seen that the motion of Mars fit the observations of Brahe with great precision if the planetary orbit was described as an ellipse. This led to the formulation of Kepler's first law, which defines the shape for the planetary orbits. Kepler's second law pinpoints the changing velocity at which the planets travel about the Sun. The third law devised by Kepler provides a relationship between the periods of the planets and their mean distance from the Sun.

Put simply, Kepler's three laws are as follows:

1. Planets describe an elliptical path around their centers of gravitation.
2. In equal times, equal areas are swept out by the radius vector of a planet.
3. The square of the period of a planet about a center of attraction is proportional to the cube of the planet's semimajor axis and can be written numerically as

$$\tau^2 = ka^3 \tag{9.1}$$

where τ is the period of revolution, a is the semimajor axis of the orbit, and k is a constant of proportionality.

EXAMPLE 9.1 The Orbital Period of Mars

Use Kepler's third law to calculate the period of Mars. It is given that the period of revolution of Earth about the Sun is $\tau_1 = 365.256$ days.

$$\text{Semimajor axis of Earth orbit } a_1 = 1.49527 \times 10^{11}\ \text{m}$$

$$\text{Semimajor axis of Mars orbit } a_2 = 2.2783 \times 10^{11}\ \text{m}$$

$$\begin{aligned}\tau_2 &= \tau_1\left(\frac{a_2}{a_1}\right)^{3/2}\\ &= (365.25)\left(\frac{2.2783 \times 10^{11}}{1.49527 \times 10^{11}}\right)^{3/2}\\ &= 686.96\end{aligned}$$

Thus, the orbital period of Mars is 686.96 days.

9.3 | NEWTON'S LAWS OF MOTION AND GRAVITATION

9.3.1 Galileo's Pendulum Principle

The Italian physicist Galileo Galilei (1564–1642), introduced in Section 2.3.6, "The Renaissance," made a series of penetrating observations that later helped in the development of the laws of universal gravitation. While looking at a lamp swinging from a chain, Galileo observed that the period of time required for a pendulum to swing back and forth was always the same, regardless of the length of its swinging arc; if the pendulum traveled on a long arc, it moved more rapidly than if it traveled on a short arc.

In 1592, Galileo conducted a series of experiments proving conclusively that heavy objects and light objects fall under the influence of gravity at the same constantly accelerating rate, if drag with respect to the atmosphere is neglected. This observation ran counter to the intuitive conjecture of Aristotle, who had postulated that heavy objects fall faster. By 1604, Galileo had measured the rate at which falling objects accelerate and, as a result, formulated the famous law of uniform acceleration, which states that falling objects near the surface of Earth accelerate uniformly downward under the influence of gravity.

9.3.2 Newton's Universal Law of Gravitation

On Christmas Day, 1642, the year Galileo died, there was born a tiny infant. Sir Isaac Newton (1642–1727) was not a child prodigy, but began to perform brilliantly upon his entry to Trinity College of Cambridge University. Just after his graduation in 1665, Cambridge University was closed down, because the plague was rampant throughout England. Returning to his home in Woolsthorpe-by-Colsterworth, Newton then formulated his famous inverse-square law to describe the behavior of celestial bodies. Others had advanced the concept of the inverse-square law of gravitation, including Kepler, but Newton recognized it as the key to celestial mechanics. Furthermore, he intuitively theorized that the full force of Earth's gravity could be considered as emanating from a point source at its center. But when he checked his theory with calculations, using an imprecise figure for Earth's radius, he found he was off by enough to make him doubt his point-source assumption, and thus he set this problem aside for 20 years. However, from his deceptively simple calculations concerning the nature of the motion of a small object close to the surface of Earth (say, an apple) versus the motion of a large object far removed from Earth (say, the Moon), Newton was able to arrive at a sweeping generalization:

> Every particle in the universe attracts every other particle with the force that is directly proportional to the product of their masses and inversely proportional to the distance between their centers.

The following three laws of motion given by Newton in his 1687 publication *The Mathematical Principles of Natural Philosophy,* or commonly known as the *Principia,* are considered the axioms of mechanics:

1. Every particle persists in a state of rest or of uniform motion in a straight line unless acted on by a force.
2. If **F** is the external force acting on a particle of mass *m,* which, as a consequence, is moving with velocity *v,* then

$$F = \frac{d}{dt}(mv) \quad \textbf{[9.2]}$$

   This can be restated as the rate of change of momentum is proportional to the force and is in the same direction.
3. To every action there is an equal and opposite reaction. In other words, if particle 1 acts on particle 2 with a force F_{12} in a direction along the line adjoining the particles, while particle 2 acts on particle 1 with a force F_{21}, then $F_{12} = F_{21}$.

Using these three axioms and Kepler's law of equal areas, Newton was able to derive his law of gravitation. The law of gravitation states that two particles attract each other with a force, acting along the line joining them, which is proportional to the product of their masses and is inversely proportional to the square of the distance between them. Newton's law of gravity can be expressed mathematically as

$$F_g = -\frac{GMm}{\mathbf{r}^2} \quad \textbf{[9.3]}$$

where F_g is the force on mass *m* due to mass *M* and **r** is the vector from *M* to *m.* The universal gravitational constant *G* has the value 6.67×10^{-8} dyn(cm^2/g^2).

9.3.3 Conservation of Energy and Momentum

The gravitational potential *V* at the point (*x,y,z*) is defined as

$$V_i = G\sum_{j=1}^{n}\frac{m_j}{r_{ij}} \quad \textbf{[9.4]}$$

where *G* is the universal gravitational constant, *m* is mass, *r* is distance, and the subscripts *i* and *j* both increase consecutively from 1.

Since the potential function depends only on the distances to the other particles, it is, consequently, independent of the choice of coordinate axes. The importance of the gravitational potential derives from the property that the gradient of *V* gives the force of attraction on a particle of unit mass at (*x,y,z*).

For some purposes, it is convenient to introduce the force function *U,* defined by

$$U = \frac{1}{2}\sum_{i=1}^{n} m_i V_i \quad \textbf{[9.5]}$$

This force function is equal to the total work done by the gravitational forces in assembling the system of n point masses from a state of infinite dispersion to a given configuration. Therefore, the potential energy of the system is the same thing as the force function and is denoted by U. The concepts of potential energy and kinetic energy are familiar from physics, and the link to orbital mechanics will become evident.

If we define the kinetic energy of the system as convention dictates

$$T = \frac{1}{2}\sum_{i=1}^{n} m_i v_i^2 \quad \textbf{[9.6]}$$

where m is mass and v is velocity, we have that $T + U =$ constant, or that energy is conserved. The following section builds on the concepts of potential and kinetic energy to offer a complementary means to solve dynamics problems, or the equations of motion, through energy methods rather than Newtonian mechanics. Both methods, Newtonian and energy, solve the equations of motion and yield correct answers.

9.3.4 Equivalent Lagrangian Energy Formulation

The field of dynamics is normally dominated by the approach formulated by Newton's laws, predominantly Newton's second law. Newton's second law is, in essence, a differential equation. Thus, there is a corresponding dual problem to this differential equation.

Lagrange's energy formulation of the equations of motion of a body is often regarded as a corollary to Newton's second law; but in reality, it is a valid formulation in its own right. Lagrangian dynamics or energy methods, as they are often called, offer an alternative approach to the solution of dynamics problems in lieu of Newton's second law.

Consider the Lagrangian function, L

$$L = T - U \quad \textbf{[9.7]}$$

where T and U were defined in the previous section as kinetic and potential energy, respectively. Now, we utilize the Euler–Lagrange equation, which is accepted *quid pro quo:*

$$\frac{d}{dx_i}\left(\frac{\partial L}{\partial \dot{x}_i}\right) - \frac{\partial L}{\partial x_i} = 0 \quad \textbf{[9.8]}$$

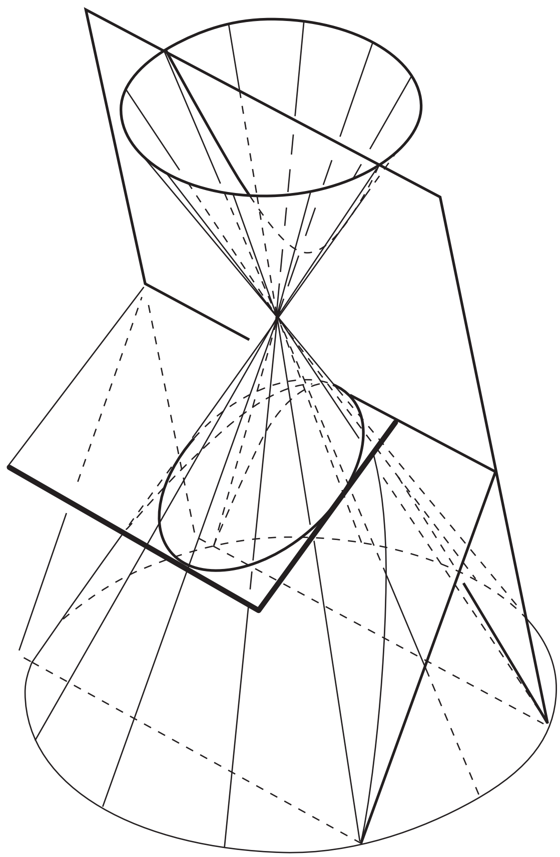
where the x_i are the coordinates in which the system is referenced. Thus, by substituting the expression for L into the Euler–Lagrange equation, the exact same equations of motion can be arrived at as through the Newtonian approach.

9.4 | TWO-BODY BOUNDARY-VALUE PROBLEMS

9.4.1 Conic Sections and Polar Coordinates

The circle, ellipse, parabola, and hyperbola are often called conic sections, because they can all be obtained as sections cut from a right circular cone by a plane. The type of conic depends on the dihedral angle between the cutting plane and the base of the cone. Thus, if the plane section is parallel to the base, the conic is a circle. If the plane is inclined to the base, but at an angle less than that between the generators of the cone and its base, the section is an ellipse. If the cutting plane is parallel to one of the generators, the section is a parabola. Finally, if the plane is inclined to the base at a still greater angle than that of the generators, the plane will also cut the cone formed by the extension of the generators. The section consisting of these two parts is a hyperbola (see Figure 9.2).

Figure 9.2 | Conic sections: circle, ellipse, parabola, and hyperbola.



Two-body orbits are circles, ellipses, parabolas, or hyperbolas. They are the locus of points whose position vectors ***r*** satisfy

$$r = p - e \cdot r \qquad \textbf{[9.9]}$$

The constant-eccentricity vector **e** of magnitude $e > 0$ lies in the orbital plane, and the parameter p is a nonnegative constant. The parameter and eccentricity can be conveniently related via the semimajor axis a:

$$p = a(1 - e^2) \qquad \textbf{[9.10]}$$

The vectors **r** and **e** originate at the focus F, and a may have any real value between plus and minus infinity.

Ellipses demonstrate three basic and well-known geometric properties: the focus-directrix property, the focal radii property, and the orbital tangents property (see Figure 9.3). The focus-directrix property states that the orbit is the locus of points whose distances from a fixed point and a fixed straight line are in constant ratio. The focal radii property declares that an ellipse is the locus of points for which the sum of the focal radii is constant. The focal radii are the distances to a point P on the ellipse from the two foci of the ellipse. The property of orbital tangents states that the focal radii to a point on an ellipse make equal angles with the orbital tangent to that point of the ellipse (see Figure 9.4). In the usual systematic development of analytic geometry, one of these properties is generally chosen as the definition of this special class of plane curves.

Figure 9.3 | Focus-Directrix geometric property of an ellipse.

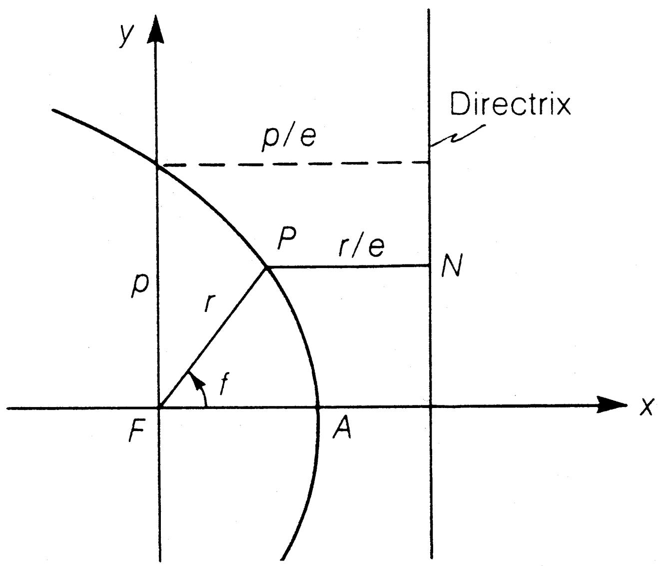
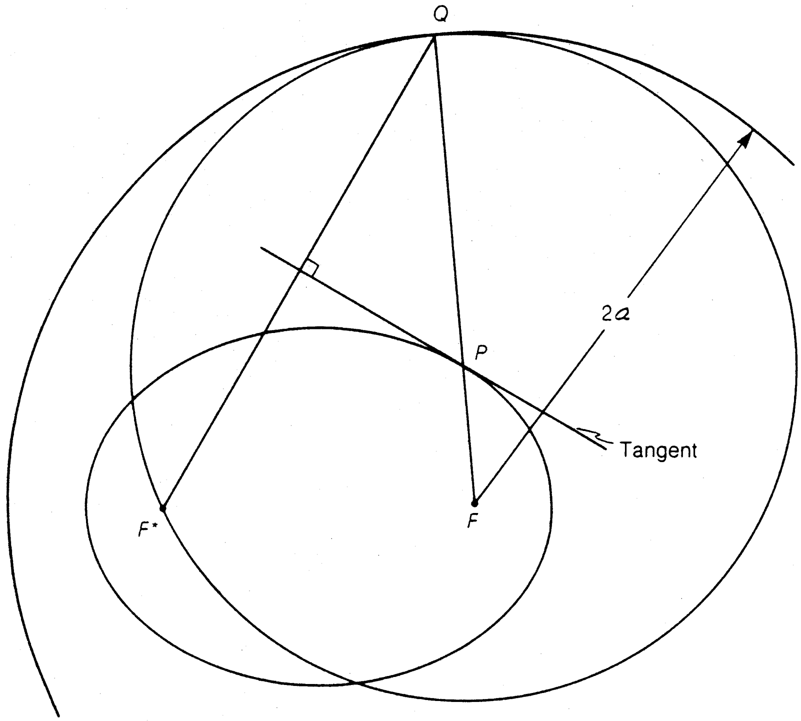


Figure 9.4 | Orbital Tangent property of an ellipse.



9.4.2 Kepler's Equation of Orbit

A direct consequence of the law of areas is Kepler's equation of orbit, which relates the orbital position with time. But, first, some nomenclature must be expounded upon. An elliptical orbit of a body can be characterized by its semimajor axis and its eccentricity. The semimajor axis a of an ellipse can be described as one-half the length of the longitudinal axis of the ellipse. The eccentricity e defines the shape of the orbit; it is quantified as the apogee radius (maximum) minus the perigee radius (minimum), divided by their sum, as defined in Equation (9.11). Figure 9.5 illustrates these parameters of an elliptical orbit.

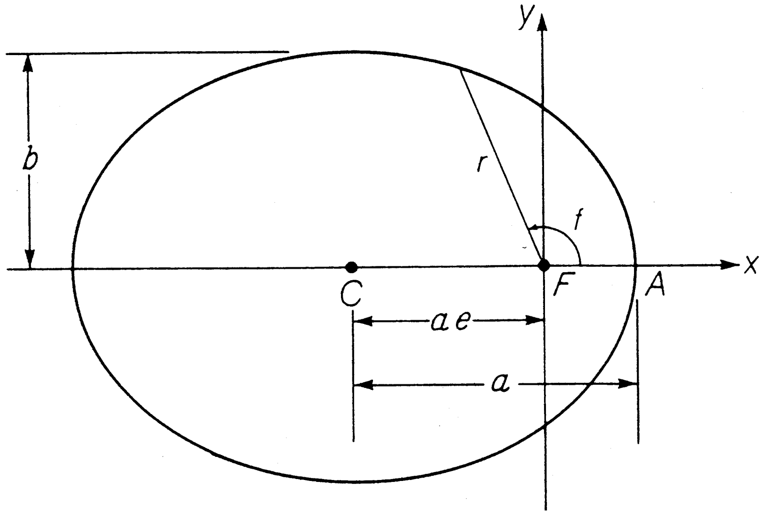
$$e = \frac{r_{\text{max}} - r_{\text{min}}}{r_{\text{max}} + r_{\text{min}}} \tag{9.11}$$

In devising his three laws of planetary motion, Kepler worked with three different angles that are still at the crux of orbital mechanics today: the *true anomaly f,* the *eccentric anomaly E,* and the *mean anomaly M.* All three of these angles are measured with respect to the perigee of the elliptical orbit. The true anomaly is the easiest of the three to understand; it is the angular position of the body in the elliptical orbit with reference to the point of perigee, as seen in

Figure 9.5. Thus, the equation linking the body's radial distance to its current true anomaly is merely the polar coordinate equation of an ellipse:

$$r = \frac{a(1 - e^2)}{1 + e\cos f} \tag{9.12}$$

Figure 9.5 | Illustration of Kepler's third law and geometry of an elliptical orbit.

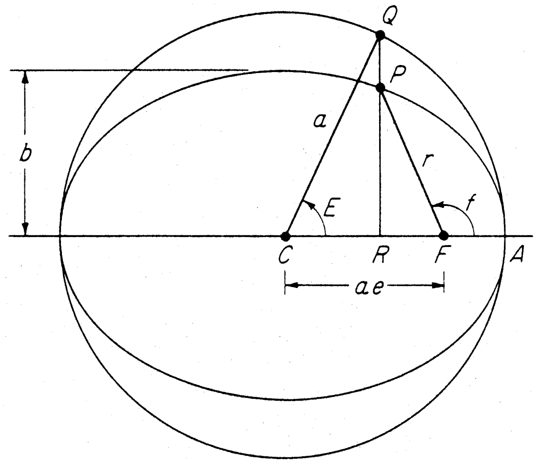


The eccentric anomaly can be constructed by circumscribing a circle around the elliptical orbit of the body; this circle is tangent to the two ends of the ellipse (at perigee and apogee for an earth orbit). A perpendicular from the semimajor axis is erected from point *R,* passing through the orbital position, *P,* of the body on the ellipse and intersecting the great circle at *Q*. A line is then drawn joining the perpendicular intersection point on the circle to the center of the ellipse, *C,* (and thus the center of the circle) (see Figure 9.6). The eccentric anomaly, *E,* is measured from the perigee point in the direction of travel of the satellite to the line joining the center of the ellipse to the intersection point. The mean anomaly, *M,* of a body for a given position and time is the angular position subtended by a fictitious body traveling for the same amount of time on a circular orbit which possesses the same period as the original body's elliptical orbit constant rate. The mean anomaly and eccentric anomaly are related through Kepler's equation:

$$M = E - e\sin E \tag{9.13}$$

Since Kepler's equation is transcendental, the determination of the orbital position for a given time cannot be expressed in a finite number of terms. Since the mean anomaly is a linear function of time, if the time elapsed since pericenter passage of the body is known, the eccentric anomaly can be calculated through

Figure 9.6 | Orbital anomalies for elliptic motion.



iterative methods. Hence, the corresponding radial distance, r, and true anomaly, f, can be calculated from Equation (9.14) and Equation (9.15).

$$r = a(1 - e\cos E) \tag{9.14}$$

$$\tan\frac{f}{2} = \sqrt{\frac{1+e}{1-e}}\tan\frac{E}{2} \tag{9.15}$$

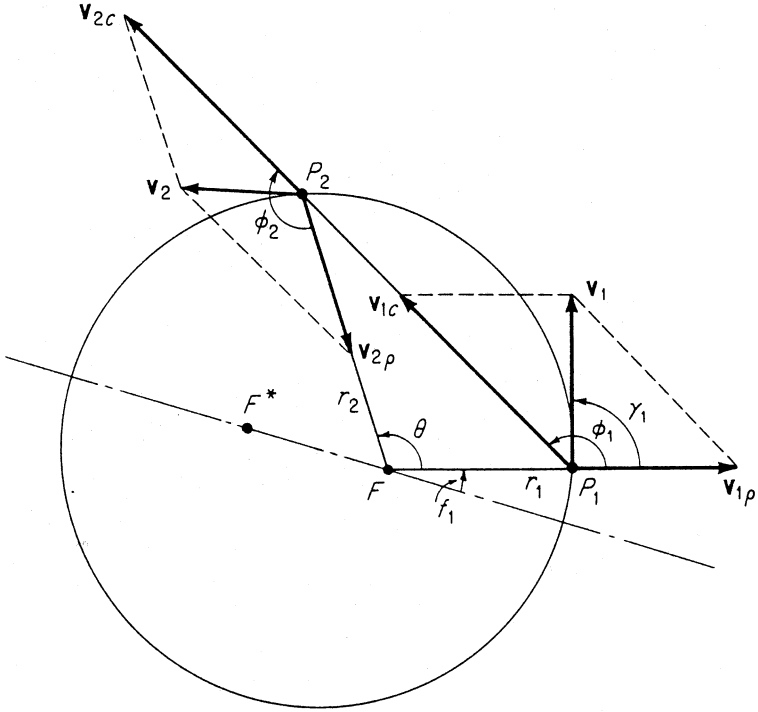
9.4.3 Orbital Velocities Solving the Boundary-Value Problem

Among the many surprising properties of conic sections is the lack of dependence on eccentricity for certain of the key orbital equations. For example, it would scarcely be anticipated that the period of elliptic motion depends only on the semimajor axis of the ellipse. The fact that a body moving in a conic orbit has a velocity magnitude, or speed, that is a function of only the distance from the center of force and the semimajor axis is another example.

Perhaps the most remarkable theorem in this connection is the one discovered by Lambert having to do with the time required to traverse an elliptic arc. Lambert conjectured that the orbital transfer time depends only upon the semimajor axis, the sum of the distances of the initial and final points of the arc from the occupied focus of the ellipse, and the length of the chord joining these points.

Consider two position vectors $\boldsymbol{r}_1$ and $\boldsymbol{r}_2$ that locate a satellite (or any planetary body) in its elliptical orbit at two distinct times t_1 and t_2. The angle between these two positions, which is simply the difference in the true anomaly between the positions at t_1 and t_2, is called the transfer angle, θ. The straight line connecting these two positions is called the chord c. If $\boldsymbol{v}_1$ and $\boldsymbol{v}_2$ are the velocity vectors for the elliptical orbit connecting the two position vectors, a magnificent result occurs if a change of coordinate system is employed. When the terminal velocity vectors $\boldsymbol{v}_1$ and $\boldsymbol{v}_2$ are resolved into components parallel to the chord connecting the endpoints and parallel to their respective radius vectors (that is, $\boldsymbol{v}_2$ is resolved parallel to c and to $\boldsymbol{r}_2$), the magnitudes of components of the velocity vectors along these skewed axes at the two terminal points are, respectively, equal. This means that the chordal and radial components of the terminal velocities of any given position vectors are always equal (see Figure 9.7).

Figure 9.7 | Orbital terminal velocity vectors.



Hence, for any given transfer orbit, the velocities can be calculated graphically if the initial radius vector, final radius vector, and transfer angle are known.

9.5 | GAUSS' METHOD FOR CALCULATING ORBITAL ELEMENTS

9.5.1 Lagrange's Time-of-Flight Equations

As discussed above, Lambert's theorem provides insight into the time to traverse an elliptic arc depending only upon the semimajor axis, the sum of the distances of the initial and final points of the arc from the occupied focus of the ellipse, and the length of the chord joining these points. Gauss went on to use this idea to create his famous algorithm to solve the boundary-value problem, given the initial and final locations of an orbit and the time taken to traverse the orbit.

9.5.2 Formulation of Gauss' Iterative Algorithm for the Boundary-Value Problem

Note that this section is only for the edification of the reader and is not meant to be investigated in depth; and it is presented quid pro quo with no mathematical derivation. It serves to explain the computer algorithm used in the accompanying spreadsheet for calculating orbital elements, and as an example. Calculations of this type are typically reserved for advanced undergraduate or graduate courses in orbital mechanics and references [67]–[73] are recommended.

In his *Theoria Motus,* Gauss gave an extremely efficient technique for solving Kepler's equation of orbit for near-parabolic orbits. Given the initial and final radius vectors of an orbit r_1 and r_2, the transfer angle θ, and the time of flight $t_2 - t_1$, the orbit of the satellite can be uniquely determined. These four pieces of information are sufficient to determine the semimajor axis, parameter, and eccentricity of the orbit. The mechanics of the mathematics of this algorithm are outlined below.

1. Given r_1 and r_2, the transfer angle θ, and the time of flight $t_2 - t_1$,

2. Compute

$$l = \frac{r_1 + r_2}{4\sqrt{r_1 r_2}\cos(\theta/2)} - \frac{1}{2} \tag{9.16}$$

$$m^2 = \frac{\mu(t_2 - t_1)^2}{[2\sqrt{r_1 r_2}\cos(\theta/2)]^3} \tag{9.17}$$

where μ is Gauss' universal gravitational constant and is given by

$$\mu = G(m_1 + m_2)$$

3. Initialize $x = 0$.

4. Calculate

$$\xi(x) = \cfrac{\frac{2}{35}x^2}{1 + \frac{2}{35}x - \cfrac{\frac{40}{63}x}{1 - \cfrac{\frac{4}{99}x}{1 - \cfrac{\frac{70}{143}x}{1 - \cfrac{\frac{18}{195}x}{1 - \cfrac{\frac{108}{255}x}{1 - \dots}}}}}} \tag{9.18}$$

and

$$h = \frac{m^2}{\frac{5}{6} + l + \xi(x)} \quad [9.19]$$

5. Solve the cubic:

$$y^3 - y^2 - hy - \frac{h}{9} = 0 \quad [9.20]$$

6. Determine the new

$$x = \frac{m^2}{y^2} - l \quad [9.21]$$

and repeat steps 4, 5, and 6 until x no longer changes from iteration to iteration.

7. Calculate the orbital elements:

$$\frac{1}{a} = \frac{8r_1 r_2 y^2 x(1 - x)(1 + \cos\theta)}{\mu(t_2 - t_1)^2} \quad [9.22]$$

$$p = \frac{r_1^2 r_2^2 y^2 \sin^2\theta}{\mu(t_2 - t_1)^2} \quad [9.23]$$

Note that e can be calculated from the relationship between p and a.

Utilizing this algorithm, the orbital elements of any orbit can be calculated iteratively. A fun and practical application is to perform the Mars Pathfinder simulation, which calculates the orbital trajectory of the Pathfinder robotic mission and graphs it, based on the departure and arrival dates of the mission. Using the provided orbital mechanics simulation software, you can calculate the orbital trajectories between any of the nine planets on any given day you choose. All the orbital parameters discussed in this chapter are provided. Specifically, the semimajor axis, eccentricity, parameter, semiminor axis, time of flight, transfer angle, longitude of the ascending node, argument of pericenter, angle of inclination, true anomaly, eccentric anomaly, and mean anomaly at launch and arrival are calculated in the orbital mechanics spreadsheet program included on the CD-ROM.

Orbit.xls

9.6 | ADDITIONAL LINKS

In addition to the enclosed orbital mechanics program there are numerous other exciting educational materials available. To explore the orbits of current satellites, the space station, and NASA space science experiments (e.g., Hubble Space Telescope, Gamma Ray Observatory, etc.), the OrbiTrack computer simulation program [74] is recommended, which you can access over the Web. Are you interested to know when the Hubble Space Telescope (HST) will pass over your hometown? With OrbiTrack you find that the HST was on an orbital trajectory over Kennedy Space Center in Florida in the early afternoon on 13 December 2001, or that the Seasat satellite with an apogee of 761 km, perigee of 761 km, and a period of 100 minutes was illuminated over Boston at 5:30 PM on New Year's Eve 2001. You can track more than 1,500 stars and 50 satellites from 150 locations around the world. For all you space simulator aficionados, a book by Nick Dargahi is recommended, specifically Chapter 6, "Understanding Two-Body Orbital Mechanics" [75]. Using this chapter on orbital mechanics and the book just mentioned, you will undoubtedly bring your Space Simulator proficiency to new heights.

9.7 | SUMMARY

There have been many people involved in the development of orbital mechanics with studies dating back to 1650 B.C. Very early on, it was postulated that the universe was geocentric. Aristarchus first proposed a heliocentric universe in 300 B.C.; however, this idea was dismissed at that time. Hipparchus was the next to put forth a major contribution to orbital mechanics by introducing epicyclical motion of the planets in the second century A.D. Ptolemy made this the principal method for predicting the motion of planets. In the Middle Ages, Pythagoras and Aristotle proposed that the Earth was spherical, which again was dismissed due to the beliefs of that time. Nasir ad-Din at-Tusi was among the first to apply mechanical principles to Ptolemy's models. Copernicus reintroduced the theory of a heliocentric universe, which met with resistance. However, this theory accounted for many of the natural phenomena observed every day. Brahe recorded very precise measurement of the planets with his enormous protractor. Using Brahe's measurements and the theory of Copernicus, Kepler was able to formulate his three laws.

Kepler's Laws

1. Planets describe an elliptic path around their centers of attraction.
2. In equal times, equal areas are swept out by the radius vector of a planet.
3. The square of the period of a planet about a center of attraction is proportional to the cube of the planet's semimajor axis.

Newton recognized the inverse square law as the key to celestial mechanics and was able to formalize his *Law of Gravitation:*

> Every particle in the universe attracts every other particle with the force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centers.

Two-Body Boundary-Value Problem

All two-body orbits are conic sections. The eccentricity of the orbit determines the shape of the orbit.

$$e = 0 \rightarrow \text{circle}$$
$$e < 1 \rightarrow \text{ellipse}$$
$$e = 1 \rightarrow \text{parabola}$$
$$e > 1 \rightarrow \text{hyperbola}$$

The three important properties of an ellipse are the focus-directrix, focal radii, and orbital tangents properties. There are several key parameters to remember for an elliptic orbit.

a—Semimajor axis: one-half the length of the major axis

b—Semiminor axis: one-half the length of the minor axis

h—Massless angular momentum: magnitude of radius crossed with velocity

μ—Gravitational constant multiplied by the sum of the two masses

p—Parameter defined as h squared divided by m

e—Eccentricity determines the shape of the orbit

Perigee—The point on the orbit that has a minimum distance measured from the focus (refers to the Earth as the center of attraction)

Apogee—The point on the orbit that has a maximum distance measured from the focus (refers to the Earth as the center of attraction)

f—True anomaly, angular position of planet referenced to perigee

Ω—Longitude of the ascending node: angular position of line of intersection of orbits

ω—Argument of pericenter: angle between eccentricity vector and the ascending node

ι (i)—Angle of inclination: angle that orbital plane is inclined to ecliptic plane

E—Eccentric anomaly

M—Mean anomaly

PROBLEMS

9.1 You are a journalist for the *World Times*. You have the unique opportunity to write an article about a scientific debate among the world's greatest scientists. Ptolemy and Copernicus present their theories on the geocentric versus heliocentric universe, respectively.

(a) Explain the positions of both scientists. Be critical of both Ptolemy's and Copernicus' theories; examine the accuracy and inaccuracy of each.

(b) Explain the ramifications of Copernicus' heliocentric theory on the church. Discuss how the church, at that time, affected science both positively and negatively by providing one example of each.

9.2 Are Kepler and Newton's laws applicable to orbital mechanics despite the fact that they were formulated significantly prior to human space exploration? Why or why not?

9.3 Kepler's law states that the square of the period of a planet about a center of attraction is proportional to the cube of the planet's semimajor axis. Recall Equation (9.1), $\tau^2 = ka^3$.

Obtain the planetary orbital elements for the nine planets in our solar system, and compute this constant k for each planet. Provide a table of your results, including (for each planet) semimajor axis, period, and k. Are the k values the same? Is the k value for Pluto consistent with the others? If not, why not?

Hint: You may want to do a Web search for "solar system" or similar and find a reliable source; or look at ssd.jpl.nasa.gov. Use data that have at least five significant figures. A spreadsheet program might also useful to perform repeated calculations.

Optional: Can you think of any reasons why the value of k changes as a function of the mean semimajor axis? Is the mass of the planet important? Qualitative explanations are fine.

9.4 For an elliptical orbit, the point of closest approach to the central body is called the periapsis, and the point of greatest distance from the central body is called the apoapsis. For Earth, the equivalent terms are perigee and apogee. Using Figure 9.6 as a reference, derive expressions for the periapsis radius r_p and the apoapsis radius r_a. Check that Equation (9.12) for the radial distance reduces to your equations for the correct values of true anomaly.

9.5 A satellite in orbit around the Earth has a mean anomaly of $M = 300°$.

(a) What is the eccentric anomaly E if the orbital eccentricity is $e = 0.3$? *Hint:* Do not try to solve for E directly from Equation (9.13); try computing it iteratively using $E_{k+1} = M + e \sin E_k$ and starting out with a good guess for E_k. What happens if you change your initial guess?

(b) The satellite also has periapsis (see Problem 9.4) radius $r_p = 14{,}000$ km. What is the current radial distance of the satellite?

9.6 The Pathfinder mission along with the Sojourner rover launched on December 4, 1996, and arrived on Mars on July 4, 1997. The radial distance of Earth from the Sun at launch was $r = 0.9855382820$ au, and the radial distance of Mars from the Sun at arrival was $r = 1.5564080490$ au. The spacecraft traveled through an angle of $\theta = 2.709837684$ rad about the Sun during the journey [67]. Answer the following questions, using the provided numerical spreadsheet (Orbits.xls).

(a) Compute the semimajor axis and parameter of the Pathfinder orbit, using Gauss' time-of-flight method (using the provided spreadsheet Orbits.xls). Note that the method presented in the chapter is valid only for transfer angles $< \pi$ rad.

(b) How quickly does Gauss' algorithm converge on a stable answer? Specify the approximate rate of convergence in terms of number of decimal places converging per iteration.

(c) How does your answer for the semimajor axis compare to the official NASA Jet Propulsion Laboratory (JPL) value of $a = 1.29157162792$ au? If they are different, can you give a reason why? (*Hint:* Think about the time of flight you used.)

Gauss' algorithm is very efficient, but there are more efficient algorithms. Professor Richard Battin at M.I.T. developed an algorithm for computing the parameter and semimajor axis that has two improvements over the Gauss algorithm. While the Gauss algorithm fails to work for certain transfer angles, the Battin algorithm converges for all possible transfer angles. (*Optional:* Find a transfer angle for which Gauss' algorithm fails to converge.) In addition, the Battin algorithm converges even faster than Gauss' algorithm.

(d) Compute the semimajor axis and parameter of the Pathfinder orbit, using Battin's time-of-flight method. How do they compare to the values computed using Gauss' method?

(e) How quickly does the Battin algorithm converge? How much faster is the convergence of the Battin algorithm than the Gauss algorithm?

9.7 Explain the difference between the sidereal period and synodic period. This distinction is not covered in the chapter, but can easily be found on the Web. One good resource is the *Encyclopaedia Britannica* that can be found at www.britannica.com/. Draw a picture to illustrate the difference, and explain which one might be more useful in orbital mechanics calculations.

9.8 Imagine that you are coasting along in your personal spacecraft on a slightly elliptical orbit around a perfectly spherical, uniform-density planet (i.e., the planet can be treated as a point mass). If your friend (in his/her personal spacecraft) is also on the same orbit as you, but is about one-eighth orbit ahead of you, what will you see if you look at your friend while orbiting? Describe what happens to the distance between you and your friend as a function of time. Also describe what you would see if you continually looked along your velocity vector (i.e., along the tangent to your orbit). (*Hint:* Try to draw some simple pictures.)

10 Chapter

Satellite Systems Engineering

Cory R. A. Hallam and Dava J. Newman

10.1 | INTRODUCTION TO SATELLITES

10.1.1 Designing Satellites

Satellite design, construction, testing, and operation are integrative engineering processes because many disciplines are required to interact to ensure mission success. It is an application of the concurrent design process mentioned in Section 12.2, "The Design Process." Most often, the optimal satellite design is a negotiated trade of subsystem performance capabilities (weight, power required, data transfer rates, heating/cooling, etc.). Space system designs can reflect a "whole" that is greater than the "sum of its parts" in terms of overall mission capability if attentive systems engineering is embraced. The primary physical design constraint for any satellite is the total mass of the system, as this cannot exceed the orbit injection capabilities of the launch vehicle. As such, many performance metrics are measured in terms of performance per unit mass, which in turn can be converted to a per unit cost metric.

10.1.2 Satellite Missions

Satellites provide humans with the ability to send electronic and mechanical equipment beyond the confines of Earth's atmosphere. We define a satellite in general terms to be any human-made craft or vehicle in a space orbit. In space exploration, this permits the study of distant celestial bodies such as the planets of the solar system (as visited by many satellites, beginning in 1977 with the Voyager series). In Earth orbit, satellites provide humans with one key benefit—altitude. The use of a satellite's altitude is the primary reason we place satellites into Earth orbit, thereby gaining a wide view of Earth. Satellite missions serve many purposes, but can generally be divided into four main categories:

- Scientific
- Military and national security
- Civil
- Commercial

Scientific Scientific missions are initiated with the intent to discover. They are typically government-funded missions assembled and operated by consortia from universities, industry, and national space administrations. The primary role of these missions is to provide answers to questions; for example, the Lunar Prospector mission's primary function was to determine if there was ice on the lunar polar caps. (Yes, there is!) See Section 10.2, "An Operational Satellite System," for details on the Lunar Prospector science mission [76–78].

Military and National Security Military and national security missions are conducted with the intent to protect, monitor, and learn about world situations pertinent to the security of a nation. These missions involve early-warning satellites, communications satellites, and reconnaissance satellites that are used to learn about what is occurring in other countries, such as weapons stockpiling and troop movements. This information is captured as visual imagery or intercepted communications. Once analyzed, the data are used to warn the communities that are affected by the situation, to plan countermeasures, and to document the events for publicity to the world at large.

Civil Civil satellites have the primary function of supporting the well-being of humans, either directly or indirectly. These satellites are usually government-funded, and they provide information that is critical for helping society. National weather satellites fall into this category, where government-funded satellites monitor the Earth's weather and provide up-to-date information to weather bureaus around the country. This service allows meteorologists to monitor and disseminate weather information that can be vital for emergencies, such as approaching hurricanes, or equally vital for farmers who need to be warned of flooding or frosts that may damage crops. In the United States, weather satellites are operated for the National Oceanic and Atmospheric Administration [79].

Commercial In recent years commercial satellites have become the major source of satellite activity, with telecommunications satellites dominating the market. Commercial satellites are ordered by companies who wish to offer a service for a fee. In the case of a telecommunications satellite, a service provider orders a satellite that is capable of routing a given amount of information at a predetermined rate. For example, current commercial capabilities for satellite data routing are on the order of 1 to 3.2 gigabits per second (Gbps) and entail a process known as trunking–uplink–downlink [80]. Data are routed through ground lines (called *trunking*), to a major switch and transmitter that pack and then send the information to the satellite (*uplink*), which then transmits the information down to another switch elsewhere in the world (*downlink*), and then data are sent via terrestrial lines to the end destination. The advent of low earth orbit (LEO) and medium earth orbit (MEO) communication constellations aimed at providing global coverage for handsets that communicate directly via satellites, to omit the trunking activity, thus providing point-to-point communication capabilities virtually anywhere on Earth with a single telephone number.

10.2 | AN OPERATIONAL SATELLITE SYSTEM

Once it is launched and placed into an orbit, there are several necessary interactive components for operating a satellite mission. The five main system components include the

- Satellite.
- Ground station.
- Command and control center.
- Data storage center.
- Data analysis and distribution center.

In some instances, the latter four components are contained in one facility. The ground station is used to receive data from the satellite and to transmit data to the satellite. The downlink provides data on the "health" of the satellite, or how well its subsystems are operating, and the mission data that are collected from the onboard payload (see Section 10.3, "Elements of a Satellite," for payload details). The uplink provides ground controllers with the capability to send command information to the satellite to perform certain functions such as orbit changes, equipment resets, or even modification of the onboard control software. In the case of telecommunications satellites, the payload is essentially a large number of receivers and transmitters that receive and retransmit data as their sole function, continuously uplinking and downlinking data.

The command and control center is the center for satellite operations. The downlinked operational information is reviewed and analyzed in this center, and consequently decisions are made about any necessary changes to the satellite's operational parameters (i.e., orbit, inclination). Likewise, some satellites have multiple missions that require several changes in orbit and operational configuration throughout their lifetimes. In both cases, the command and control center issues uplink commands to make necessary changes.

The data storage center is the main storehouse of downlinked information. This usually constitutes some form of electronic mass-data storage medium that is a repository for the health data of the satellite and the unprocessed payload data (essentially streams of bits) generated by payloads (i.e., imagery, measurements). Over time, the data storage has progressed from print and magnetic-tape systems to more advanced optical drive and optical tape storage devices. If one considers a satellite with a sensor that takes 8 bit data (a number between 1 and 255), sampling at a rate of 10 Hz (10 times per second) for 1 year, you acquire approximately 2.5 Gbits of data, as you can see:

$$\frac{8 \text{ bits}}{\text{sample}} \cdot \frac{10 \text{ samples}}{\text{s}} \cdot \frac{3{,}600 \text{ s}}{\text{day}} \cdot \frac{24 \text{ h}}{\text{day}} \cdot \frac{365 \text{ days}}{\text{y}} = 2.5 \times 10^9 \text{ bits}$$

If you decide to use high-resolution 32 bit data and create an array of 100 sensors, this number increases to 1 terabit (Tbit) (10^{12} bits) of stored information every year!

The data analysis and distribution center is responsible for processing the raw downlinked data into some form of interpretable information. In the case of many remote-sensing satellites, high-spatial-resolution data ($<$ 10 m resolution) are converted to images used for city or regional planning. The final images are then digitally archived, allowing the original raw data to be destroyed. However, in the case of some scientific missions, the raw data are kept for many years to allow multiple researchers to investigate the information. This places a significant requirement on the type of storage medium used in the data storage centers, especially as some forms of data storage are prone to time-induced data loss (i.e., magnetic tapes that can demagnetize over time) and media storage technologies are likely to significantly change about 10 times during a 20 year archival span. As a result, the data may be well archived, but the means to access them will no longer exist.

All the above satellite system components, with the exception of the satellite itself, can be contained in one facility. If the amount of data being collected is small enough, as with a small university satellite, most of the communication, command, control, data storage, and data processing can be handled with personal computers. For larger telecommunications systems, some of the functions are distributed across local networks, or even internationally when the resources of several entities are needed.

Interactive examples and real-time Lunar Prospector Data Visualization, (~2 s) after Mission Control. Explore the models in NASA's visualization website [76]–[78].

An Example: The Lunar Prospector Operational Satellite System The evidence for ice has been found on the Moon! The Lunar Prospector satellite is an excellent example of a successful scientific mission. Sample scientific data and three-dimensional models and maps are available from NASA.

10.3 | ELEMENTS OF A SATELLITE

There are three main elements of any satellite: the payload, the bus, and the launch vehicle adapter assembly. The payload is defined as the equipment that performs the satellite mission function. For example, a telecommunication satellite's payload would be defined as the equipment that receives, processes, and transmits communication data. The satellite bus is defined as the systems and structure within the satellite, which provide functions to allow the payload to perform its intended mission. This includes providing power, thermal protection, stability, and orbital control so the payload performs within its design limits. The launch vehicle adapter assembly acts as the interface between the satellite bus and the launch vehicle that boosts the satellite into orbit. The adapter assembly is typically custom-designed for individual types of satellites. The launch vehicle provider issues a payload interface document describing how and where the satellite can be attached to the launch vehicle. Some launch vehicle companies retain design ownership of the adapter assembly.

The satellite designer plans according to three budgets: the mass budget, the power budget, and the cost budget. The mass budget is the primary concern, since the satellite can only be launched by existing launch vehicles, all of which have a limit on the amount of mass they can place into orbit. The power budget is the next most important, as power is required to maintain and operate the satellite once on orbit. Finally, the satellite cost budget must be maintained. A good satellite design meets all three budgetary requirements [81].

10.4 | SATELLITE BUS SUBSYSTEMS

There are two design philosophies used in satellite configuration and design, namely, spin-stabilized satellites and 3-axis stabilized satellites. The former uses the angular momentum of the rotating satellite to maintain stability and control, while the latter maintains a stable platform using large momentum wheels and onboard thrusters for stability and control.

A satellite bus is typically composed of the following subsystems that all interact to ensure the mission payload operates successfully [82]:

Satellite.gif, Satellite2.gif

Online resource.

- Structures and mechanisms.
- Power.
- Communications and Telemetry.
- Thermal control.
- Attitude determination and control.
- Propulsion and station keeping.

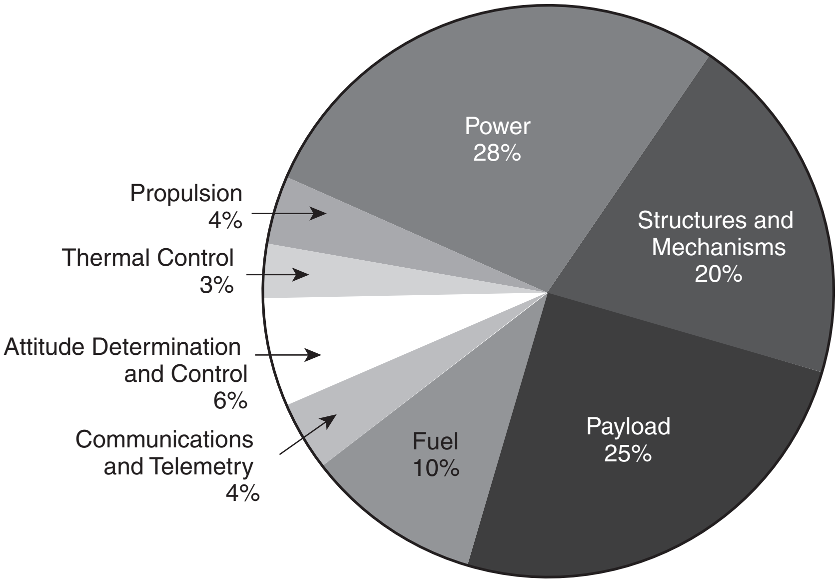
As a first-order estimate, a satellite's total weight can be represented by the percentages shown in Figure 10.1, based on historical data of 15 satellites [41].

The satellite structure provides the main components to which all subsystem and payload components are attached. The various structures must be strong enough to withstand launch forces, be of minimal mass, and provide damping to avoid structural oscillations while in orbit.

The power subsystem is the energy source of the satellite. It is usually composed of two energy systems, namely, a short-term energy system and a long-term energy system. The short-term energy system is used for prelaunch and initial orbit acquisition activities, while the long-term energy system functions throughout the satellite's operational life.

The communications and telemetry subsystem orchestrates the flow of data between onboard subsystem components and between the satellite and the ground station. This subsystem is typically composed of the communications portion, and the telemetry, tracking, and control (TT&C) portion. For the purposes of simplicity, we discuss them as a single subsystem. The communications and telemetry subsystem handles data flow between all the satellite subsystems,

Figure 10.1 | Satellite mass as represented by percentage of the overall design [41].



reports operational status, sends payload data to the ground station, and receives uplinked commands from ground controllers.

The thermal control subsystem is responsible for maintaining the components of the satellite within operational temperature limits. This can be accomplished via passive methods, such as reflection and radiation, or active methods that involve on-board heat exchangers and mechanically activated deflectors. The lack of convective cooling in space, due to a lack of atmosphere, makes the thermal control task a challenge for high-power satellites.

The attitude determination and control subsystem (ADCS) maintains the pointing accuracy of the satellite by controlling the motion of the satellite in any of the pitch, roll, or yaw axes. The required orbital pointing accuracy is primarily determined by the mission requirements of the payload, but may be influenced by the type of antenna used in the satellite design. Both active and passive attitude controls are available, and sometimes a combination of both is implemented.

The propulsion and station-keeping subsystem functions to keep the satellite in its intended orbit. It can also perform desired orbital changes as dictated by the mission. The subsystem is usually composed of thrusters and a source of fuel and oxidizer, or liquefied gas, whose limited volume usually determines the duration of the mission. Although the electrical systems of a satellite may continue to function long after the station-keeping fuel has run out, the mission will most likely be unable to continue due to the subsequent orbit degradation and loss of satellite control.

The six satellite subsystems are described in greater detail in the following sections.

10.4.1 Structures, Mechanisms, and Materials

Satellite structures act to support all the spacecraft subsystem components and provide a means for attaching the satellite to the launch vehicle. The design of the structures must meet the strength and stiffness requirements necessary to survive the launch environment and on-orbit operational environment. The launch environment is characterized by

- High linear accelerations due to the vehicle acceleration (3 to 12 G's sustained).
- Shocks from stage separations and stage firings (2,000 G's).
- Acoustically induced vibration from engine sound pressure waves reflecting off the launch pad structure (140 dB at 0 to 20,000 Hz).
- High-energy structural vibrations from any of the above sources that excite the natural frequency of structural members in the launch vehicle and are transmitted to the satellite being launched.

The launch loads require structures to be sized and designed to avoid structural failure. The on-orbit loads are much smaller than the launch loads, but are equally important since structural stiffness is typically needed to ensure normal satellite operations. Highly flexible structures that do not dampen vibrations are not conducive to high pointing accuracy for satellite payloads. On-orbit loads are created by

- Internal motion of momentum wheels and gyroscopes.
- Attitude control adjustments.
- Mechanism deployment (i.e., solar arrays).
- Thermal stresses.

Ultimately the satellite cannot be heavier than the capability of the launch vehicle that boosts it into orbit. The result of this constraint is that satellite structural design comes down to a trade between mass and cost—the designer wants to use the lightest materials possible. This allows for more fuel or a larger satellite payload to be placed in orbit, or a smaller launch vehicle to be used. However, many light materials are more expensive to use in designing and manufacturing a satellite (i.e., composites), resulting in the elimination of the cost savings gained by using the lighter materials.

Primary structures carry the major loads on a satellite and are considered *mission-critical* (i.e., they cannot be allowed to fail). Secondary structures have non-mission-critical roles of supporting small components ($<$ 5 kg) whose failure will not necessarily lead to the failure of the entire satellite or mission. Structural designers normally use a factor of safety of 1.5 times the yield stress of the material as a design limit. The yield stress is the stress level that causes permanent deformation of a material. This translates to a factor of safety of about 2 on the ultimate stress. The ultimate stress is the stress level that causes the material to break, fracture, or tear apart catastrophically. To minimize mass, some secondary structures are designed with a lower safety factor, as deformation of the secondary structure will not cause a mission failure.

When choosing materials for structures, one must be wary of the space environment. Historically, aluminum has been the design material of choice for satellite structures—it is lightweight, can be alloyed and heat-treated for stiffness, is relatively nonreactive (chemically), is readily available, is cheap, and is easy to work with. Composite materials might offer greater stiffness with a lighter mass, but they are more costly and suffer from material degradation in space caused by the outgassing of trapped gases in the matrix materials. Additionally, composites are poor thermal conductors and do not facilitate heat dissipation from on-board electronics.

Materials used for insulating and plating satellite components can also suffer degradation in the space environment. For example, cadmium plating tends to migrate to cold surfaces, which can be detrimental to infrared camera lenses that operate at extremely low temperatures. Atomic oxygen, a highly reactive radical, exists at altitudes up to 800 km. Atomic oxygen erodes many polymers, such as Kapton multilayer insulation (MLI), a popular thermal insulating material in spacecraft.

As satellite designs progress in the future, the trend will be toward materials of high specific stiffness and specific strength that meet the cost and longevity requirements associated with satellite mission requirements.

10.4.2 Power Systems

A satellite's power system performs three main functions. It must provide/produce energy; store energy; and regulate, distribute, and control power flow. Early spacecraft carried battery packs that would provide low voltage for a matter of hours or days, after which the satellite would be inoperable. It was quickly realized that for any long-term use of satellites, on-orbit energy production would be needed. The result was two design philosophies: solar photovoltaic cells and nuclear isotopes.

Solar cells can provide energy conversion efficiencies of 14 percent (silicon) to 18 percent (gallium arsenide) of the local radiant solar power. For Earth orbit, with an average solar flux of 1,358 W/m^2, this translates to 190 to 240 W/m^2, of solar panel under direct solar light (i.e., perpendicular to the sun's incident radiation). However, as satellites travel deeper into the solar system, the available solar energy flux decreases with the square of the distance from the Sun, resulting in insufficient energy density to power satellites. For these missions, nuclear isotope-based energy sources are used.

Power is described as being available from two sources, primary sources and secondary sources. Primary sources provide energy for the duration of the mission (i.e., solar cells for Earth orbit). Secondary power sources are used for short-duration power requirements, such as from the time a satellite is launched until the solar panels are deployed and operational. Secondary power sources usually consist of some form of battery.

The spacecraft designer must keep a power budget of all onboard systems. This sets the preliminary size of the power system. For solar panels, the end-of-life efficiency of the cells must be used in the calculation, since the efficiency of the cells decreases several percent over a 5 to 10 year period in orbit. For silicon solar cells this results in a power production decrease of between 2.5 and 3.5 percent per year [41]. Additionally, a power margin must be built in since there can be peak loads that need to be covered above and beyond nominal loads. Some of this peak loading can be provided by batteries that are charged by the panels during off-peak periods. These batteries will eventually be needed to supply all the power during periods of eclipse for solar-powered satellites.

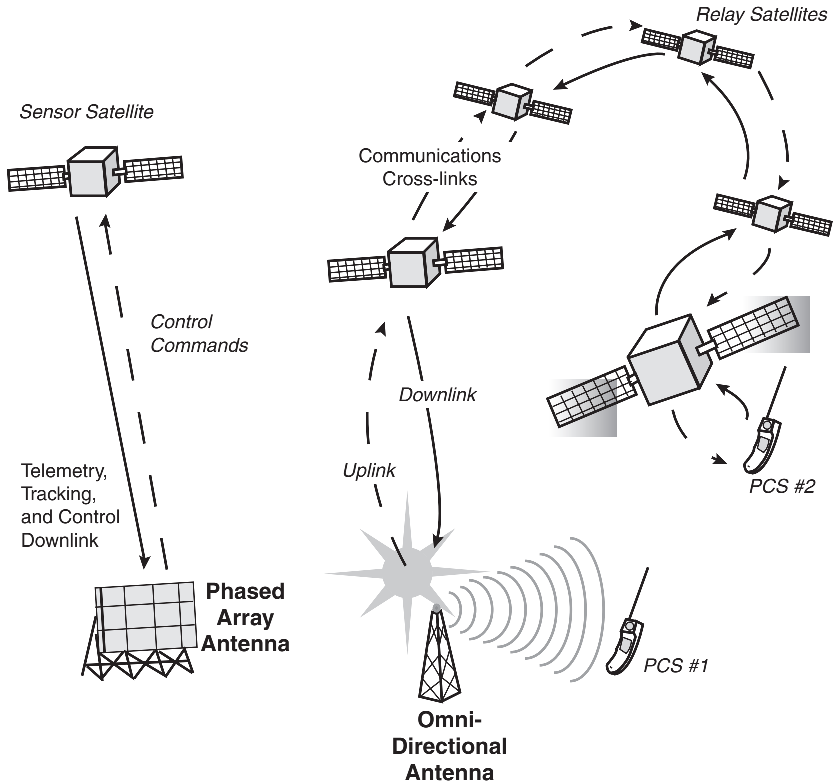
Having done the preliminary sizing of the power system, the designer then updates the weight and inertial characteristics of the satellite, which will then impact the ADCS, which may then require larger actuators and hence more power. Thus the iterative design process continues until a balance of all subsystem requirements can be met. In the case of a telecommunications satellite, this is a trade-intensive process since the size of antenna (i.e., larger = less transmission power needed) is traded against the size of the solar arrays (i.e., larger = more power produced for transmitting more channels), both of which are constrained by the capability of the launch vehicle (i.e., you cannot launch more than your rocket can carry). This trade process has become extremely iterative and integrative as satellites have gone from hundreds of watts of power to current telecommunications satellites that operate at 15 kW. For the near future, deep space missions will still rely on nuclear isotope power sources, while Earth-orbiting satellites will use solar panels.

10.4.3 Communication and Telemetry

The operation of a satellite requires knowing a satellite's location in space (tracking), the health of the onboard subsystems and payload (telemetry), and an ability to tell the satellite what to do (control). All these procedures require some form of communication between the satellite and a ground station (see Figure 10.2).

To communicate there must be a transmitter at one end of the link and a receiver at the other. Of great importance to the designer of the communication system is the antenna design since it impacts the weight and power requirements of the satellite. An antenna radiates energy that dissipates as you go farther from the antenna. Everyone has experienced this phenomenon when listening to a radio—it is louder if you sit closer to the speakers and gets quieter as you move away from the speakers. Although the radio is still using the same amount of energy and outputting the same power level, the sound appears louder as you get closer, because the power in the sound waves has only filled a small volume of space. As you move farther away, the volume that the sound fills increases, and this results in a lower power density (watts per square meter) at your new position. The same is true for transmitters and antennas: The power density decreases as you move away from the source. The simplest design is an omnidirectional transmitter or antenna, like you have on a car. This type of transmitter sends signals out in all directions, creating a propagating sphere of energy. The power of the signal at any given point is thus proportional to the inverse of the square of the distance (directly related to the surface area of the sphere).

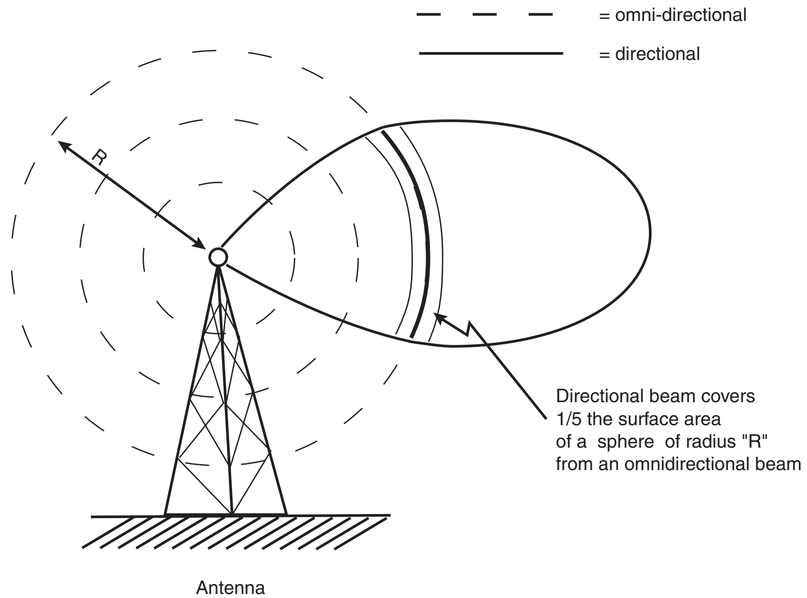
Figure 10.2 | Schematic of communication and telemetry data flow paths showing uplink and downlink.



The antenna requires a signal that is powerful enough to be recognized by the electronics that decode the signal. Thus orbital altitude can be used to determine a preliminary power requirement for sizing the communications system (i.e., set the altitude, determine the minimum signal strength that can be received, and calculate the required power for the satellite transmitter).

Antenna design has moved a long way from the simple omnidirectional antenna. Parabolic dishes and phased-array antennas can direct the communications signal energy and result in all the energy being focused in a given direction (Figure 10.3). This is called gain. Gain is a measure of a transmitter's or antenna's power density compared to an omnidirectional design. For example, in Figure 10.3, the highly directional antenna is able to create a beam whose power is spread over one-fifth the surface area of a sphere at a radius *R*. An omnidirectional design would spread the power over the whole surface at this radius; thus the gain of the directional antenna is 5. The implications of this are twofold. You can transmit a much stronger signal than with an omnidirectional design at a given distance; or you can build a smaller, lighter, and less powerful directional antenna to do the same job as a larger omnidirectional antenna. In its simplest

Figure 10.3 | Propagating waves and proportionality for power density for a directional antenna.



form (ignoring transmission losses and signal attenuation through the atmosphere), the communications link power budget is given by

$$P_{\text{rec}} = P_t G_r G_t \frac{\lambda}{4\pi R} \qquad \textbf{[10.1]}$$

where

P_{rec} = power required at receiver, W
P_t = transmitter power, W
G_r = receiver antenna gain (nondimensional)
G_t = transmitter antenna gain (nondimensional)
λ = wavelength of transmitted signal, m
R = distance between the transmitter and receiver, m

To communicate, the transmitter and antenna must be within view of each other. Communications links between ground stations and satellites use frequencies above 100 MHz to be able to penetrate Earth's ionosphere. Lower frequencies than this are easily attenuated and prevent the completion of a communications link.

Telemetry data are multiplexed into a single stream that contains subsystem information, including component temperatures, bus voltages, battery supplies, and attitude parameters. Synchronization and reference codes are included in the data stream to allow the receiver to sort and report the data to a ground station controller. Data rates for telemetry depend on the number of variables one wishes to monitor. For example, there may be 10 bus voltage sensors that need to transmit a 5 bit value once every second. This would require a rate of 50 bits per second (bps) to accomplish. Combining all the subsystems that need to be monitored, each with varying resolution (i.e., number of bits per measure), telemetry rates can be anywhere from hundreds to millions of bits per second.

Telemetry data streams can typically provide a loop path for a ground signal used for tracking purposes. A typical tracking scheme measures range by sending signals to the satellite and having them returned on the telemetry downlink. The phase shift of the signal then provides the necessary information to calculate the range R of the satellite

$$R = \frac{1}{2}c\tau \tag{10.2}$$

where

c = speed of electromagnetic wave propagation (3×10^8 m/s)

τ = time for signal to travel to satellite and back, s

The satellite control functions are used to tell the satellite what to do (e.g., change orbit, point in a new direction). Based on the telemetry data of all the subsystems and payload, the ground station operators monitor the satellite and determine if operational corrections need to be made. Control transmission rates are typically very low, on the order of hundreds to thousands of bits per second when transmitting.

Satellite payloads often have higher communication rate requirements than telemetry and command, and are thus the driving design parameter for the communication system. For example, an Earth imagery satellite that scans an area of 10,000 km^2 with 5 meter resolution (i.e., 1 pixel sees 25 m^2) in a 2 min time frame needs to transmit at a rate of about 3 Mbps ($3 - 10^6$ bps). Thus a communications bandwidth of at least 3 Mbps is required by the satellite.

The communications frequency bands used on satellites have been developed by the International Telecommunications Union (ITU) and the World Administrative Radio Conference (WARC). In the United States, the Federal Communications Commission (FCC) administers the commercial frequencies, while the Interdepartmental Radio Advisory Committee administers frequencies for military uses. Table 10.1 provides a list of the allocated communication frequency

Table 10.1 | Satellite communication frequency bands (comsat=communications satellite) [41]

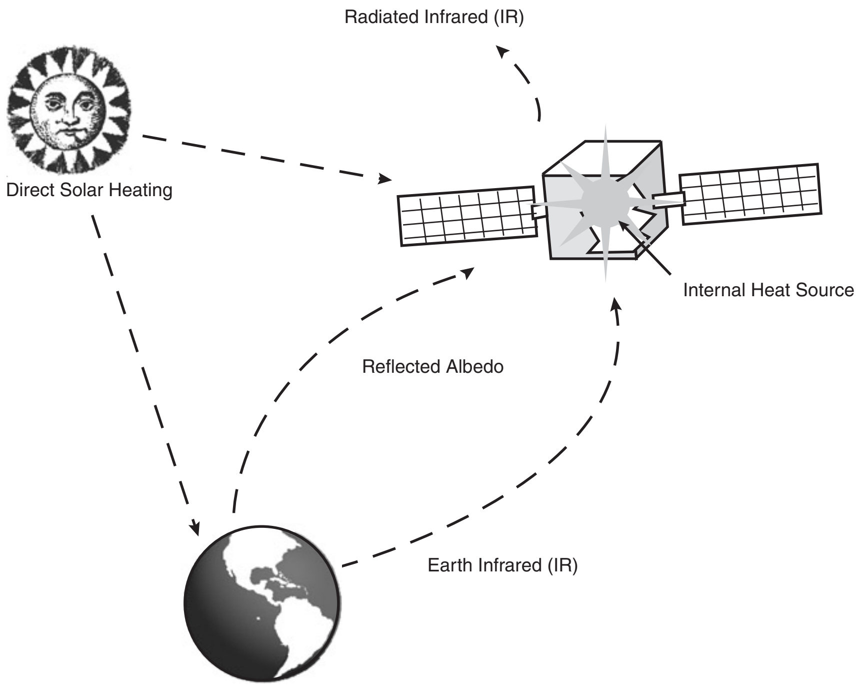
Frequency band	Frequency uplink	Range (Ghz) downlink	User
UHF	0.2–0.45	0.2–0.45	Military
L	1.635–1.66	1.535–1.56	Maritime/navigation
S	2.65–2.69	2.5–2.54	Broadcast
C	5.9–6.4	3.7–4.2	Domestic comsat
X	7.9–8.4	7.25–7.75	Military comsat
Ku	14.0–14.5	12.5–12.75	Domestic comsat
Ka	27.5–31.0	17.7–19.7	Domestic comsat
SHF/EHF	43.5–45.5	19.7–20.7	Military comsat
V	60	60	Satellite crosslink

bands. U.S. commercial satellite operators must apply to the FCC for permission to use frequency bands [41].

10.4.4 Thermal Control

Satellite thermal design is necessary to ensure that onboard satellite components operate within tolerable temperature limits and that structural components not bend beyond acceptable limits or even fail due to thermal stresses. In space, there are four primary heat sources for satellites, as shown in Figure 10.4, including direct solar heating, reflected solar energy from Earth's albedo, Earth's infra-red energy, and onboard sources (i.e., electronics).

Figure 10.4 | The four primary heat sources for satellites: direct solar heating, reflected solar energy from the Earth's albedo, the Earth's infrared energy, and on-board sources.



The only way to dissipate heat from a satellite is by radiating heat away from the satellite, as there is no atmosphere in space for convective cooling. On board the satellite, heat is transported via conduction between elements, heat pipes that use a working fluid, and internal radiation. The thermal designer must utilize arrangements of materials, coatings, and heat conduits on board satellites to maintain the components within their operating limits. In some cases heaters must also be added to maintain temperatures within acceptable limits. An example of temperature ranges to be maintained for satellite components is shown in Table 10.2.

Table 10.2 | Design temperature ranges for satellite components [41]

Satellite component	Temperature range (K)	Temperature range (°C)
Electronics	273–313	0–40
Batteries	278–293	5–20
Solar arrays	173–373	−100–100
Liquid propellant	280–308	7–35
Structural elements	228–338	−45–65
Infrared sensors	73–193	−200–−80

As discussed in Chapter 8, "The Space Environment: An Engineering Perspective," all materials have the ability to absorb, reflect, and emit certain amounts of thermal energy. The absorptivity α and emisivity ε of a surface are the fractions of energy emitted or absorbed compared to a perfect black body. Materials that absorb a large amount of heat are said to have high absorptivity. Likewise, materials that have the ability to radiate a large amount of energy are said to have high emissivity. Examples of material properties used in satellite applications are given in Table 10.3.

Table 10.3 | Selected satellite material emissivities and absorptivities

Material	Emissivity ε	Absorptivity α
Aluminum	0.38	0.035
Gold	0.30	0.023
Titanium	0.77	0.47
White paint	0.25	0.85
Black paint	0.98	0.87
Aluminized Teflon	0.16	0.80

The only practical way to expel heat from a satellite is via radiation. Radiation is a function of the object temperature to the fourth power [84]; and the total emitted, or radiated, power P_{emitted} from a body was given in Equation (8.3) and can be written as

$$P_{\text{emitted}} = A_{\text{rad}} \varepsilon \sigma T^4 \tag{10.3}$$

where

P_{emitted} = total radiated power, W
A_{rad} = surface area of radiator, m^2
ε = emissivity of radiator (no units)
σ = Stefan–Boltzmann constant = 5.669×10^{-8} W/(m$^2 \cdot$ K^4)
T = surface temperature of radiator, K

To design and analyze the thermal control capability of any satellite, the process begins by setting the sum of the heat inputs equal to the sum of the heat outputs and calculating the steady-state temperature. Material properties and component locations must be continuously iterated until overall operating temperatures are met.

EXAMPLE 10.1 MetalSat in Orbit

Combining knowledge gained in Chapter 8 with that gained in this section, you can assume the role of lead thermal designer for a satellite team. There is an aluminum spherical satellite floating in orbit, which we call MetalSat. For this example, we assume no major thermal inputs from onboard electronics, Earth IR, and albedo heat. Considering the thermal environment and input power, propose a valid satellite design.

From Equation (8.3), the power absorbed, or input, from the sun is

$$P_{\text{absorbed}} = \alpha\left(\frac{P_s}{4\pi d^2}\right)\pi r^2$$

where the frontal area of the satellite is πr^2 and the Sun's average energy density in Earth orbit is represented by the solar constant

$$\frac{P_s}{4\pi d^2}$$

which has a peak value of 1,486.33 W/m^2 and an average value of 1,358 W/m^2. The power dissipated, or emitted, was given by Equation (8.4),

$$P_{\text{emitted}} = (\varepsilon\sigma T^4)(4\pi r^2)$$

where the radiating surface area of the spherical satellite is $4\pi r^2$, or A_r. Kirchhoff's law gives the equilibrium temperature, or the steady-state condition. The temperature equation can be written as

$$T = \sqrt[4]{\frac{G_s A_s \alpha}{A_r \sigma \varepsilon}}$$

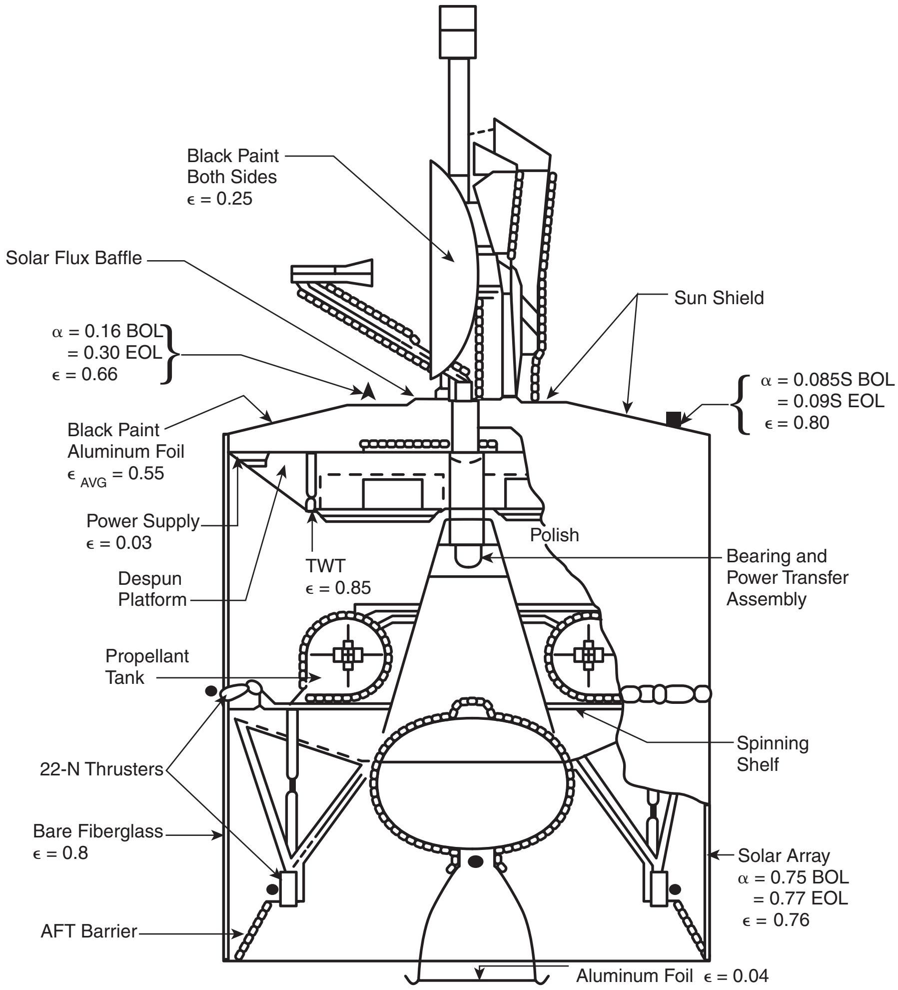
where G_s represents the Sun's average energy density and A_s and A_r are the satellite frontal area and total surface area, respectively, where $A_r = 4A_s$. The equation for satellite temperature simplifies to

$$T = \left(\frac{G_s \alpha}{4\varepsilon\sigma}\right)^{0.25}$$

Using the values in Table 10.3 for aluminum, we have $\alpha = 0.38$ and $\varepsilon = 0.035$. Using these values in the temperature equation, we get a steady-state temperature of 505 K (232°C), which is far too hot for any electronics equipment. We therefore need to select a surface coating that radiates more heat. If we paint our satellite black, we have $\alpha = 0.87$ and $\varepsilon = 0.98$. Calculating, we get a steady-state temperature of 270 K (−3°C), which is approaching the acceptable operating temperature for most onboard equipment.

The task of the thermal design becomes much more difficult as internal heat-dissipating components are added and orbital effects such as eclipse (temporary loss of Sun's thermal input) are experienced by the satellite. The thermal design process comes down to a series of iterations that result in a satellite with many different coatings and surface materials. See Figure 10.5. Finally, the thermal stresses induced by large temperature gradients across structures must be dealt with to ensure there are no structural failures and that thermal bending does not hinder the functionality of the payload.

Figure 10.5 | Representative material selection for satellite components.



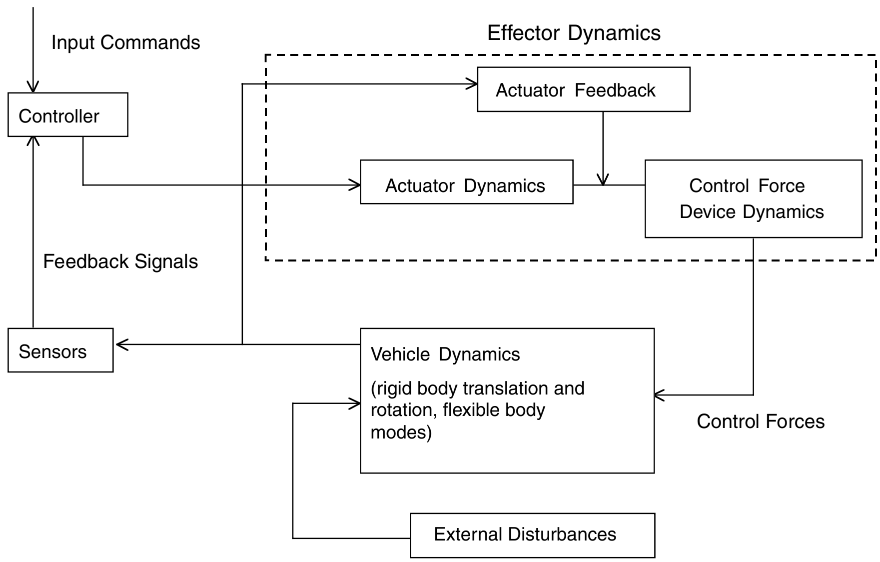
10.4.5 Attitude Determination and Control

Spacecraft are continuously subjected to perturbation torques while in orbit. Onboard torques can be caused by the motion of mechanisms, momentum wheels, or the firing of thrusters. External torques are produced by Earth's gravity gradient, interaction with Earth's magnetic field, solar radiation pressure, thermally induced flexure in satellite structures, and aerodynamic drag in LEO. It is the job of the attitude determination and control subsystem (ADCS) to measure and counter these perturbations to ensure the spacecraft can perform its mission. These adjustments include maintaining orbital position and satellite pointing accuracy.

Orbital position maintenance is quoted in terms of North–South and East–West station keeping. North–South is with respect to latitude, while East–West is with respect to longitude. Station keeping can typically be maintained to within ±0.1° which translates to approximately ±13 km from an altitude of 1,000 km.

The ADCS requires four main elements to function, including a reference from which to take measurements, a sensor, a controller, and an actuator. First, references must be selected for pointing knowledge. Second, a series of sensors observe the references, allowing for determination of position and relative attitude with respect to the reference. Based on the position and attitude, the controller determines the difference between the actual and the desired position and attitude. Using mathematical models of the dynamics of the spacecraft, the controller sends command signals to actuators that act to restore the satellite to its desired position and attitude. The entire control process is shown in Figure 10.6.

Figure 10.6 | Attitude determination and control subsystem block diagram.



Five major references are typically used in satellite design, including the Sun, the Earth, Earth's magnetic field, stars and planets, and inertial sensors (gyroscopes). The Sun is undoubtedly a bright and unambiguous light source. Optical Sun sensors require relatively little power and are lightweight. However, satellites in LEO can lose the Sun reference if eclipsed. Additionally, the Sun only provides measurement about two independent axes. Earth is an excellent reference for Earth-orbiting satellites as it is close and bright. Earth sensors scan to detect the horizon, the boundary between the blackness of space and the brightness of Earth. Earth sensors must be protected from sunlight as they are more sensitive.

The Earth's magnetic field works well for low-altitude missions. The sensors measure alignment of the magnetic field with respect to the satellite-centric coordinate frame. The sensors are low-weight and low-power, but require that the satellite be magnetically clean. The intensity of Earth's magnetic field decreases with the cube of the distance from Earth, and thus becomes very small at geostationary orbits. As such, magnetic sensors work better in lower orbits [85]. Stars and planets (other than the Sun and Earth) are by far the most accurate references, providing pointing reference of up to 0.0008° as measured by star sensors [86]. However, star sensors are heavy, complex sensors that require Sun protection and take periodic readings. The sensor takes a snapshot of its surrounding field of view and matches the image to an electronic database of star maps.

The only satellite-based reference is an inertial measurement unit (IMU). The motion of the satellite can be measured with respect to a stabilized gyroscopic unit carried onboard. These are available for almost any mission; however, the drift of the gyroscope associated with friction losses in the spinning mechanisms results in increasing measurement errors over time. Thus, the IMU needs to be regularly updated (or reset) from other onboard sensors. Although accurate over short periods of time, IMUs require strict manufacturing quality control and may need to be carried in redundant configurations to ensure mission reliability.

There is an expectation from some that the global positioning (satellite) system (GPS) might provide a reliable reference. Currently, experiments are being flown to characterize GPS signal quality in LEO to determine if GPS can be used as a reference for on-orbit satellite position and attitude determination.

Once the satellite's attitude has been determined, the control processor determines the necessary orientation changes that the satellite must make to be within operational tolerances, and sends control commands to actuators to make the orientation changes. These orientation changes are made by thrusters, magnetic torquers, and/or momentum wheels.

Magnetic torquers are simply electromagnets, or wound magnetic coils, that generate a magnetic dipole moment. A magnetic torquer produces a torque that is perpendicular and proportional to Earth's varying magnetic field. A magnetometer is used to sense the magnetic field, and a wire-wrapped metal rod in each axis is used to create a torque on the satellite. At higher orbits (>1,000 km) magnetic torquers become less effective due to the diminishing strength of Earth's magnetic field. Although small, magnetic torquers offer the advantage of no moving parts, no fuel, and relative simplicity of design, integration, and testing.

Reaction wheels are torque motors that have high-inertia rotors. The spinning of the rotor in either direction provides one axis of control for the satellite. (*Note:* For every action there is an equal and opposite reaction; thus, if you spin a high-inertia rotor clockwise, the satellite begins to spin counterclockwise.) Momentum wheels are a class of reaction wheel that maintains a nominal spin rate to provide gyroscopic stiffness to the satellite in two axes, and pointing accuracy in a third axis with the use of a control motor on the wheel to slow it down or speed it up. To control a satellite's orientation about 3 axes, three wheels are required with non-coplanar spin axes. With no means of self-repair for mechanical systems on satellites, redundant wheels are often added to a satellite for reliability. Satellite geometry may ultimately result in the need for a combination of control devices to ensure pointing accuracy and system reliability.

10.4.6 Propulsion and Station Keeping

Once in orbit, the propulsion system provides a satellite with several operational roles, including

- Initial spin-up.
- Station keeping (North–South, East–West).
- Attitude control.
- Satellite orbit change.
- Angular-momentum management.
- Satellite end-of-life (EOL) disposal.

Initial spin-up is performed on spin-stabilized satellites, whose large angular momentum is used to provide stability. The satellite must gain this angular momentum by being spun once it is placed in orbit. Offset thrusters are used to torque the satellite to rates typically ranging from 1 to 50 rpm.

Perturbations to the satellite orbit result in the satellite's moving from its optimal design orbit. Station keeping is performed to maintain orbital position and consumes the largest portion of on-orbit fuel. Attitude control thrusters are much smaller and are fired for brief periods to affect small changes to a satellite's orientation.

Satellite missions sometime require orbit changes. This may be driven by missions that require multiple orbits. The *delta vee* (Δv, change in satellite velocity vector) necessary for these maneuvers can consume substantial amounts of fuel.

Momentum management is required when momentum wheels gain excessive energy from the satellite. This requires thrusters that fire and create an opposing torque on the satellite, allowing the excess energy in the momentum wheels to be dissipated.

Finally, EOL satellite disposal is becoming more and more critical with the increasing amount of orbital debris in space, as mentioned in Chapter 8. Satellites are now being designed with an EOL disposal reserve of fuel so that they can be deorbited to burn up during reentry into Earth's atmosphere, or placed in nonuseful parking orbits. However, parking orbits for defunct satellites do not lessen the problem of orbital debris, but merely make the existing satellite's orbital slot available for use by another satellite at the end of its life [87].

The propulsion system and fuel can account for up to 20 percent of the satellite's mass. Onboard fuel storage capacity can limit a satellite's useful life to 7 to 10 years (although some satellites are being considered for longer on-orbit duration).

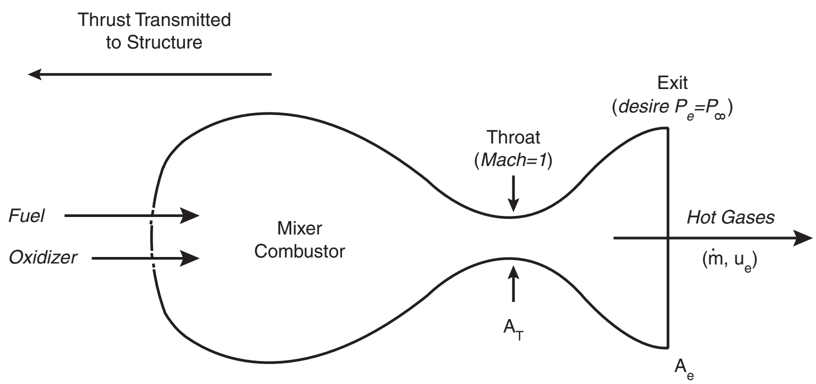
The two classes of propulsion systems used are monopropellant (single liquid) and bipropellant (dual liquid, oxidation reaction). Monopropellant systems require a pressure vessel for storage of the liquid. Generally, monopropellant systems have low specific impulse [a measure of efficiency, see Equation (10.6)], but are much less complex than bipropellant systems. Conversely, bipropellant systems are more complex, requiring fuel and oxidizer storage tanks and a mixing and combustion chamber, but have a much higher specific impulse than monopropellant systems. This results in a much greater energy density per unit mass of propellant, which translates into more thrust than for a monopropellant system of comparable mass. The rocket equation is derived in the following section to enable analysis of satellite thrusters.

The Rocket Equation Many of the orbit and control maneuvers performed by satellites require thrusters or rockets. In either case, the thruster/rocket can be thought of as a pressure vessel ejecting high-pressure gas(es) in one direction, resulting in a net thrust in the opposite direction (Figure 10.7). This thrust comes from two elements of the expelled gas, the jet velocity of the gas v_e and the pressure difference ΔP between the exiting gas and the ambient conditions, which can be expressed as

$$T = \dot{m}v_e + A_e(P_e - P_\infty) = \dot{m}v_e + A_e\,\Delta P_e \qquad [10.4]$$

where T = thrust, N; $\dot{m}$ = exhaust mass flow rate, kg/s; v_e = exit velocity of gas(es), m/s; A_e = area of rocket nozzle exit, m^2; P_e = gas pressure at exit of nozzle, N/m^2; P_∞ = ambient pressure of environment, N/m^2 (assume 0 for space).

Figure 10.7 | Bi-propellant rocket nozzle schematic.



For ideal situations, the thrust can be maximized by expanding the exiting gas(es) fully to the ambient pressure of the surrounding environment. For first-order estimates, this reduces Equation (10.4) to

$$T = \dot{m}v_e \qquad [10.5]$$

For comparison of rocket types, it is common to hear people speak of the specific impulse. The specific impulse is quoted in seconds and is a measure of the rocket thrust, divided by the force flow rate of the fuel—essentially a measure of how well it converts its fuel into thrust.

$$I_{sp} = \frac{T}{\dot{m}g} \qquad [10.6]$$

where I_{sp} is specific impulse, s; T is thrust, N; and G is acceleration due to gravity at Earth's surface, 9.81 m/s^2.

Table 10.4 provides an overview of some rocket types and their associated specific impulse and thrust range. For comparison purposes, the first two rocket types are for large-thrust rockets, whereas the others are for satellite thrusters. The point of interest is that a high-*I*sp rocket, although highly desirable from a propulsive efficiency standpoint, may only have a maximum thrust output that limits it to certain applications. As an example, ion engines offer an incredibly high *I*sp compared to the liquid oxygen/hydrogen main engines of the Space Shuttle. However, the ion engines can only produce thrusts of under 1 N—not very effective for putting satellites into orbit, but effective for very small satellite maneuvers. For satellite control and maneuvers in orbit, small attitude control thrusters range from 0.1 to 50 N, while large orbit control thrusters can range from 100 to 2,500 N.

Table 10.4 | Various rocket types, specific impulse, and thrust range

Rocket type	I_{sp} (s)	Thrust range (N)
Solid fuel	280–300	$50–5 \times 10^6$
Liquid bipropellant (O_2/H_2, N_2O_4/MMH)	300–450	$5–5 \times 10^6$
Cold gas monopropellant	50–75	0.05–200
Liquid monopropellant (N_2H_2, H_2O_2)	150–225	0.05–0.5
Arcjet (NH_3, N_2H_4, H_2)	450–1,500	0.05–0.5
Ion (He, Xe, Cs)	2,000– 5,500	5×10^{-6}–0.5
Pulsed plasma (Teflon)	1,500	5×10^{-6}–0.05

To design the satellite's propulsion system, you need to decide on the number, type, and size of thrusters as well as the amount of fuel needed for the mission. The orbit chosen for the mission helps determine the types of perturbations for which the thrusters need to compensate. Orbital maneuvers are typically quoted in terms of velocity changes, or Δv. To calculate Δv, start with Newton's law:

$$F = ma$$

We know that acceleration is the time derivative of velocity

$$a = \frac{dv}{dt}$$

So obtaining the following relation for force yields

$$F = m\frac{dv}{dt}$$

For rockets, the thrust T is equal and opposite to the force

$$F = -T$$

Substituting and rearranging the equations for the time derivative of velocity yield

$$\frac{dv}{dt} = \frac{-T}{m}$$

Substituting Equation (10.6) for thrust yields

$$\frac{dv}{dt} = \frac{gI_{sp}}{m}\frac{dm}{dt} \quad \textbf{[10.7]}$$

which can be rewritten as a differential equation in terms of the velocity and mass

$$dv = -GI_{sp}\frac{dm}{m} \quad [10.8]$$

Integrating Equation (10.8) yields

$$\int_{v_i}^{v_f} dv = -GI_{sp}\int_{m_i}^{m_f}\frac{1}{m}dm \quad [10.9]$$

Obtain a relationship for the change in velocity as a function of initial and final masses (m_i and m_f, respectively) of the rocket. *Note:* The final mass is simply the initial mass minus the mass of spent fuel.

$$v_f - v_i = -GI_{sp}(\ln m_f - \ln m_i) \quad [10.10]$$

Rearranging yields

$$v_f - v_i = GI_{sp}(\ln m_i - \ln m_f) \quad [10.11]$$

Using the property that the difference of two natural logarithms is the natural logarithm of the ratio of the two numbers, we obtain the formal relationship for the change in velocity, or delta of a satellite

$$\Delta v = GI_{sp}\ln\frac{m_i}{m_f} \quad [10.12]$$

Equation (10.12) can be solved for the final mass of the system after the rocket firing. If we subtract this final mass from the initial mass, we get the relation for the mass of propellant used ($m_p{=}m_i{-}m_f$) based on either the initial system mass or the final mass.

$$m_p = m_i(1 - e^{-\Delta v/(GI_{sp})}) = m_f(e^{\Delta v/(GI_{sp})} - 1) \quad [10.13]$$

Summing these propellant masses for every rocket firing over the life of the satellite gives an estimate of the total fuel mass needed onboard a satellite. Additional fuel is needed to account for leaks and residual fuel left in the fuel system.

The major satellite subsystems have been described. The following section highlights various satellite missions to close with the concept of overall mission objectives and requirements. For each mission you can envision the design of specific satellites to accomplish the specified objectives.

10.5 | SPACE MISSION CASE STUDIES

10.5.1 Mission Design Introduction

As reflected in Chapters 1 to 7, aircraft exist in a wide variety and span a broad range of performance. For example, while a Boeing 747-400 aircraft accommodates about 400 passengers over a range of more than 12,875 km (8,000 mi), a Boeing 737-400 aircraft is designed to carry around 150 passengers over 3,862 km (2,400 mi). Just as different aircraft are designed and optimized to operate and carry out various missions that we loosely define as a number of passengers over a given range, specific spacecraft are designed for different space missions, as stated in Section 10.1.2, "Satellite Missions."

This section provides case studies of four current satellite missions. Each example is introduced with the broad mission statement for the system. A mission statement specifies the purpose of the spacecraft (i.e., what we want the spacecraft to accomplish). The *mission statement* drives the definition of mission *goals* and *objectives.* With the mission statement, goals, and objectives clearly identified, the satellite system *design parameters* are formulated. Finally, the resulting satellite system is fabricated, integrated, tested, launched, and operated. The following four case studies bring the chapter to a close by emphasizing the engineering systems applications of current satellites.

10.5.2 Four Satellite Case Studies

Section 10.1, "Introduction to Satellites," listed four types of satellite missions, namely, scientific, military, civil, and commercial. The selected case studies discuss scientific, public, and commercial satellite mission applications. These satellite missions truly cover space, as the missions extend from low earth orbit (which roughly extends from 200 km altitude to the first Van Allen belt around 1,400 km) to geostationary Earth orbit (GEO) at 36,000 km, and an interplanetary satellite probe. The four case studies are

1. The Topex/Poseidon mission, a satellite dedicated to monitoring the global ocean circulation and improving global climate predictions (scientific, public).
2. The Landsat 7 remote-sensing satellite and instruments provide low-cost, multipurpose, land remote-sensing data for Earth with a focus on technology and images applicable for the next century (commercial, public).
3. The Thuraya system, a space-based telecommunication system that consists of two satellites in GEO offering mobile telephone services (commercial).
4. The Magellan interplanetary spacecraft designed to reveal Venus's surface (volcanic lava flows, quake faults, and other features) through the planet's thick atmosphere (scientific, public).

Topex/Poseidon: An Oceanographic Mission Topex/Poseidon is a joint mission of the National Aeronautics and Space Administration (NASA) and the French space agency, Centre National d'Etudes Spatiales (CNES). Its mission statement is

> To measure the precise shape of the ocean's surface and how this surface changes through time.

This mission is of a scientific and public nature where scientists and engineers calculate ocean currents, identify climate trends, and improve weather forecasting models. More precisely, there are seven scientific goals of the mission:

1. Make precise and accurate measurements of sea level worldwide.
2. Determine the global ocean circulation and its change through time.

3. Understand ocean tides and the relationship between the ocean circulation and climate changes.
4. Describe the nature of ocean dynamics.
5. Compute how the heat, water mass, nutrients, and salt are transported in the oceans.
6. Analyze the interaction between currents and waves.
7. Understand how the oceans affect the atmosphere and world climate.

These mission objectives led to the design of the Topex/Poseidon satellite, which encompasses two major components, namely, the satellite bus and the instrument module. The satellite bus design was taken from an existing multi-mission modular spacecraft (MMS), and it consists of four primary modules and two submodules. The primary modules include the power, altitude control, command, and propulsion. Additional submodules include an Earth sensor assembly module and the signal conditioning and control unit. The instrument module (IM), which is a large aluminum box attached to the MMS, consists of all the scientific sensors and systems required for data collection, communication, and solar power. Images on the CD-ROM include a schematic of the two major satellite components and various subsystems and instruments. Table 10.5 lists some key design parameters that describe the spacecraft.

TOPEX.tif, TOPEX2.jpg, TOPEX3.gif

Table 10.5 | Topex/Poseidon spacecraft description

Design lifetime	3 years for prime plus 2 for extended mission
Mass	2,169.4 kg (4,782.7 lb) with dry tank, 2,388.4 kg (5,265.5 lb) with full tank
Length	5.5 m (18 ft)
Span	11.5 m (37.7 ft)
Height	6.6 m (21.7 ft)
Width	2.8 m (9.2 ft)
Solar panel	8.89 m × 3.30 m (29.2 ft × 10.8 ft)
Power	3,385 W (BOL), 2100 W (at 5 years—EOL)
Communication rate	0.125 to 1,024 Kbytes

The satellite was launched on August 10, 1992 on an Ariane 42P from the European Space Agency's Guiana Space Center located in Kourou, French Guiana. It orbits Earth at an altitude of 1,336 km (830 mi) with an inclination angle of 66° and a period of 112 min, carrying two altimeters onboard built by NASA and CNES. The satellite measures the height of the ocean at the same location every 10 days using two laser altimeters. Topex/Poseidon distributes the data to 38 science investigators from nine countries. Topex/Poseidon measures the satellite altitude above the sea surface while three independent satellite tracking systems measure the satellite's position, that is, the distance between the satellite and the center of Earth (geocenter). Then the altimetric measurements are subtracted from the satellite position, resulting in a precise height measurement of the ocean above the geocenter, which is the sea level. The satellite measurement system is shown on the CD-ROM.

Landsat 7: A Remote-Sensing Mission Landsat 7 is the last of a series of six satellites with the mission statement for the entire satellite system (spacecraft plus ground segment) to

> Supply data users worldwide with low cost, multi-purpose, land remote sensing data into the next century.

The first Landsat, originally called ERTS for earth resources technology satellite, was developed and launched by NASA in July 1972. Landsat 5 was designed in the late 1970s and launched in March 1984; it is still transmitting images. Unfortunately, Landsat 6, launched in October 1993, failed to make its orbit. The mission failure of Landsat 6 resulted in enormous pressure to design and develop a new spacecraft that could ensure the continuity of the remote-sensing data gathered by the previous Landsats. Indeed, in 1992 the Land Remote Sensing Policy Act identified data continuity as the fundamental goal of the Landsat program. The scientific mission of Landsat 7 is entirely consistent with this legislated goal, which is to extend and improve upon the more than 26 year record of images of Earth's continental surfaces provided by the earlier Landsat satellites.

Landsat 7 carries a single instrument onboard called the ETM+ for Enhanced Thematic Mapper Plus. It is a passive sensor that measures solar radiation reflected or emitted by Earth. The instrument has eight bands sensitive to different wavelengths of visible and infrared radiation with a resolution ranging from 15 to 60 m.

Landsat 7 was launched on April 1999 from the Western Test Range on a Delta-II launch vehicle. At launch, the satellite weighed approximately 2,200 kg (4,800 lb). The spacecraft is about 4.3 m (14 ft) in length and 2.8 m (9 ft) in diameter. It consists of a spacecraft bus and the ETM+ instrument. The satellite orbits Earth at an altitude of 705 km ($\pm$5 km at the equator) in a Sun-synchronous polar orbit with an inclination of 98.2°+0.15°. Table 10.6 lists some of the design specifications.

Table 10.6 | Landsat 7 mission specifications

Design lifetime	5 year design life of expendables for 6 years
	Sun-synchronous, polar
	Altitude: 705 ± 5 km (at equator)
	Inclination: 98.2° ±0.15°
	Descending node: 10:00 a.m. local time, ±15 min
Orbit	Period: 98.9 min
	Collect and transmit up to 532 scenes/day
Overall system objective	Scene size: 170 km along-track
	Pointing: 180 arcsec
Attitude control	Rate: 15 arcsec/s
	Weight: 2,200 kg (4,350 lb)
	Power: 1,550 W (EOL)
	Length: 4.3 m (14 ft)
Satellite	Diameter: 2.8 m (9 ft)
Instrument	Enhanced thematic mapper+

Images on the CD-ROM show examples of the high-resolution Earth remote-sensing data from the Landsat 7 satellite. Table 10.7 gives examples of the Landsat data applications.

Landsat.pct, LandsatSF.jpg

Table 10.7 | The Landsat 7 remote-sensing data applications

Agriculture, forestry, and range	**Land use and mapping**	**Geology**	**Water resource**
Discrimination of vegetative, crop, and timber types	Cartographic mapping and map updating	Recognition of certain rock types	Mapping of floods and flood plains
Estimating crop yields	Monitoring urban growth	Revising geologic maps	Determination of extent of snow and ice
Forest harvest monitoring	Regional planning	Mapping recent volcanic surface deposits	Measurement of glacier features
Determination of soil conditions	Mapping of transportation networks	Determination of regional structures	Estimating snow melt runoff

Thuraya: A Space-Based Telecommunication System The Thuraya mobile telecommunications satellite system mission statement is

> To meet the need for affordable, high-quality mobile phone service in some of the world's most populous regions: the Middle East, North and Central Africa, Europe, Central Asia and the Indian subcontinent.

The Thuraya system is a commercial endeavor of Hughes Space and Communications International consisting of two satellites (an operational and a spare). Thuraya's satellites have been designed to achieve a network capacity of about 13,750 telephone channels. The first satellite was launched in May 2000 and has been designed for a life span of 12 to 15 years. The system provides

- Voice telephony.
- Fax.
- Data.
- Location determination.
- Emergency services.
- High-power alerting.

Table 10.8 lists key design features of the space segment.

Magellan: A Mission to Venus The Magellan spacecraft, named after the 16th-century Portuguese explorer whose expedition first circumnavigated Earth, was launched on May 4, 1989, and arrived at Venus on August 10, 1990. The satellite mission objectives are to

- Obtain near-global radar images of Venus's surface, with resolution equivalent to optical imaging of 1 km per line pair.

Table 10.8 | Thuraya basic design parameters

Number of satellites	2
Type of orbit	Geosynchronous orbit with 6° inclination
Service life	12 years
Power	Beginning of life 13 kW
	End of life 11 kW
Dimensions	Length of solar arrays, 34.5 m (113 ft)
	Width of antenna, 17 m (55.7 ft)
Mass	5,250 kg (11,576 lb) launch
	3,200 kg (7,056 lb) in orbit
Payload	12.25 m aperture deployable satellite antenna
	Onboard digital signal processing (DSP)
	Digital beam-forming capability

- Obtain a near-global topographic map with 50 km spatial and 100 m vertical resolution.
- Obtain near-global gravity field data with 700 km resolution.
- Develop an understanding of the geological structure of the planet, including its density distribution and dynamics.

Magellan.jpg, MagVenEmiss.jpg

The Magellan spacecraft was built partially with spare parts from other missions, and it is 4.6 m (15.4 ft) long, topped with a 3.7 m (12 ft) high-gain antenna. Mated to its retrorocket and fully tanked with propellants, the spacecraft weighs a total of 3,460 kg (7,612 lb) at launch [91].

Because Venus is shrouded by a dense, opaque atmosphere, conventional optical cameras cannot be used to capture its surface. Instead, Magellan used a sophisticated imaging radar that sends bursts of microwave energy somewhat like a camera flash to illuminate the planet's surface to make highly detailed maps of Venus. Besides its use in imaging, Magellan's radar system was used to collect altimetry data showing the elevations of various surface features. In this mode, pulses were sent directly downward, and Magellan measured the time it took a radar pulse to reach Venus and return, in order to determine the distance between the spacecraft and the planet. After concluding its radar mapping, Magellan also made global maps of Venus's gravity field.

The Magellan spacecraft made a dramatic conclusion to its highly successful mission at Venus when it was commanded from Mission Control to plunge into the planet's dense atmosphere on October 11, 1994. The purpose of the crash landing, which sacrificed the spacecraft, was to gain data on the planet's atmosphere and on the performance of the spacecraft during the descent.

10.5.3 Summary of Mission Objectives

Now that we have briefly discussed satellite missions, reflection on the process of designing a space mission is useful. Developing a satellite space system consists of

1. Creating system requirements based on the mission objectives.
2. Translating the system requirements to subsystem specifications.

3. Translating subsystem specifications to a subsystem design that can be fabricated and tested.
4. Integrating the subsystems into a complete system that can be tested.
5. Integrating the system and the launch vehicle.
6. Launching and operating the space segment of the mission.
7. Eventually phasing out and ending the mission.

PROBLEMS

10.1 Satellites are used for various purposes, including scientific, defense and national security, public, and commercial. Find one article in a newspaper, magazine, or journal about satellites used for any of these purposes. What is the use of the satellite information? How does this information aid in achieving the mission objective?

10.2 In one sentence for each, describe the role of the engineer at each stage of the life cycle of a satellite:

(a) Design
(b) Propulsion
(c) Station keeping
(d) Satellite operations
(e) End-of-life disposal

10.3 In this problem you will estimate some of the parameters of the Space Shuttle main engine (SSME) using engine performance data. Specifications for the SSME are given in Table 10.9. Note that the diameter of the engine (not necessarily the same as the exit diameter) is given. As you can guess, the engine diameter is an upper bound for the exit diameter since the nozzle will have some nonzero wall thickness.

Table 10.9 | Space Shuttle main engine specifications (Marshall Space Flight Center website, shuttle.msfc.nasa.gov/ssmespecs.htm)

Specification	Value	
Height, ft	13.9	
Diameter, ft	7.0	
Weight, lb	5,000	
Throttle range, %	65 to 109	
Engine performance	***Sea level***	***Vacuum***
Thrust, lb	393,800	470,000
Specific impulse, s	385	425

(a) Draw a picture of a stereotypical rocket nozzle, and explain each term in the rocket equation [Equation (10.4)].

(b) Assume that the shuttle is in space and that the nozzle is ideally expanded (exit pressure equal to ambient pressure). What is the value of $\dot{m}v_e$ in pounds? What is the value of P_e?

(c) Now assume that the shuttle is at sea level and is taking off. Using the same value of P_e as in part (b), compute the SSME exit area and diameter (assume a circular exit area). Ambient pressure at sea level is 14.4 lb/in^2. How does your calculated exit diameter agree with the SSME specifications?

(d) Compute the mass flow rate $\dot{m}$ (slugs/s or lb_{mass}/s) for a single SSME at sea level and in a vacuum. You will need to use the given specific impulse (I_{sp}) data.

(e) Now go back to the rocket equation and compute the exit velocity of the SSME. The theoretical maximum exit velocity for a chemical rocket engine is about 5 km/s. What fraction of this maximum theoretical exit velocity is achieved by the SSME?

10.4 Characterize the key uplink/downlink schemes of the Orbcomm network and the Iridium network (key ideas: crosslinks, store and forward, ground stations, information routing). Describe what happens when you send a page on the Orbcomm network and how that is different from making a phone call on the Iridium network in terms of data flow.

10.5 In this problem you will perform a simple trade analysis and optimization. Imagine that you are a systems engineer for a small satellite that will be placed in orbit around Earth. Imagine that the design requirement for peak power has just been increased by some factor η and that you now have to redesign the solar array. Your goal is to achieve the new required peak power by either enlarging the solar array or using a more efficient solar array, while minimizing cost. (With this type of design optimization for a real spacecraft, there would be other possibilities to consider. For example, you could use secondary batteries to help meet the peak power requirement without increasing the solar array area or efficiency.)

The increase in cost of your system is a function of two factors: (1) the increased cost of the solar array, due to using more expensive solar cells, and/or a larger array area, and (2) the cost of reducing the mass of other parts of the system if you choose to increase the solar array area. The second factor models the case where the launch mass is constrained, and so if you increase the solar array area, you must decrease the mass of other parts of the vehicle to compensate.

The initial parameters of your spacecraft are as shown in Table 10.10.

Table 10.10 | Satellite design trade analysis

Parameter	Symbol	Value	Units
Cost	C_0	1.00E+06	US $
Array area	A_0	5	m^2
Array efficiency	ε_0	0.19	None
Solar flux	F	1,384	W/m^2
Power	P_0	1,314.8	W
Power required	$P_{0,\text{req}}$	1,314.8	W

If we define η_1 and η_2, the factors by which we increase the array area and array efficiency in our final design, we can write

$$A = A_0\eta_1$$
$$\varepsilon = \varepsilon_0\eta_2$$

We can also write the power (in optimum conditions, i.e., pointing in the right direction in direct sun) as $P = A\varepsilon F = A_0\eta_1\varepsilon_0\eta_2F = P_0\eta$, where $\eta = \eta_1\eta_2$ is the factor by which the power requirement is increased. In this problem assume that the power requirement went up by 20 percent, and therefore $\eta = 1.2$.

In this simplified model, assume that the cost function (in U.S. dollars) is given by

$$C = 8Ae^{38\varepsilon} + 5 \times 10^6 \cdot \left(\frac{A - A_0}{A_0}\right)^2 + 9.453 \times 10^5$$

Rewritten in terms of initial parameters and the design parameters η_1 and η_2, this yields

$$C = 8\,A_0\,\eta_1 e^{38\varepsilon_0\eta_2} + 5 \times 10^6 \cdot (\eta_1 - 1)^2 + 9.453 \times 10^5$$

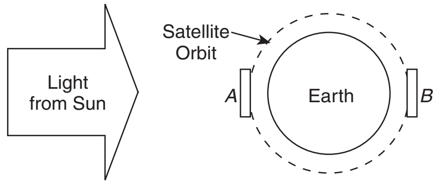
The first term in this function represents the cost of the solar array and is exponential in form because the cost of the array is driven by the cost of the solar cells. The second term represents the cost increase due to the required mass reduction for other components of the satellite, necessitated by increases in the array area. The third term is a constant term representing the cost of the rest of your (very) small satellite.

(a) What would be the percentage change in cost of the system if the new power requirement were met only by changing the area of the solar array ($\eta_1 = 1.2$, $\eta_2 = 1$)?

(b) What would be the percentage change in cost of the system if the new power requirement were met only by changing the efficiency of the solar array ($\eta_1 = 1$, $\eta_2 = 1.2$)?

(c) What are the optimum values of η_1 and η_2 (to within 0.01) to achieve the design requirement at a minimum of cost? (*Hint:* Calculate the total cost in a spreadsheet as a function of η_1 by eliminating η_2 from the cost function. Direct calculus methods for finding the minimum of a function could also work, but the spreadsheet iterative approach is usually significantly easier.)

10.6 Consider a satellite in low Earth orbit at two points in its orbit, *A* and *B,* as shown in the figure. This simple satellite can be modeled as a thin aluminum plate: The surface on one side of the plate is bare aluminum ($\alpha_A = 0.379$, $\varepsilon_A = 0.0346$), and the surface on the other side of the plate is a silvered Teflon coating ($\alpha_T = 0.379$, $\varepsilon_T = 0.0346$). In this problem it will be helpful to know that the mean IR power flux from Earth can be approximated by $G_I = 237$ W/m^2.



(a) If the bare aluminum side of the satellite is always directly facing the sun, what is the equilibrium temperature of the satellite at points A and B? You can assume that the thermal capacitance of the satellite is small enough that equilibrium will be reached in a really small amount of time. In other words, power in is equal to power out. Be sure to consider the power received from reflection of the sun off the earth:

$$P_{\text{Earth}_{\text{reflection}}} \approx G_S A \alpha a K_a$$

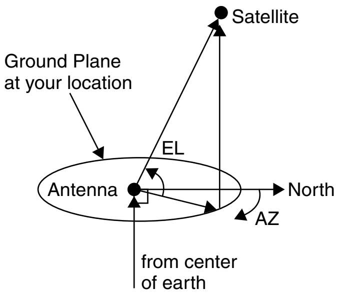
where G_S is the solar flux, A is the affected area of the spacecraft, α is the absorptivity of the affected spacecraft surface, a is the albedo (about 30 percent for Earth), and K_a is a proportionality constant. Take K_a to be 0.5.

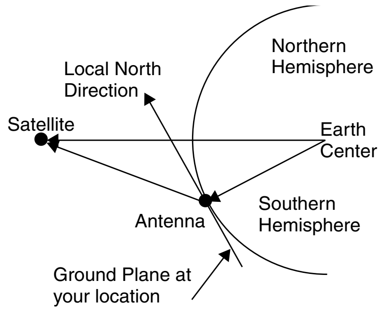
(b) If the Teflon side of the satellite is always directly facing the sun, what is the equilibrium temperature of the satellite at points A and B?

(c) Now imagine that you could rotate the satellite so that one of the faces (either the Teflon or the aluminum face) would always point at Earth. If your goal is to minimize the temperature swing between the equilibrium temperatures at points A and B, which side should be pointed at Earth? What is the temperature swing ΔT for this situation?

10.7 You are on a trip in the Australian Outback, and you need to send a problem set back to your home university for one of your professors. Since the nearest town is more than 100 mi away, you decide to use your satellite workstation fax to send your problem set to your professor's fax machine. To do this, you will need to make use of the nearest Inmarsat geosynchronous satellite. You know that you are in the satellite's footprint, so your remaining task is to aim the antenna of your workstation. Your antenna is a planar antenna with some gain, so you want to have the normal vector of your antenna plane point at the satellite. Once you do this, a digital version of your problem set will be sent to the satellite, relayed to a ground station, and passed through the standard phone network to your professor's fax machine.

To properly point your antenna, you need to determine the correct elevation angle EL and the correct azimuth AZ. The azimuth and elevation angles are defined in the figure below.





(a) If the vector from the center of Earth to the satellite is $\boldsymbol{r}_1$ and the vector from the center of Earth to your current position in the outback is $\boldsymbol{r}_2$, compute the elevation angle EL required to properly aim your antenna at the satellite.

(b) Now that you've calculated the elevation angle of the satellite, you decide that you don't feel like computing the azimuth angle. Instead you decide to use the "beep feature" of the satellite workstation. The beep feature, when turned on, causes the workstation to beep with the beep frequency (in beeps per minute) in proportion to the power received by your antenna from the satellite carrier signal. Describe qualitatively how you might locate the satellite, using your knowledge of the satellite's position and the beep feature.

10.8 The gain margin of a communications system is the ratio of the actual power received by the antenna to the power required to achieve the design goal. Why might satellite systems using frequencies above about 5 GHz have to carry a significant gain margin (a ratio of 5 to 10) for their communication systems? What kinds of losses might occur in that range of frequencies?

10.9 Collect some information from the Web about one of the JPL planetary exploration missions including the mission statement and goals of the mission. Also find a description of the vehicle(s) built to accomplish the mission including mass, physical dimensions, communications systems, power requirements, etc. Compare your chosen mission to one of the four case studies presented in the chapter. Specifically comment on similarities and differences between the two missions and how these differences are reflected in the spacecraft designs and other elements of the mission (such as the ground segment).

11 Chapter

Human Space Exploration

Dava J. Newman

11.1 | INTRODUCTION

Human exploration of space captivates us as no other endeavor. Human spaceflight missions have four main goals:

- To increase knowledge of nature's processes, using the space environment.
- To explore and settle the solar system.
- To achieve affordable, routine space travel.
- To enrich life on Earth through people living and working in space.

The history of research, technology, and spaceflight missions focused on sending humans into the space environment and beyond teaches us numerous lessons. From the first human spaceflight on April 12, 1961, of Yuri Gagarin in Vostok I to the International Space Station currently being assembled for habitation early in the new millennium, exciting human spaceflight adventures have shaped humankind. Defining the goals for future human space endeavors is a challenge now facing all space-faring nations. Given the high costs and associated risks of sending humans into Earth orbit and beyond—to the Moon, Mars, asteroid belt, or Europa—the nature and extent of human participation in space exploration and habitation are key considerations. Adequate protection for humans in orbital space or planetary surface environments must be provided. The Gemini, Apollo, Salyut-Soyuz, Skylab, Space Shuttle, and Mir space station programs have demonstrated that humans can also survive outside of the spacecraft, performing successful extravehicular activity (EVA), or space walks.

Since the beginning of human exploration above and below the surface of Earth, the main challenge has been to provide the basic necessities for human life support that are normally provided by nature. A person encountering the near vacuum of space would survive only a few minutes unprotected by a spacecraft or spacesuit. Body fluids would vaporize without a means to supply pressure and an atmosphere, and expanded gas would quickly form in the lungs and other tissues, preventing circulation and respiration. A focus of this chapter is to highlight astronaut EVA space activities in which crew members leave the confines of their spacecraft and are provided life support by a spacesuit, which is a necessary operational resource for long-duration missions that will establish human presence beyond Earth into the solar system. The different designs and choices pursued by the U.S. and Soviet/Russian space programs serve as case studies for the design of human space exploration systems. To meet the challenge of keeping humans alive in the space environment, many factors including human physiology, atmospheric composition and pressure, thermal control, radiation protection, and human performance are addressed.

Human presence on space missions offers many advantages to accomplish mission success. An astronaut present at the work site has the following capabilities: flexibility, dexterous manipulation, human visual interpretation, human cognitive ability, and real-time approaches to problems. Factors that may degrade performance include pressure suit encumbrance, prebreathe requirements, insufficient working volume, limited duration, sensory deprivation, and poor task or tool design [92]. EVA, as well as robotics and automation, expands the scope of space operations. A thorough understanding of astronaut capabilities will help bring about the integration of humans and machines for future missions. In addition to microgravity performance, the partial gravity environments of the Moon and Mars require advanced technology, hardware, and performance capabilities for successful human space endeavors.

11.2 | HISTORICAL BACKGROUND

11.2.1 Human Spaceflight

In the United States, five major programs preceded the current Space Shuttle and International Space Station activities: Mercury, Gemini, Apollo, Skylab, and the Shuttle-Mir (denoted as phase I of ISS). The goals and objectives of these programs are briefly reviewed. Then the milestone EVAs of history are recounted. The Soviets/Russians accomplished many firsts in human spaceflight under seven main programs, namely, Sputnik, Vostok, Voskhod, Soyuz (Soyuz and Kosmos launches), Lunar (Zond and Kosmos launches), Salyut, and Mir [93].

11.2.2 Mercury

Project Mercury was the United States' first human space program, initiated in 1958 and completed in 1963. The Mercury program goal was to demonstrate that humans could survive in space. The objectives of the program, which culminated in six human spaceflights between 1961 and 1963, were

- To orbit a human-occupied spacecraft around Earth.
- To investigate a human's ability to function in space.
- To recover both the crew and spacecraft safely.

Figure 11.1 | Earth as seen from the Moon by the crew of the Apollo 17 mission.

Mercury.jpg

Project Mercury required the development of life support systems for operation under conditions of thermal extremes, acceleration, and microgravity. The Mercury missions were valuable for both dispelling and verifying numerous medical concerns. The primary biomedical findings were weight loss, mostly due to dehydration, and some impairment of cardiovascular function. Cardiovascular data from the final and longest Mercury flight showed postflight orthostatic intolerance, or dizziness upon return to Earth when standing. I recommend *This New Ocean: A History of Project Mercury* [94] for a comprehensive look at the Mercury program. Astronauts John H. Glenn, Virgil I. Grissom, and Alan B. Shepard, Jr., are shown standing by the Redstone rocket in their spacesuits.

11.2.3 Gemini

Project Gemini, the second U.S. human space program, was announced in January 1962. The name comes from the two-person crew, Gemini, for the third constellation of the Zodiac and its twin stars, Castor and Pollux. Gemini involved 12 flights, including two flight tests of the equipment without crew. Between March 1965 and November 1966, the United States flew 10 Gemini two-person spacecraft. The Gemini objectives were to

- Demonstrate the feasibility of spaceflight lasting long enough to complete a lunar landing.
- Perfect the techniques and procedures for orbital rendezvous and docking of two spacecraft.

- Achieve precisely controlled reentry and landing capability.
- Establish capability in extravehicular activity.
- Enhance flight and ground crew proficiency.

A major focus of the Gemini human medical investigations was evaluation of the changes in cardiovascular function noted in the Mercury program. Cardiovascular changes were regarded as an adaptive response to body fluid loss and redistribution resulting from exposure to microgravity. The key question was whether the observed cardiovascular deconditioning was a self-limiting adjustment. New changes such as bone mineral loss were noted. Animal experiments focused on the effects that the absence of gravity might have on fertilization and egg development, but no abnormalities were noted [95]. *On the Shoulders of Titans: A History of Project Gemini* is a recommended reference [96].

Gem1.jpg, Gem2.jpg

11.2.4 Apollo

> I believe this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to Earth. No single space project in this period will be more impressive to [hu]mankind, or more important in the long-range exploration of space; and none will be so difficult or expensive to accomplish. (John F. Kennedy, Special Joint Session of Congress, May 25, 1961)

The Apollo program included a large number of uncrewed test missions and 11 human missions. The human missions included two Earth orbiting missions, two lunar orbiting missions, a lunar swingby, and six Moon landing missions. The Apollo program was designed to land humans on the Moon and bring them safely back to Earth. Six of the missions (Apollos 11, 12, 14, 15, 16, and 17) achieved this goal. Lunar surface experiments included soil mechanics, meteoroids, seismic, heat flow, lunar ranging, magnetic fields, and solar wind experiments. Apollos 7, which tested the Command Module, and 9, which tested both the Command Module and Lunar Module, were Earth orbiting missions. Apollos 8 and 10 tested critical components while orbiting the Moon and returned photography of the lunar surface. Apollo 13 did not land on the lunar surface due to a life support system malfunction, but during the brief orbit around the Moon, the crew was able to collect photographs. It is noteworthy that this successful program was well funded with a budget allocation of 34 percent of the total NASA budget.

Kennedy.mpg

The goal of the Apollo program was singular and straightforward—to land a man on the Moon and return him safely to Earth "before this decade is out," stated President John F. Kennedy in 1961. The goal was in fact achieved with the Apollo 11 mission in July 1969. Overall the Apollo program included 29 astronauts, 12 of whom spent time on the lunar surface.

Because the crew time and weight restrictions were very critical during the Apollo missions, only human investigations and science experiments requiring no or only small additional hardware items were flown, one example being a small container to measure the effects of radiation on biological samples. Overall, 21 life science experiments were conducted during the Apollo and Apollo-Soyuz programs. The Apollo biomedical program had three major goals:

- Ensure the safety and health of crew members (e.g., precautions for in-flight sickness because during a lunar mission no fast recovery was possible).
- Prevent contamination of Earth by extraterrestrial organisms. To ensure that unwanted microorganisms were not transported in either direction, strict quarantine and decontamination procedures were implemented before and after each mission.
- Study specific effects of human exposure to microgravity. The mission provided the opportunity to study more closely the cardiovascular and bone adaptations observed during the Mercury and Gemini programs. In addition, biology investigations were conducted, including studies of radiation effects.

Aldrin.JPG, Rover.jpg

During the Apollo program test data from various medical tests conducted before the mission were compared to the results of postflight tests. The findings were neurovestibular disturbances (inner ear balance and disorientation), less than optimal food consumption (1,260 to 2,903 kcal/day), postflight dehydration and weight loss (recovery within 1 week), increased postflight orthostatic intolerance, reduced postflight exercise tolerance, decreased red cell mass (2 to 10 percent) and plasma volume (4 to 9 percent), and cardiac arrhythmias during one mission. A plethora of references exist detailing the Apollo program and the monumental accomplishments of humankind's first journey to another planetary body [98–107].

11.2.5 Skylab

Skylab provided the United States' first experimental space station. Designed for long-duration mission, Skylab program objectives were twofold: to prove that humans could live and work in space for extended periods and to expand our knowledge of solar astronomy well beyond Earth-based observations. Successful in all respects despite early mechanical difficulties, three three-person crews occupied the Skylab workshop for a total of 171 days, 13 h. It was the site of nearly 300 scientific and technical experiments: medical experiments on humans' adaptability to microgravity, solar observations, and detailed Earth resources experiments. The empty Skylab spacecraft returned to Earth on July 11, 1979, scattering debris over the Indian Ocean and a bit of western Australia [109].

11.2.6 Apollo-Soyuz

A remarkable joint mission was undertaken by the Americans and Russians in 1975, namely, the Apollo-Soyuz Test Project (ASTP). The mission started with the Russian Soyuz launch on July 15, 1975, followed by the U.S. Apollo launch on the same day. The mission lasted 9 days, and docking in space of the two craft occurred on July 17 with the Soyuz and Apollo spacecraft docked for 2 days while the crews exchanged visits and conducted joint operations. The primary

Figure 11.2 | Skylab demonstration of the microgravity environment, or weightlessness.

mission objective was to test rendezvous and docking systems that might be needed during international space-rescue missions. A second objective was to conduct a program of scientific experiments and technologic applications.

The biomedical analyses of skeletal muscle function in leg and arm muscles showed that the muscle dysfunction characteristics found after 59 days of microgravity exposure during the Skylab 3 mission were also present after 9 days of the ASTP mission. Short-term microgravity exposure also produced fatigue in muscle tissue, particularly in the antigravity muscles. During reentry the crew members were exposed to toxic gases, mostly nitrogen tetroxide, which resulted in the development of chemical pneumonitis symptoms. The crew was hospitalized, and most of the planned postflight medical experiments were sacrificed. Fortunately, both spacecraft landed safely and on schedule [110].

11.2.7 The Space Shuttle

The Space Shuttle is a significant part of human space exploration. Standing as one of NASA's foremost projects, the Shuttle has accomplished many tasks that have enhanced the quality of life on Earth. The Space Shuttle is the world's first reusable spacecraft and the first U.S. vehicle having a standard sea-level atmospheric pressure and composition. Mercury, Gemini, and Apollo all operated at 33.4 kPa (5 lb/in^2 or 0.33 atm) pressure and 100 percent oxygen composition. The capabilities of the Shuttle allow scientists to conduct experiments routinely to explore the effects of the space environment, particularly microgravity, on human physiology under conditions that cannot be duplicated on Earth.

A key feature of the Shuttle is the pressurized Spacelab module (developed by the European Space Agency), a space laboratory to conduct research in Earth orbit. The Spacelab concept is to equip the Shuttle's cargo bay with a laboratory facility where the crew can operate instruments and perform experiments. The success of human spaceflight and the Space Shuttle is well documented, and I recommend *Toward a History of the Space Shuttle* [111].

Figure 11.3 | Launch of Shuttle Mission STS-96, also called ISS mission 2A.1, to resupply the ISS on 27 May 1999.

Online resource.

Between March 1995 and May 1998, NASA astronauts flew onboard the Russian space station Mir in a collaborative effort. The NASA program supporting this endeavor is commonly known as International Space Station Phase I (or Shuttle-Mir), encompassing 11 Space Shuttle flights and joint Soyuz flights. The international program resulted in joint space experience for the crew and the start of joint scientific research. Shuttle-Mir participants (crew members, principal investigators, mission control staff) investigated vital questions about the future of human life in space. Mir is a test site for three main areas of experience and investigation:

- Designing, building, and staffing the International Space Station. Participants drew from the experience and resources of many nations to learn how to work together and learn from one another.
- Investigation. Mir offers a unique opportunity for long-duration data gathering. Station designers used Mir as a test site for space station hardware, materials, and construction methods. Mir crew members utilized

the microgravity environment to conduct scientific investigations into biological and material studies.

- Operation. In the almost 40 year history of human spaceflight, no previous program required so many transport vehicles and so much interdependent operation between organizations. Shuttle-Mir experience gave participants an opportunity to prepare for the formidable cooperative effort required on the International Space Station.

Mir Space Station.PCT, MirShuttle.JPG

Results from Shuttle-Mir Science Experiments More than 100 investigations were conducted aboard Mir or during docked Space Shuttle operations. Many investigators had previously flown experiments on Shuttle and Spacelab missions, and their goal was to conduct similar experiments on Mir to compare the results from short-duration and long-duration spaceflights. A central theme of science investigations aboard the Mir was the study of the astronauts themselves and their responses to long periods in weightlessness. Researchers are able to better characterize human physiology and psychology in space, in particular, changes in bones and muscles, in the neurovestibular system (responsible for human balance and orientation), and in the interactions among crew members and their ground support teams during a long mission.

Highlights of the scientific investigations aboard the Mir included these:

- The exercise countermeasures developed by the Russians over the past quarter century to minimize the physiological deconditioning effects of long-term weightlessness were studied. These countermeasures appear to be effective. Learning from the Russians, U.S. researchers found that targeting specific muscles for exercise can help offset the long-term effects of weightlessness. Exercising the neck muscles, for example, is very important. Researchers found that the rate of bone loss on the Mir, a chronic problem for space explorers, does not lessen over time, as previously thought. Astronauts average a 10-fold greater loss in bone mineral density in the lower hips and spine per month than when living on Earth. This has helped focus researchers on developing specific countermeasures.
- On the Space Shuttle, a previous series of experiments grew tissue cultures. Due to the effects of gravity, this type of research cannot be done on Earth. With access to Mir, the tissue growth work was extended from 10 days to 4 months with the successful culturing of cartilage cells in a device known as the bioreactor. The cartilage cells grew into a three-dimensional spherical structure more as tissue would grow in a living organism. This research holds tremendous promise in the future aboard the International Space Station, and the value of long-duration growth was validated aboard the Mir.
- For the first time in history, a complete natural cycle of plant growth has been accomplished in space. Seeds harvested from plants grown aboard Mir were in turn germinated and produced new plants—the first “seed-to-seed” experiment.
- Benefiting from increased time aloft and using new cutting-edge techniques, U.S. astronauts have dramatically increased the number of protein crystals

grown in space—30 times more than by using conventional techniques. The crystals form the basis for improved drug design for a wide variety of illnesses.

Mir.tif

Case Study: The Enhanced Dynamic Load Sensors (EDLS) on Mir

One of the key missions of the International Space Station is to perform microgravity experiments that require a quiescent environment (~10^{-4} to 10^{-7} G's), that is, to perform experiments that make use of the almost complete absence of any accelerations as a vehicle orbits Earth. For this reason we conduct spaceflight experiments for the ISS program that investigate how astronauts move about in space as well as how they potentially disturb the spacecraft microgravity environment. While some microgravity experiments can be conducted fully automatically, many require astronauts to execute or supervise them. While the astronauts play a critical role in the success of experiments, we wanted to make sure that the experiments were not a significant disturbance source to the spacecraft acceleratory environment, and hence scientific research efforts. When astronauts move inside the cabin, they impart impulses and forces on the vehicle. External disturbances such as aerodynamic drag or solar pressure can be estimated quite easily from vehicle and environmental parameters. Similarly, disturbances inside the spacecraft due to the operation of mechanical equipment such as pumps and fans can be predicted. Astronaut-induced disturbances represent a far more challenging task to analyze due to the inherent randomness.

Phase I of the International Space Station program provided the United States the opportunity to send astronauts to the Russian space station Mir and conduct long-duration spaceflight experiments. Seven U.S. astronauts stayed aboard Mir during Phase I. Within the framework of this program, the Massachusetts Institute of Technology (M.I.T.) conducted the enhanced dynamic load sensors (EDLS) experiment on Mir to quantify the disturbances to the microgravity environment due to the presence of astronauts. The experiment was designed with two objectives in mind. The primary objective was to assess nominal astronaut-induced forces and torques during long-duration space station missions. In other words, everyday activities and induced loads were measured with *smart* sensors, called restraints. The secondary objective of the research effort was to achieve a detailed understanding of how astronauts adapt their strategies for moving about in microgravity as they propel themselves with their hands and float from module to module.

MirAstronaut.tif, EDLS.tif

The experimental setup consisted of four load sensors and a specially designed computer. The sensors included an instrumented handhold, push-off pad, and two foot restraints, and provided the same functionality as the foot loops and handrails built into the Space Shuttle Orbiter and the Mir orbital complex for astronauts to secure themselves. The push-off pad's functionality was envisioned to be that of a flat surface the astronauts would use to push themselves off with either their hands or feet.

The astronauts were instructed to activate the computer and go about their regular on-orbit activities. Whenever the computer detected that the measured forces and torques exceeded a specified threshold force, data were recorded on the storage medium. The experiment was conducted during the stay of U.S. astronauts Shannon Lucid (March to September 1996) and Jerry Linenger (January to May 1997) aboard Mir. The overall data recording time was 133 h over the two periods. The storage media with data were returned to Earth with the Space Shuttle and then processed and analyzed at M.I.T.

The results of the experiment showed that seven typical astronaut motions are used for locomotion, or floating movements in microgravity (see Table 11.1). These motions are quite different from the standing, walking, and running that constitute bipedal motion on Earth.

Table 11.1 | Characteristic astronaut motions

Characteristic motion	Description
Landing	Flying across module and landing
Push-off	Pushing off and flying
Flexion/extension	Flexing limb or extending limb
Single support	Using one limb for support
Double support	Using two limbs for support
Twisting	Twisting body motion
Reorienting	Usually small correction for posture control

An examination of the NASA 2 and NASA 4 EDLS mission data led to the identification of several typical astronaut motions and the quantification of the associated load levels exerted on the spacecraft. For 2,806 astronaut activities recorded by the foot restraints and handhold sensor on Mir, the highest force magnitude was 137 N. For about 95 percent of the time the maximum force magnitude was below 60 N, and for about 99 percent of the time the maximum force magnitude was below 90 N. For 95 percent of the astronaut motions, the root mean square force level was below 9.0 N. An analysis of the torques recorded showed that 99 percent of all events were less than 11 $N \cdot m$, and the overall average moment was 2.35 $N \cdot m$. The average momentum imparted by the astronauts on the Mir space station was 83 ± 228 $kg \cdot m/s$ with 99 percent of all events having a total momentum of less than 600 $kg \cdot m/s$. It can be concluded that expected astronaut-induced loads on the ISS from usual astronaut intravehicular activity are considerably less than previously thought and will not significantly disturb the ISS microgravity environment [112]. These are very low forces when compared to typical Earth forces. Actually, they are an order of magnitude less. For example, every step you take, you exert 1 BW, or 510 N (for a 52 kg person). Imagine how many steps you take every day. Essentially, the data prove that the astronauts in microgravity adopt the appropriate strategy for their new weightless environment and use “finger push-offs” and “toe-offs” as they move about in space. The good news is that astronauts do not disturb the microgravity environment as they go about their daily activities. After living in space for months, astronauts are like highly trained athletes, or professional ballet dancers, who move about with grace and control all the while exerting very low forces during vehicle interactions.

11.2.8 International Space Station

The International Space Station will offer a world-class research laboratory in low Earth orbit. Once assembled, the ISS will afford scientists, engineers, and entrepreneurs an unprecedented platform on which to perform complex, long-duration, and repeatable experiments in the unique environment of space. The ISS's invaluable assets include prolonged exposure to microgravity and the presence of human experimenters in the research process. Yet the ISS is much more than just a world-class laboratory in a novel environment; it is an international human experiment—an exciting "city in space"—a place where we will learn how to live and work "off planet" in an international way [113].

The primary purposes for the ISS are to serve as

ISScolor.jpg

- An advanced test bed for technology and human exploration.
- A world-class research facility.
- A commercial platform for space research and development.

The governments of the United States, Canada, Europe,[1] Japan, and Russia are collaborating with their commercial, academic, and other international affiliates in the design, operation, and utilization of the ISS. The benefit from an orbiting laboratory, such as the ISS, lies in generating a wealth of knowledge to apply in the fields of commerce, science, engineering, education, and space exploration.

Student projects have an opportunity to fly on the ISS, and educational experiences will be achieved through interactive videoconferencing and telescience from the ISS by using technology to control and manipulate experiments from the ground. Advancing communications and information technologies will allow Earth-bound investigators to enjoy a "virtual presence" onboard the ISS.

As previously stated in Chapter 8, "The Space Environment: An Engineering Perspective," a major purpose of ISS is to provide a platform for long-duration microgravity experiments in the life and physical sciences. A summary of nine important engineering and scientific questions to be investigated on ISS includes these [46–49]:

Take a 3D tour of Mir or the ISS

1. How did the universe, galaxies, stars, and planets form and evolve?
2. How does the Earth environment change over time, and what are the causes of these changes?
3. What is the role of gravity in the evolution, development, structure, and function of life-forms, and as a result of gravity, what are the life-forms' interactions with their environment?
4. What is required to ensure the health, safety, and productivity for humans living and working in space?

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1. European states are represented through membership in the European Space Agency (ESA). Current ESA members cooperating on the ISS are Belgium, Denmark, France, Germany, Great Britain, Italy, The Netherlands, Norway, Spain, Sweden, and Switzerland.

5. What technologies are best suited for long-duration missions of human space exploration?
6. What are the controlling mechanisms in the growth of cells, organisms, organs, and other biologically interesting structures?
7. What is the optimum relationship between the process used to form a material and its resultant properties, and how can we achieve this in space and on the ground?
8. How can the space environment help us obtain fundamental physical measurements of the highest accuracy?
9. What is the most effective energy conversion process involving combustion, and how can we achieve that? What are the fundamental forces affecting fluid behavior?

The Skylab and Mir space station experience demonstrated that crew members become very skilled in performing tasks on long-duration missions. After approximately 60 days in orbit, the crew members' knowledge of the laboratory, of stowage locations, of relationships among crew members, of procedures, and of the integration of many elements on the vehicle is extensive. This experience-based knowledge and understanding is great when compared to missions 2 weeks or less in duration. Crew members on long-duration space missions fully adapt to space—sleep well, eat well, exercise regularly, etc. The completed ISS will be powered by almost an acre of solar panels and have a mass of almost 453,600 kg. (1 million lb.). The pressurized volume of the station will be roughly equivalent to the space inside two jumbo jets. The final ISS assembly mission is flight 16A where the U.S. habitation module is delivered to enhance crew accommodations and provide for a station crew with as many as seven members (see Figure 11.4).

Future human exploration missions will require crew members to live and work productively for extended periods in space and on other planets. Key biomedical, life support, and human factors questions must be answered on the ISS to ensure crew health, well-being, and productivity for future exploration missions.

WWW

A comprehensive timeline of planetary exploration missions.

11.3 | EXTRAVEHICULAR ACTIVITY

Human space exploration is epitomized by space walks, or extravehicular activity. In March of 1965, cosmonaut Alexei Leonov became the first human to walk in space. Attached to a 5 m long umbilical that supplied him with air and communications, Leonov floated free of the Voskhod spacecraft for more than 10 min. In June of the same year, Edward White became the first U.S. astronaut to egress his spacecraft while in orbit. White performed his spectacular space walk during the third orbit of the Gemini–Titan 4 flight. Figure 11.5 summarizes Russian and U.S. extravehicular activity to date.

WWW

View a pictorial history of EVA spacesuits.

Although some of the early EVA efforts of both programs were plagued with problems, the feasibility of placing humans in free space was demonstrated. The Gemini EVAs showed the necessity of providing adequate body restraints to

Figure 11.4 | The ISS fully assembled after mission 16A ("A" denotes an American launch of the final component, the U.S. habitation module, shaded in drawing).

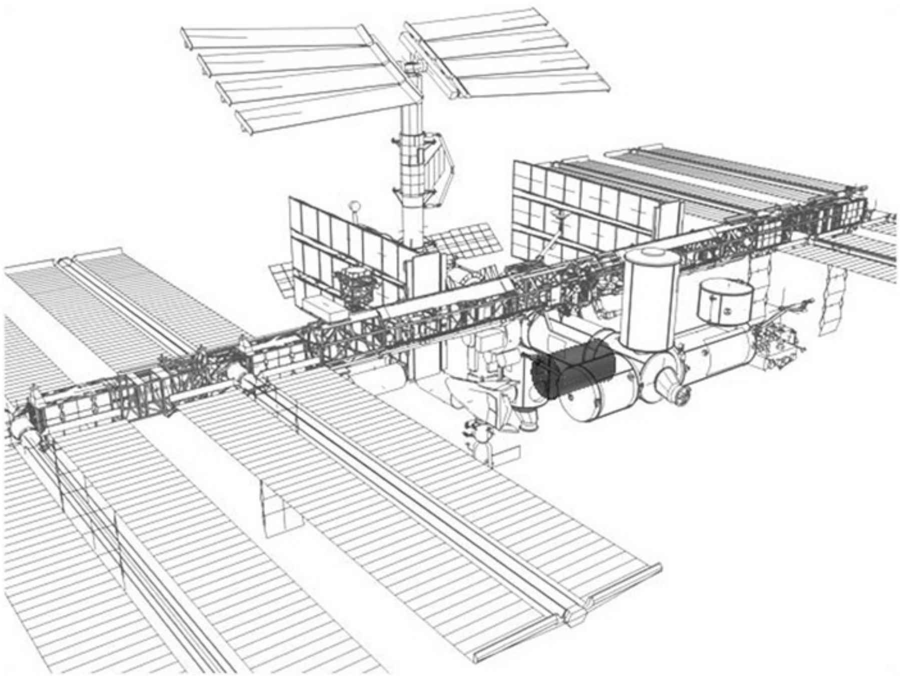
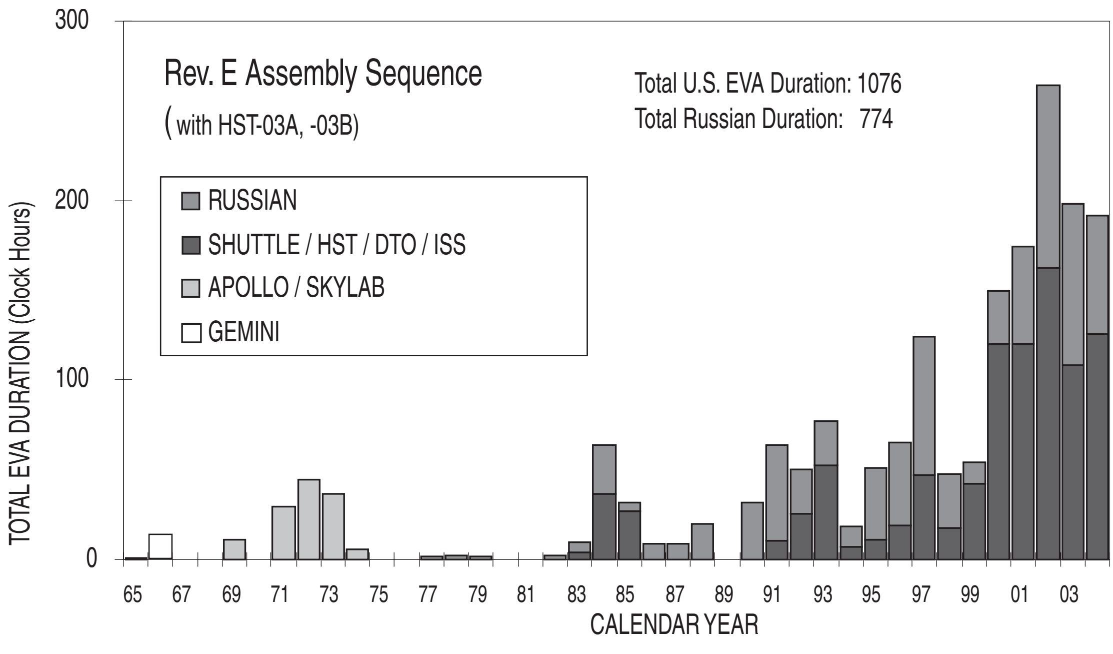


Figure 11.5 | The "Wall of EVA" illustrating the history of EVA and the three-fold increase in EVAs required for ISS assembly.



conduct EVA and demonstrated the value of neutral buoyancy simulation for extended-duration training in weightlessness. During the Apollo program, EVA became a useful mode of functioning in space, rather than just an experimental activity. Twelve crew members spent a total of 160 h in spacesuits on the moon, covering 100 km (60 mi) on foot and with the lunar rover, while collecting 2,196 soil and rock samples. The Apollo EVAs were of unprecedented historical importance as Neil Armstrong and Buzz Aldrin became the first humans to set foot on another celestial body. The EVA spacesuits were pressurized to 26.2 kPa (3.9 lb/in^2) with 100 percent oxygen, and the Apollo cabin pressure was 34.4 kPa (5 lb/in^2) with 100 percent oxygen. During pre-launch, the Apollo cabin was maintained at 101.3 kPa (14.7 lb/in^2) with a normal air (21 percent oxygen and 79 percent nitrogen) composition. Just before liftoff, the cabin was depressurized to 34.4 kPa (5 lb/in^2). To counteract the risk of decompression sickness after this depressurization, the astronauts prebreathed 100 percent oxygen for 3 h prior to launch (this will be discussed in greater detail subsequently).

The potential benefits of EVA were nowhere more evident than in the Skylab missions. When the crew first entered Skylab, the internal temperature was up to 71°C (160°F), rendering the spacecraft nearly uninhabitable. The extreme temperatures resulted from the loss of a portion of the vehicle's outer skin as well as a lost solar panel. After failure of a second solar panel deployment and the consequent loss of power and cooling capability, astronauts Joseph Kerwin and Charles "Pete" Conrad salvaged the entire project by rigging a solar shade through the science airlock and freeing the remaining solar panel during EVA. The paramount flexibility offered by humans performing EVA to accomplish successful space missions, operations, and scientific endeavors was realized during Skylab.

Cosmonaut Georgi Grechko performed a critical EVA to examine the cone of the Salyut 6 docking unit that was thought to be damaged. Additional EVAs were performed during Salyut 6 in order to replace equipment and to return experimental equipment to Earth that had been subjected to solar radiation for 10 months. The success of the Salyut 6 program during 1977–1981 brought about the Salyut 7 space station program. Successful astronaut EVAs were performed to continue studying cosmic radiation and the methods and equipment for assembly of space structures. Ten EVAs were performed during the Salyut 7–Soyuz missions; experience and expertise in space construction, telemetry, and materials science were gained. On 25 July 1984 during her second spaceflight (her first flight was in August 1982), cosmonaut Svetlana Savitskaya became the first woman to perform an EVA, during which she used a portable electron beam device to cut, weld, and solder metal plates.[2]

EVAs that were performed during Space Shuttle (officially called the STS or Space Transportation System) missions have accomplished many significant tasks to enable long-term human space exploration. During these missions,

2. Of historical note is the flight of Valentina Tereshkova, the first woman in space. She flew on Vostok 6, launched 16 June 1963 and landed 19 June 1963.

trained crew members have responded in real time to both planned mission objectives and unplanned contingencies. Evaluation and demonstration of the Extravehicular Mobility Unit (EMU), a 29.6 kPa (4.3 lb/in^2) spacesuit; the Manned Maneuvering Unit (MMU); the Safety Aid For EVA Rescue (SAFER); the Remote Manipulator System (RMS); and specialized tools have resulted in the repair of modules, the capture and berthing of satellites, and the assembly of space structures. The Shuttle EMU is self-contained; therefore, an umbilical for its life support and communications systems is unnecessary. Advanced spacesuit concepts incorporate self-contained life support systems (both the U.S. and Russian spacesuits) and modular components (the U.S. spacesuit). Modularity allows for ease of resizing to fit humans ranging in size from 5th-percentile females to 95th-percentile males, a distinct advantage over the custom-fitted suits previously used.

The Hubble Space Telescope (HST) EVAs set numerous records during five consecutive days of EVA. Astronauts F. Story Musgrave (payload commander), Jeff Hoffman, Thomas Akers, and Kathryn Thornton replaced failed rate sensors (containing gyroscopes used to point Hubble precisely), electronic control units, solar arrays, Hubble's wide field/planetary camera, and a second set of corrective optics. This EVA rescue mission has been followed by others just as successful for continuous Hubble repairs and upgrades.

EVA has been successfully and continually performed by Russian cosmonauts. Yuri Romanenko and Alexander Laveikin performed an unscheduled EVA on 12 April 1987 in order to solve a docking problem between the Mir and Kvant modules. Prior to the contingency EVA, a rehearsal by backup cosmonauts in the hydrotank facility in the Zvezdny Gorodok training center (better known as Star City) was performed. As a result, cosmonauts Romanenko and Laveikin were able to remove an obstruction (most likely a sheet) that was fouling the docking system. Docking between Kvant and Mir was accomplished, and the mission was salvaged [114]. An exciting EVA took place on 18 July 1990 when cosmonauts Alexander Balandin and Anatoly Solovyov exited the Mir space station and used a small ladder extended from the Kvant 2 module to the Soyuz TM-9 capsule in order to repair the shield-vacuum heat insulation blankets [115]. The ladder was employed in order to allow for maximum stability during the repairs. Problems developed during reentry to the station due to an improperly closed airlock and emergency entry occurred through a small secondary hatch [Radio Moscow in Russian, 17 July 1990]. Cosmonauts have fixed faulty hatches and worked on the Mir space station exterior repeatedly. Russian EVAs have been remarkable for their successful accomplishments near the end of long-duration flights, when physiological deconditioning is expected to be significant.

The Russian Orlan spacesuit, nominally operated at 40.6 kPa (5.88 lb/in^2) with the capability for short-term operation at 27.6 kPa (4 lb/in^2), is used for EVA. During periods when increased hand/finger dexterity is required, spacesuit pressure may be decreased for short periods, but this has only been done twice and is generally not an option that is utilized. The pressure was lowered once to ingress an airlock during a tight fit, and the second time the pressure was accidentally lowered.

Successful EVAs to date have been accomplished with crew members wearing a variety of spacesuits. These spacesuits have evolved from the umbilical models of the Voskhod and Gemini era into the self-contained, modular spacesuits currently used. Further spacesuit evolution will yield advanced spacesuits for microgravity, lunar, and Martian environments. Section 11.4, "Spacesuit Design," describes the American EMU and the current Russian Orlan spacesuit, portrays the different design philosophies followed in the two programs, and suggests some tradeoffs for advanced spacesuit design.

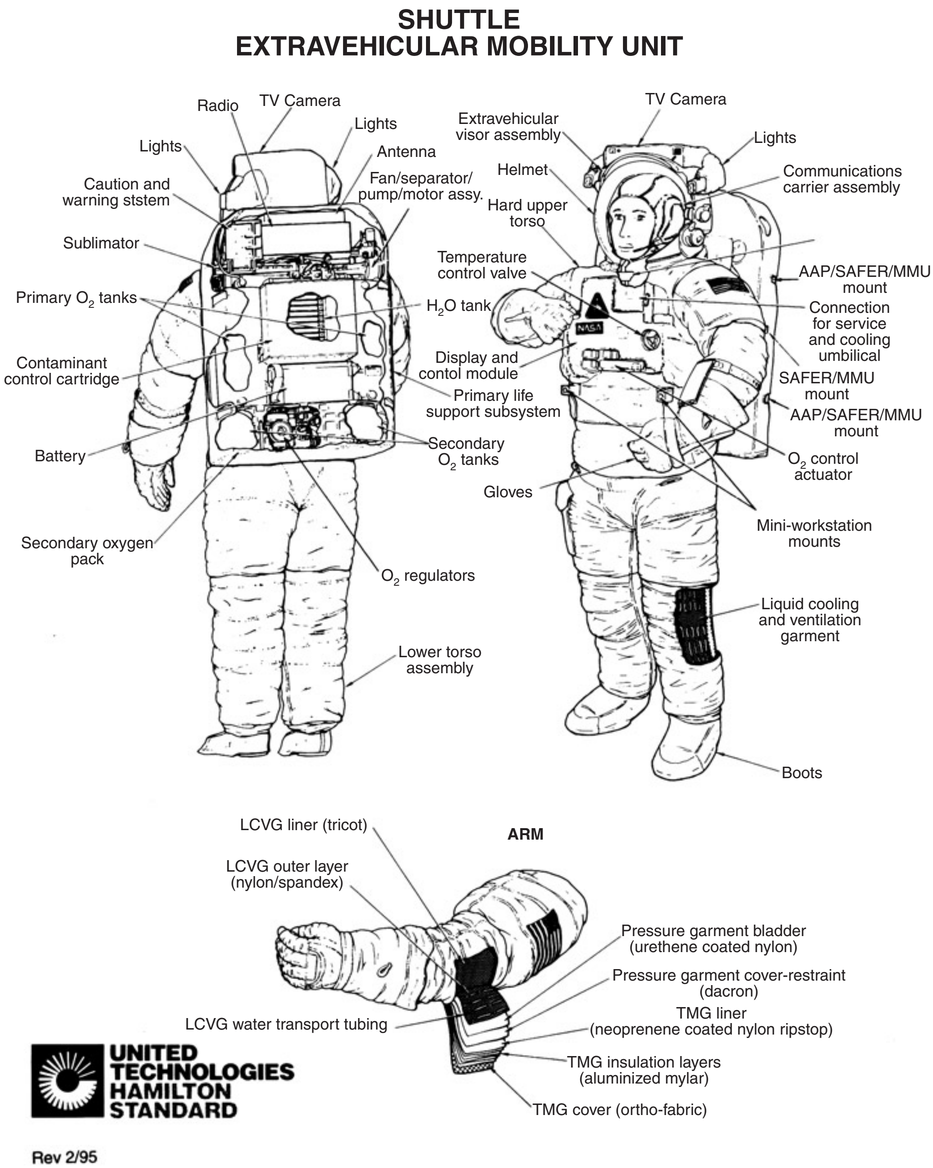
11.4 | SPACESUIT DESIGN

11.4.1 Space Shuttle Extravehicular Mobility Unit

The current Space Shuttle EVA system, known as the Extravehicular Mobility Unit or EMU, consists of a spacesuit assembly (SSA), an integrated life support system (LSS), and the EMU support equipment. The SSA is a 29.6 kPa (4.3 lb/in^2), 100 percent oxygen spacesuit made of multiple fabric layers attached to an aluminum/fiberglass hard upper torso unit (known as the HUT). The SSA retains the oxygen pressure required for breathing and ventilation and protects the crew member against bright sunlight and temperature extremes. The LSS controls the internal oxygen pressure, makes up oxygen losses due to leakage and metabolism, and circulates ventilation gas flow and cooling water to the crew member. The LSS also removes the carbon dioxide, water vapor, and trace contaminants released by the crew member. The spacesuit and life support system weigh approximately 118 kg (260 lb$_m$) when fully charged with consumables for EVA [116]. The EMU support equipment stays in the airlock during an EVA; primary functions are to replenish consumables and to assist the crew member with EMU donning and doffing (putting on and taking off). The EMU spacesuit components are discussed in greater detail below and shown in Figure 11.6.

The HUT is the primary structural member of the EMU. The helmet, arms, lower torso assembly (LTA), and primary life support system (PLSS) all mount to the HUT. The HUT incorporates scye bearings to accommodate a wide range of shoulder motions. The spacesuit helmet is a transparent polycarbonate bubble that protects the crew member and directs ventilation flow over the head for cooling. The helmet neck ring disconnect mounts to the HUT. The helmet is equipped with a visor that has a movable sunshade as well as camera and light mounts. The crew member's earphones and microphones are held in place by a fabric head cover, known as the "Snoopy cap." The spacesuit arms are fabric components equipped with upper arm, elbow, and wrist bearings that allow for elbow extension and flexion as well as elbow and wrist rotations. The LTA includes the legs and boots and is equipped with a bearing that allows waist rotation while the fabric legs permit hip and knee flexion. The PLSS, or backpack, houses most of the LSS and a two-way AM radio for communications and bioinstrumentation monitoring. Typically, EVA is scheduled for up to 6 h, but the PLSS is equipped with 7 h of oxygen and carbon dioxide scrubbing capability for nominal metabolic rates. A secondary oxygen pack located at the bottom of

Figure 11.6 | The NASA spacesuit, or extravehicular mobility unit (EMU).



the PLSS provides an additional 30 min (minimum) of oxygen at a reduced pressure of 26.9 kPa (3.9 lb/in^2) in case of an emergency. A silver–zinc cell battery powers the LSS machinery and communications and is recharged in place between EVAs. All the displays and controls for the crew member to activate and monitor are mounted on the front of the HUT. The temperature control valve is on the crew member's upper left, and the oxygen control actuator is on the lower right. The large controls are designed to be simple to operate, even by a crew member wearing pressurized spacesuit gloves. The spacesuit is equipped with a disposable urine collection device.

Metabolic expenditures and crew performance during EVA are integrally tied to the mobility of the spacesuit and the capabilities of the life support system. The liquid cooling and ventilation garment (LCVG) is the innermost layer of the spacesuit and provides thermal control by circulating air and water (cooled by a sublimator) over the crew member's body. The LCVG can handle peak loads of up to 500 kcal/h (2,000 Btu/h) for 15 min, 400 kcal/h (1,600 Btu/h) for up to 1 h, or 250 kcal/h (1,000 Btu/h) for up to 7 h. Average metabolic rates for past missions are included in Table 11.2.

Table 11.2 | Average metabolic rates for past space missions [117, 118, 119]

Spacesuit	Gravity (*g*)	Metabolic rate (kcal/h)
Apollo	1/6	235 (suited)
	Microgravity	151 (cabin)
Skylab	Microgravity	238
Space Shuttle	Microgravity	197

The reduction in workload seen during the Shuttle missions is ascribable to the EMU itself, EVA support tools (i.e., foot restraints, handholds, and specialized tools), and EVA training. Most EVA training takes place underwater in the neutral buoyancy laboratory (NBL) at NASA's Johnson Space Center in Houston, Texas. Crew members extensively practice scheduled EVAs in the neutral buoyancy setting to simulate weightlessness.

Monitoring of carbon dioxide concentration and other suit parameters occurs via telemetry to the ground, with updates every 2 min. Carbon dioxide is kept below 0.99 kPa (0.15 lb/in^2) and is absorbed by lithium hydroxide canisters. Electrocardiographic leads are worn to allow constant monitoring of the heart rate and rhythm throughout the EVA. To provide sustenance for the crew member, a food bar and up to 21 oz of water are provided in the EMU.

The spacesuit gloves are the crew member's interface to the equipment and tools that he or she uses. The EMU gloves connect to the arms at the wrist joint. The gloves have jointed fingers and palm. The EMU glove includes a pressure bladder, a restraint layer, and the protective thermal outer layer. The glove fingertips are made from silicone rubber caps to enhance tactility. The design of the gloves is the hardest engineering problem in spacesuit design. A dexterous spacesuit glove that provides ideal finger motion and feedback has not yet been realized.

EMU Spacesuit Construction This section briefly describes the EMU fabric, or soft goods, construction. The fabric components of the EMU are made from numerous layers. The crew member first puts on the LCVG, which is the innermost garment and resembles a pair of long underwear. The LCVG is made of nylon/spandex which is lined with tricot. Ethylene-vinyl-acetate plastic tubing is woven throughout the spandex to route the water close to the crew member's skin for body cooling. Next, the spacesuit has pressure garment modules to retain pressure over the arms, legs, and feet. These pressure garment modules are made of urethane-coated nylon and are covered by a woven dacron restraint layer. Sizing strips are used to adjust the length of the restraint layer. The thermal meteoroid (protection) garment (TMG) comprises the final layers of the EMU fabric components. The TMG liner is neoprene-coated ripstop nylon, and it provides puncture, abrasion, and tear protection. The next five layers are aluminized mylar thermal insulation which prevents radiant heat transfer [116]. The outer layer is the familiar white covering to the spacesuit, and it is made of ortho fabric, which consists of a woven blend of Kevlar and nomex synthetic fibers. The ortho fabric itself is very strong and resistant to puncture, abrasion, and tearing and is coated with Teflon to stay clean during training on Earth. Sunlight is reflected by the white color of this outer TMG layer. The TMG covers the entire EMU except the helmet, controls and displays, and glove fingertips. The TMG and LSS cooling system limit skin contact temperature to the range of 10 to 45°C (50 to 113°F), and additional thermal mittens are used for grasping objects whose temperatures can range from −118°C (−180°F) on the shadow side of an orbit to +113°C (+235°F) on the light side of an orbit. The following section provides an analytical tutorial on the design of EMU fabric components.

11.4.2 EMU Spacesuit Design Tutorial

This section analyzes design issues related to the cylindrical fabric components of the EMU (the limb components). Specifically, basic equations for volumetric, thermodynamic, and work requirements as they pertain to spacesuit design are presented. The calculations give the reader a feel for real numbers and may be useful for design projects (adopted from [117]).

Assume a simple cylindrical shape for the fabric EMU components. As the astronaut bends the suit joint, the fabric cylinder develops folds on the inner side of the bend and the outer side remains at its initial length. This bending action causes the volume of the joint to decrease, and the work required W is the force F required to bend the cylinder times the distance d through which the force acts [see Equation (11.1)]. The work can also be viewed as the work required to decrease the volume plus the work required to bend the fabric. From experience, the latter is a small force (e.g., not noticeable during a typical joint movement).

$$W = Fd \qquad \textbf{[11.1]}$$

From thermodynamics, in a constant-pressure process, the work required to change the volume of gas is given by Equation (11.2) [the EMU spacesuit is regulated to stay at a constant pressure of 29.6 kPa (4.3 lb/in^2)]:

$$W = \int_1^2 -p\, dV = -p(V_2 - V_1) = p(V_1 - V_2) \qquad [11.2]$$

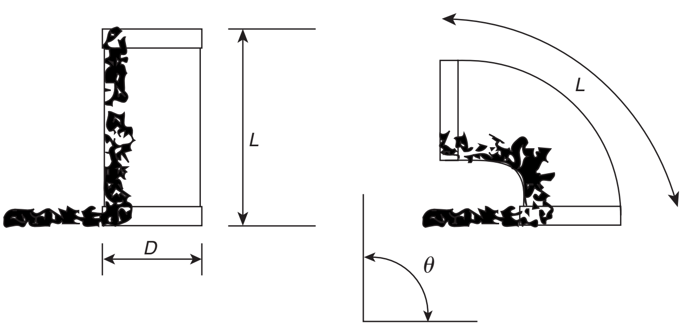
where p is pressure and V is volume. The initial volume V_1 of the joint is the area of the cylinder cross section A times the joint length L:

$$V_1 = AL = \frac{\pi}{4} D^2 L \qquad [11.3]$$

where D is the cylinder diameter.

Assuming that the cross section remains circular and the inner and outer edges can be approximated as circles, the final volume V_2 of the joint can be calculated as the area of the cross section times the centerline length C of the deformed joint, as seen in Figure 11.7 and represented by Equation (11.4).

Figure 11.7 | Cylindrical fabric spacesuit component upright (left) and deformed joint (right).



$$V_2 = AC = \frac{\pi D^2}{4}\left(L - \frac{D\theta}{2}\right) = \frac{\pi D^2 L}{4} - \frac{\pi D^3 \theta}{8} \qquad [11.4]$$

where θ is the deformation joint angle. Substituting into Eqn. (11.2) yields

$$W = p(V_1 - V_2) = p\left[\frac{\pi D^2 L}{4} - \left(\frac{\pi D^2 L}{4} - \frac{\pi D^3 \theta}{8}\right)\right] = \frac{p\pi D^3 \theta}{8} \qquad [11.5]$$

The joint activation force can be calculated from this expression if an approximation is made for the length through which the activation force operates. Using a reasonably good approximation for this distance $L\theta/2$ leads to

$$F = \frac{W}{d} = \frac{p\pi D^3\theta/8}{L\theta/2} = \frac{p\pi D^3}{4L} \qquad [11.6]$$

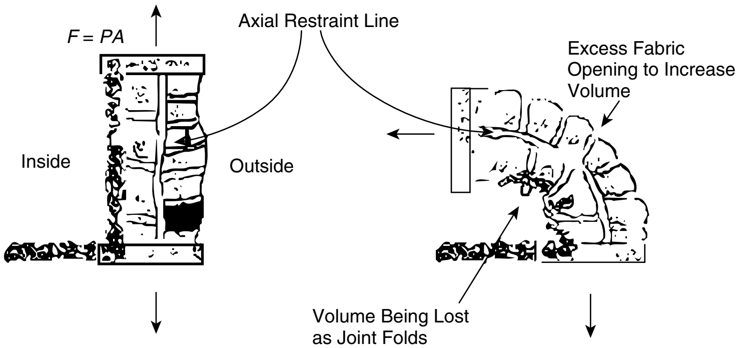
By using Equation (11.6), the forces for the various joints in a spacesuit are calculated and tabulated in Table 11.3. These data reveal joint operation forces which are almost at the crew member's maximum capability, or in the case of the waist joint, show that waist bending would be impossible. That is why the Gemini spacesuit incorporated a block-and-tackle arrangement to allow for bending at the waist. The crew members would tire very rapidly if abiding by the required forces in these calculations. Table 11.3 also reveals the design specification of the EMU. From the past discussion it is easy to see why the secret of spacesuit design lies in the ability to maintain constant volume. Obviously, the EMU designers do an excellent job at keeping constant volume in the suit.

Table 11.3 | Calculated forces for spacesuit joints

Joint	Diameter *D* [cm (in)]	Length *L* [cm (in)]	Force calculated [N (lb)]	Force design [N (lb)]	Human capability [N (lb)]
Finger	2.5 (1)	5.1 (2)	7.6 (1.7)	—	31–71 (7–16)
Wrist	10.2 (4)	12.7 (5)	192.2 (43.2)	—	—
Elbow	12.7 (5)	20.3 (8)	235.0 (52.8)	6.7 (1.5)	155.8 (~35)
Knee	15.2 (6)	12.7 (5)	405.8 (91.2)	6.7 (1.5)	—
Waist	45.7 (18)	30.5 (12)	7,302 (1,641)	17.8 (4)	890 (200)

There are several ways to accomplish the design of a constant-volume fabric component. The EMU is constructed so that as the volume of the fabric component decreases inside, it increases by the same amount outside the joint. This is accomplished by holding the centerline of the joint at constant length instead of the outside of the joint. An elbow joint designed on this principle looks like the diagram in Figure 11.8. The axial restraint lines, located across the diagonal of the fabric cylinder, take the pressure load that tries to elongate the joint. This prevents the fabric cylinder part of the joint from carrying that load and allows for excess fabric to be placed on the outside of the joint. Without the axial restraint line, the pressure would cause the joint to elongate until all the excess fabric were placed in tension. As the joint is bent with use, the inside of the joint folds up just as it did in the fabric cylinder. As that happens, the outside of the joint where the excess fabric has been placed expands to compensate for the lost volume. The flexed joint is depicted in Figure 11.8. If this figure is considered as a free-body diagram of a spacesuit joint, careful observation shows that the forces are not balanced. In practice, a spacesuit joint does not bend so that the centerline is in the shape of a circle, as shown in the figure; but rather, the centerline shifts slightly to the outside and compensates for the otherwise unbalanced forces. In addition, the axial restraint lines are not placed exactly at the joints'centerline, but they are slightly offset so that the joint will be balanced and stable. If the placement of the axial restraint line is not done carefully, either the joint is very difficult to bend, or it might actually bend itself over when pressurized. Therefore, well-designed joints are stable and remain where they are placed with little restraining or springback force.

Figure 11.8 | Spacesuit elbow joint with constant centerline length and flexed spacesuit joint. The force trying to elongate the joint due to spacesuit internal pressure, $F = PA$.



11.4.3 Russian EVA Spacesuit

EMU spacesuit model in QTVR.

The current spacesuit used for Mir space station EVAs is a derivative of the semirigid suit used during the Salyut–Soyuz program.The Orlan spacesuit has undergone continuous modification and is a fifth-generation model currently used for EVA operations. Similar to the American EMU, the Orlan spacesuit has an integrated life support system to enable EVA operations from Mir. As previously stated, the 100 percent oxygen spacesuit nominally operates at 40.6 kPa (5.88 lb/in^2). The spacesuit weighs approximately 70 kg (154 lb) [121], but that is only suit weight without a fully charged PLSS. It is an adjustable, universally sized suit with a metal upper torso and fabric arms and legs. Metal ball bearings and sizing adjustments are notable suit features. An advancement and difference from the EMU is the entry into the Orlan which occurs through a rear hatch, with unassisted spacesuit entry requiring 2 to 3 min [122].

The spacesuit has self-contained integrated pressure and O_2 systems in the PLSS. The suit has a backpack-type PLSS which can be maintained on orbit. The oxygen supply system includes reserve oxygen storage and equipment for controlling and maintaining the pressure. The ventilation system and environmental gas composition control system include CO_2 and contaminant removal units along with gas circulation control equipment. The spacesuit has no umbilical lines. Oxygen, water supplies, pumps, and blowers are located in the cover of the rear hatch.

Adequate microclimate conditions in the suit are provided by a closed-loop regenerative life support system. The suit's thermal control system maintains the cosmonaut's body temperature and humidity level within acceptable limits and utilizes an efficient sublimating heat exchanger. The LCVG concept was initially used for thermal control by English fighter pilots and was later adopted by the Russian and U.S. space programs. The cosmonaut wears a liquid-cooled garment comprised of a network of plastic tubes. The temperature can be maintained manually on a comfort basis or automatically by the spacecraft temperature regulation system. The heat exchanger and LCVG provide a nominal thermal mode for sustained operation at practically any metabolic workload [121]. Materials and colors which reflect strong solar radiation are used, and the spacesuit has layers of protection against extreme temperatures. The non-hermetically sealed outside layer is a protective vacuum insulator. The hermetically sealed inside layer is a special rubber suit that retains the pressure.

In summary, the spacesuit's designer, Guy Severin of Svezda, lists the following seven attributes of the semirigid Orlan spacesuit [121]:

1. Minimal overall dimensions of suit torso in a pressurized state.
2. Ease of rapid donning/doffing.
3. Easy handling capabilities and improved reliability of lines connecting the life support system and suit.
4. Reliability of hatch sealing system.
5. Single spacesuit for crew members of different anthropometric dimensions.
6. Easy replacement of consumable elements.
7. Easy maintainability due to ease of access to units.

Severin has stated that future Russian spacesuit research and development activities are aimed toward improving suit performance characteristics (specifically mobility), decreasing the payload weight delivered to orbit in order to replenish spacesuit consumables, extending the spacesuit operating life, and using microprocessors to control and monitor spacesuit systems. Ideas to decrease the necessarily delivered payload weight include regeneration of CO_2 absorbers, heat removal without evaporative water loss, decreasing spacesuit O_2 leak rates, and use of advanced O_2 supplies [121].

11.4.4 Different Design Choices

Many instructive design lessons emerge from a comparison of the U.S. and Russian spacesuits. Foremost among them is that NASA has had a different spacesuit design for each of its main human spaceflight programs (except Apollo/Skylab and Shuttle/ISS) whereas the Russians have had essentially one evolutionary spacesuit throughout their human spaceflight programs. This is a design choice—there is no right or wrong answer, perhaps a different philosophy. In the case of NASA's spacesuits, many industrial and academic partners have had influence on the multiplicity of unique designs selected for each human spaceflight program. In Russia, *the* spacesuit designer was looked to to provide *a* spacesuit, and then that suit was adopted and enhanced for various programs. The former brings about creativity and cost savings as the most unique and lowest bidder is typically awarded the contract for the suit. The latter philosophy relies on an original design from a master designer that is tested throughout time and altered very little, resulting in a robust, reliable system.[3]

3. The NASA and Russian space programs have followed similar design philosophies for space vehicles as well as spacesuit where NASA typically designs and builds a new craft for each major program and the Russians rely more on mass production of similarly designed evolutionary spacecraft.

The *need* always drives the design requirement, and the *requirements* are met by a successful design. Both the EMU and Orlan spacesuits meet the need of providing life support for the crew members while performing extravehicular activity. The design requirements of a spacesuit can be deduced from Section 11.4.1 and Section 11.4.3 and might be summarized as follows:

- To provide life support for the extravehicular crew member including pressure, oxygen supply, carbon dioxide and trace gas removal, humidity and temperature control, environmental protection.
- To provide mobility and dexterity to successfully accomplish EVA tasks, especially in the gloves.
- To create a system that is as light as possible.
- To provide continuous operation for the duration of the EVA excursion.

Both the EMU and Orlan spacesuits meet the design requirements, although much improvement could be realized in the second and third requirements. Each suit has its own strengths and limitations. For example, the EMU provides better mobility than the Orlan primarily because of the lower operating pressure, which allows greater joint and glove motion in the EMU. A secondary reason for the enhanced mobility is the incorporation of advanced materials into the EMU design, which also extends the spacesuit design life. However, when we consider donning and doffing (putting on and taking off) the spacesuit, the Orlan design is clearly superior to the EMU design. The Orlan rear hatch entry allows the crew member to don and doff the spacesuit individually, whereas in theory a single crew member can don and doff the EMU, but in practice, it requires the EVA crew member and an assistant to get into the two-piece spacesuit. The Orlan system has a distinct advantage over the EMU in terms of lower mass, hence lower weight. For space station operations in a weightless environment, designers tend to discard mass as a critical spacesuit design requirement; but for a future planetary spacesuit, a low-mass suit will most likely result in the most promising design.

Table 11.4 compares the different design outcomes of the EMU and Orlan spacesuits, both with advantages and disadvantages.

IntelEMU

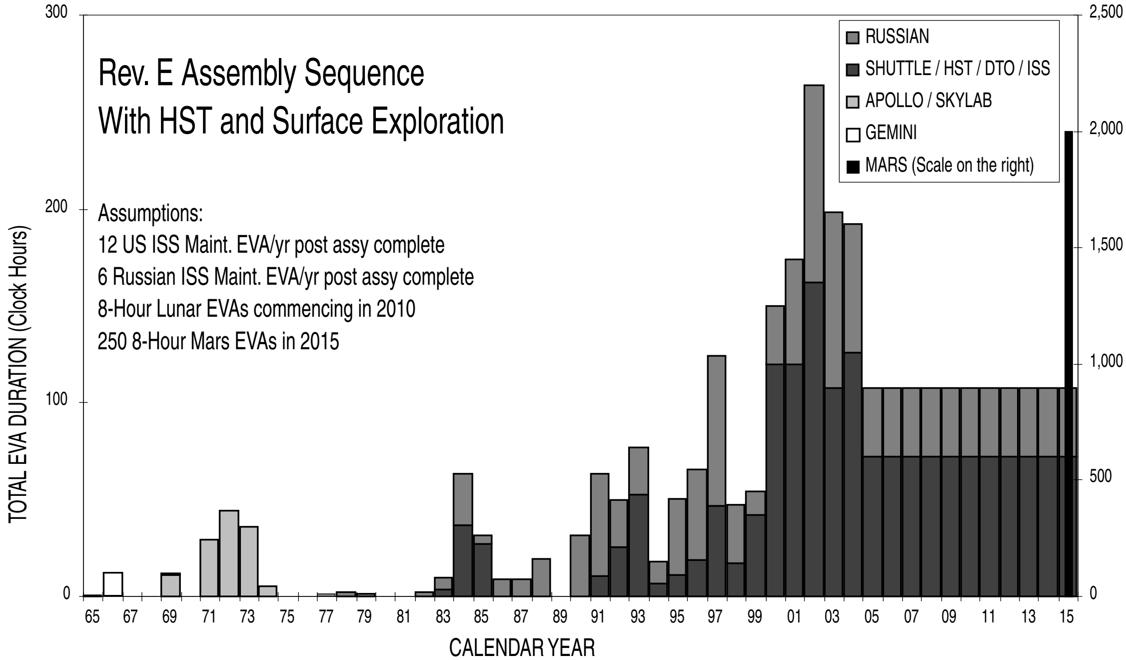
11.4.5 Advanced Spacesuit Considerations

Realizing the benefits and limitations of existing spacesuits, future EVA suits should incorporate technologically advanced designs. Increased levels of EVA capability will be required for the extensive construction and maintenance of future space stations as well as for planetary EVA. To meet the threefold increase in number of EVAs for ISS assembly (recall Figure 11.5, "the wall of EVA") and a possible 40-fold increase for planetary EVA (see Figure 11.9), *revolutionary* spacesuit design concepts should be considered. An advanced spacesuit might be more like everyday clothes or something radically different such as a pod with robotic actuators. There is no rule that future spacesuit designs should look similar to current suit designs. The only design *rule* is that the spacesuit requirements be met through an innovative design. Ideally, advanced spacesuits will provide the crew member with a protective, mobile, regenerable life support system for use in orbit, as well as on planetary surfaces.

Table 11.4 | Comparison between the U.S. and Russian spacesuit [123], p.43

NASA Space Shuttle Extravehicular Mobility Unit	Orlan-DMA Spacesuit
Manufacturer	
United Technologies, Hamilton Sundstrand Windsor Locks, CT	Zvezda Research, Development, and Production Enterprise Tomilio, Russia
Suit operating pressure	
30 kPa (4.3 lb/in^2) differential	40 and 26 kPa (5.8 and 3.8 lb/in^2) differential
Nominal maximum mission duration	
7 h	6 h
Emergency life support useful life	
30 min	30 min
Sizing	
Modular assembly to fit 5th-percentile female to 95th-percentile male	One adjustable size with axial restraint system allowing on-orbit sizing
11 suit assembly items	Two glove sizes
Construction of suit assembly	
Urethane-coated, nylon pressure bladder	Semirigid with latex-rubber dual pressure bladder in arms and legs
Ortho fabric and aluminized Mylar thermal/meteoroid garment	Dual-layer helmet
Fiberglass hard upper torso	Dual-seal bearings in shoulder and wrist
Ball-bearing joints	Liquid-cooling undergarment
Liquid cooling/ventilation undergarment	Rear-entry suit design
Polycarbonate helmet and visors	On-orbit limb sizing
Construction of life support system	
Closed-loop, pure oxygen, regenerative	Closed-loop, pure oxygen, regenerative
Seven interchangeable subsystem modules	On-orbit servicing through rear-entry door
Expendables replaceable or rechargeable on orbit	Redundant life-critical features
Donning	
15 min (typically with assistance)	Self-donning, rapid
Weight	
117 kg (258 lb$_m$)	105 kg (231 lb$_m$)
Work aids	
Compatible with: Workstations Manual and power tools Helmet-mounted TV and lights Tethers and foot restraints Manned maneuvering unit Self-rescue device	Compatible with: Workstations Manual and power tools Helmet-mounted lights Tethers and foot restraints Manned maneuvering unit
Design life	
Up to 30 years with maintenance	4 years / 10 missions

Figure 11.9 | Possible EVA requirements for a planetary mission where HST is Hubble Space Telescope and DTO stands for a detailed test objective, or additional EVA opportunities.



Advanced spacesuits should provide the following: working pressures that allow shirtsleeve mobility, dexterous gloves or actuators, longevity, ease of maintenance, and adequate environmental protection. Mobile joint systems must allow for minimum energy expenditures during EVA tasks. Gloves should be certified for long-duration use at high pressures. Improved technology and materials should allow for durable spacesuit design. Advanced reliable primary life support systems should be regenerable, low-mass, and modular. A broad metabolic loading range between 63 and 625 kcal/h (250 and 2500 Btu/h) should be realized with automatic thermal control systems [124]. A modular, evolvable design is advantageous. Technological advances should lead to real-time environmental monitoring systems and innovative display and vision systems. A Martian EVA will most likely entail rappelling down shear cliffs and traversing monumental canyons. A radical new approach to spacesuit design could best realize these challenges.

11.4.6 Planetary EVA

MarsEVA.jpg

Microgravity EVA has been admirably demonstrated. While significant improvements are necessary for long-term space station EVA, quantum improvements are required for planetary EVA. In microgravity the crew member primarily uses her or his small musculature of the upper body to move about rather than the large musculature of the lower body. Planetary EVA dictates a true locomotion spacesuit because the large muscles of the legs will be called upon for locomotion in the $\frac{3}{8}\,g$ environment, and the upper body muscles will be relied upon for accomplishing EVA tasks other than self-locomotion. Apollo 17 EVA astronaut Harrison Schmitt praised the Apollo spacesuits for working without a serious malfunction for up to 22 h of exposure to the lunar environment, but his recommendations for future planetary spacesuits should be heeded. Jones and Schmitt [125] suggest that improvements in mobility and suit flexibility will have a significant impact on astronaut productivity. They also recount instances where "(lunar EVA) astronauts fell repeatedly" [125, p. 2] and state that improvements in manual dexterity and reduction of muscle fatigue and abrasion-induced damage to the hands would have the greatest impacts. The fine dust particles of lunar regolith caused notable problems with the Apollo suits, and dust will pose quite an obstacle when EVA is performed on a continuous, daily basis from lunar and Martian habitats. All these comments suggest that the future design and development of planetary spacesuits will be challenging. The following discussion lists additional issues to consider in planetary spacesuit design, which is followed by sections covering the mechanics of locomotion and experimental data for human performance in simulated partial-gravity environments. Based on the preliminary information presented in this planetary EVA section, the reader is encouraged to come up with novel design concepts for future lunar and Martian spacesuits.

Try to imagine what *a day in the life of a lunar astronaut/construction worker* might involve. One of the crew member's simplest tasks might be to set up a telescope. The astronaut would suit up in the airlock, assemble the necessary tools (including only the hand tools that can be carried—but what about necessary standard construction equipment such as bulldozers, loaders, and cranes?), leave the lunar habitat through the airlock, and begin the day's task. The construction worker either drives or uses self-locomotion to arrive at the site. In either case, a light, mobile spacesuit and LSS are required. Once at the site the crew member surveys the lunar terrain, which requires agility, traction, tools, and possibly illumination. The crew member probably has to move some lunar regolith and flatten the desired plot, and there is likely to be dust everywhere, fouling the spacesuit bearings and hampering the rover's machinery. Next, the crew member starts assembling the platform for the telescope. Once assembled, the platform is leveled, and the actual assembly of the telescope commences. The assembly of and adjustments to the telescope require extreme finger dexterity. It is evident that the simple task of deploying a telescope requires a rather involved EVA. Planetary EVAs for building habitats, setting up laboratories, and conducting field science are orders of magnitude more complicated than the cited example and will require EVA systems and crew member skills that do not currently exist.

Whatever the EVA task may be, the crew member must be provided with adequate life support, protection from the environment, and appropriate tools and equipment. The design requirements previously mentioned are still applicable to planetary spacesuits with a few additional requirements due to human factors. For our hypothetical planetary EVA, designs must ensure adequate mobility; natural, efficient locomotion; crew member balance and orientation; reasonable physical loads imparted on the crew member, the spacesuit, and the life support system; adequate lighting and power; and continued emphasis on dexterous spacesuit gloves. These requirements will only be met through extensive research and design efforts. Perhaps a spacesuit that incorporates mechanical pressure rather than air pressure will provide the crew member with a light, form-fitting spacesuit. If an optimal locomotion spacesuit cannot be realized, concepts like full-body enclosures with manipulators might prove to be successful. However, at this early stage in the conceptual design, the field is wide open and all designs and methodologies should be considered. The following section, "Mechanics of Locomotion," provides a brief introduction to the 1G mechanics of walking. This information is included to acquaint the reader with some characteristics associated with walking and to provide necessary 1G biomechanics background for the following section, "Human Performance in Partial-Gravity Environments."

Mechanics of Locomotion The notions of minimizing energy expenditure and forces are basic hypotheses behind human movement. The functional significance of the determinants of gait is to minimize vertical and lateral oscillations of the center of gravity (cg) during walking, thus minimizing energy expenditures and perhaps minimizing muscular force generation. There are numerous descriptions of the motions of the limbs during locomotion, and the six characteristics of walking that should be incorporated into the design of future locomotion spacesuits are presented.

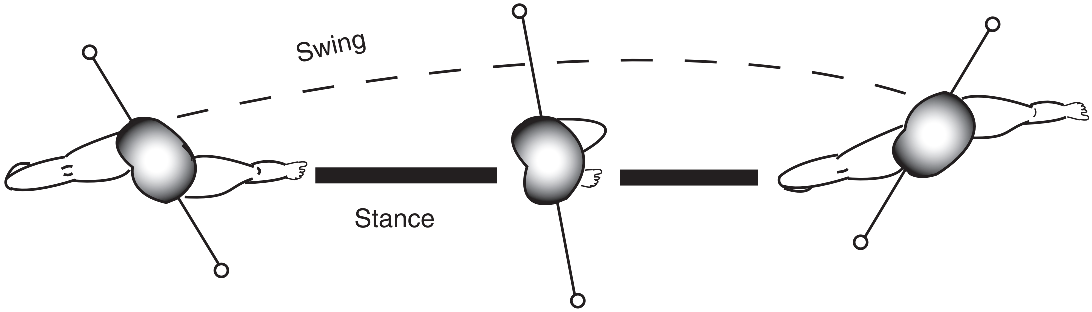
The six characteristics of walking include

- Pelvic rotation.
- Pelvic tilt.
- Knee flexion during the stance phase.
- Heel strike and heel-off interactions with the knee.
- Trunk lateral flexion.
- Trunk anteroposterior flexion.

The first distinguishing characteristic, *pelvic rotation,* describes the pelvis rotating from side to side about the body's longitudinal (vertical) axis for normal walking. During the swing phase of the leg, medial rotation at the weight-bearing (stance) hip advances the contralateral (swing-phase) hip (see Figure 11.10). The effective increased leg length from pelvic rotation lengthens the step and flattens out the arcuate trajectory of the cg, ensuring a smoother ride as the radii of the arcs of the hip increase; thus, a reduction in energy expenditure occurs. The pelvis is tilted downward about 5° on the swing-phase side. This occurs with pelvic adduction at the hip joint on the stance-phase side. *Pelvic tilt* further flattens the arcs of the hip, allowing for a smooth ride during walking.

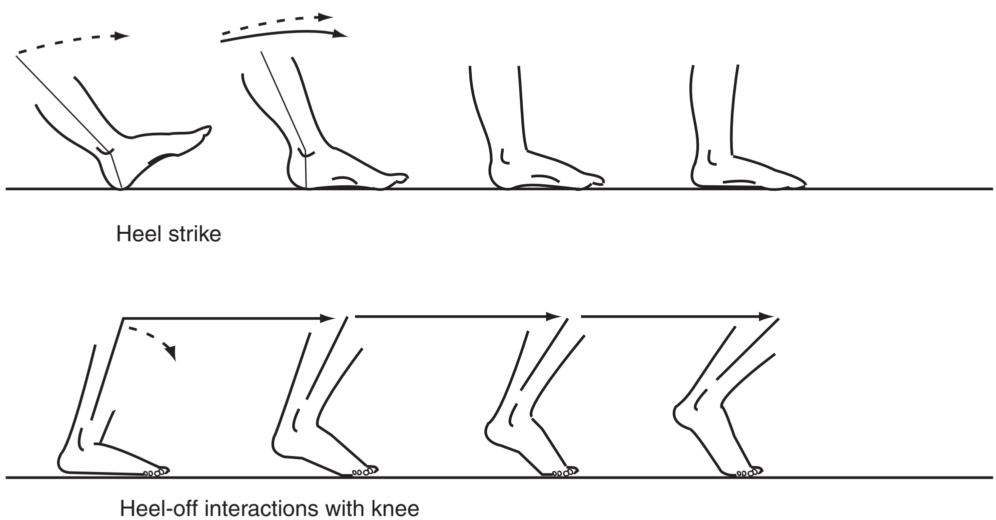
The third determinant of gait is *knee flexion* during the stance (support) phase. At heel strike the knee is extended, but then begins to flex. At heel-off, just prior to the middle of the support phase, the knee extends again. This extension-flexion-extension sequence reduces the excursion of the center of gravity's arcuate trajectory and absorbs shock during a stride cycle. If the knee joint is absent, the travel of the cg is not reduced, which is very costly in terms of energy expenditure. *Heel strike* and *heel-off interactions with the knee* comprise the fourth

Figure 11.10 | Pelvic rotation during walking. The pelvis is rotated from side-to-side about the longitudinal axis of the body.



characteristic of gait. At heel strike the foot plantar flexes (rotates downward about an axis formed at heel contact), thus lowering the ankle as the foot makes full contact with the ground (see Figure 11.11). A fused ankle joint (immobile) without plantar flexion would cause the cg to rise as if the leg were a stilt. Ankle plantar flexion affects gait similarly to ankle flexion in that the trajectory of the cg is reduced and shock absorption is noted at heel strike. The heel-off phase provides a horizontal cg trajectory as the ankle rotates upward about an axis formed at the ball of the foot. The *trunk flexes* both *laterally* and *anteroposteriorly* during walking to make up the final characteristics of walking. The ipsilateral flexion of the vertebral column toward the stance-phase side causes a 1 to 2 cm displacement. The anteroposterior flexion of the trunk reveals maximum backward flexion at the beginning of the support phase and maximum forward flexion toward the end of the support phase, resulting in small 1 to 2 cm deflections.

Figure 11.11 | Top. Heel strike. The foot plantar flexes which lowers the ankle as the foot contacts the ground. Bottom. Heel-off interactions with the knee. Heel-off keeps the excursion of the center of gravity to a minimum.



In sum, the characteristics of walking described above were seen to minimize oscillations of the cg and optimize efficiency during locomotion due to minimum energy expenditure. Many of the characteristics of gait absorb shock during a stride cycle, which has the effect of reducing the force exerted on the ground. This equivalently reduces the reactionary force on the skeletal system and human body. As applied to locomotion spacesuit design, recommendations are to provide a waist bearing that allows for both pelvic rotation and tilt; a knee joint to enable flexion; an ankle joint for plantar and dorsiflexion; and a hip/waist/upper body capability that accommodates trunk flexion. The next section reveals data from partial-gravity studies.

Human Performance in Partial-Gravity Environments This section highlights some experimental studies and provides data on human performance in partial gravity. Quantifying partial-gravity performance allows for efficient spacesuit and life support system designs. The three primary techniques to simulate partial gravity (before we make it back to the Moon or Mars) are underwater immersion, parabolic flight, and suspension. During underwater immersion tests, a neutrally buoyant subject is ballasted to simulate the desired partial-gravity loading. For example, one-sixth of the subject's body mass is added in ballast if a lunar simulation is desired. Water immersion offers the subject unlimited duration and freedom of movement, but the hydrodynamic drag is disadvantageous for movement studies. In parabolic flight, the NASA KC-135 aircraft or the Russian IL-76 aircraft is typically used to simulate partial gravity by flying Keplerian trajectories through the sky. This technique provides approximately 20, 30, and 40 s for microgravity, lunar gravity, and Martian gravity tests, respectively. Parabolic flight is the only way to affect true partial gravity on Earth, but experiments are expensive and limited in time. Many partial-gravity suspension systems have been designed and used since the Apollo program. The cable suspension method typically uses vertical cables to suspend the major segments of the body and relieve some of the weight exerted by the subject on the ground, thus simulating partial gravity. Suspension systems often afford the most economical partial-gravity simulation technique, but limit the degrees of freedom for movement.

View underwater, KC-135, and suspension partial gravity simulations on the CD-ROM.

Force traces help quantify the peak force exerted by a crew member during locomotion. These data pertain to spacesuit design as well as to the human physiologic effects of musculoskeletal deconditioning during long-duration spaceflight. There is a significant reduction in peak force during locomotion in partial gravity and a general trend toward loping (between a run and a skip) as gravity decreases from 1 G (see Figure 11.12). Figure 11.13 shows actual data from the Apollo 11 lunar mission. Stepping frequency is displayed for the Apollo 11 data, underwater simulated lunar gravity data, and 1 G data. There is scatter in the Apollo data, but the simulated lunar stepping rates are seen to correlate well with the actual Apollo data. The stepping frequencies at 1 G are significantly higher than the lunar stepping frequencies ($p < 0.05$). Since the time available to apply muscular force to the ground during locomotion is constant across gravity levels, a reduction in metabolic costs for low gravity levels is anticipated because the

Figure 11.12 | Locomotion force traces at 1 g, and simulated Martian gravity and lunar gravity showing a significant reduction in peak force (f_{max}) for each stride during Martian and lunar locomotion as compared to 1 G locomotion. The time of foot ground contact is denoted by t_c, time of flight (or aerial time, t_a), and the time for the entire stride, t_{stride}.

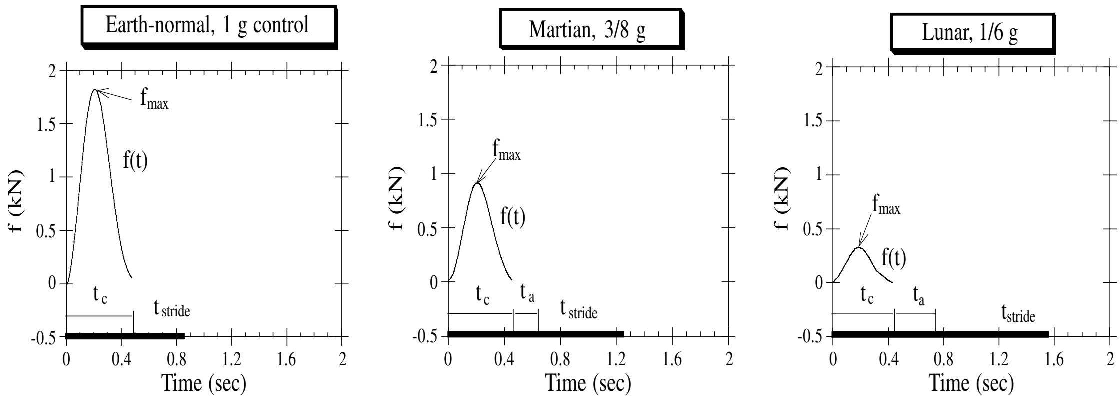
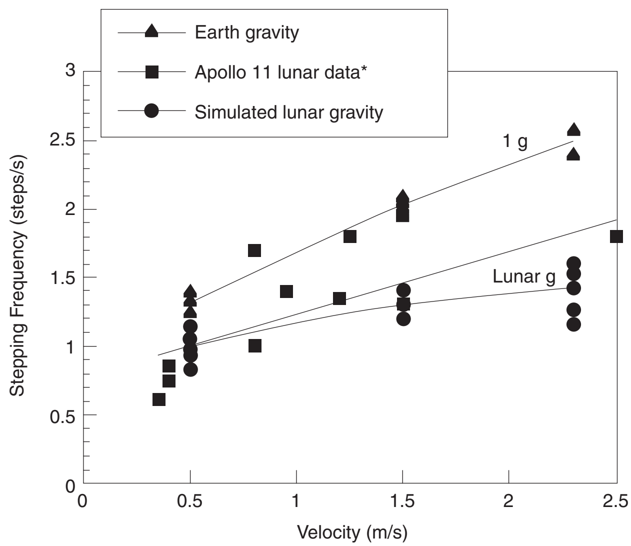


Figure 11.13 | Stepping frequency for Apollo 11 and simulated lunar gravity. Stepping frequency for terrestrial locomotion is also plotted. The Apollo data and simulated lunar data show a reduction in stepping frequency as compared to 1 G, especially for locomotion at velocities of 1.5 m/s and 2.3 m/s [126].



*Stone, R. W. (1971) Man in Space.

peak force results reveal that less muscular force is required for locomotion at reduced gravity levels. The combination of decreases in stride frequency and constant values of contact time also suggests an increase in aerial time for partial-gravity locomotion. A significantly extended aerial phase typifies loping in which subjects essentially propel themselves into an aerial trajectory for a few hundred milliseconds during the stride [126].

Recall that Section 11.4.6 claimed that the functional significance of the characteristics of gait is to minimize energy expenditures. Bioenergetics (oxygen consumption) data drive the design requirements for planetary EVA life support systems. Results show surprising information for partial-gravity locomotion. There exists a well-documented optimal cost of transport for terrestrial walking at the speed of 1 m/s [127]. In terms of metabolic expenditure, it costs about one-half the amount of energy to walk 1.67 km (1 mi) as it does to run 1.67 km. However, walking at 1 m/s is not the optimal method of transporting 1 kg of body mass over 1 m in partial gravity. Cost of transport for the lunar (1/6 G) and Martian (3.8 G) environments decreases as speed increases, suggesting that quicker locomotion is cheaper in terms of cost of transport. Results from underwater immersion and suspension simulators indicate that above 1/2 G, walking requires a lower cost of transport than running, but from 1/4 G to 1/2 G running is cheaper than walking [128, 129].

The successful design of future planetary spacesuits depends on providing improved mobility, improved glove performance, adequate operating pressures, improved radiation shielding, mass reductions, regenerable life support systems, and improved human/machine interfaces. Locomotion spacesuits should incorporate suggestions from past Apollo experience and current research efforts, keeping in mind the change in mechanics for locomotion in partial-gravity environments. The relationship between humans and machines is still undefined in EVA operations, and further research could lead to optimal mission planning with EVA crew members being assisted by robotics. Medical risks to the crew members will also be a driving force in planetary spacesuit design. Next Section 11.5 briefly discusses necessary life support system design requirements to ensure successful human space exploration.

11.5 | LIFE SUPPORT SYSTEMS

In examining some of the normal physiological and potentially adverse aspects of human spaceflight, one need only peruse the list of human requirements given in the previous sections and speculate on the effects of partial or complete system failures. In terms of life support, we would like to provide the essentials: air, water, food, and habitability as well as address the necessary physical factors that affect living in space, namely, thermal, pressure, vibration, noise, radiation, and gravitational requirements.

Life support functions fall into two categories: nonregenerative and regenerative, where the amount of system closure is denoted as ranging from open loop to closed loop. In an open-loop life support system, matter continuously flows in and out of the system. Air, water, and oxygen are supplied from stored sources. The quantity of resources supplied equals the quantity of resources used. The advantage of open-loop LSSs is that they are simple and use highly reliable technologies. The disadvantage is that resource requirements continue to increase linearly with space mission duration and crew size. Moving from a completely open LSS toward some closure might take on the following scenario, where the initial supplies are from Earth, and then the non-useful waste products are processed on orbit to recover useful resources. As loop closure increases, resupplied quantities decrease. The advantage of closed LSSs is a one-time-only transport of mass to orbit with minor resupply of irrecoverable losses. The disadvantages are that the technology is at a lower maturity level, and there are increased power and thermal requirements onboard the spacecraft. Closed-loop regenerative functions can be performed with physical chemical systems, which traditionally have been used. They are well understood and compact, require low maintenance, and have quick response times. The downside of physical chemical LSSs is that they consume a lot of energy (expensive to produce) and cannot replenish food stocks (they must still be resupplied), and solid wastes must be collected, pretreated, and stored. On the other hand, biological (or bioregenerative) LSSs are less well understood, but offer the potential to provide food during a space mission. Bioregenerative systems tend to have large volumes, are power- and maintenance-intensive, and have slow response times. This leads us to consider the design requirements between open and closed life support systems [130].

An iterative process can be followed to evolve from an open- to closed-loop LSS. Tradeoffs between reduced resupply of closed-loop systems and the high cost, power, and volume must be considered. When considering what amount of closure is optimum, we see that the answer is clearly mission-dependent and involves multiple steps. First, we should determine human requirements and critical life support functions to be provided. Then we should identify the necessary LSS technologies and finally select the appropriate technologies. Suggested design criteria to be evaluated include

- Relative cost of power, weight, and volume.
- Availability of in situ resources.
- Resupply capability.
- Crew size.
- Mission duration.

The six major life support subsystems for a human mission are outlined, using the planned space station LSS as an example:

1. Atmosphere control and supply (ACS)
   - O_2N_2 storage, distribution and resupply, venting, relief, and dumping
   - O_2N_2 partial and total pressure control
2. Atmosphere revitalization (AR)
   - CO_2 removal
   - CO_2 reduction

- O_2 generation
- Trace chemical contamination control and monitoring

3. Temperature and humidity control (THC)
- Air temperature control
- Thermal conditioning
- Humidity control
- Ventilation
- Equipment air cooling
- Airborne particulate and microbial control

4. Water recovery and management (WRM)
- Urine water recovery
- Washwater processing
- Potable water processing
- Water storage and distribution
- Water quality monitoring

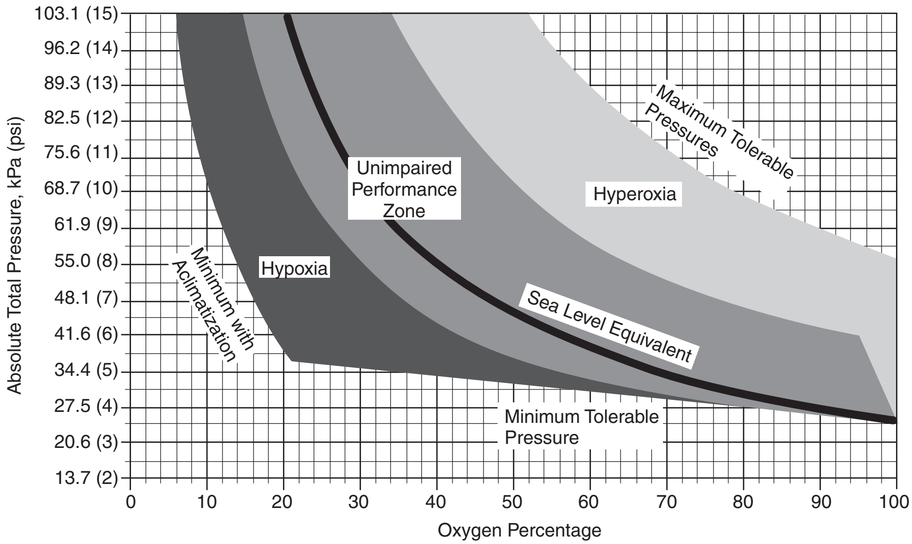
5. Waste management (WM)
- Fecal waste collection
- Processing and storage
- Fecal return waste storage and handling

6. Fire detection and suppression (FDS)
- Fire detection and fire suppression

Atmosphere production, revitalization, and water recovery are basic functions that are part of most scenarios for future human missions. All space vehicles, habitats, and spacesuits must provide essential LSS functions to the crew. A simple but vital concept in discussing closed gas systems, such as the life support of a vehicle or EVA spacesuit, is that the biological responses of most gases are dependent on their partial pressures, rather than their overall concentrations. At sea level, with an O_2 concentration of 21 percent and a partial pressure of O_2 (ppO_2) of 21 kPa (158 mmHg, or 3.1 lb/in^2), the respirable atmosphere is said to be normoxic (=normal oxygen concentration). The same 21 percent is hypoxic (lack of oxygen) at altitude, where ppO_2 diminishes in step with total pressure, and hyperoxic in hyperbaric atmospheres. Either of these conditions may be detrimental. Adverse physiological effects of such hypoxia include decreased night vision, impaired memory and coordination, unconsciousness, convulsions, and death of nerve tissue. These effects can begin within a few seconds of O_2 deprivation, depending on the degree of hypoxia, so an adequate O_2 supply is an essential design requirement. Similarly, the toxic effects of CO_2 are partial-pressure-dependent; thus, what may be an acceptable concentration at sea level (e.g., 3 percent) may be unacceptably toxic at hyperbaric pressures of a few atmospheres [131].

Airborne contaminant control is extremely important for long-duration missions since long-term exposure to even minute amounts of some chemicals can be deleterious to people. On Earth many of these functions are performed by plants and microorganisms which transform CO_2 into O_2 via photosynthesis and purify air via other metabolic reactions. Evaporation from the oceans is the major process for purifying water, but plants also purify water via transpiration. Microorganisms are also important for purifying water by transforming contaminants into usable or benign forms. Biological life support systems based on these natural processes are being studied for space habitats, but they are not yet sufficiently well defined or understood, so we rely on our understanding of physical and chemical processes to support human life away from Earth. The allowable ranges of O_2 percentages for a range of total atmospheric pressures are shown in Figure 11.14.

Figure 11.14 | Oxygen requirements for space flight.



Note: Extracted from NASA-STD-3000 Vol. 1 Rev. A

On all U.S. missions to date, the O_2 has been supplied from tanks that carried sufficient O_2 for the duration of the mission. For longer-duration missions, the storage or resupply penalty is excessive, and some method of recovering O_2 from waste mass is required. For the International Space Station, the O_2 will initially be resupplied, but will later be generated by electrolysis of recovered wastewater. Other methods include electrolysis of water vapor and electrolysis of CO_2. There are also biological methods for generating O_2, including algae or other microorganisms and higher plants such as salad vegetables [132].

In situ resources, or living off the land, were previously mentioned as a possible contributor to an exploration mission LSS. If there was no possible resupply from Earth, a human exploration mission could potentially rely on in situ resources. History tells us that the successful early exploration missions to

Antarctica and the Arctic relied on in situ resources and the natural environment. In contrast, many unsuccessful exploration missions of the past failed because the explorers relied on resupply and initially stocked up on all their life support needs at the expense of huge vehicles and cost. As the closure of LSS increases with various regenerative technologies, utilization of in situ resources may be needed to produce products and by-products that can be used for life support, power, and propulsion. Continuous supply of carbon, O_2, hydrogen, and N_2 is needed for a self-sustaining LSS. The recovery and availability of these elements from extraterrestrial in situ resources are required to provide approximately 0.9 kg/(person · day) of O_2, 25 kg/(person · day) of water, 0.6 kg/(person · day) of dry food, energy, and other expendable materials.[4]

The five major in situ resources are regolith (dirt), subsurface, polar caps, atmospheric gases of extraterrestrial bodies, and solar energy. What about the availability of water? Oxygen is plentiful in the lunar and Martian regolith, and water has recently been found on the Moon; however, hydrogen is more scarce. Frozen water and CO_2 are available at the subsurface and polar caps of Mars and on both moons of Mars, Phobos and Deimos. Along with small amounts of water vapor, N_2, and argon, CO_2 is available in the atmospheric gases to produce O_2 for life support. On the lunar surface we might possibly obtain water and extract nutrients from lunar soil to support agricultural activities. More advanced lunar colonies might use thorium and uranium in the lunar soil to produce nuclear fuel for energy. Since lunar soil is rich in oxygen and minerals, propellants such as liquid oxygen, liquid hydrogen, and silane also have the potential for being manufactured on the Moon. On the Martian surface, like lunar regolith, the soil is rich in O_2 and minerals. The soil could provide raw material to produce micronutrients for plant growth. Atmospheric gases of Mars are rich in CO_2. The water and CO_2 available at the Martian poles and on the moons are extremely valuable resources. Sunlight is a vast resource on Mars and an important in situ resource for the operation of energy-intensive regenerative life support technology. Finally, propellants, such as liquid hydrogen, liquid oxygen, methane, and silane, may also be produced from Martian resources.

In sum, in situ resource utilization (ISRU) could be used for future human exploration missions by producing LSS materials in the following ways:

1. Recovery of O_2 and other materials from regolith.
2. Recovery of hydrogen and N_2 from fine regolith.
3. Recovery of potable water from polar caps and the subsurface.
4. Generation of O_2 from water and CO_2.
5. Production of propellants.
6. Generation of electrical energy.
7. Production of food.

---

4. Based on Earth-normal requirements. Studies have shown that less oxygen is needed in partial-gravity environments [129].

PROBLEMS

11.1 Compare and contrast four different design choices between the current Russian and U.S. spacesuits.

11.2 List two major problems associated with human extravehicular activity in space. What measures are currently employed to counteract these problems? List one future proposed effort to aid astronaut EVA.

11.3 Discuss the physiological effects of extravehicular activity on the human body. What efforts are being made to stop these effects?

11.4 Humans should be replaced with machines for extravehicular activity in space. Agree or disagree with this statement, and defend your position.

11.5 Give a one-paragraph description of your own design for a Martian spacesuit. Discuss the improvements over existing spacesuits.

Chapter 12

Design: Lighter-Than-Air (LTA) Vehicle Module

Dava J. Newman

This chapter emphasizes design as a critical component of engineering education. The integration of theory and practice is realized in the hands-on, lighter-than-air (LTA) vehicle design project. The goal of the LTA vehicle design project is to achieve an active learning environment for acquiring the skills of conceptualizing, problem solving, and teamwork, thus, comprehending engineering concepts that will be carried as tools throughout your professional engineering career.

This chapter initially presents a general discussion of design in Section 12.1, "What Is Design?" and Section 12.2, "The Design Process." Section 12.3, "An Introduction to Design Drawing," is a brief overview of basic drawing concepts, which are essential for design. The chapter culminates in Section 12.4, "Lighter-Than-Air Vehicle Design Project." This section includes a discussion of the rules and objectives of the LTA vehicle project as well as a description of the LTA vehicle kit recommended for team blimp design. This section requires extensive oral and written communications through the preliminary design review (PDR), completed design review (CDR), and personal design portfolio (PDP) assignments. These three engineering design and communications exercises are critical components of the LTA design experience. After the completed design review, construction of the LTA vehicles commences. Finally, a friendly competition race is proposed for the LTA vehicles. The LTA vehicle design project objectives are to foster an understanding of the principles of system design, team-oriented design, and most importantly, to provide a hands-on engineering experience.

12.1 | WHAT IS DESIGN?

In brief, *design* is defined as the bridging of the science of engineering with the creativity of art. Until recently, designers relied almost exclusively on intuitive methods, and the ability to design was widely thought to be innate and largely unteachable. For example, the highly influential French Beaux Arts school of design considered the most important factors contributing to the nature of the design to be those associated with the final outcome or end product. Under this system, projects were assigned and then taken to studios to be worked on with little or no instructor interaction until the completed final drawings were presented for review. The design schemes were graded on the complexity of the solution, and indeed the project was described more as the task of producing a solution than of solving a problem. Unfortunately, this method is often used in traditional engineering projects; the design focus is on the final product rather than on the design process. This chapter challenges these preconceived notions, emphasizing design as a continuum, an elegant process with many necessary steps.

One can cite an abundant number of areas requiring the expertise of the professional designer. Yet, the majority of designers focus on the creation of designs for people. Designers must understand their users, whether it is the ergonomics of a cockpit or the structural characteristics and aesthetics of skis. From social science to art and technology, much of the difficulty and fascination of designing lies in the need to embrace so many different types of thought and knowledge. A scientist can do his or her job perfectly well without even the thought of art. The artist rarely depends upon scientific method when painting or sculpting. For the designer, life is not so simple; she or he must appreciate the nature of both art and science in harmony to design. What, then, exactly is this activity called design? We can see that it involves a highly organized mental process capable of manipulating many types of information in the formation of ideas. From those ideas, the designer generates a realization of what becomes the final design. The word *design* then refers not merely to a product, but to a process, and might be considered an acquired skill.

12.1.1 Design as a Skill

Remember, design is a highly complex and sophisticated skill. It is not a mystical ability only given to a chosen few. With dedication, design can be learned and practiced, rather like playing a sport or a musical instrument. Consider the following two passages:

> Given a basic understanding of a *golf* swing and the aerodynamics of the ball in flight, the golfer will have more success at achieving the desired results by visualizing and then acting on the following tips.
>
> The swing plane or position of the club throughout the swing determine the initial direction of the flight of the ball. A plane that is too steep results in an outside to inside clubhead path. A plane that is too flat results in a clubhead path that is inside to outside.
>
> The clubface position determines the spin of the ball during flight. A closed clubface imparts a hooking spin to the ball. An open clubface results in a slicing spin. Ideally, the clubface is square to the ball upon impact to assure straight flight. (Lance Newman, golf professional, on the skill of golfing, 2001)

> *Singing* starts with a deep breath—deep, not high. When the diaphragm pulls down the lungs and causes the vacuum which leads to inhalation, you will feel the mus-

> cular action below your belly button, and your belly will stick out. Lying on your back and just feeling yourself breathe helps you discover the right muscles. Take a deep breath and hiss for as long as you comfortably can while keeping your rib cage expanded; this helps build the diaphragm and intercostal muscles you need, and also helps to re-set the carbon dioxide/oxygen switch in your lungs which causes you to imagine that you need to take a breath when you don't. Breathing is the engine that sets the resonators going; once you are comfortable with that, we can talk about freeing the resonators to allow your sound to flow freely. (Marion Leeds Carroll, soprano, on singing technique, 2001)

These two passages come from experts on the skills of playing golf and singing. They consist mainly of a series of suggestions as to where the learner should direct attention. A few rare individuals can pick up a golf club and swing it naturally, or easily sound a note. For these individuals books and lessons may be of little assistance; however, for the vast majority these skills must be acquired by attention to detail. Once a skill is highly developed, it can then be performed unconsciously. The professional golfer is not thinking about his or her swing, but about the course; and the singer forgets her or his intercostal muscle and concentrates on the score. After all, who can give expression to music while the mind is full of too much advice about the diaphragm? So it is also with design. The best work is achieved when the least thought is placed on technique. The novice must first analyze and practice all the elements of the skill, the most important skill being the ability to think. The famous British philosopher Ryle pronounced that "thought is very much a matter of drills and skills," and noted psychologist Bartlett proclaimed that "thinking should be treated as a complex and high level kind of skill." There have been many writers who have exhorted their readers to practice the skill of thinking. One of the most notable, Edward de Bono, best summarizes the message. "On the whole, it must be more important to be skillful in thinking than to be stuffed with facts" [131]. The following section suggests a process for developing the skill of design.

12.2 | THE DESIGN PROCESS

The design process may be summarized by four stages: problem definition; incubation and synthesis; analysis; and evaluation. Rather than sequentially stepping through these four stages, they are actually performed multiple times and in parallel. This is the notion of concurrent engineering, transforming a linear design process into a parallel design cycle. Concurrent engineering most accurately represents the design state of the art [134], as described in Section 12.2.1.

- Problem definition and idea generation.
- Incubation and synthesis.
- Analysis.
- Evaluation.

Design Thinking In many engineering disciplines, solving problems and obtaining the *correct* answer are stressed; however, real-world problems do not have just one correct answer. Traditionally, *logic* constrains individuals' creativity because old ideas are preserved. Methodical, problem-solving skills are essential for an engineer to acquire, but not at the sacrifice of trapping one into binary thought processes of yes/no vertical thinking. Rather, designers must accept that lateral thinking is necessary for idea generation. In order to properly define a problem, it is most helpful to think creatively about it. The need to move from a yes/no viewpoint to a lateral thinking viewpoint is imperative. Two fundamental differences are highlighted below:

- In yes/no thinking, one must be correct at each step; in lateral thinking *right* is not important.
- In yes/no thinking one limits the problem, preferring it to be well defined. In lateral thinking, one may initially expand the problem to better comprehend it.

These two differences lead to three concepts for lateral (creative) idea generation and the suggestions that these concepts lead to in practice (see Table 12.1).

Table 12.1 | Concepts for lateral design thinking

In theory	In practice
Protect new ideas from sharp initial judgment.	Take a walk on the *wild* side.
Challenge old judgments and classifications.	Use random juxtaposition (i.e., initially, consider absurd possibilities).
Look for new ways of doing things without rejecting the current way first.	Be radical, yet conservative (i.e., it may work, but can you make it better?).

Try These Thought Examples To thoroughly understand your design problem, come up with wild ideas—the *intermediate impossibilities*. For example, consider the problem of parking in a large metropolitan city. A plausible *wild* idea might be to let all drivers park wherever they want, rather than having designated spaces, parking meters, and parking police. To see relationships between ideas, use random juxtaposition. For instance, take lighter-than-air flight and cement. These absurdities can actually clarify relationships. How can one be radical, yet conservative? The conservative idea is to appreciate and understand what is already in existence, and then to take a radical approach to what needs to be accomplished. Design brings forth an endless series of questions. By clearly articulating the design problem and objective, a novel answer can be found (see CD-ROM exercise on Design under LTA multimedia).

LTA multimedia.

12.2.1 Concurrent Engineering

Design is a creative process; initial ideas should be innovative, crazy, and risky because they aid in starting the thought process. The initial step should be to jot down ideas on paper. For the case of the LTA vehicle design, the *problem* is defined a priori (design and fly a vehicle around the course), but the initial phase of *creative idea generation* must still occur. At this stage, new ways of thinking are encouraged. Once the ideas are formulated, time is needed to think and to *synthesize* numerous interesting ideas into the notion of a system. Time is essential for ideas to *gel,* and apparent connections and relations between ideas emerge with time. These inspirations can arise at any given instant; allow them to flow freely. Forcing connections and relationships typically does not work. Struggling with an idea, then finding that it has no relation to other ideas results in two possibilities. Either the idea is so powerful that it suggests a completely new direction, *or* the idea is not critical to the final goal and can be dismissed, for it will not become an integral part of the design. The *analysis* stage relies on the knowledge of the fundamentals of mathematics, physics, chemistry, and biology. Design analysis requires understanding the interrelationships of these disciplines. For example, the lift and drag of an LTA vehicle can be approximated from physics and mathematics, but one has to envision the vehicle with a certain number of balloons, a structure, engines, and the actual radio-controlled flight around the gymnasium. The design is beginning to formulate on a systems level, and the analysis will help to verify the original problem statement. At this stage, it is easier to define the problem and objectives more precisely after performing a preliminary analysis.

Evaluation entails performance assessment, and modeling and simulation often proves useful during this stage. It is recommended that prototypes and geometric models be built to evaluate probable and improbable design features. This is just the beginning; a preliminary design might be reached, but it is essential to reengage in the four stages repeatedly to ensure a successful final design. Vincent van Gogh reminds us that "artistic innovation is not linear, the way forward sometimes comes from looking back" [135]. This circular path leads to the best designs. Section 12.4.4, "Preliminary Design Review," and Section 12.4.5, "Completed Design Review," further illustrate concurrent engineering with emphasis on the analysis and evaluation stages. In summary, try to follow these suggestions for honing design skills:

van Gogh's Green Vineyard.

Stand on your head to see your design differently.

Get inside each stage of the design process and crawl around in it.

"Simplify, simplify, simplify" or in the words of Albert Einstein, "Everything should be made as simple as possible, but not simpler."

12.3 | AN INTRODUCTION TO DESIGN DRAWING

One of the challenging problems to solve in the early stages of a design is how to represent three-dimensional objects on a two-dimensional surface. Throughout human history, visual systems have evolved, and empirical methods, theories, and principles describe how to represent objects' three-dimensional nature on two-dimensional paper. Numerous examples of orthographic and oblique projections are seen in Egyptian, Roman, Greek, Indian, Chinese, and Japanese art. This section provides an essential introductory lesson on drawing systems.

To begin, this section acquaints the reader with drawing terminology. A *projection* is a method to represent a three-dimensional object by extending all its points with straight lines to a picture plane, or the plane of projection. The three main types of projection systems include *orthographic, oblique,* and *perspective* projection. The relationship between a straight line and its angle with the projection plane is the distinguishing characteristic of the three projection systems. The pictorial *images* created by using the projection systems include *multiview, paraline,* and *perspective* drawings. The remainder of this section introduces basic nomenclature and provides examples of *orthographic* projection through *multiview* and *paraline* drawings. For more detailed discussion of drawing systems, Ching is recommended [136].

Modern engineers are sometimes hesitant to pick up a pencil and draw. Before we discuss multiview drawings, it is important to overcome this drawing anxiety. Although possibly untapped, there is an artist within every person. Frank [137] promotes a valuable notion of seeing/drawing where the capacity to see rather than to *look at* is the key to unlocking the essence of the artist within. Perhaps one needs to see as a child, observing, becoming, and living in the moment of whatever image he or she sees. As adults, one still has eyes, but how often do they really *see*?

> Seeing/drawing is an immunization against the addiction to looking-at: it restores the gift of seeing—that is: of Being, of being fully alive. [137]

To begin, all that is needed is paper, pencil, and the desire to try. Frank recommends starting with *the dry run* as a prelude to drawing [137, pp. 60–69]. It consists of gesturing on the paper with one's hands the place, shape, and size of whatever one is going to draw before using a pencil. The *gesturing* helps imprint the image in the mind and establish the physical dimensions and relations of the drawing. This is a simple step that helps avoid those inevitable misproportioned sketches. During *gesturing,* the finger can repeat the process on a smaller scale until the figure fits the available page's space. Most importantly, one establishes the relationships between objects and familiarizes oneself with the entire process necessary to accomplish the desired drawing. Next, draw whatever was gestured; try to look not at the paper, only at the chosen object. For practice, start with something basic, such as a leaf, before embarking on the more complex LTA flight system. Go through the gesturing exercise. At this point, neither technique nor talent is important—not nearly as important as trying to *see* the leaf. Hopefully, the creative process starts to unfold. Let the artist within be a guide through the drawing process. Continue to draw, draw, draw. What did Leonardo da Vinci or Michelangelo see before they drew? Their great images arose in the mind (see Figure 12.1).

To practice *seeing,* think about a *reflex arc* where an image hits the eye and runs through the entire being via the reflex arc. There should be no pauses or labels attached to the image, just a flow from the retina through the *hsin* (ancient Chinese word denoting both heart and mind) to the hand.

> This did not come about overnight. On the contrary, it was the result of endless practice in coordinating eye and hand, of jotting down whatever I saw. There is no trick to it, there are no shortcuts. There are no manuals for sale on how to draw . . . You just go on drawing. For every drawing is your latest exercise in the fine-tuned coordination of eye and hand, ever more sensitively, ever more truthfully [137].

Figure 12.1 | Hands of Creation.

12.3.1 Drawing Techniques

This section introduces the essential, old-fashioned tools and techniques of drawing, starting with an introduction on how to use a T square, triangle, pencil, and scale and ending with suggestions on how to draw lines (straight, parallel, perpendicular, and angled). Even if you choose to draw utilizing CAD (computer-aided design), the basic drawing information presented here serves as a basis. Section 12.3.2 defines drawing systems, highlighting multiview systems and perspective. Empowered with these tools and techniques, you can start communicating your design.

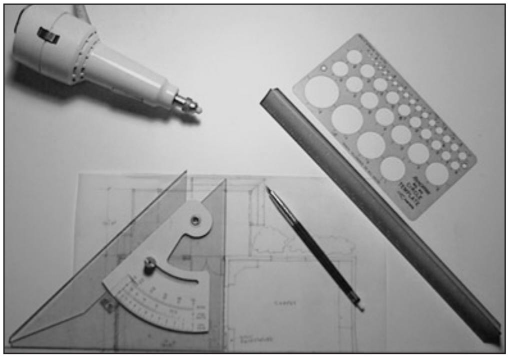
Introduction to Drawing Tools

1. *T square.* The *T square* is the tool to draw parallel lines. It is made up of a long, straight *drawing edge* and a shorter piece arranged perpendicular to that edge. Because this configuration is always maintained, parallel lines can be drawn by snugly aligning the short piece with a third edge, such as a table. This, of course, assumes that the edge of the table follows a straight line.

2. *Triangle.* By drawing parallel lines we construct the base lines of a Cartesian coordinate system. The T square only allows the drawing of horizontal lines. To draw in other directions one uses the *triangle,* always using parallel lines made by employing the T square as a reference.

As suggested by the name, the *triangle* is a drawing tool cut into a right triangle. There are three main types of triangles. There are 30, 60, 90 triangles; 45, 45, 90 triangles; and adjustable triangles, always with one right angle. The right angle is important for it aids in the drawing of perpendicular lines. This is done by placing one of the legs of the triangle flush with the drawing edge of the T square. Similarly, angles can be drawn by using different edges of the triangle as the drawing edge. Figure 12.2 shows drawing tools.

Figure 12.2 | A parallel bar, triangle, scale, template for drawing circles, and electric eraser are shown on a drafting table used for drawing.



3. *Pencils.* Once a method of moving around the drawing plane is established, the next concern is with marking the drawing plane. Many tools can be used to do this, but in designing, the ability to erase is very important. A well-sharpened, clean pencil is best to make sharp lines of varying weights (discussed later) while allowing the designer to erase at any time.

The main feature that differentiates one pencil from another is called the hardness or softness. A hard pencil produces a soft or light line whereas a soft pencil produces a dark or heavy line. Similarly, a line produced by a hard pencil will be less likely to smudge. For this reason it is best to draw first with hard pencils and to use softer pencils for darkened lines as the drawing is near completion, always leaving the darkest lines for last.

Pencils are not simply hard or soft; they come in a gradient of these qualities. Typical classifications are 2B, B, H, 2H, 3H, etc. Hardness increases as the leads move from 2B to 3H and up. To start, an H, 2H, and 3H are ideal. Ultimately, use the lead that is most comfortable for the need.

4. *Scale.* Another important aspect to design drawing is scale. Many times a design cannot easily fit onto a drawing plane of reasonable size. By scaling, the design can easily be displayed on one page, while maintaining all the correct proportions. This ensures that parts are compatible.

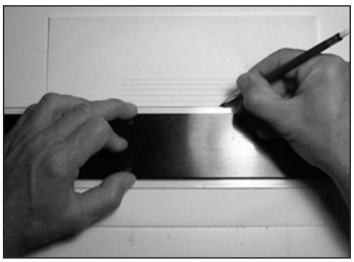
The *scale* is a tool that lessens the tedium of conversion factors by displaying common conversion markings along its edges. The three major types of scales are architectural, engineering, and metric. Architectural scales display conversions typically from 3/32 in = 1 ft to 3 in = 1 ft, with divisions of scaled inches (12 divisions between marks). Engineering scales are typically used for larger projects. They contain marks every inch and are numbered according to the specific scaling used. For example, one edge of an engineering scale might display the scale 1 in = 50 ft. Because engineering scales are subdivided into tenths, the 1 in = 50 ft scale can very easily be used for 1 in = 500 ft. The metric scale represents conversions between centimeters and meters. Scales are conveyed with ratios which indicate the reduction of the drawing from real life. For example, one side might display 1:500. This explains that the drawing is 500 times smaller than the actual structure, or that every 2 mm (one-fifth of a centimeter) is equivalent to 1 m. Like the engineer's scale, the metric scale contains 10 subdivisions and can thus convert easily to a factor of 10 larger or smaller.

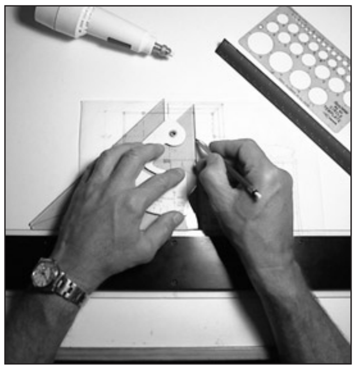
Although using a scale can be complicated at first, it soon becomes a convenient timesaving device, with a little practice.

Drawing Lines

Straight Lines Straight lines are drawn using an edge to guide the pencil. Pressure must be applied to ensure a crisp, dark line, but the line should flow without too much effort. The pencil should be tilted slightly in the direction of the line to prevent uneven lines and tearing of the paper (see Figure 12.3 for hand placement). The hand should rest solely on the pencil and not on the paper or straightedge. This prevents movement of the straightedge and smudging of previously drawn lines.

Figure 12.3 | An example of the proper technique for drawing straight lines.





Make sure the point of the pencil is always sharp and clean. After sharpening the lead, wipe the tip with a tissue to remove excess graphite. Then, with a scrap of paper slightly dull the tip of the lead so that it does not break when the tip is placed to the paper. Breaking the pencil tip will not only cause frustration, but also make an uneven line and cause graphite shavings to smear the drawing. To keep the point sharp while drawing, the pencil can be rotated in the hand. This technique takes some getting used to, but it ensures that the lead is worn down evenly, preserving the point.

Parallel Lines Just like straight lines, parallel lines are drawn by using the edge of either the T square or the triangle. Using a T square, horizontal parallel lines can be drawn by simply moving the T square up and down the face of the paper. To make an accurate measurement of the distance between parallel lines, a vertical line should first be drawn with the triangle.

With a triangle vertical or angled, parallel lines can be drawn by moving the triangle along the edge of the T square. To make an accurate measurement of the distance between parallel lines, perpendicular lines must be drawn.

To avoid smudging when you move any tool over the surface of the paper, lift it ever so slightly above the drawing surface before moving the tool. With the triangle, rest it on its bottom edge before sliding it from left to right. Dragging the tools does more harm as one gets closer to the completion of the drawing, since this is when softer leads are used to produce darker lines that smudge more easily.

Perpendicular Lines Perpendicular lines can be drawn using the T square and triangle together or by the triangle solely. The triangle can only be used solely if the axes are not aligned horizontally or vertically. To draw perpendicular vertical and horizontal lines, first draw a line using either a leg of the triangle or the drawing edge of the T square. The next line is drawn by the other tool.

If the perpendicular lines are not aligned perfectly horizontally or vertically, the triangle can be used alone such that the triangle's edges are only used to align the pencil. The triangle is always used in conjunction with the T square to ensure accurate angle measurement. To make the perpendicular lines, place the hypotenuse of the triangle against the drawing edge of the T square. The other two edges are mutually perpendicular.

Angles Angled lines are drawn by using a triangle. When an adjustable triangle is used, any desired angle can be set. Although calculating a specific angle can take more time with set triangles, increments of 15° can be achieved. In either case, align the triangle with the T square, and draw the line. Note that it is not necessary to align the vertex of the triangle with the beginning of the line. As long as the T square is correctly aligned, the beginning point of the line can fall anywhere along the drawing edge of the triangle.

The power, relevance, and beauty of the technique of old-fashioned drawing by hand are revealed in Figure 12.4. This magnificent drawing of a space station serves as inspiration to all.

12.3.2 Engineering Drawing and Perspective

In order to communicate a three-dimensional design on a two-dimensional drawing surface, different systems of drawings have been established. Each system is defined by how an object is oriented with respect to the plane of the drawing, an imaginary plane onto which the object is projected. In addition, each system is defined by how the projectors—the lines of projection from points on the drawing to the plane—are oriented with respect to one another and the drawing plane. Multiview and perspective drawings are essential in the initial engineering design phase—the paper design phase—before prototypes and working models are produced.

Multiview Drawings (or Orthographic Projections) Multiview drawings represent what we know about a design, but are abstract in the sense that they do not match optical reality. In other words, a typical multiview drawing contains a top view, side view, and front view of a system design; but these independent

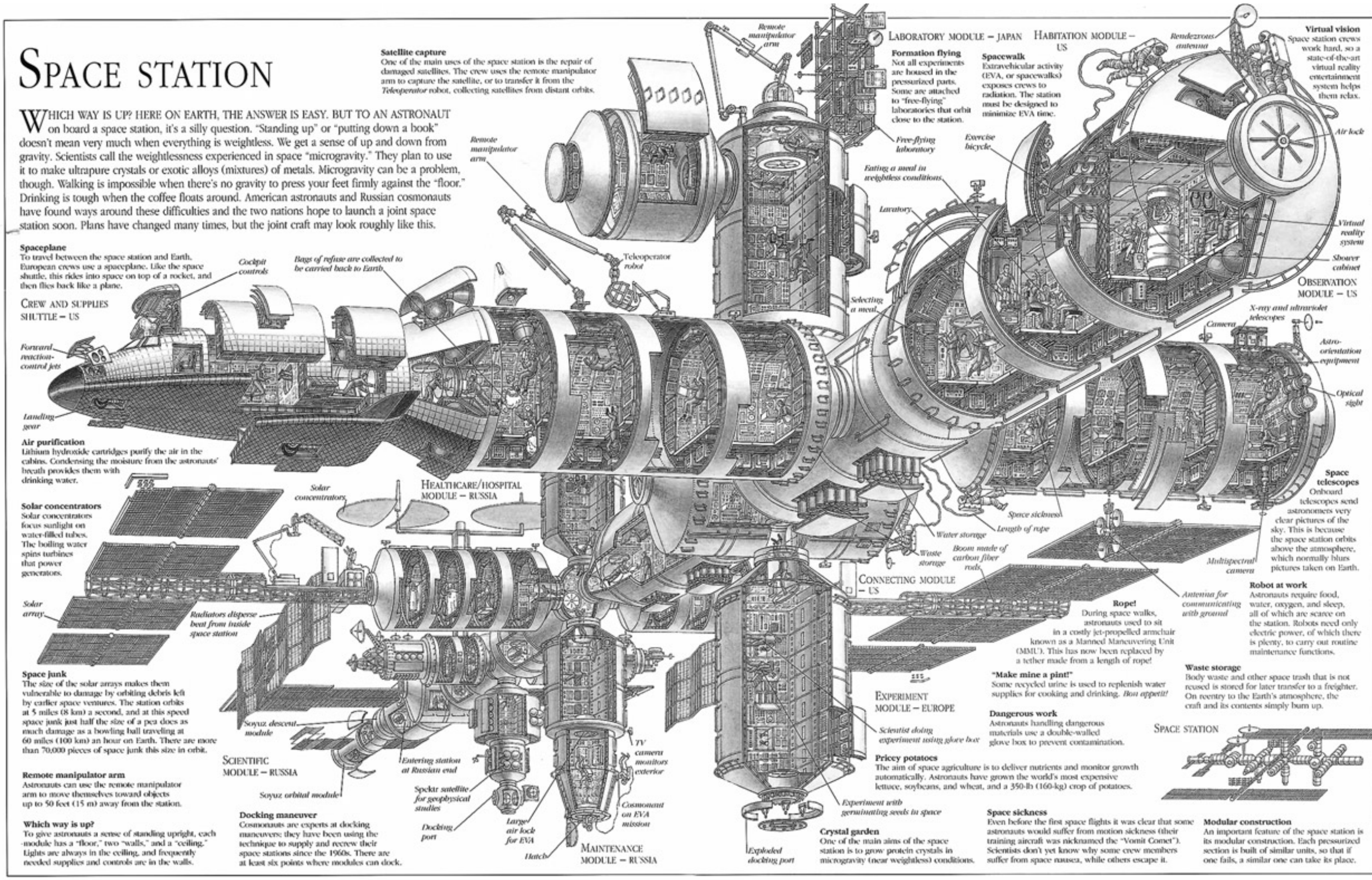
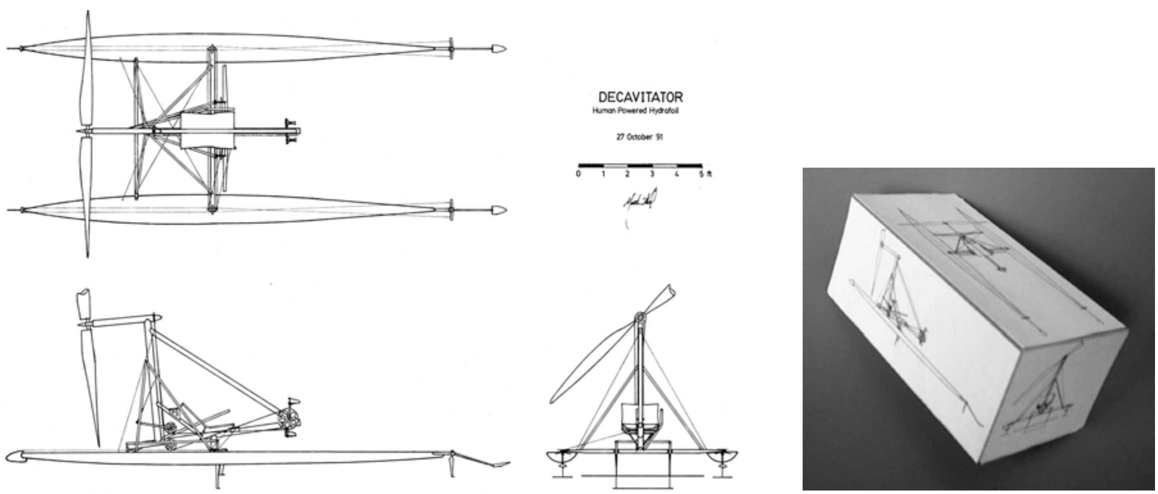


Figure 12.4 | An artist's conception of a space station.

planar drawings are conceptual rather than actually represent the way we see the entire engineering system/vehicle from a point in space. Each of the three multiviews is an orthographic projection of a particular aspect of the design; therefore, multiview drawings are also referred to as orthographic projections. An orthographic projection consists of parallel projectors that meet the picture plane at right angles. Any feature of the design that is parallel to the picture plane remains true in size, shape, and configuration. The major advantage of multiview drawings is that precise points, lengths, shapes, and slopes of lines can be precisely located. Each individual orthographic drawing (top, side, front, back, bottom) reveals partial information about the overall design. There is an inherent ambiguity of depth in each multiview because the third dimension is flattened onto the picture plane. A series of three distinct but related views fully describes the three-dimensional nature of a design.

A multiview drawing with its three picture planes forms three sides of a cube, as seen in Figure 12.5. In the multiview drawing the top view is positioned to the top left, the side view directly below the top view to the bottom left, and the front view to the bottom right. To display the drawings coherently, unfold the faces of the cube while maintaining the relationship. To show where the same points are located on different drawings, lines perpendicular to the fold lines can be used. These lines should be lighter than the multiview drawings so as not to distract the viewer.

Figure 12.5 | Decavitator multiview drawing.



The following multiview drawing points are recommended by Ching [136]:

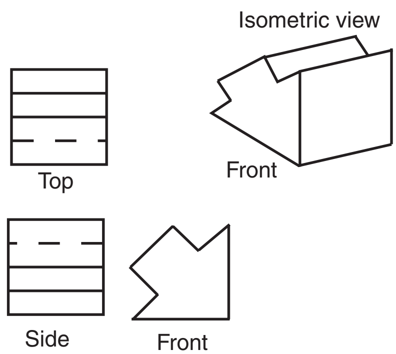
- All points are projected perpendicular to the picture plane.
- Main faces are parallel to the plane of the picture plane.
- All lines parallel to the picture plane are drawn to scale.

- Lines at oblique angles to the picture plane are shortened.
- Lines that are parallel in three dimensions remain parallel.
- To help in construction of multiview drawings, draw the simplest face first and then use this to figure out the shortening of lines.
- *Plan:* A drawing in plan, otherwise known as *top view,* displays the horizontal plane of the design. In engineering this view is usually drawn as an overall view of the object, but sometimes it can be a horizontal slice through the design.
- *Elevation:* An elevation, sometimes called *side view,* shows a vertical face of the design. This term is solely used to describe a view of the whole object (it does not refer to a vertical slice through the design).
- *Section:* The term *section* refers to a drawing of a vertical slice through the design. This drawing allows the viewing of interior complexities.

Figure 12.5 shows a multiview drawing that was constructed using the above suggestions and communicates the design of a human-powered hydrofoil, namely, the Decavitator (see CD-ROM for Human-Powered Flight Designs).

An isometric drawing is a special type of orthographic projection, sometimes referred to as a single-view drawing to distinguish it from multiview drawings. In an isometric view, all three primary axes are at equal angles to the picture plane. On the picture plane, all axes are 120° apart. All parallel lines of an object, regardless of their orientation, remain parallel in the drawn isometric view. Isometric drawings have a pictorial nature and are great for visualizing an emerging idea in three dimensions early in the design process. Isometric views are not true perspective drawings because they do not converge to vanishing points, but can substitute for a bird's-eye perspective. They present either an aerial view looking down on the object or a bug's-eye view looking upward. Advantages to isometric drawings are that they can be cut or made transparent to see inside and through objects, or expanded to show spatial relationships, and the view is revealed from an infinite set of positions rather than from a specific point in space. Figure 12.6 shows a top, side, front, and isometric view of an object.

Figure 12.6 | Multiview and Isometric drawings depicted.

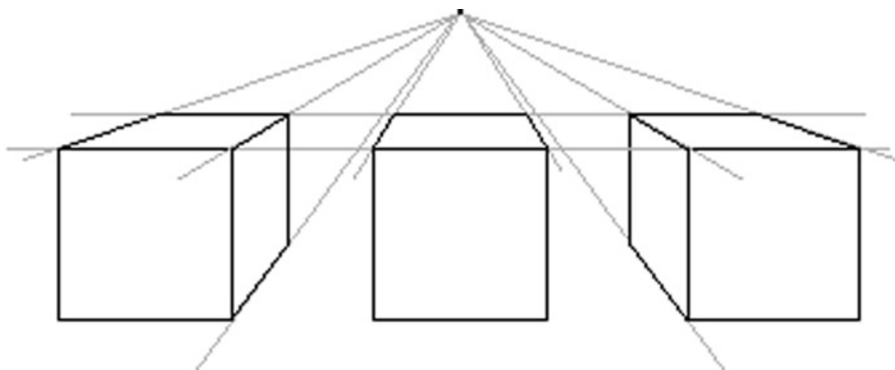


Drawing in Perspective Perspective drawing falls between freehand drawing and engineering drawing. This type of drawing is important in design applications, but not as often used for strictly engineering purposes. Perspective drawings are limited in terms of communicating dimensions and parameters, but very accurately describe how we actually see objects. Perspective drawing aims to represent the actual three-dimensional aspect of an object from a given point of view with all the angular distortion and foreshortening that is seen by the eye. This view that the eye perceives is known as the picture plane. Linear perspective drawings portray the way objects optically appear to grow smaller as they recede with growing distance. Imagine looking down a pair of railroad tracks; the two rails appear to grow smaller and closer together until they finally converge on the horizon. The point at which parallel lines converge is known as the vanishing point.

Online resource.

One-Point Perspective: A one-point perspective drawing contains only one vanishing point. It is used to represent objects that have a principal plane parallel to the picture plane (see Figure 12.7).

Figure 12.7 | Illustration of one-point perspective.



Two-Point Perspective: A two-point perspective drawing contains two vanishing points. It is used when a principal plane of the object is not parallel to the picture plane; however, a set of parallel lines on the object may remain parallel to the picture plane. For example, imagine looking at the corner of a building or at the intersection of two streets (the lines of each street converge to their own vanishing point) (see Figure 12.8).

Three-Point Perspective: A three-point perspective drawing contains three vanishing points. It is used when neither a principal plane of the object nor any set of lines is parallel to the picture plane (see Figure 12.9).

Special Drawing Topics There are a few additional details to pay attention to during design drawing. These include *hidden lines, dimensioning,* and *tolerances.* These are mentioned briefly now.

Figure 12.8 | Illustration of two-point perspective.

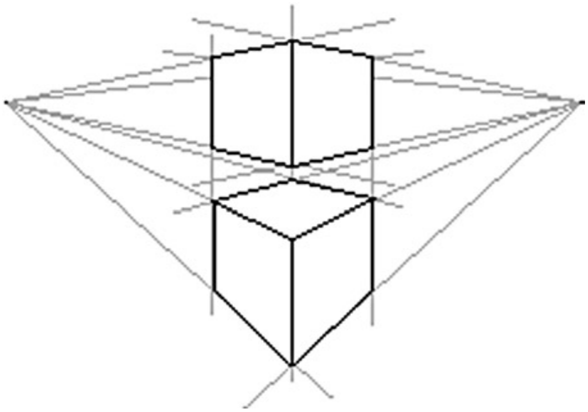
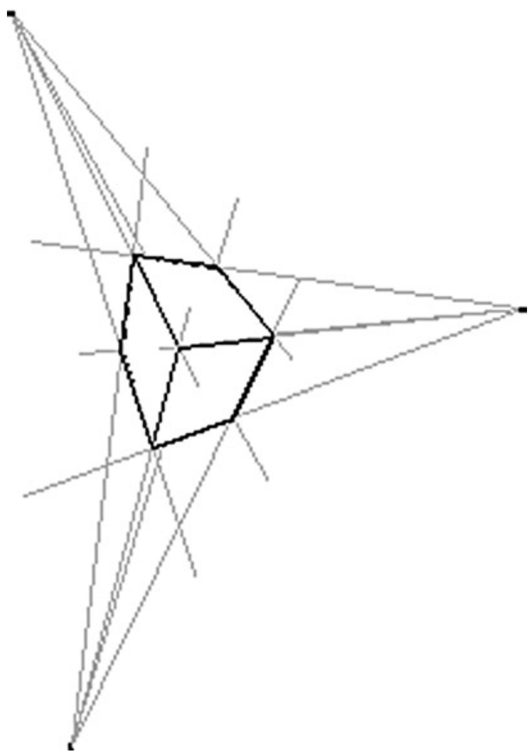


Figure 12.9 | Illustration of three-point perspective.



Hidden Lines: When an aspect of the design prevents the viewing of a key feature, hidden lines must be used. Usually, hidden lines are depicted as dashed lines.

Dimensioning: Dimensioning allows the viewer to construct a design. From overall dimensions to the dimensions of fine details, all must be given. Dimensions can be displayed in many ways: from edge to edge, from edge to center of the feature (the width of the feature must be given as well), or a mix of the two (try to avoid this). When dimensioning your drawing, draw lines perpendicular to the face being dimensioned, to indicate the points from which the dimensions are to be taken. Lines drawn parallel to the dimensioned face display the numerical dimension. Small arrowheads should be placed on either end of these lines to clearly depict from which points the dimensions are taken. Always name the units to prevent confusion. Finally, label the drawing with the outermost dimension as the overall dimension and work inward, labeling smaller dimensions and smaller features.

Tolerances: Tolerances make the design reader aware how far she or he can stray from the specified dimensions. The tolerance must be small enough to ensure that pieces will fit properly when the design is built. A lower tolerance requires greater precision, is harder to manufacture, and is more expensive to produce. If all tolerances are the same, the tolerance should be displayed generally, but more often various dimensions have different tolerances. Tolerances are denoted by a "plus or minus" sign after the dimension. For example 4.4 ± 0.1 cm means that the part must be between 4.3 and 4.5 cm. Sometimes a part can be smaller, but not bigger, or vice versa. Here you can use two different tolerances, or just the important one. For example, $4.4 + 0.1$ cm means that the part dimension must be between 4.4 and 4.5 cm (ideally 4.4 cm). There is an implied tolerance in the number of significant digits. If a part can stray from the given dimension by 0.1 cm, do not write the dimension as 5.30 cm because this notation states that the dimension can only stray by 0.01 cm. As a precautionary measure, always write the tolerance after the dimension.

Now that the basics of drawing have been introduced, Section 12.3.3, "Computer-Aided Engineering (CAE)," reveals the state of the art in computer-aided engineering and design drawing.

12.3.3 Computer-Aided Engineering (CAE)

Computer-aided engineering is generally accepted to be a blanket term referring to a number of computational methodologies used to assist in engineering design and analysis. Subcategories include

- Computer-aided design / drafting (CAD)
- Computer-aided machining (CAM)
- Mechanism design / multibody dynamics
- Finite element meshing (FEM)

- Finite element analysis (FEA)
- Systems analysis
- Database management

There is a variety of other methodologies that might be incorporated under the term *computer-aided design,* but we restrict our attention to the seven listed above.

Computer-Aided Design The term *computer-aided design* refers to the process of creating models of mechanical or electrical parts that are either eventually manufactured or used in analysis. Originally, computer-aided design started out as computer-aided drafting, in which parts to be manufactured were drawn directly in two-dimensional isometric projection views in an engineering drawing format that was then simply printed out (or plotted) and sent to a machine shop for fabrication of the part. This was merely an extension of the older practice of drafting in which two-dimensional views of parts were depicted using paper and pencil/pen. The main advantage of computerizing this process was the greater speed at which drawings could be generated and the ease of making changes. Once computers were employed in this process, it quickly became apparent that it was more convenient and powerful to create the geometry of parts in a three-dimensional computer representation. Two-dimensional projected views of the part could then be automatically generated, and the appropriate dimensioning and annotation added in an engineering drawing format that was then sent to the shop. At first, parts were created in a wire-frame format in which only the edges of the part were defined. Later, surfacing was introduced that made it possible to enclose volumes and define solid sections, a process known now as solid modeling. The advantage of solid modeling is that it allows engineers to create parts in much the same way in which they are fabricated, for instance, by starting out with a solid block and then cutting it into a particular shape or creating holes. In this way, many edges and surfaces are generated in a single operation. Some examples of popular CAD programs include CadKey, ANVIL, and AutoCAD.

Computer-Aided Machining Computer-aided machining is an extension of CAD usually following from solid modeling, in which the tool paths for fabrication are defined within the computer model. These definitions are then used to generate a program that directly operates the computer-controlled machine (e.g., a lathe or milling machine) used in fabrication. Most commonly, the shop machinists will set up these CAM programs based on drawings supplied by an engineer or drafter.

Mechanism Design / Multibody Dynamics A natural extension of solid modeling is the ability to specify constraints between interconnected parts in a linkage or assembly. This makes it possible to analyze motions (kinematics) performed by these linkages during operation. Examples of such linkages are robot arms or a car steering mechanism. More recently, programs have been developed that account for the inertial properties of parts and, through mathematical formulation of equations of motion, the forces and torques involved (kinetics or dynamics). Examples of such programs include SD/FAST, I-DEAS, and JACK.

Finite Element Meshing Finite element meshing, although considered a separate function, is really just a stepping stone from CAD to FEA. It consists of geometric routines that are used to subdivide complex volumes (or surfaces in a two-dimensional model) into simple discrete subvolumes, namely, finite elements.

Finite Element Analysis The finite elements generated by FEM may be analyzed by applying mathematical relations (stress-strain, heat transfer, etc.) in a discrete fashion to each element and then applying continuity principles to generate the information about the model as a whole. Examples of popular FEA programs are ABAQUS, PATRAN, NASTRAN, and ADYNA. Many of these FEA packages include their own FEM modules.

Systems Analysis Computers are commonly used to analyze complex systems that may be defined using mathematical relations. Examples are a rocket propulsion system including fuel and oxidizer tanks, turbopump, combustion chamber, and nozzle; or a satellite attitude control system.

Database Management A large engineering project, for example, the design of a new helicopter, requires keeping track of a tremendous number of engineering drawings and other documentation. This task becomes particularly labor-intensive when changes are made that affect several parts in an assembly. Such projects are increasingly relying on shared computer databases.

Computer-Aided Engineering Software Packages Traditionally, commercial software packages have provided only one of the primary functions discussed above, and most software companies have specialized in a single methodology. Recently, however, some companies have developed software that combines a variety of methodologies into a single package. One example is I-DEAS (SDRC, Milford OH), which combines CAD, mechanism design, FEM, FEA, and database management into a single modular package. Another such program that has gained popularity is Pro/ENGINEER (Parametric Technology Corp., Waltham, MA). These packages cover such a wide range of capabilities that they are often referred to as CAE packages. One of their strengths is the use of parametric technology, allowing the user to alter a single parameter of a model (e.g., a length dimension), and the entire model (or even assembly) is updated.

This was a brief introduction to the design process and preliminary drawing techniques and systems. Now it is time to apply this knowledge to the lighter-than-air vehicle design project. The LTA design project is the culmination of Chapter 12. With a basic knowledge and understanding of what design is, one can formulate an individual working definition of design. It is time to embark on the journey of the design process. Remember to be creative, analytical, and open-minded, but most importantly, learn from mistakes as well as successes.

12.4 | LIGHTER-THAN-AIR VEHICLE DESIGN PROJECT

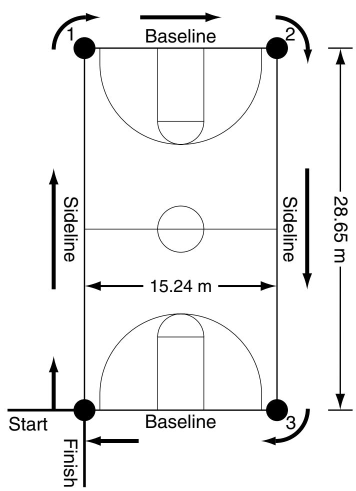
The lighter-than-air vehicle design competition provides an opportunity to apply the fundamental concepts and approaches of aerospace engineering in the context of the design. Teams of four to six students per group develop paper schematics, communicate their ideas through oral design reviews (PDR and CDR), and then build a flying vehicle. The LTA vehicle project follows the design process, beginning with the conception of ideas utilizing brainstorming. Next, several preliminary design possibilities are suggested at the preliminary design review. By the completed design review, a final design is prototyped and selected. Prototypes lead to actual working LTA vehicle components and, finally, a flying LTA vehicle blimp. The culmination of the design effort occurs on race day when teams engage in friendly competition with other student groups. Further discussion of the PDR and CDR are included in Section 12.4.4 and Section 12.4.5, respectively. Furthermore, at this point, you might want to thoroughly explore the interactive multimedia LTA vehicle design project available on the accompanying CD-ROM.

12.4.1 Objective, Rules, and Judging Criteria

This section outlines the LTA vehicle design competition. The race objectives, course, LTA vehicle constraints, LTA design kit, data on components, milestones, and logistics are discussed.

Objective The main objective of the lighter-than-air vehicle design project is to design and construct a *controllable, stable,* and *reliable* craft such that it is able to traverse a specified course (see Figure 12.10) in the minimum amount of time with the maximum amount of payload. The goal of the project is to foster an understanding of the principles of system design and team-oriented engineering design.

Figure 12.10 | Lighter-than-air (LTA) vehicle race course around a gymnasium.



Rules There are several rules required to successfully complete the lighter-than-air vehicle design project. The vehicles are restricted to a gross mass not to exceed 1.75 kg. The trimmed vehicle mass will be assessed on the trial day. The teams are restricted to four to six members. It is at the discretion of the instructor to allow teams of fewer or more members. The vehicles are limited to no more than five balloons. The materials are restricted to those provided by the instructor. Additional materials may be substituted at the instructor's discretion.

Judging Criteria Three categories are judged to select the winners of the competition. In the *mass per unit time category,* the winning team must achieve the maximum amount of payload (mass over and above the entire vehicle mass) flown through the course in the least amount of time. The winner of the *reliability category* is selected based on the vehicle that achieves the maximum number of successful flights around the entire course during the trial and race day competitions. The final category is *aesthetics.* The winning vehicle in this category is found to exhibit the most creative and elegant design.

Trial and Race Day Events

- LTA vehicles are weighed. The vehicle and payload are measured separately.
- The teams are cued a minute prior to the beginning of the race.
- Each LTA vehicle traverses the course separately.
- The start time is recorded when the nose of the blimp crosses the start line.
- Blimps are navigated around three balloons marking the corners of the rectangular course. The total course distance is 87.8 m.
- The final time is recorded when the tail of the craft crosses the finish line.
- Head-to-head competition is performed after all vehicles have made solo flights.
- Tallying of scores and judging of vehicles are performed after all blimps have competed.

12.4.2 LTA Design Kits and Materials Specifications

All teams are provided with an LTA vehicle design kit. Make sure that your kit includes the following:

- *Balsa wood:* available in sheets and strips. Balsa density = 160 kg/m^3, balsa yield strength in grain = 20 MPa.
- *Epoxy*: yield strength = 30 MPa.
- *Weather balloons:* made of latex, 1 m in diameter, mass per balloon = 70 g.
- *Helium:* density = 0.174 kg/m^3.
- *Standard issue motors.*

Each team is given the choice to use several *large* or *small* motors (number to be determined by the design analysis). Data from the large Pittman motors with the propeller attached are provided in Table 12.2. The motor works approximately two-thirds as well in reverse due to propeller inefficiencies.

Table 12.2 | Large-motor (210 g) performance

Voltage (V)	Current (A)	Power (W)	Thrust (N)
0	0	0	0
6	0.79	4.8	0.32
7	0.93	6.5	0.40
8	1.18	9.4	0.58
9	1.36	12.2	0.70
10	1.60	16.0	0.88
11	1.90	21.0	1.06
12	2.25	27.0	1.30
13	2.50	32.0	1.50
14	3.00	42.0	1.80
15	3.29	49.5	2.10
16	3.60	57.6	2.30
17	4.20	71.4	2.80
18	4.45	80.0	3.00

Motor mass = 210 g.
Propeller mass = 5.2 g.
Total radio control mass = 290.6 g.
Battery energy density ~30 Wh/kg.

Smaller motors are also available. Data from the smaller Edmund Scientific drive motors with the propeller attached are provided in Table 12.3. The motor works approximately two-thirds as well in reverse due to propeller inefficiencies.

Table 12.3 | Small-motor (89.7 g) performance

Voltage (V)	Current (A)	Power (W)	Thrust (N)
0	0	0	0
6	0.80	4.8	0.05
7	0.91	6.4	0.07
8	1.00	8.0	0.10
9	1.17	10.5	0.13
10	1.30	13.0	0.17
11	1.44	15.8	0.20
12	1.60	19.2	0.24
13	1.76	22.9	0.27
14	1.87	26.2	0.32
15	2.00	30.0	0.36

Motor mass = 89.7g.
Propeller mass = 5.3 g.
Total RC mass = 290.6 g.
Battery energy density ~30 Wh/kg.

- *Radio control equipment:* Futaba four-channel system including an *AM transmitter and battery* (not on craft), *receiver* (27 g), *receiver battery* (94 g, 4.8 V, 500 mAh) used to run servos but can be used to run motors, *servos* (43 g each).
- *Motor Batteries*: Any voltage is permitted, specifications for AA batteries include mass = 50 g each, power = 1.25 V, 1.2 A.

12.4.3 Ornithopter Laboratory Electronics Exercise

The provided ornithopter multimedia laboratory exercise offers hands-on experience with electronic components. A brief history of the attempts to design an ornithopter to provide human flight is given, followed by the objectives of the laboratory. Then the basics of electronics are highlighted, and required materials are outlined. All materials for this laboratory can be obtained for a few dollars per flapping creature. After the introductions, a step-by-step tutorial on how to build your own ornithopter is presented. The entire laboratory session takes approximately 3 h.

Ornithopter laboratory.

The final steps before you jump into the actual construction of the LTA vehicle are the necessary design process reviews, namely, the preliminary and completed design reviews. Following this prescribed design process will lead to a successful operational vehicle for the race competition.

12.4.4 Preliminary Design Review

PDR multimedia review.

A preliminary design review is a formal presentation of the documented team design process and proposed design concepts. The goal of a PDR is to evaluate the validity of each preliminary design in a structured learning environment. The outcome is a constructive design evaluation leading to a better understanding of the optimal design path. The teams should strive for a 15 min presentation (10 min presentation and 5 min for questions). Each team member is expected to participate. Team grades will be given based on the presentation of their designs. Teams are encouraged to present their materials electronically. A template is provided as a guide for World Wide Web presentations. Basic instructions for editing the templates for the creation of unique presentations are also provided. All templates and instructions are available on this textbook's accompanying CD-ROM. The PDR template includes the following necessary components for each team presentation:

1. Introduction including team name and team members.
2. The objective of the team's PDR presentation.
3. Discussion and analysis of proposed designs.
4. Selection of proposed design.
5. Schematic of selected design showing approximate relative sizes of balloons, propulsion system, and attitude control system.
6. Aerodynamic analysis of selected design:
   - Helium volume.
   - Vehicle mass estimates.

- Estimates of vehicle drag.
- Estimates of vehicle thrust.
- Number and placement of motors and prop.
- Number, size, and placement of batteries.
- Method of attitude control and maneuvering.
- Expected vehicle velocity and duration of flight.
- Approximate dimensions and layout.

7. Request for supplemental materials needed, including quantity and costs.

8. The timeline of vehicle construction and testing leading up to the LTA vehicle trials and race competition.

9. Conclusion.

For an example of a team's completed LTA vehicle preliminary design review, please review this textbook's accompanying CD-ROM.

12.4.5 Completed Design Review

CDR multimedia review.

A completed design review, also called the Critical Design Review, is a formal presentation of a team's final design. The time leading up to the CDR is spent honing each team member's special skills and working toward a common goal. The goal of the CDR is to present the team's final design for final critical analysis by instructors and peers. The outcome is a completed design ready for production. Each team should prepare a 15 min (10 min presentation and 5 min for questions) CDR. Each team member is expected to participate. Team grades for the CDR are based on the presentation and final design. Teams are encouraged to present their materials electronically. A template is provided as a guide for World Wide Web–based presentations. Basic instructions for editing the templates for the creation of unique presentations are also provided. All templates and instructions are available on this textbook's accompanying CD-ROM. The CDR presentation includes refined versions of the elements included in the PDR, and in addition, *all drawings should be to scale,* with units and scale denoted. Figure 12.11 and Figure 12.12 show a multiview scale drawing, a photograph of a prototype, and perspective scale drawing examples. The CDR template includes the following necessary components for each team's presentation:

1. Introduction including team name and team members with roles in project.

2. The objective of the team's CDR presentation.

3. Introduction to team's final design.

4. Scale drawing of team's final design.

5. Control systems for team's final design.

6. Aerodynamic analysis of team's final design.

7. Final design evolution and analysis.

8. Conclusion.

For an example of a team's completed LTA vehicle completed design review, please review this textbook's accompanying CD-ROM.

Figure 12.11 | Dimensioned LTA vehicle drawing from the CDR.

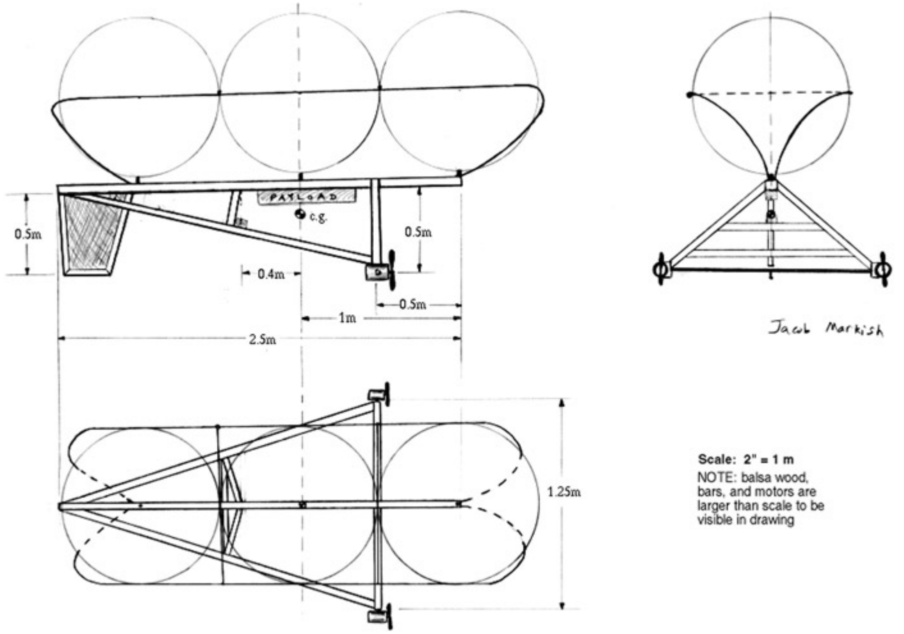
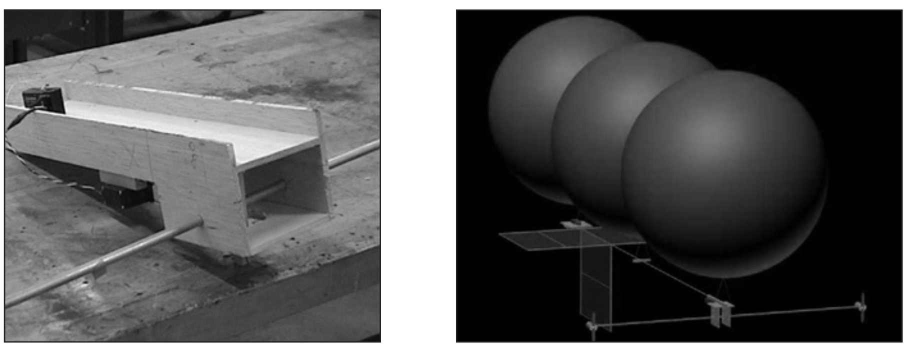


Figure 12.12 | Examples of prototype pitch control and rendered LTA vehicle presented during a CDR.



12.4.6 Personal Design Portfolio

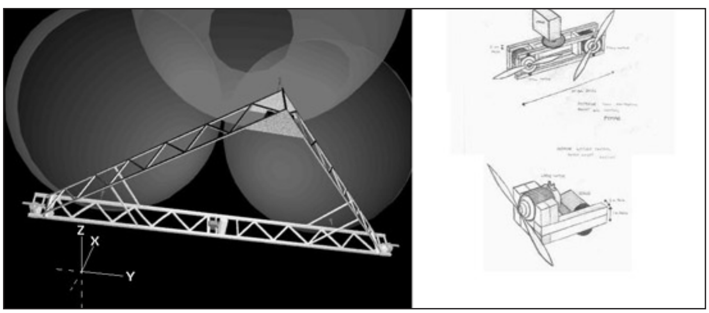
Design Portfolio multimedia review.

Documenting the entire design process can be achieved by preparing a design portfolio (individual personal design portfolios). A personal design portfolio (PDP) is a compilation of a student's work throughout an entire course, enabling the student to take a proactive role in the learning process. The goal of the PDP is to review an individual's work, engaging in a process of reflection, selection, and description. The outcome of the PDP is self-direction over the learning process, gaining a comprehension of engineering concepts that will be carried as tools throughout one's professional engineering career. A template is provided as a guide for World Wide Web–based portfolios. Basic instructions for editing the templates for the creation of unique portfolios are also provided. All templates and instructions are available on this textbook's accompanying CD-ROM. Portfolios should include both the specific contributions to the team's LTA vehicle team design and any additional self-inspired individual designs, ideas, or configurations that were not included in the team's final LTA vehicle design. The PDP template includes the following necessary components for each portfolio:

1. Notes and synthesis including individual log, team meeting minutes, and class notes and observations as related to the LTA design process.
2. Sketches including preliminary sketches and drawings emphasizing the brainstorming process.
3. Concepts correlating fundamental aerodynamics and structures with the design process.
4. Drawings including schematics of preliminary as well as final designs. These are to be hand- and/or computer-drawn.
5. Scale drawings of the final design.
6. Critical aerodynamic analysis of the final design.
7. LTA prototype including photographs of prototypes in various stages.
8. Race vehicle design including photos of the LTA vehicle. Add photos of trials or race day if available.

For examples from individuals' completed personal design portfolios, please review this textbook's accompanying CD-ROM. Figure 12.13 shows a CAD perspective drawing and sketches of motor mounts and propellers from students' portfolios.

Figure 12.13 | Personal design portfolio examples.



The following is an example showing a typical portfolio description of the design process.

Design is a fickle thing. While it does involve equations, mass estimates, and numerical analysis, a great deal of the design process incorporates human intuition and gut instinct. It is not always precise, either, nor does it always need to be. For example, when we designed our first prototype, I had in mind a beautifully assembled work of art that mimicked the eventual design, but on a much smaller scale. As we began experimenting with things that would make a good prototype, we had two considerations:

The materials needed to provide enough rigidity to reasonably hold the structure together.

The materials needed to be dirt-cheap (this was, after all, only a prototype).

As luck would have it, the best materials at this stage in the process turned out to be wooden chopsticks (the kind you get for free with cheap sushi), duct tape, and typing paper. This proved very advantageous because the length of a singular chopstick exactly matched the diameter of one of the small-scale balloons we used. This made scaling the dimensions up to full-size much easier: everything got multiplied by the same factor. Additionally, we discovered that a duct tape joint is surprisingly strong, at least on a model made of chopsticks.

So, from this very simple example, I learned a great lesson about the design process: The most important part of design is not concerned with predicting what will happen, but rather with getting one's hands dirty and experiencing what is happening. (D. Carpenter)

12.4.7 LTA Vehicle Design Hints

There are two especially difficult and critical issues to consider when thinking about the operational LTA vehicle. To successfully navigate the race course in the shortest time possible, the lighter-than-air craft must be both *controllable* and *stable,* qualities which have been reviewed in Chapter 3, "Aerodynamics," Chapter 4, "Aircraft Performance," and Chapter 7, "Introduction to Airplane Stability and Control." The following section provides additional design hints on these concepts from a student's perspective to achieve the desired results: a flying controllable, stable LTA vehicle.

Control: Control is the ability of the team to dictate the direction that the blimp flies. Essential to control is the ability to turn and to gain and lose altitude.

Stability: A stable craft is able to maintain a constant altitude without control inputs. An unstable craft, when given the control input to turn or change altitude, will continue to do so until an opposing command is given. A stable craft will cease to turn or change altitude once the control input is removed, returning to straight and level flight.

LTA vehicle multimedia design hints.

Making an LTA Vehicle Controllable There are three axes of flight that need to be considered when thinking about control.

Yaw: movement about the vertical axis.

Pitch: movement about the lateral axis.

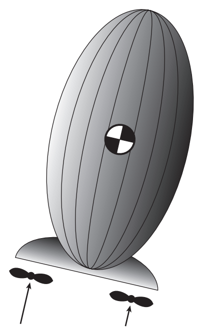
Roll: movement about the longitudinal axis.

To control your blimp about these axes of flight, two methods can be used, control surfaces and vectored thrust.

- *Control surfaces:* Ailerons, rudders, and elevators are used. The blimp will be moving much *too slowly* for the control surfaces to be effective; however, control surfaces offer many other valuable contributions to stability.

- *Vectored thrust:* Vectored thrust uses the thrust of the motors to direct the motion of the craft. There are many different configurations for motor placement. Each placement will affect yaw, pitch, and roll. This example (Figure 12.14) demonstrates the use of motor placement to control yaw. In this placement, thrust is vectored horizontally.

Figure 12.14 | Using vectored thrust to yaw an airship (see animation in LTA Interactive on the accompanying CD-ROM).



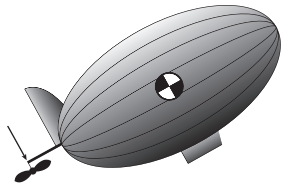
The important thing to remember about this configuration is that it is most effective when the crossbar, the bar with the motors, is placed at the center of gravity. The longer the bar is, the more turning power one will realize for a given thrust. Torque = force × distance, where force is the force applied by the motor and distance is the length of the bar from the motor to the craft's center of gravity.

Pitch is controlled in the same manner as yaw, except the thrust is vectored vertically. Pitch controls are necessary to control the LTA's attitude. There are several different ways that motors can be configured to achieve this. The LTA can be designed to control attitude by

- Raising the front.
- Lowering the front.
- Raising the rear.
- Lowering the rear.
- Using a combination of these options.

Even if one establishes the appropriate pitch angle, the blimp will not ascend or descend properly unless *roll* is also controlled. Roll becomes an even greater problem if structures are placed far from the vehicle's center of gravity along the lateral axis. The best way to control roll is to have a vehicle that is well balanced in all directions. See Figure 12.15.

Figure 12.15 | Using vectored thrust to pitch an airship (see animation in LTA Interactive on the accompanying CD-ROM).



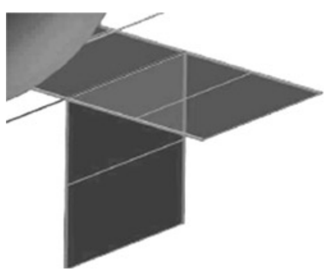
Finally, the best designs are the ones that use control mechanisms to apply vectored thrust around more than one axis.

Stability An unstable LTA vehicle will require excessive control inputs to make it fly a desired course; therefore, a stable aircraft will be faster and easier to fly. A good test for stability is whether the vehicle will fly straight and level with no control inputs and will stop turning when a control input is discontinued. In order for a craft to be stable, the LTA vehicle must be well balanced, and the motors must return to their neutral position when the control input is stopped. One method for increasing stability is to use stabilizers. There are two main configurations to consider.

- Horizontal stabilizer
- Vertical stabilizer

Stabilizers will add to the stability about all three axes (roll, pitch, and yaw). See Figure 12.16. These stabilizers use air resistance to steady the craft. The air resistance is an effective way to counterbalance the vectored thrust forces produced by the motor and propeller. When an input force is applied to turn the craft, air creates an equal opposing force against the stabilizer. When the turning force is removed, air resistance against the stabilizer slows the turning motion, returning it to straight and level flight. There are many different ways stabilizers can be incorporated into the LTA vehicle design.

Figure 12.16 | Vertical and horizontal stabilizers on an LTA vehicle.



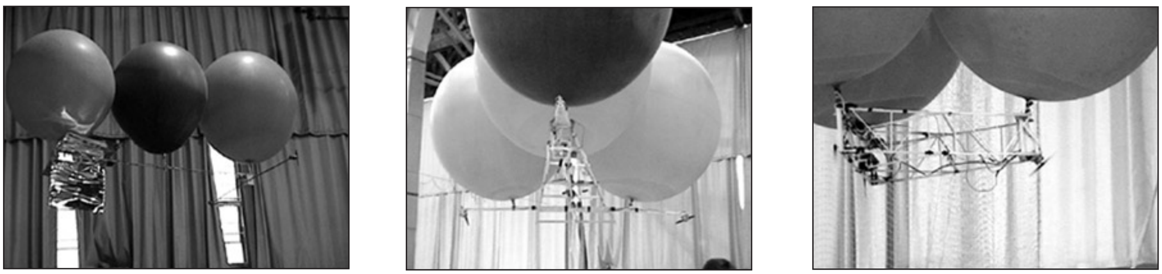
12.4.8 The LTA Vehicles Take Flight

LTA vehicle race day.

The LTA vehicle design competition culminates in the two days when the vehicles are flown, during the *trials* and *race* day. The teams learn invaluable lessons at the LTA trials when their design becomes reality. Factors that may have been overlooked in the design stage become glaringly obvious during trials, such as *how much lift* four helium-filled weather balloons can actually provide, *what control really means* as the pilot attempts to negotiate the first corner of the course, and the new-found meaning of *stability* when balloons in series start to oscillate during the flight. LTA vehicle teams endure structural failures, drained batteries, and improperly mounted propellers to learn perhaps the most important systems design lesson—any flying machine is a complex system.

Finally, a semester of diligence and teamwork is realized on race day as the blimps once again take flight (see Figure 12.17). One by one, each team flies its final design around the marked course. This is a time of glorious victory even for the teams whose LTA vehicles do not place in the competition; the ultimate victory is the realization of the design process and for the first time knowing what it is to be a designer. This initial excitement of design from the LTA experience is carried over to a fulfilling career in engineering.

Figure 12.17 | LTA vehicles take flight during the race competition.



12.5 | DESIGN SUMMARY

Design is an all-encompassing word. One can describe what a designer does or display a beautifully designed product without fully defining the word *design.* How is it that an engineer may be said to design a new gearbox for a car while an art designer may also be said to design a new fashion? The process that gives rise to a new gearbox is surely precise, predetermined, systematic, and mathematical in its nature. These are hardly the qualities associated with fashion design which, by contrast, seems rather free-flowing, spontaneous, inspired, and imaginative. To make matters even more complicated, many kinds of design call for a process that combines both these extremes in varying proportions along the spectrum of design. Urban design, architecture, industrial, and graphic design, to name a few, involve elements that may seem both precise and free-flowing, systematic and inspired, mathematical and imaginative. One thing all designs have in common is their main objective to create objects or places that have a purpose for humans and are intended to be looked at and/or used. Design is not extremes; it falls somewhere along a vast continuum. Even the engineer must be imaginative, and the fashion designer must use precision.

One determines that design is neither black nor white, but many shades of gray. This still does not define design. Classifying design by its end product seems to be rather illogical; the solution is something that is formed by a process, and in turn the product may not have even existed in advance of this process. The real reason for classifying design by its product has very little to do with the design process, but is a reflection of a world with increasingly specialized technologies and technological education. Unfortunately, engineering specialization can easily become a straightjacket for the designer, directing his or her mental processes toward a predefined goal. This problem of tunneling energy into a goal instead of expanding the mind to reach the optimal solution is reflected in this tale of the scientist, engineer, and artist.

19th century barometer.

Once there were three friends: a scientist, an engineer, and an artist. One day the three were standing outside the church, debating the height of the church tower, when a local shopkeeper who was passing by suggested a competition. The shopkeeper was very proud of a new barometer that he now stocked in his shop, and in order to advertise it, he offered a prize to the one who could most accurately discover the height of the tower using one of his barometers. The trio stated they were up to the challenge. The scientist carefully measured the barometric pressure at the foot of the tower and again at the top, and from the difference she calculated the height. The engineer, scorning this technique, climbed to the top, dropped the barometer, and timed the period of its fall, stating this was the only accurate way to find the solution. However, it was the artist, to the surprise of all, who was the most accurate. She simply went inside the church and offered the barometer to the priest in exchange for allowing her to examine the original drawings of the church!

Admiring the attributes of this clever artist, this chapter offers a unique design definition. Design is a process, the skill of thinking. This skill encourages the expansion over narrowing of ideas in search of optimal solutions. It requires diligence, creativity, and inspiration, as well as highly developed mathematical and scientific thought. Design breaks free from the traditional scientific method that encourages a step-by-step process where one sets out to prove something is true or false. Instead, it encourages one to call on all forms of knowledge and experience, then in a circular method, hone thoughts and ideas to find the best solution. Once one truly understands design, he or she is no longer a scientist, an engineer, or an artist; he or she becomes a designer.

PROBLEMS

12.1 Arthur Ganson's designs

We read objects in motion on both the objective and subjective levels. A machine may be about fabric or grease, but it may also be about thick liquid and sensuous movement. A bit deeper, it may be about meditation or the sense of release. And taken yet another step, it may be about pure invention and the joyfulness in the heart of its creator. (Arthur Ganson)

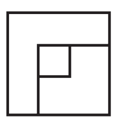
Sculptor/inventor Arthur Ganson's whimsical mechanical sculptures embody the qualities least associated with machines. Self-described as a cross between an engineer and a choreographer, Ganson creates contraptions composed of a range of materials from delicate wire to welded steel and concrete. Most are viewer-activated or driven by electric motors. All are driven by a wry sense of humor or a probing philosophical concept. "When making a sculpture," Ganson says, "it's always a challenge to say enough but not say too much, to coax with some kind of recognizable bait, then leave the viewer to draw his or her own conclusions and thereby find personal meaning."

Watch the video of Arthur Ganson's design and sculpture on this textbook's accompanying CD-ROM. In no more than two pages, critique one of Ganson's sculptural engineering designs that fascinated you. Provide the following in your critique:

Ganson.mov

(a) An introduction to the specific design you have chosen.
(b) A discussion of how you think it works, mechanically or electrically.
(c) A discussion of what you think of the aesthetics of the design.
(d) Recommendations you have to change or enhance your chosen design.
(e) A summary statement about how Arthur Ganson's designs will affect your own engineering designs.

12.2 The following puzzles (in Problems 12.2 through 12.4) are meant to give you practice with orthographic projections, specifically, multiviews. For each puzzle shown, a top view and front view are provided. Sketch the side and isometric views. Make sure your drawings are neat.



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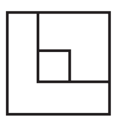
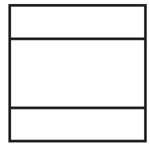


Front

12.3 Follow the instructions given in Problem 12.2.



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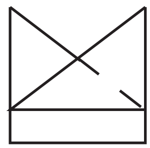
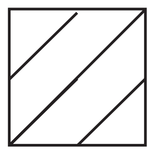


Front

12.4 Follow the instructions given in Problem 12.2.



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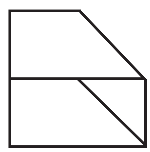


Front

12.5 Select an everyday object, and draw a multiview orthographic projection of it. Next, take your drawings to class. In small in-class groups, display your drawings. Show each view one at a time. After each view is shown, allow your classmates to guess your object.

(a) How many views did your classmates have to see prior to correctly guessing the object?

(b) How did the object's detail affect the ease with which your classmates identified it?

12.6 You are a first-year college student; you arrive on campus to find that there is not enough housing for every student. After all the rooms have been filled, there are still 100 students who need placement. You are asked to be part of a task force to solve this issue.

(a) Think of two “intermediate impossibilities.”
(b) Discuss the feasibility of these possibilities.
(c) Outline the steps to solve the problem.

12.7 For the Human-Powered Flight Daedalus Project contained on the CD-ROM:
(a) Discuss the aerodynamic speed constraints for Daedalus. Then mention how these same constraints might influence your lighter-than-air vehicle design.
(b) What are the major contributors to drag for the Daedalus aircraft? Again, discuss how these or similar considerations might influence your LTA vehicle design.
(c) Given the human power plant, would you recommend a large, powerful pilot or a smaller, slightly less powerful pilot? Why?

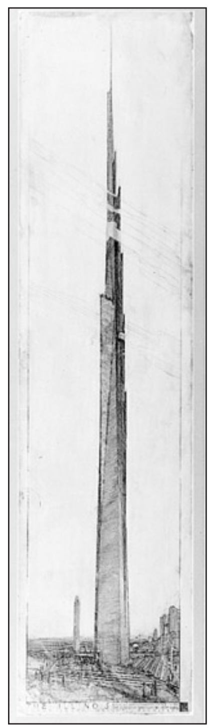
Human power: Daedelus.

12.8 Using the Human-Powered Flight Decavitator Project on the CD-ROM, answer the following:
(a) From the Decavitator human-powered hydrofoil slide presentation, what are the main issues to ensure sufficient stability and control?
(b) What is the main design lesson learned from the Decavitator experience?

Human power: Decavitator.

12.9 Perform a Web search on Frank Lloyd Wright. Describe his design for the mile-high building in Chicago (see Figure 12.18) in one paragraph. List all references used according to the format specified in Mayfield Handbook URL (http://tute.mit.edu:8001/course/21/21.guide/www/home.htm).

Figure 12.18 | Architect Frank Lloyd Wright’s mile-high building concept.



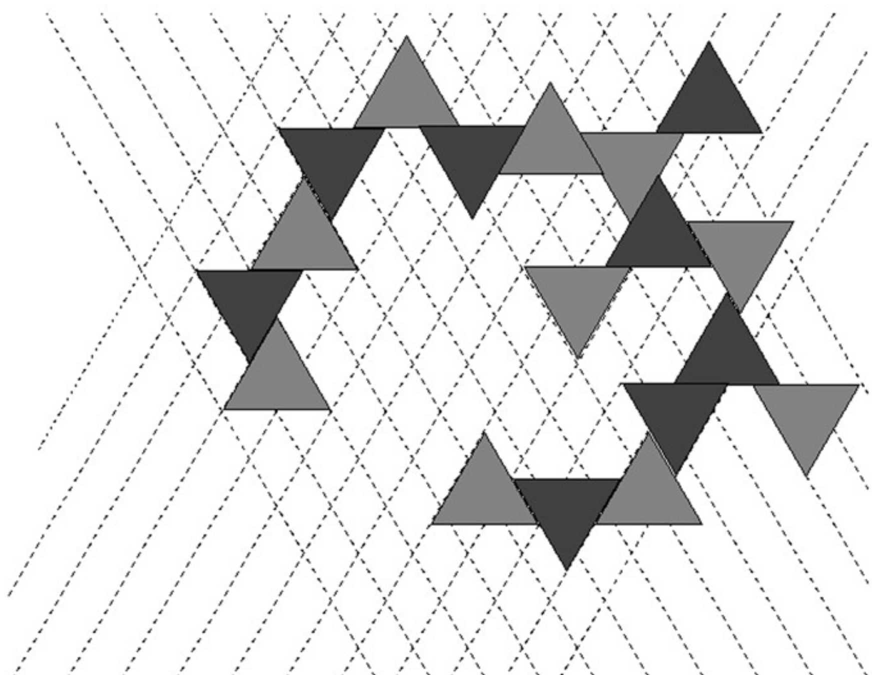
12.10 The Delta Design game activity is recommended as a teamwork exercise, which takes a minimum of two class periods. © Professor Louis Bucciarelli, llbjr@MIT.EDU. Through the Delta Design experience, teams act out the design process for the construction of a two-dimensional house for the space aliens of planet DeltaP. The game builds team working skills and rewards creativity. Delta Design is a team exercise developed for engineering education at any level, undergraduate, graduate, or professional. Life on DeltaP, residential and otherwise, is quite different from that on Earth. First, DeltaP is a place, not a planet, so teams will be designing in two-dimensional, rather than three-dimensional, space. If the final design meets expectations and is considered attractive and functional by the Deltan clients, one view on a single sheet of paper will convey to those responsible for constructing it all the information they need to do so.

The design team is organized such that each member will be responsible for a subset of the design goals. Specific instructions for each role will be handed out prior to the game. One member will be the project manager. The project manager’s main concerns will be with cost and schedule, the interpretation and reconciliation of performance specifications, and negotiations with the contractor and client. The project manager wants to keep costs and time-to-build at a minimum, but not at the expense of quality. When the team submits its final design, the project manager must report the estimated cost (in zwigs) and the time (in wex) that it will take to build.

Another member will be the structural engineer. The structural engineer's main concern will be to see that the design "holds together" as a physical structure under prescribed loading conditions. The structural engineer must see to it that the two points at which the structure is tied to ground are appropriately chosen and that continuity of the structure is maintained. When the team submits its final design, the structural engineer must attest to its integrity by identifying the strongest and weakest joints and estimating the average load on all the joints, expressed as a percentage of the failure load.

A third member will be the thermal engineer. It is the thermal engineer's responsibility to ensure that the design meets the "comfort-zone" conditions specified in terms of an average temperature. He or she must also ensure that the temperature of all individual deltas stays within certain bounds. When the team submits its final design, the thermal engineer must estimate the internal temperature and identify the hottest and coldest deltas.

Figure 12.19 | Delta Design two-dimensional game board.



Finally, one member will be the architect. His or her concern is with both the form of the design in and of itself and how it stands in its setting. The architect must see to it that the interior of the residence takes an appropriate form and that egress is convenient. He or she should also develop a design with character. When the team submits its final design, the architect should be prepared to present a sketch and discuss generally how and why the Deltans will find the residence attractive and functional. The architect will also be asked to estimate a few more quantitative measures of architectural performance.

12.11 The lighter-than-air vehicle design, build, and fly project is recommended for teams of four to six students during the second half of a semester-long course (see Section 12.4, "Lighter-Than-Air (LTA) Vehicle Design Project," and the accompanying CD-ROM design presentations and templates).

LTA vehicle design multimedia.

(a) Preliminary design review.
(b) Completed/Critical design review.
(c) Personal design portfolio.
(d) LTA vehicle trials competition.
(e) LTA vehicle race competition.

A Appendix

Unit Systems and Unit Conversion Factors

Amir R. Amir

Three quantities are considered *fundamental mechanical quantities:* length, mass, and time. From these all nonelectrical and nonmagnetic quantities can be derived. To define electrical and magnetic quantities, one electrical or magnetic unit such as current needs to be added.

A.1 | THE INTERNATIONAL SYSTEM OF UNITS (SI)

The International System of units, referred to as *SI,* is the most comprehensive and advanced system of units. SI units are divided into three categories: (1) base units, (2) supplementary units, and (3) derived units. The base units are seven well-defined units which are dimensionally independent. They are listed in Table A.1.

Table A.1 | SI base units

Quantity	Unit name	SI symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

The units for plane angle and solid angle are supplementary in SI. The radian is defined as the plane angle between two radii of a circle which cut off on the circumference an arc equal in length to the radius. The steradian is defined as the solid angle which, having its vertex in the center of the sphere, cuts off an area of the sphere equal to that of a square with sides of length equal to the radius of the sphere. See Figure A.1.

Since the radian is the ratio of two lengths and the solid angle is a ratio of two areas, the supplementary units are dimensionless. The plane angle in a full circle is equal to 2π rad, and the solid angle of a complete sphere is equal to 4π steradians (sr). Derived units are units of physical quantities that can be expressed algebraically in terms of base and supplementary units as well as previously formulated and accepted derived units. Frequently used derived units with special names are listed in Table A.2.

Figure A.1 | Definition of the plane angle SI unit, radian, and the solid angle SI unit, steradian.

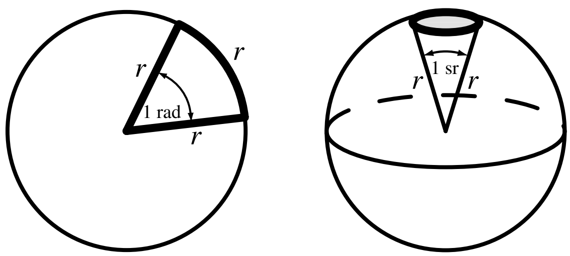


Table A.2 | Derived units with special names

Quantity	Derived unit	Symbol	Expression in other SI units
Frequency	hertz	Hz	s^{-1}
Force	newton	N	$kg \cdot m/s^2$
Pressure	pascal	Pa	N/m^2
Energy, work, heat	joule	J	$N \cdot m$
Power	watt	W	J/s
Electric charge	coulomb	C	$A \cdot s$
Electric potential	volt	V	W/A
Electric capacitance	farad	F	C/V
Electric resistance	ohm	W	V/A
Conductance	siemens	S	A/V
Magnetic flux	weber	Wb	$V \cdot s$
Magnetic flux density	tesla	T	Wb/m^2
Inductance	henry	H	Wb/A
Luminous flux	lumen	lm	$cd \cdot sr$
Illuminance	lux	lx	lm/m^2
Activity of a radionuclide	becquerel	Bq	s^{-1}
Absorbed dose	gray	Gy	J/kg
Dose equivalent	sievert	Sv	J/kg

In order to eliminate insignificant digits and to provide a convenient substitute for writing powers of 10, a series of prefixes to form names and symbols of SI units exist, which are listed in Table A.3.

Table A.3 | SI prefixes[1]

Multiplication factor	Prefix	Symbol	Multiplication factor	Prefix	Symbol
10^{18}	exa	E	10^{-18}	atto	a
10^{15}	peta	P	10^{-15}	femto	f
10^{12}	tera	T	10^{-12}	pico	p
10^{9}	giga	G	10^{-9}	nano	n
10^{6}	mega	M	10^{-6}	micro	m
10^{3}	kilo	k	10^{-3}	milli	m
10^{2}	hecto	h	10^{-2}	centi	c
10^{1}	deka	da	10^{-1}	deci	d

[1]Use of the prefixes in the shaded table cells is not recommended.

Prefixes should be chosen such that the numerical part of the expression is greater than 0.1 and less than 1,000. When a multiple of a compound is formed, only one prefix should be used. With the exception of the kilogram, the prefix is always attached to the numerator when the units involve a fraction.

A.2 | ENGLISH UNITS

Table A.4 summarizes the customary English units used in the United States. The *English engineering system of units* is the set of units used by engineers in the United States, Britain, and a few other countries. The fundamental units of length, mass, and time are the foot, slug, and the second. In this system one pound is the force required to accelerate a mass of one slug by one foot per second squared. The temperature scale in the English engineering system is the Rankine (°R) scale, which, like the kelvin (K) scale, is an absolute temperature scale. The Fahrenheit (°F) scale is related to the Rankine scale by the formula

$$T_{°F} = T_{°R} + 459.67° \qquad \textbf{[A.1]}$$

Note that zero degrees Rankine is equal to zero kelvins. The unit of pressure is the psi (pound-force per square inch). Quite commonly used is also the standard atmosphere unit (atm). The unit of energy is the foot pound-force (ft · lb), but in thermodynamics applications, the British thermal unit (Btu) is used more frequently, where

$$1 \text{ Btu} = 778.17 \text{ ft} \cdot \text{lbf}$$

The unit of power is the horsepower (hp), which is defined as follows

$$1 \text{ hp} = 550 \text{ ft} \cdot \text{lbf/s} = 2{,}544 \text{ Btu/h}$$

Table A.4 | Customary English units used in the United States

Length
1 statute mile = 1,760 yards = 5,280 feet
1 nautical mile = 1,852 meters
1 yard = 3 feet = 36 inches
1 foot = 12 inches
1 mil = 0.001 inch
Area
1 square mile ≈ 639.9974 acres = 3,097,600 square yards
1 acre ≈ 4 ,840.0194 square yards ≈ 43 ,560.174 square feet
Capacity or Volume
1 gallon = 4 quarts = 8 pints = 128 fluid ounces = 231 cubic inches
Weight
1 ton = 2,000 pounds = 32,000 ounces
1 pound = 16 ounces

A.3 | UNIT CONVERSION FACTORS

To convert temperatures between the Celsius, Fahrenheit, Kelvin, and Rankine scales, use the following formulas:

$$T_{\circ\mathrm{C}} = \frac{5}{9}(T_{\circ\mathrm{F}} - 32) = \frac{5}{9}(T_{\circ\mathrm{R}} - 491.67) = T_{\mathrm{K}} - 273.15 \qquad \textbf{[A.2]}$$

$$T_{\circ\mathrm{F}} = 1.8(T_{\circ\mathrm{C}} + 32) = T_{\circ\mathrm{R}} - 459.67 = 1.8(T_{\mathrm{K}} - 255.37) \qquad \textbf{[A.3]}$$

$$T_{\mathrm{K}} = T_{\circ\mathrm{C}} + 273.15 = \frac{5}{9}(T_{\circ\mathrm{F}} + 459.67) = \frac{5}{9}T_{\circ\mathrm{R}} \qquad \textbf{[A.4]}$$

$$T_{\circ\mathrm{R}} = 1.8(T_{\circ\mathrm{C}} + 273.15) = T_{\circ\mathrm{F}} + 459.67 = 1.8T_{\mathrm{K}} \qquad \textbf{[A.5]}$$

Table A.5 provides conversion factors for common units.

Table A.5 | Unit conversion factors

Angle (Planar)
1 degree = 60′ = 3,600″ = 0.01745329 rad
1 arc minute = (1/60)° = 60″ = 0.01745329 rad
1 arc second = (1/3,600)° = (1/60)′ = 4.8481368 × 10^{-6} rad
1 rad = 57.2957951° = 3.4377468 × 10^{3}′ = 2.0626481 × 10^{5}″
Area
1 acre = 4.3560174 × 10^4 ft^2 = 4.0468726 × 10^3 m^2 = 4.840019360 × 10^3 yd^2
1 foot squared = 2.2956749 × 10^{-5} acre = 9.290304 × 10^{-2} m^2 = (1/9) yd^2
1 meter squared = 2.471043930 × 10^{-4} acre = 10.76391042 ft^2 = 1.1959901 yd^2

(continued)

Table A.5 *(continued)*

Energy, Heat, Work
1 int. British thermal unit = 251.9957611 cal = 778.1692623 ft · lb = 1.0550559×10^3 J
1 calorie = 3.9683207×10^{-3} Btu = 778.1692623 ft · lb = 1.0550559×10^3 J
1 foot pound = 1.2850675×10^{-3} Btu = 0.32383155 cal = 1.355818 J
1 joule = 9.4781713×10^{-4} Btu = 0.2388459 cal = 0.73756215 ft · lb

Force, Weight
1 pound force = 4.4482216 N
1 newton = 0.22480894 lb

Length
1 foot = 12 in = 0.3048 m = (1/5,280) mi = 1.6457883×10^{-4} nmi
1 inch = 0.0254 m = 1.5782828×10^{-5} mi = 1.3714903×10^{-5} nmi
1 meter = (1/0.3048) ft = (1/0.0254) in = 6.2137119×10^{-4} mi = (1/1,1,852) nmi = (1/0.9144) yd
1 int. statute mile = 5,280 ft = 63,360 in = 0.86897624 nmi = 1,760 yd
1 int. nautical mile = 6.0761155×10^3 ft = 1,852 m = 1.1507794 mi = 2.0253718×10^3 yd
1 yard = 3 ft = 0.9144 m = (1/1,760) mi = 4.937365×10^{-4} nmi

Mass
1 kilogram = 2.2046226 lb_m = 1.1023113×10^{-3} short ton = 0.06852177 slug
1 pound mass = 0.45359237 kg = (1/2,000) short ton = 0.031080950 slug
1 short ton = 907.18474 kg = 2,000 lb_m = 62.16190034 slug
1 slug = 14.59390294 kg = 32.17404856 lb_m = 0.01608702 short ton

Power
1 Btu per second = 778.1692623 ft · lb/s = 1.4148532 hp = 1.0550559×10^3 W
1 foot pound per second = 1.2850675×10^{-3} Btu/s = (1/550) hp = 1.355818 W
1 horsepower = 3.333378030 Btu/s = 550 ft · lb/s = 745.6998716 W
1 watt = 9.4781712×10^{-4} Btu/s = 0.73756215 ft · lb/s = $1.341022090 \times 10^{-3}$ hp

Pressure
1 bar = 29.52998330 inHg = 1×10^5 Pa = 14.50377363 psi = 750.0616827 torr
1 inch of mercury = 0.03386388 bar = 3.3863882×10^3 Pa = 0.49115414 psi = 25.4 torr
1 pascal = 1×10^{-5} bar = 2.9529987×10^{-4} inHg = 1.4503774×10^{-4} psi = 7.5006168×10^{-3} torr
1 pound per square inch = 0.06894757 bar = 2.036021 inHg = 6.8947573×10^3 Pa = 51.71493257 torr
1 torr = 1.3332237×10^{-3} bar = 0.03937008 inHg = 133.3223684 Pa = 0.01933678 psi

Velocity
1 foot per second = 1.09728 km/h = 0.5924838 kn = 0.3048 m/s = (15/22) mi/h
1 kilometer per hour = 0.91134441 ft/s = 0.5399568 kn = (1/3.6) m/s = 0.62137119 mi/h
1 knot = 1.6878099 ft/s = 1.852 km/h = 0.51444444 m/s = 1.1507794 mi/h
1 meter per second = (1/0.3048) ft/s = 3.61 km/h = 1.9438445 kn = 2.2369363 mi/h
1 mile per hour = (22/15) ft/s = 1.609344 km/h = 0.86897624 kn = 0.44704 m/s

Volume
1 U.S. gallon = 231 in^3 = 3.7854118 L = 3.7854118×10^{-3} m^3 = 128 oz
1 cubic inch = (1/231) gal = 0.01638706 L = 1.6387064×10^{-5} m^3 = 0.55411255 oz
1 liter = 0.26417205 gal = 61.02374409 in^3 = 0.001 m^3 = 3.81402270 oz
1 cubic meter = 264.17205236 gal = 6.1023744×10^4 in^3 = 1,000 L = 3.381402270×10^4 oz
1 ounce = 7.8125×10^{-3} gal = 1.8046875 in^3 = 0.029573530 L = 2.957353×10^{-5} m^3

Appendix B

Physical Constants and Miscellaneous Values

Amir R. Amir

Table B.1 | Physical constants

Quantity	Symbol	Value
Speed of light in vacuum	c	299,792,458 m/s
Permeability of vacuum	μ_0	$4\pi \times 10^{-7}$ N/A^2
Permittivity of vacuum	ε_0	8.854×10^{-12} F/m
Universal gravitational constant	G	6.673×10^{-11} m^3/(kg · s^2)
Planck's constant	h	6.626×10^{-34} J · s
Dirac's constant	$\bar{h}$	1.055×10^{-34} J · s
Elementary charge	e	1.602×10^{-19} C
Electron mass	m_e	9.109×10^{-31} kg
Proton mass	m_p	1.673×10^{-27} kg
Neutron mass	m_n	1.675×10^{-27} kg
Avogadro's number	N_A, L	6.022×10^{23} mol^{-1}
Atomic mass constant	m_u	1.661×10^{-27} kg
Faraday's constant	$N_A h$	3.990×10^{-10} J · s/mol
Molar gas constant	$\bar{R}$	8.315 J/(mol · K)
Boltzmann's constant	k	1.381×10^{-23} J/K
Molar volume of an ideal gas at STP	V_m	22.414 L/mol
Stefan-Boltzmann's constant	σ	5.671×10^{-8} W/(K · m)

Table B.2 | Astronomical values

Quantity	Symbol	Value
Distance from Earth to Sun	au	1.4960×10^{11} m
Solar mass		1.99×10^{30} kg
Earth mass		5.97×10^{24} kg
Standard gravitational acceleration	g_0	9.80665 m/s^2
Moon mass		7.35×10^{22} kg
Earth orbital velocity	V_I	7.91 km/s
Earth escape velocity	V_{II}	11.19 km/s
Solar system escape velocity	V_{III}	16.67 km/s

Table B.3 | Properties of air[1]

Quantity	Symbol	Value
Density	ρ	1.161×10^{-3} kg/m^3
Specific heat capacity at constant pressure	C_P	1,003.5 J/(kg · K)
Specific heat capacity at constant volume	C_V	716.5 J/(kg · K)
Ratio of specific heat capacities	γ	1.4006
Specific gas constant	R	287 J/(kg · K)
Speed of sound	a	343 m/s
Viscosity	μ	1.7894×10^{-5} kg/m · s

[1]Dry air at a temperature of 20°C and a pressure of 1 atm.

Table B.4 | Properties of selected engineering materials

Property	Aluminum alloy 2014-T6	Steel (structural ASTM-A36)	Titanium alloy
Density, kg/m^3	2,800	7,860	4,460
Ultimate strength, tension, MPa	480	400	900
Yield strength, tension, MPa	410	250	825
Modulus of elasticity, GPa	72	200	114
Poisson's ratio	0.33	0.27–0.30	0.33

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