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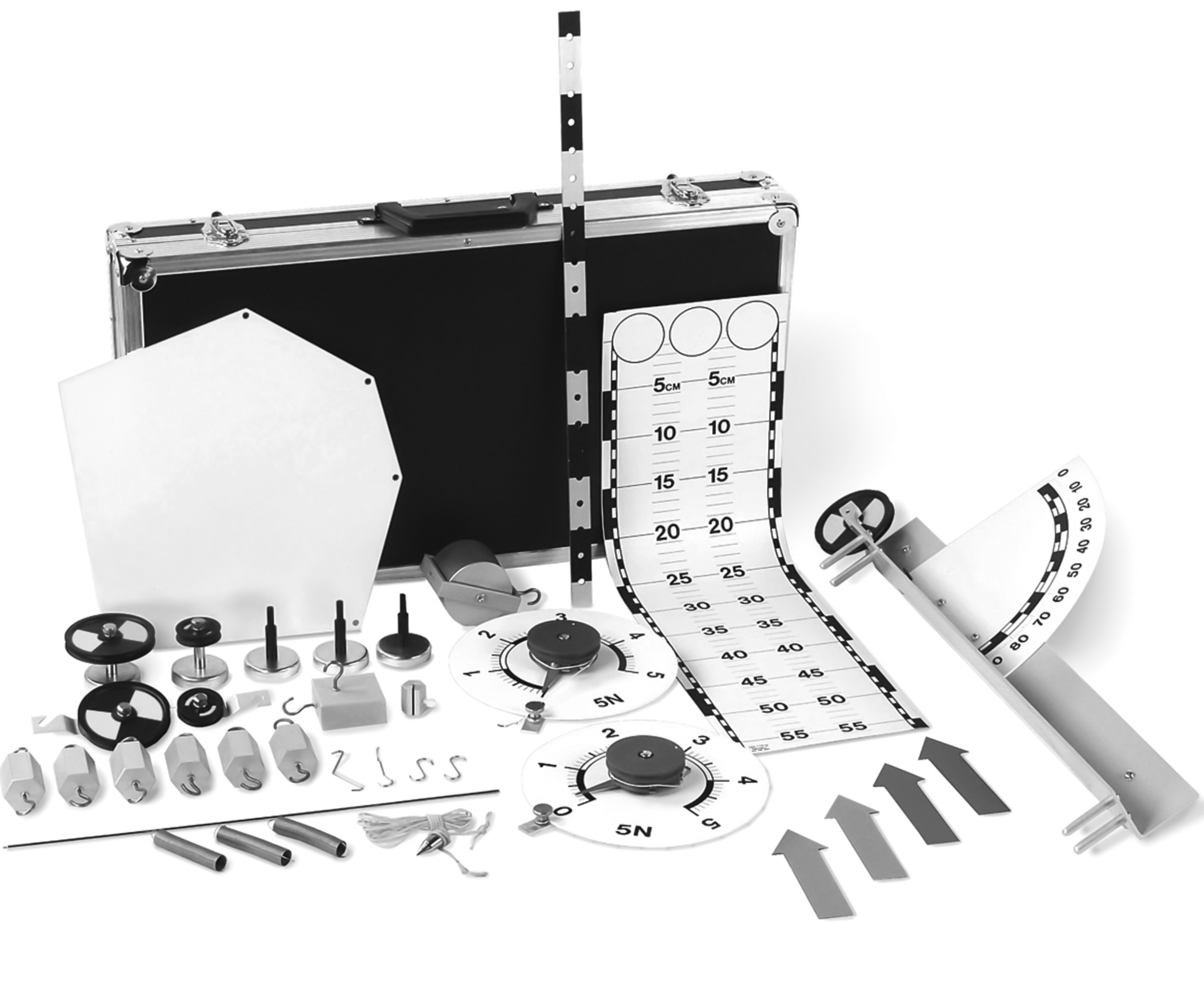
# BLACKBOARD MECHANICS™

## EXPERIMENT MANUAL

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## THE SIGNIFICANCE OF SMA

(Static Mechanical Advantage)

The actual mechanical advantage (AMA) of any physical machine is a *dynamic* parameter which takes friction into account and can be determined only when the machine is in motion. To measure AMA experimentally, it is necessary to apply that particular effort force (E) which will cause the resistance (R) to move with constant speed after the system is initially set in motion by an external force. Thus:

$$AMA = \frac{R}{E} \quad \text{(R moving uniformly)}$$

The photographs in this Bulletin are by necessity *static* in nature; they are presented to provide the teacher with graphic illustrations which help him or her to visualize the component placements and linkages for the various experiments. Referring to Figure 2, for example, the angle of the inclined plane was adjusted so that a visible effort force of 2 newtons (F) would keep the system in equilibrium when the 5-newton hooked roller was placed on the plane surface. When the experiment is performed in class, however, the teacher would add a few small weights to F in order to cause the hooked weights to move downward at a constant slow speed after they have been started by a small downward thrust. The AMA would then be the ratio of the resistance (R or W) to the actual effort (E or F) in this case consisting of the 2-newton weight plus the weight that was added previously. Suppose that the presence of friction in the pulley and the roller bearing required that an additional weight of, say, 0.1 newton be added to bring about the desired effect. In this case, the AMA would be:

$$AMA = \frac{R}{E} = \frac{W}{F} = \frac{5\,N}{2.1\,N} = 2.38$$

Now... looking at Figure 2, one sees a 2.0 N effort supporting a 5.0-newton resistance on the plane. The ratio of the resistance to effort in the photograph is 5/2 or 2.5. Clearly, this is *not* the AMA of the system because it does not take into account the reduction of force multiplication caused by friction. Consequently, we have elected to designate this "mechanical advantage" as the *static* parameter of the system and have referred to it in the photographs as the SMA.

$$SMA = \frac{R}{E} \quad \text{(system in equilibrium)}$$

We should like to emphasize that the teacher need never refer to the SMA in the classroom as long as the AMA of each machine demonstrated is measured in the dynamic mode. For our inclined plane example, taking the length of the plane as 60 cm and its height as 23 cm, the IMA would be L/H = 60/23 = 2.61 and since the AMA is 2.38, the efficiency would be AMA/IMA = 2.38/2.61 = 91.2%.

Thus, the SMA as we have defined it is an error-free convenience for describing experimental results shown in a still picture; it is not intended for use in the classroom.

## EXPERIMENT #1

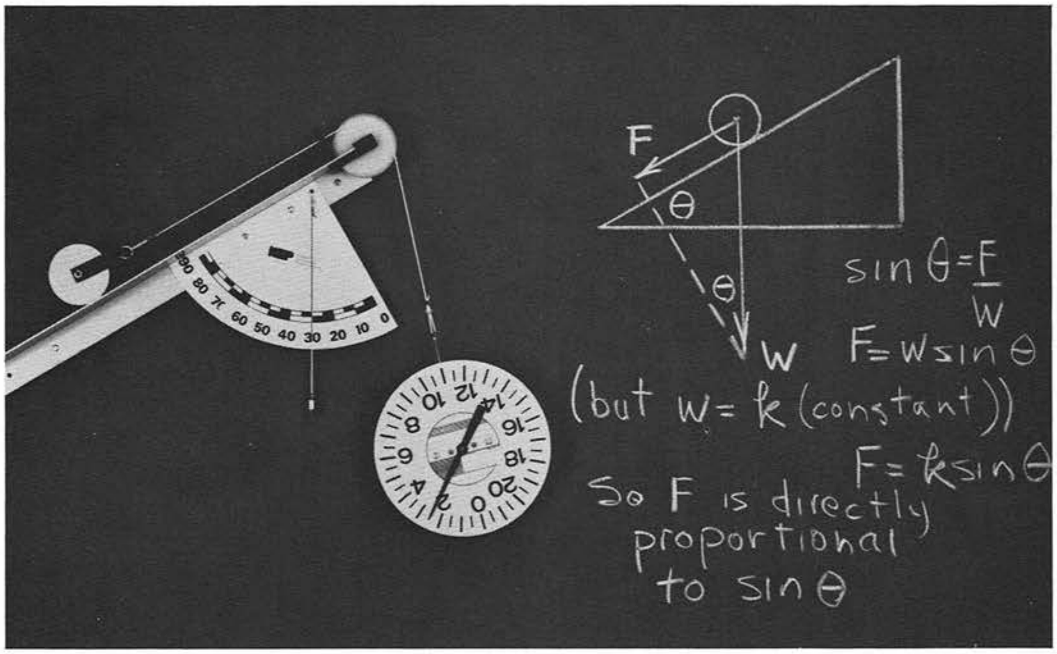



Figure 1

**Objective:** (a) To show qualitatively that the force required to hold an object in equilibrium on a frictionless plane increases as the angle of the plane to the horizontal is increased.

(b) To prove that the force needed for equilibrium is directly proportional to the sine of the angle.

**Method:** The plane, roller, plumb line, and dynamometer are positioned as shown in Figure 1, and the dial reading noted. The left end of the plane is then moved downward so that it pivots around the right end in a slow continuous motion. As this is done, it is observed that the angle shown on the protractor increases while the dial reading increases.

For quantitative results, the plane is first placed at 10° to the horizontal and similarly rotated in steps of 10° until it reaches the 50° or 60° position. The angle and dial reading are both observed and noted as data. The sine of each angle is then entered in the appropriate column and row as shown below. The proportionality may then be verified by comparing successive ratios or by plotting dial deflections against the sines of the angles. The linear graph thus obtained is characteristic of a direct proportion.

**Typical Data**

| Angle | Dyn. Rdg. (N) | Ratios | Sines | Ratios |
|---|---|---|---|---|
| 10° | 0.8 | 0.44 | .174 | 0.44 |
| 20° | 1.8 | 0.67 | .342 | 0.68 |
| 30° | 2.7 | 0.77 | .500 | 0.78 |
| 40° | 3.6 | 0.84 | .643 | 0.84 |
| 50° | 4.3 | | .766 | |

## EXPERIMENT #2

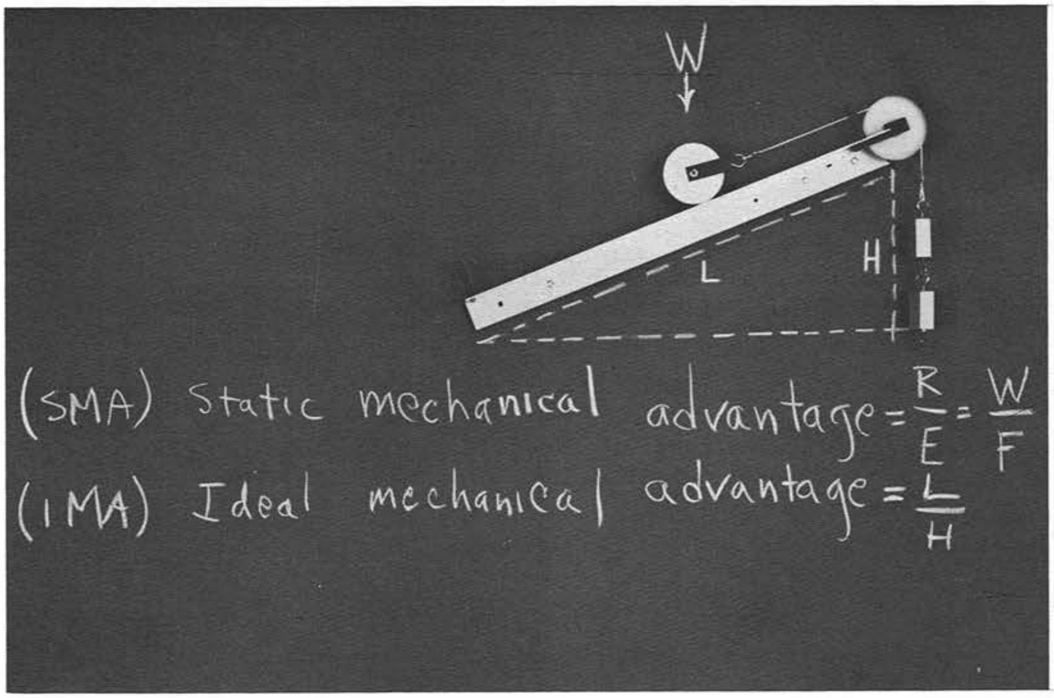



Figure 2

**Objective:** To measure and compare the actual mechanical advantage (AMA) and the ideal mechanical advantage (IMA) of an inclined plane.

**Method:** The plane is placed near the top of the board and set at an arbitrary angle to the horizontal between 10 and 40 degrees. The AMA is first determined by hanging two or three hooked weights on the vertical section of the string and carefully adjusting the angle of incline until the roller shows an inclination to move slowly and uniformly upward when released near the center of the plane. Since W and F are now both known, the AMA is computed from the relationship AMA = $\frac{W}{F}$.

The roller and hooked weights are then removed and the chalked lines shown in Figure 2 are drawn in with the aid of a meter stick and the plumb line. If the plane were frictionless (ideal), the potential energy gained by the roller would be equal to the work done on the roller over the length of the plane. Hence, for an ideal plane . . .

PE gained = work done

but PE = WH

so $WH = FL$

and $\frac{W}{F} = \frac{L}{H}$

For an ideal plane, therefore, the mechanical advantage would be $\frac{L}{H}$. The IMA can therefore be calculated since L and H are measurable, and may then be compared with the AMA.

## EXPERIMENT #3

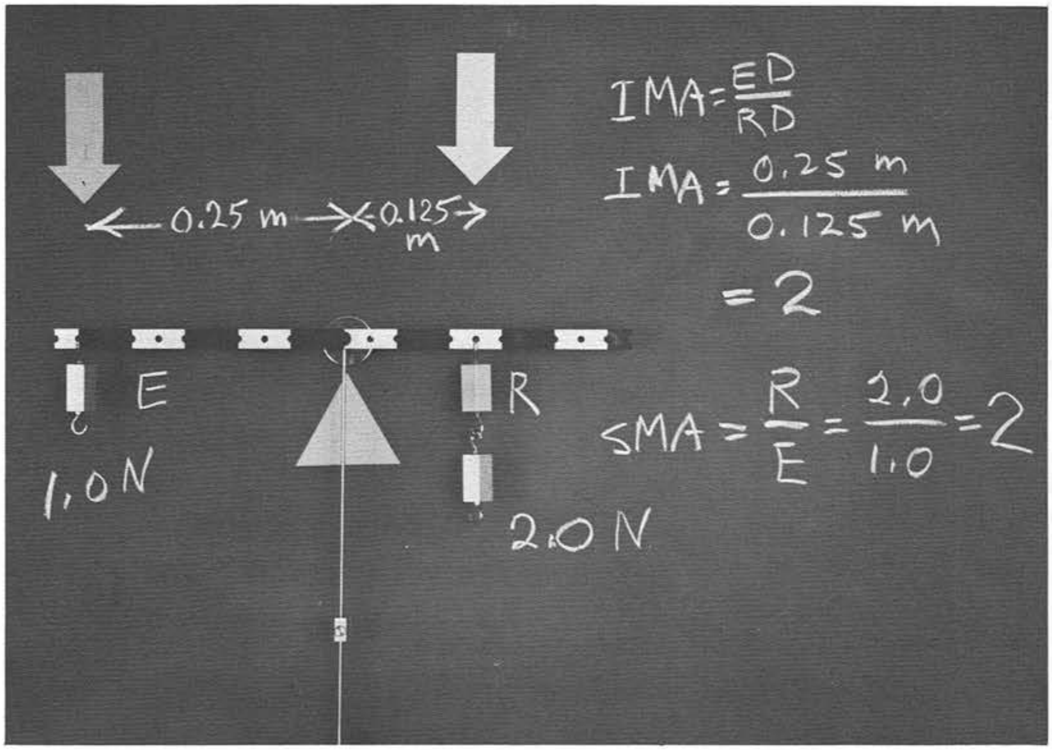



Figure 3

**Objective:** To measure and compare the actual mechanical advantage (AMA) and the ideal mechanical advantage (IMA) of a lever in which the fulcrum is located between the points of application of the effort and resistance. (Sometimes called a first class lever.)

**Method:** A single anchor post through the center of mass of the beam supports the equipment high up on the chalkboard. The applied force (effort) is shown in this illustration at a distance of 25 cm from the fulcrum while the resistance (R) is suspended from the 12.5 cm division. The IMA is, therefore, immediately obtained from the ratio of the effort arm (EA) to the resistance arm (RA) as 25/12.5 or 2. Since the effort (E) = 1.0 N and the resistance (R) = 2.0 N, the AMA in this equilibrium condition is also equal to 2. The friction at the fulcrum is sufficiently small to permit the beam to return to the horizontal position when it is displaced by rotating it over a large angle and then released. By judicious placement of various combinations of the 6 weights provided in the kit, a number of other values of mechanical advantage may be readily compared.

**EXPERIMENT #4**

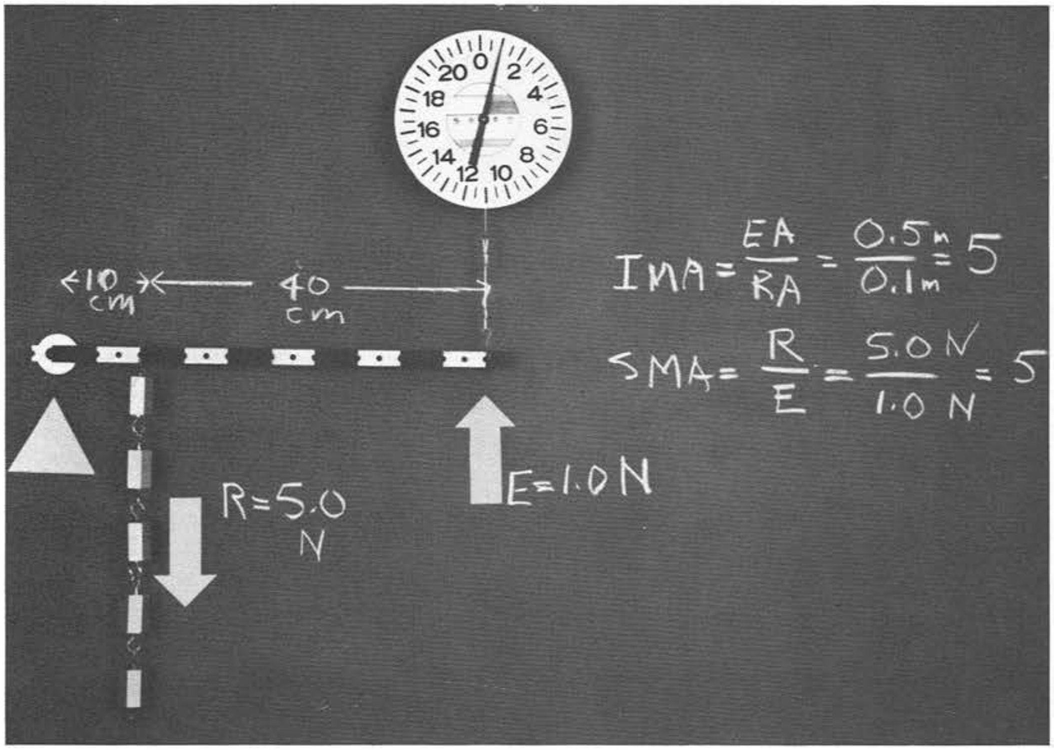



Figure 4

**Objective:** To measure and compare the actual mechanical advantage (AMA) and the ideal mechanical advantage (IMA) of a lever in which the fulcrum is located at one end of the beam with the resistance placed between the fulcrum and the point of application of the effort. (Second class lever.)

**Method:** The beam is first placed in position without the suspended hooked weights and the dynamometer needle adjusted for zero. This effectively cancels the torque produced by the beam. In this example, the resistance consists of 5 hooked weights for a total of 5 N hung from a point 10 cm (0.10 m) from the fulcrum. The effort, supplied by the spring of the dynamometer, is read as 1 N. Using the ratio of lever arms, the IMA in this case is 0.5 m / 0.1 m = 5. Note that the effort arm is measured from the fulcrum to the point at which the effort is applied. In the equilibrium state, as may be seen from the photo, the AMA = R/E = 5N / 1N = 5.

It is interesting to add a bit of dynamics to this demonstation by holding the dynamometer in the hand, away from the chalkboard, and slowly moving it upward while observing the dial reading. The friction at the fulcrum is so small that there is no visible increase in the dynamometer reading during the motion. It is thus possible to demonstrate that the AMA closely approaches the IMA for dynamic conditions in which the friction force is held to a minimum. Again, many different combinations of weights and positions may be used to vary the MAs.

# EXPERIMENT #5

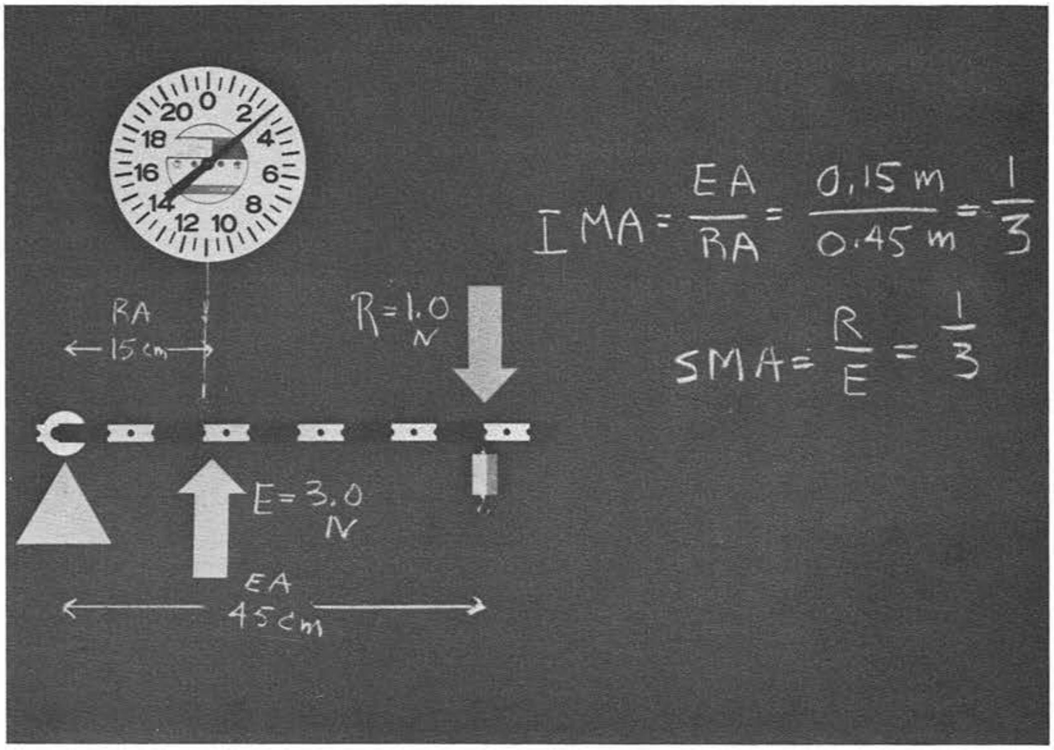



Figure 5

**Objective:** To measure and compare the actual mechanical advantage (AMA) and the ideal mechanical advantage (IMA) of a lever in which the fulcrum is located at one end of the beam with the effort placed between the fulcrum and the point of application of the resistance. (Third class lever.)

**Method:** In this type of lever, a fractional mechanical advantage is tolerated in favor of a positive gain in the distance through which the resistance moves for a given effort movement. The example in Figure 5 displays an IMA of 1/3 as a result of the ratio EA/RA = 0.15 m/0.45 m = 1/3. The AMA, again based on equilibrium, is R/E = 1N/3N = 1/3.

As in all simple machines, the friction present in the fulcrum determines how much of the equilibrium AMA will be lost under dynamic conditions. In general, levers are highly efficient machines because this kind of friction is relatively easy to hold at a minimum. In any event, the AMA in a real machine can never equal or exceed the IMA nor can the ratio of work output to work input ever equal or exceed unity.

The lever in this example should be altered by changing weights and arms in several different ways to demonstrate the various values of mechanical advantage which can thus be obtained.

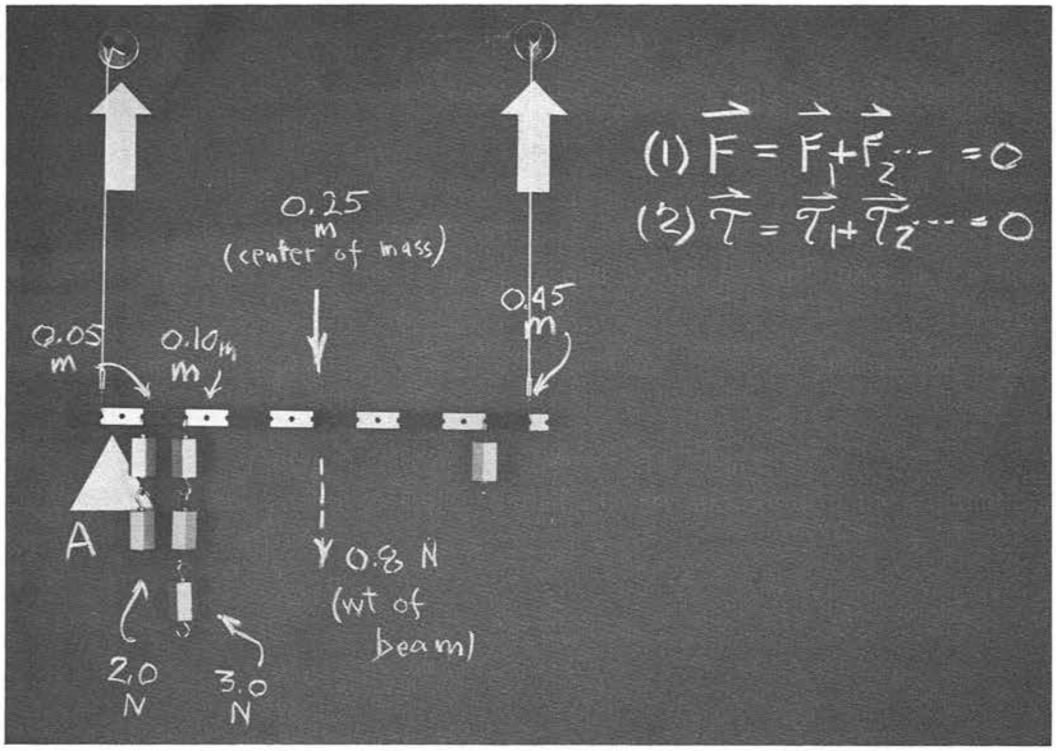



Figure 6

**Objective:** To study the conditions required for equilibrium of a rigid body.

**Method:** The multipurpose beam system is set up using any combination of weights and arms. An arrangement similar to that in Figure 6 is recommended. The procedure outlined below is followed to prove that two conditions are needed to establish equilibrium of a rigid body such as a model of a truss bridge. That is:

(1) $\vec{F} = \vec{F}_1 + \vec{F}_2 + \ldots = 0$ in which F = force

and (2) $\vec{t} = \vec{t} + \vec{t} + \ldots = 0$ in which t = torque

(1) Select a suitable point as a fulcrum such as point A in the diagram;

(2) Calculate the sum of the downward **forces**. According to equation (1), this must be equal to the sum of the upward forces.

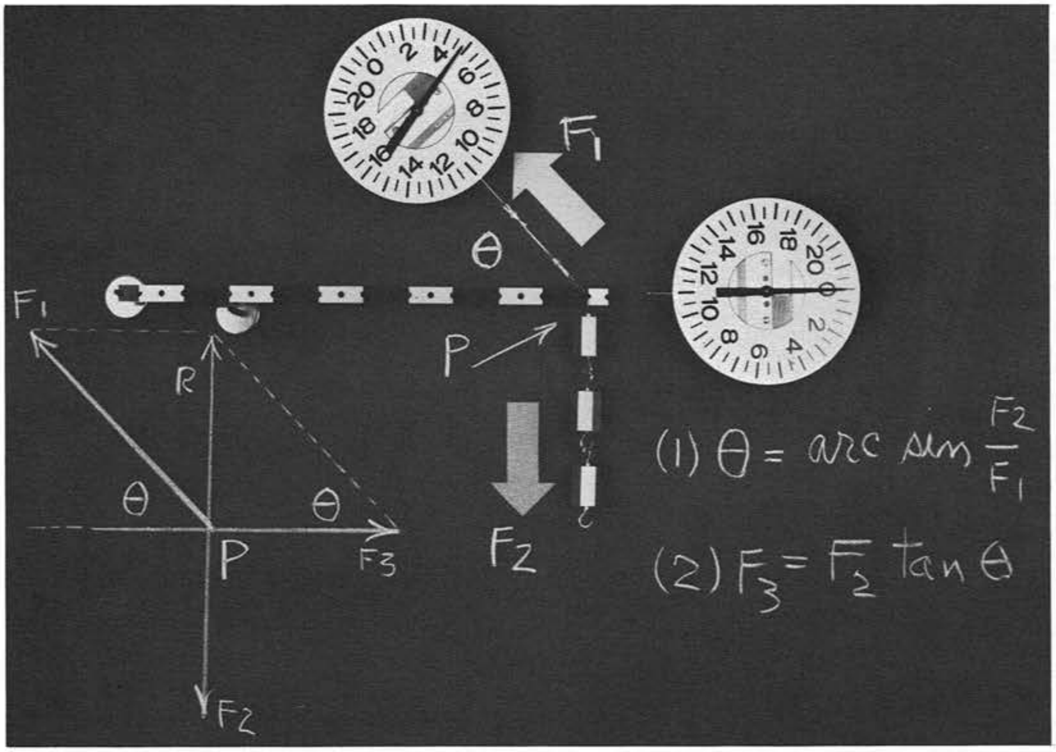
(3) Calculate the sum of the clockwise **torques**. As indicated in equation (2), this must be equal to the sum of the counterclockwise torques. (Note: in this example, there is only one counterclockwise torque, that is, the torque provided by the upward force at the right end of the beam.)

(4) Find the value of the upward force exerted at B by the string attached to the right-hand anchor post using equation (2).

(5) Determine the value of the upward force at A by applying equation (1).

Now replace the anchor posts by dynamometers and confirm the calculations.

## EXPERIMENT #7




**Objective:** To determine the forces acting on a model crane.

**Method:** In the arrangement illustrated in Figure 7, the multipurpose beam serves as a crane boom supported at the left end by the **notch** (not the hole) in the beam. A safety post to the right of the fulcrum does not touch the beam; it is placed near the beam to prevent it from falling should it be pulled away from the fulcrum post inadvertently. The slanted dynamometer reads the magnitude of $F_1$ which is applied at an angle $\theta$ to the horizontal boom. Force $F_2$ acts vertically downward and is equal to the sum of the weights hung from point P. The second dynamometer at the right is not in use at the instant shown in the photograph.

The thrust of the boom ($F_3$) may be determined graphically by means of the scaled vector diagram shown, or it may be found analytically by using equations (1) and (2). In the graphic method, $F_1$ and $F_2$ are drawn to scale at the proper angles; vector R is then constructed equal in magnitude and opposite in direction to $F_2$. Since R is the equilibrant for $F_2$, it must also be the resultant of $F_1$ and $F_3$, hence the parallelogram is readily constructed to find the magnitude of $F_3$. The analytical method involves the determination of $\theta$ by means of equation (1) ($F_2$ and $F_1$ are both known), and the calculation of $F_3$ with equation (2). The result is then verified by attaching the second dynamometer to the end of the boom and gradually pulling to the right until the left end disengages slightly from the notch.

Quantitative conclusions regarding the effect of changing the boom angle are readily obtained by sliding the fulcrum post downward or upward while observing the change in the reading of the upper dynamometer.

Note that the weight of the beam may be ignored if measurements and results are confined to two significant digits.

## EXPERIMENT #8

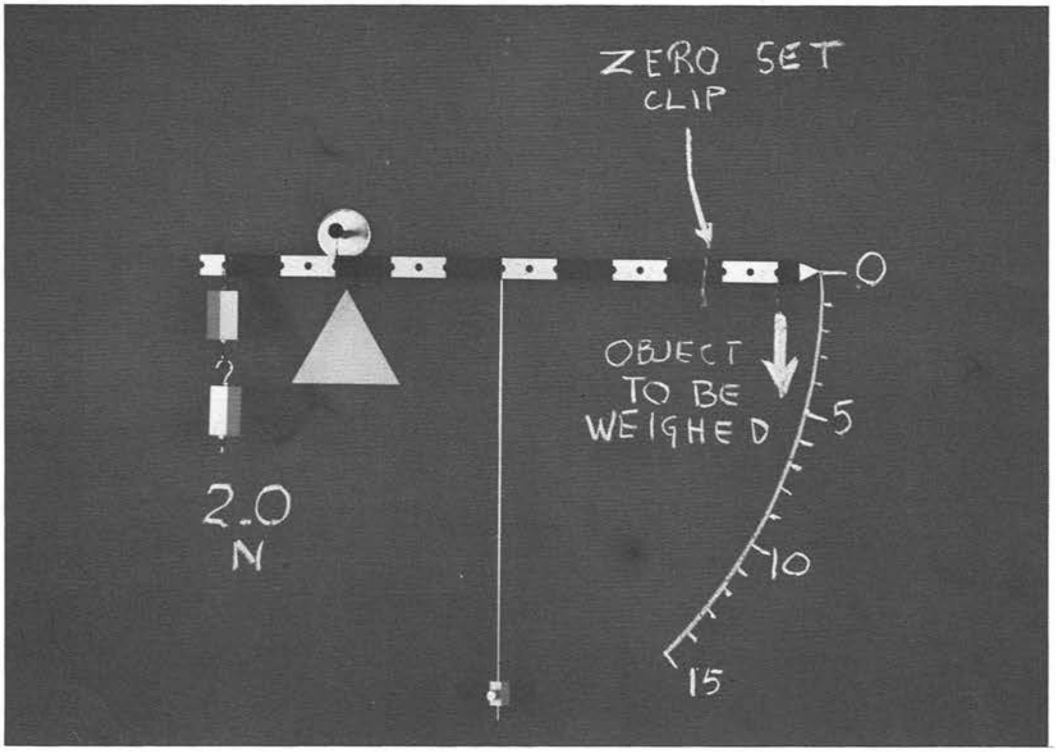



Figure 8

**Objective:** To construct and calibrate a model of a "fisherman's scale."

**Method:** The multipurpose beam is suspended from the 10 cm hole by means of a hook fashioned from an ordinary paper clip looped around an anchor post. (This suspension reduces friction at the fulcrum dramatically.) Two of the 1-newton weights are hung from the 0 cm hole and the beam index rod is threaded into place with the counterweight secured near the lower end. Another paper clip is bent to form a hook passed through the 50 cm hole to serve as a point where small objects may be suspended in the weighing process. A third paper clip is spread so that it sits on top of the beam; this clip is used as a zeroing device. The balance is completed by taping a small cardboard pointer to the right end.

The arc scale was initially drawn utilizing the beam itself as a compass. The calibrations along the arc are positioned by successfully hanging identical small masses such as large paper clips, steel nuts, or short equal lengths of wire from the hook at the right.

This home-grown scale is amazingly precise and repeatable.

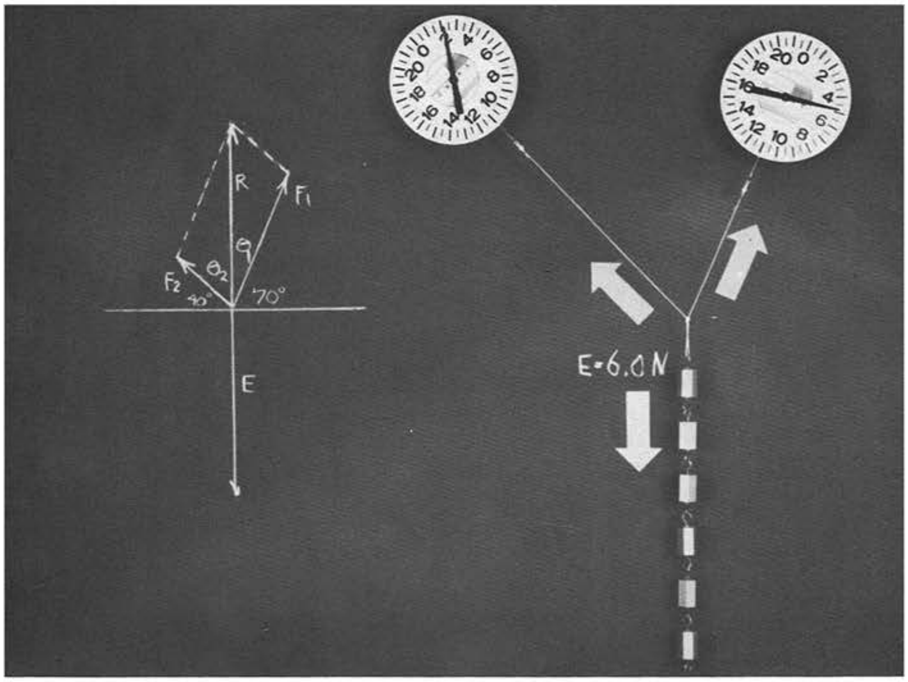



Figure 9

**Objective:** To set up and solve a problem in composition of concurrent forces by (a) graphical method; (b) trigonometric method.

**Method:** (a) Three short lengths of the braided nylon string are used in the set-up illustrated in Figure 9. The lengths of string and the positions of the dynamometers are adjusted to yield any angles desired. (In the photo, the angle between the two dynamometer strings is approximately 70° with the angle to the x-axis approximately 70° as well.) The dynamometers must be rotated so that their hooks fall along a straight line between the 11 N and 0 N markings; they should also be zeroed in their final positions before attaching the strings. The dynamometer readings are recorded in the equilibrium position with 6 N of weight providing the major force.

By sighting straight back to the chalkboard to avoid significant parallactic errors, dots of chalkmarks are placed behind each string and the knot joining the strings. The equipment is then removed from the chalkboard and the vector diagram illustrated in the photo insert is drawn directly along the chalk dots previously marked. The 6 N weight serves as the equilibrant of the two dynamometer forces. Using a suitable scale, the force components are drawn and the resultant constructed. When done with care, errors of less than 2% may be consistently expected.

(b) The trigonometric method involves summing up the vertical components of $F_1$ and $F_2$ to find the resultant. The magnitude of R should, of course, turn out to be very nearly the same as the magnitude of E.

(V comp of $F_1$) = $R_1 = F_1 \cos\theta_1 = (4.8)(\cos 20°)$

(V comp of $F_2$) = $R_2 = F_2 \cos\theta_2 = (2.2)(\cos 50°)$

$R_1 = (4.8)(0.940) = 4.5$ N

$R_2 = (2.2)(0.643) = 1.4$ N

Thus R = 4.5 N + 1.4 N = 5.9 N by experiment;

R = E = 6 N theoretically

The error is 1 part out of 60 or 1.7%.

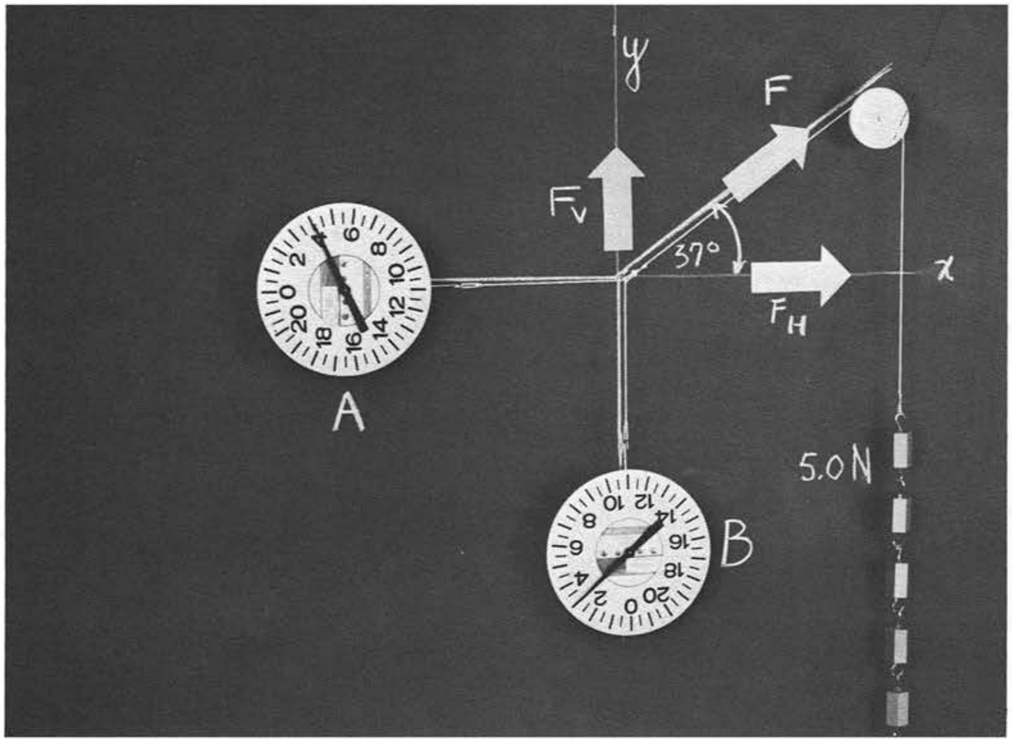



Figure 10

**Objective:** To resolve a force into its vertical and horizontal components.

**Method:** X- and Y-axes are drawn on the chalkboard as guide lines for setting up the apparatus. A chalkline at 37° to the X-axis is drawn from the origin. The two dynamometers and pulley are then positioned along the guide lines as illustrated in Figure 10. The dynamometers are then carefully zeroed and strings attached to their hooks; the long string is threaded around the pulley and five 1 N weights are suspended from the end. The point of application must lie at the origin of the axes; minor adjustments in position are now made to insure that all the angles are correct. The dynamometer readings are recorded.

The vector diagram is then drawn on the chalkboard (not shown). Since F = 5 N and its angle to the horizontal axis is 37°, the triangle formed at the origin is a 3:4:5 case, hence $F_h$ = 4 N and $F_v$ = 3 N. Balance A, therefore, reads 4 N and Balance B reads 3 N.

Various angles may be used to show that:

$F_h = F \cos \theta$ for any angle,

and $F_v = F \sin \theta$ for any angle.

## EXPERIMENT #11

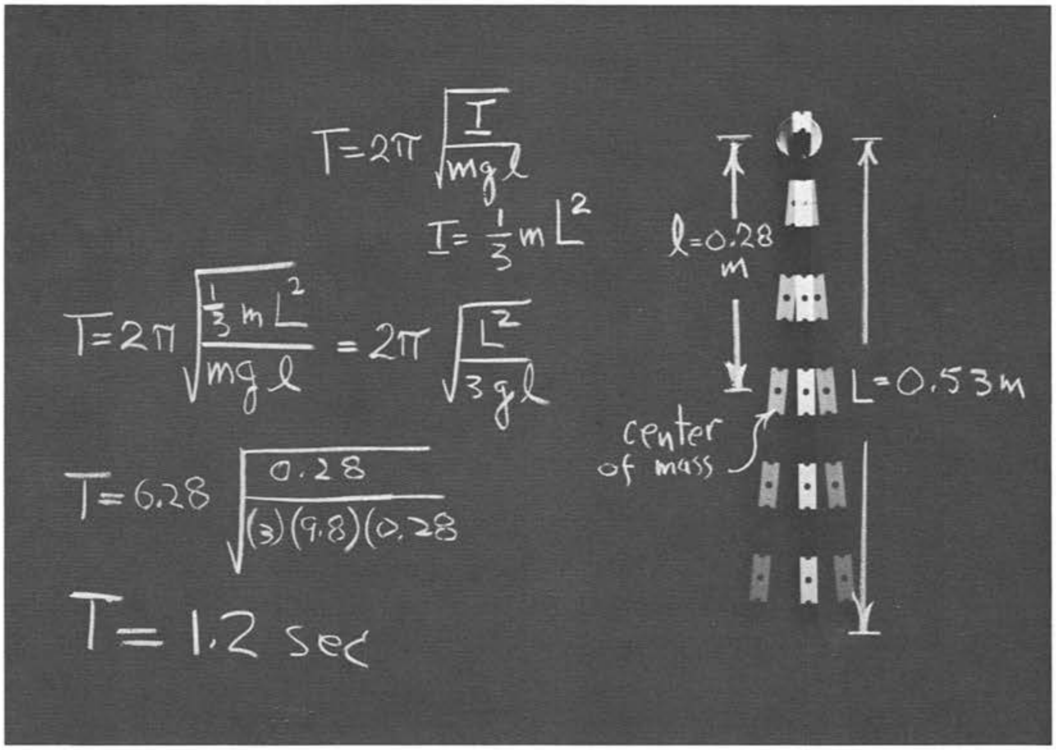



Figure 11

**Objective:** To verify the equation for the period of a physical pendulum.

**Method:** The multipurpose beam is suspended from an anchor post at either end hole. It is then made to vibrate over a small amplitude while it is timed with a stopwatch for 10 complete cycles in order to determine its period.

Most teachers prefer to calculate the period of the multipurpose beam when used as a physical pendulum prior to measuring it. This calculation is performed on the chalkboard using characteristics of the beam as numerical substitutions in the appropriate equations. The beam is treated as a long, slender rod for which the moment of inertia (I) is:

$$I = \frac{1}{3} mL^2$$

in which m = mass and L = distance between point of support and the remote end of the beam. This value of the moment of inertia is then substituted in:

$$T = 2\pi\sqrt{\frac{I}{mg\ell}}$$

in which g = gravitational acceleration and $\ell$ = the distance between the pivot of the pendulum and its center of mass.

The calculations shown on the chalkboard of Figure 11 are performed on two significant digits using the characteristics of the multipurpose beam. The actual measured period checks within $\pm$ 0.1 sec.

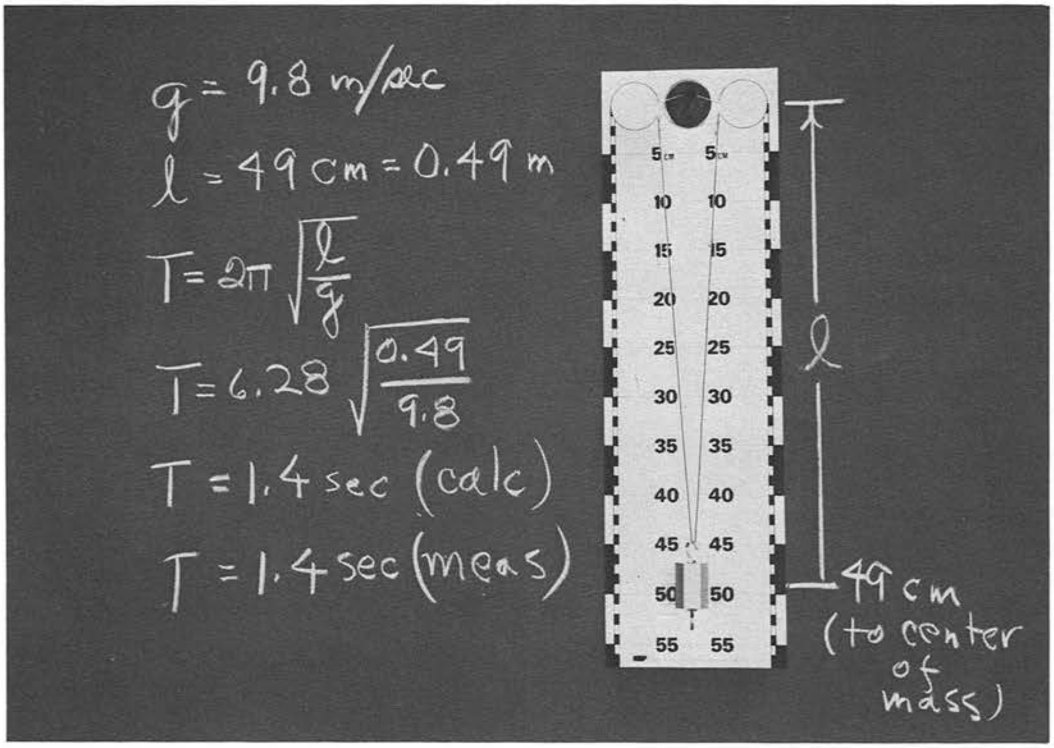



Figure 12

**Objective:** To measure the period of a modified simple pendulum and compare the result with the period predicted by formula.

**Method:** As illustrated in Figure 12, a bifilar suspension is used to prevent twisting of the string and to add stability. A paper clip spreader rests on an anchor post and serves as the actual pivot for the swinging pendulum. This suspension method results in a greatly reduced friction so that the pendulum swings for a long interval despite a small initial amplitude. The vinyl scale is placed behind the pendulum to enable the user to read the distance between the point of suspension and the center of mass of the bob. Since the latter is symmetrical, its center of mass is at its geometric center.

The period is determined by timing 10 or 20 oscillations of the pendulum over a small amplitude – perhaps 3 cm each side of center. The process is repeated with various lengths to acquire a data set that may be plotted or handled qualitatively, if desired. A sample of the checking calculation is displayed on the chalkboard in the photo.

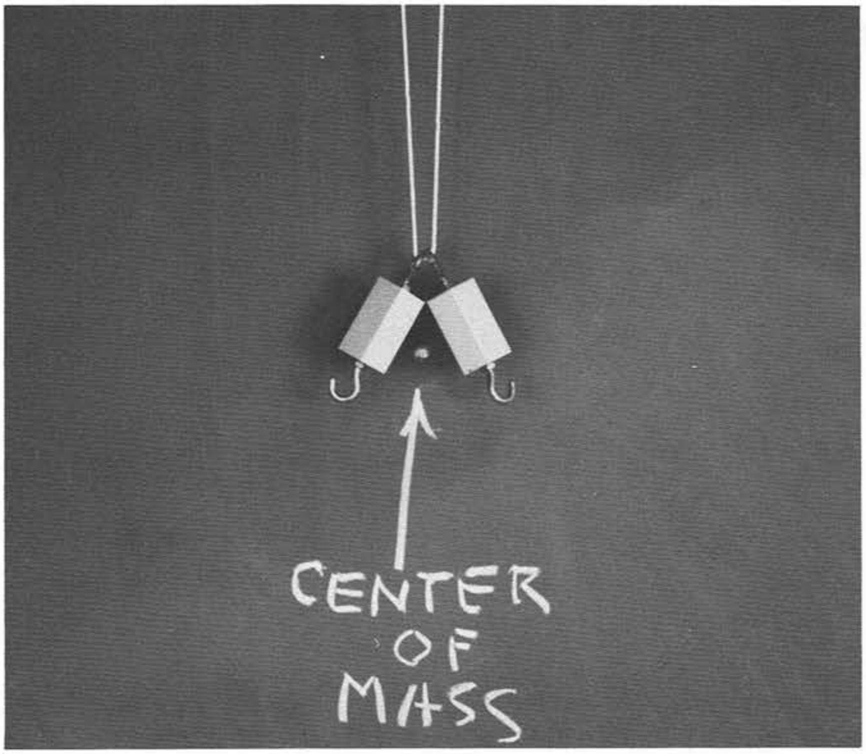



Figure 13

**Objective:** To demonstrate that the period of a simple pendulum is independent of the mass of the bob.

**Method:** The modified pendulum is set up as in Figure 13, using two 1 N weights as the "bob." The period is measured in identically the same manner as in Experiment #12. It will be found to be the same as before with little or no deviation, showing that the period is independent of the mass of the bob as implied by the equation:

$$T = 2\pi\sqrt{\frac{\ell}{g}}$$

in which $\ell$ = the length of the pendulum measured from the point of suspension to the center of mass of the bob assembly (meters) and g = local gravitational acceleration, normally taken as 9.8 m/sec$^2$.

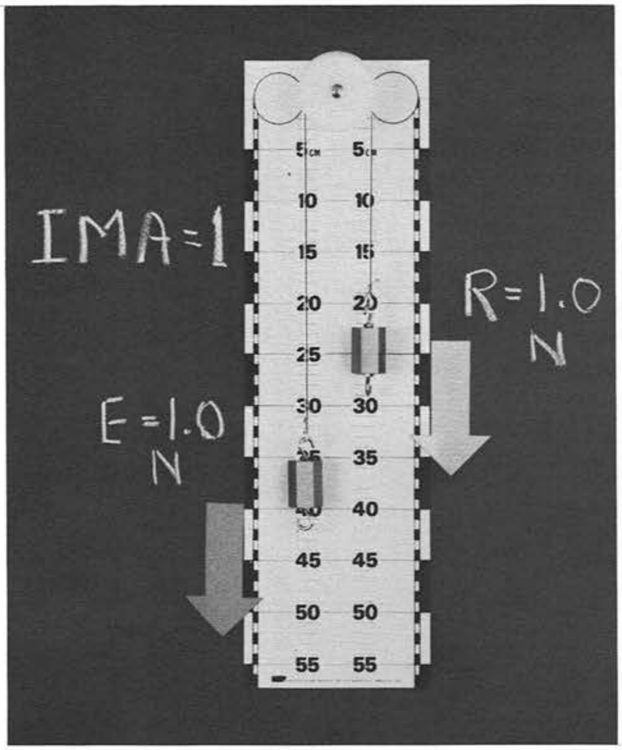



Figure 14

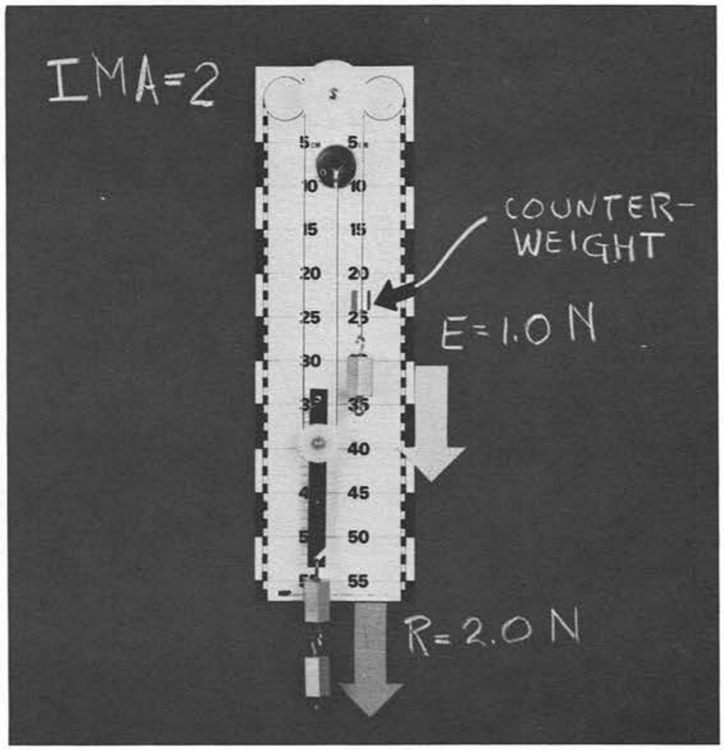



Figure 15

**Objective:** To investigate the IMAs and AMAs of various block-and-tackle systems.

**Method:** All fixed pulleys are magnetically anchored to the steel chalkboard; the movable block may be used with both pulleys in place, or by removing either so that only one appears in the set-up. In general, the counterweight should be used to neutralize the weight of the movable block as shown in the various figures. For those arrangements in which a dynamometer is used as the source of the effort force, the needle may be zeroed with the movable block (but no weights) in position instead of adding the counterweight.

In each experiment, the IMA should be determined by measuring the distance moved by the effort and the resistance using the magnetic vinyl scale. For a **frictionless** machine, the work output must equal the work input, hence:

$$\text{Work output} = R \times RD$$

$$\text{Work input} = E \times ED$$

$$R \times RD = E \times ED$$

$$\text{hence} \quad \frac{ED}{RD} = \frac{R}{E} = \text{AMA}$$

Thus, the IMA $= \frac{ED}{RD}$. The static mechanical advantage (SMA) is the ratio of the resistance to the effort or R/E.

It is helpful, too, to remind students that there is a convenient ancillary rule for determining the IMA of a block and tackle system, that is, that the IMA is equal to the number of strands supporting the **movable** block.

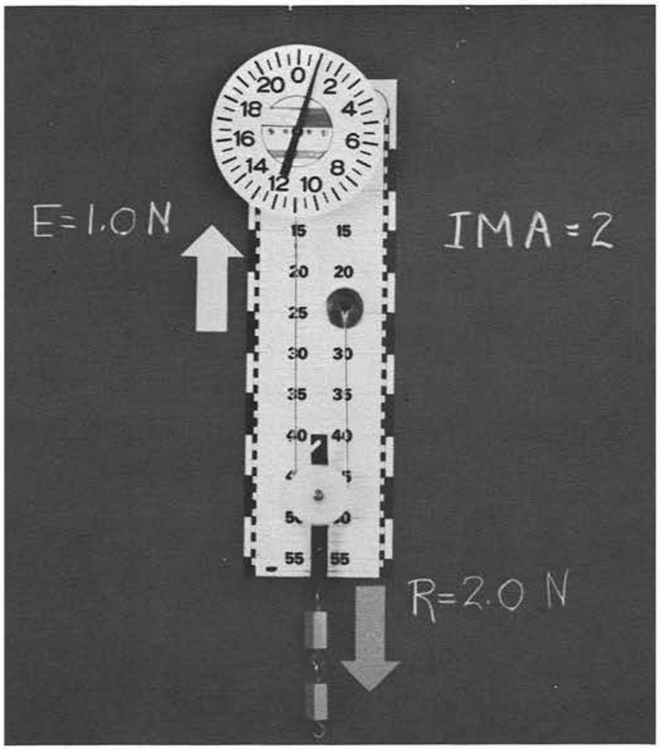



Figure 16

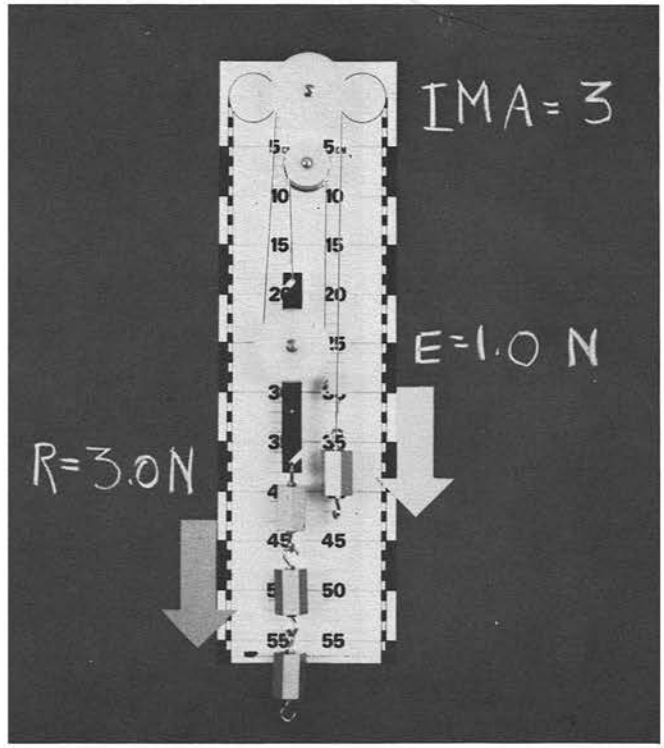



Figure 17

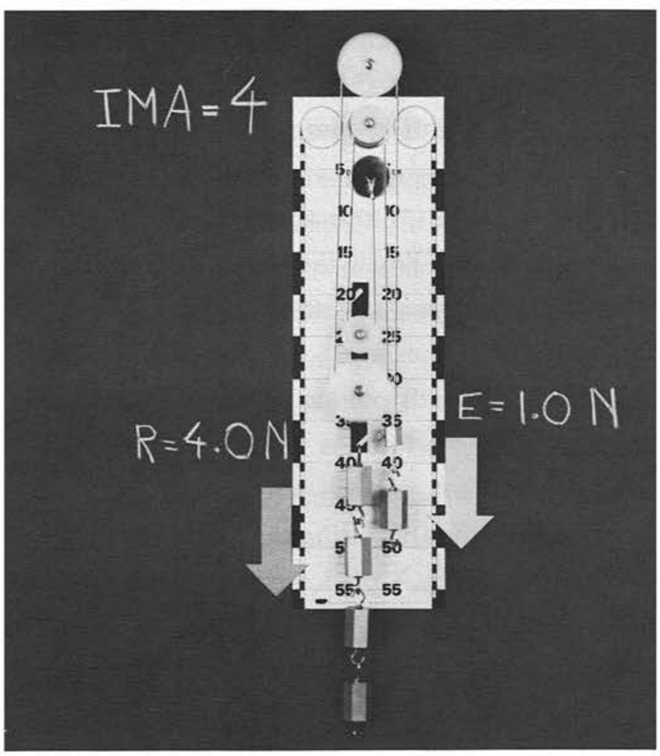



Figure 18

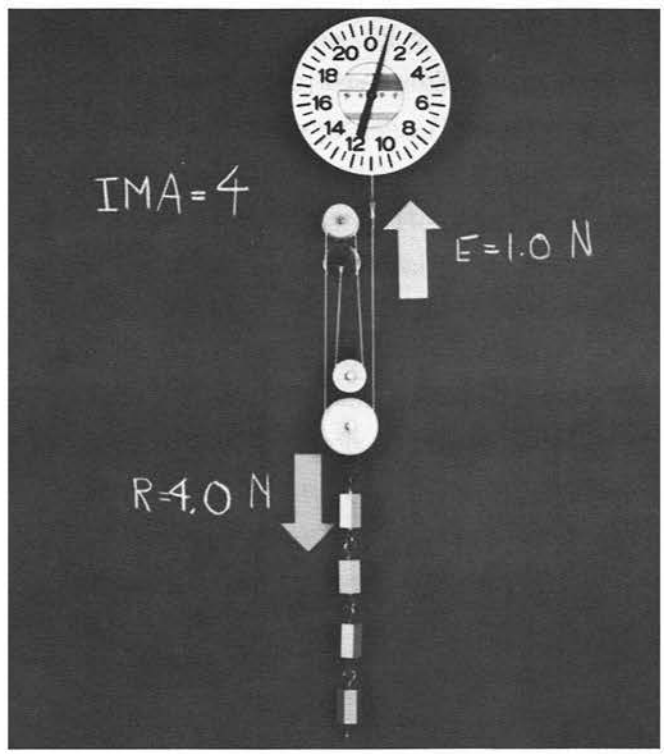



Figure 19

## EXPERIMENT #20

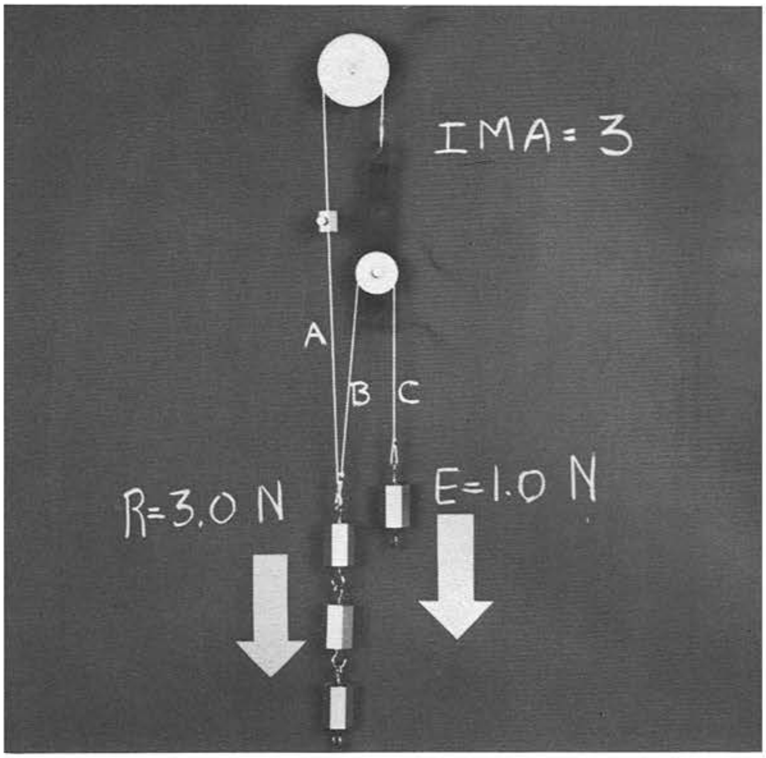
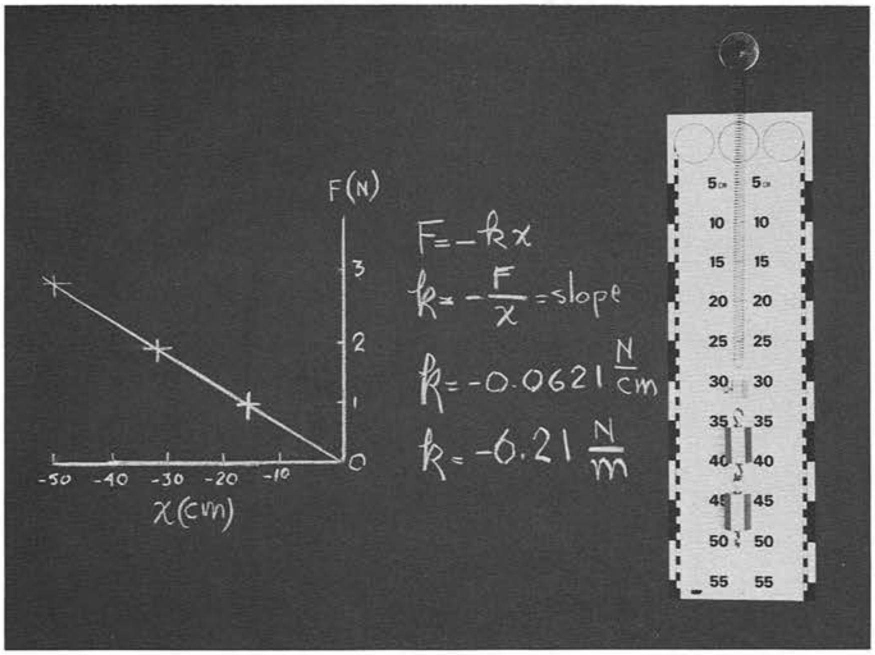



Figure 20

**Objective:** To set up and study a single Spanish Burton pulley system.

**Method:** The large pulley is removed from the movable block and the equipment is set up as shown in Figure 20. It is found that the IMA = 3 using the ED/RD method and the magnetic vinyl scale. This is corroborated by the fact that 1 N of effort supports 3 N of resistance. The "strand-count" rule, however, cannot be used to determine IMA in this system; it is necessary to analyze the force distribution to do this.

Consider the system to be ideal and in perfect equilibrium. If this is so, then there must be a total of 3 N of force acting upward on the resistance, R. When the effort (1 N) acts downward on string C, it is transformed into a 1 N force acting upward on string B; this accounts, then, for 1 N upward on the resistance. However, string B exerts a reaction force of 1 N downward on the small movable pulley so, since C and B are both pulling downward with 1 N each, the total downward force on the small pulley is 2 N. This force is transmitted without change by the large fixed pulley, hence the upward force transmitted through string A is 2 N also acting on the resistance. When this is added to upward force due to string B, the total upward force on the resistance is then 3 N. The conditions for an IMA of 3 are thus satisfied.



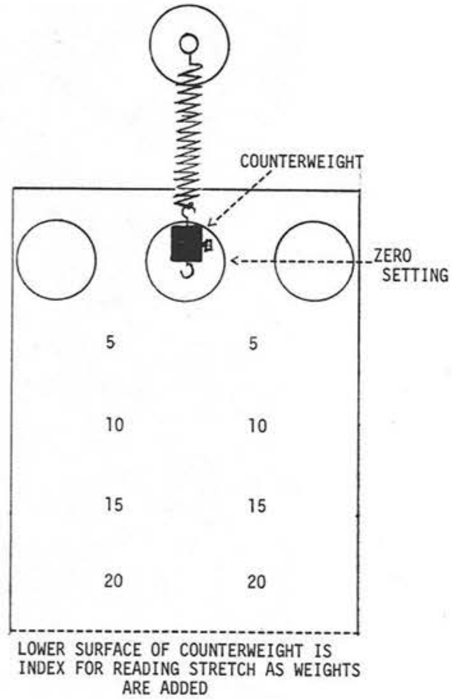




Figure 21

**Objective:** To verify Hooke's Law and determine the spring constant.

**Method:** An S-hook with a straight shank is secured in the slit of the counterweight. The latter is then suspended from a spring supported by an anchor post as illustrated above. The anchor post is then shifted in position until its lower surface is opposite the zero on the vinyl scale. The counterweight provides the initial stretch of the spring and its lower surface serves as the INDEX for reading spring extensions as weights are added to the system.

A 1 N weight is then suspended from the lower loop of the S-hook. The extension of the spring is then read and recorded to the nearest 0.1 centimeter along the index surface of the counterweight. This is repeated for two additional 1 N weights to obtain data for three positions below zero. The results below were obtained in an actual experiment performed using this method.

| Wt. (N) | Scale (cm) |
|---|---|
| 0 | 0.0 |
| 1 | 16.1 |
| 2 | 32.2 |
| 3 | 48.3 |

In Hooke's Law: $F = -kx$ in which F is the restoring force acting on the extended spring, **x** is the stretch due to the total weight, and **k** is a proportionality constant called the **spring constant**. The negative sign indicates that the displacement (downward) and the restoring force (upward) have opposite directions.

The spring constant **k** may be obtained from the mean of the extensions or from the slope of the graph as shown in the photo for this experiment. In this case, the spring constant turned out to be −6.21 N/m or −0.0621 N/cm.

## EXPERIMENT #22

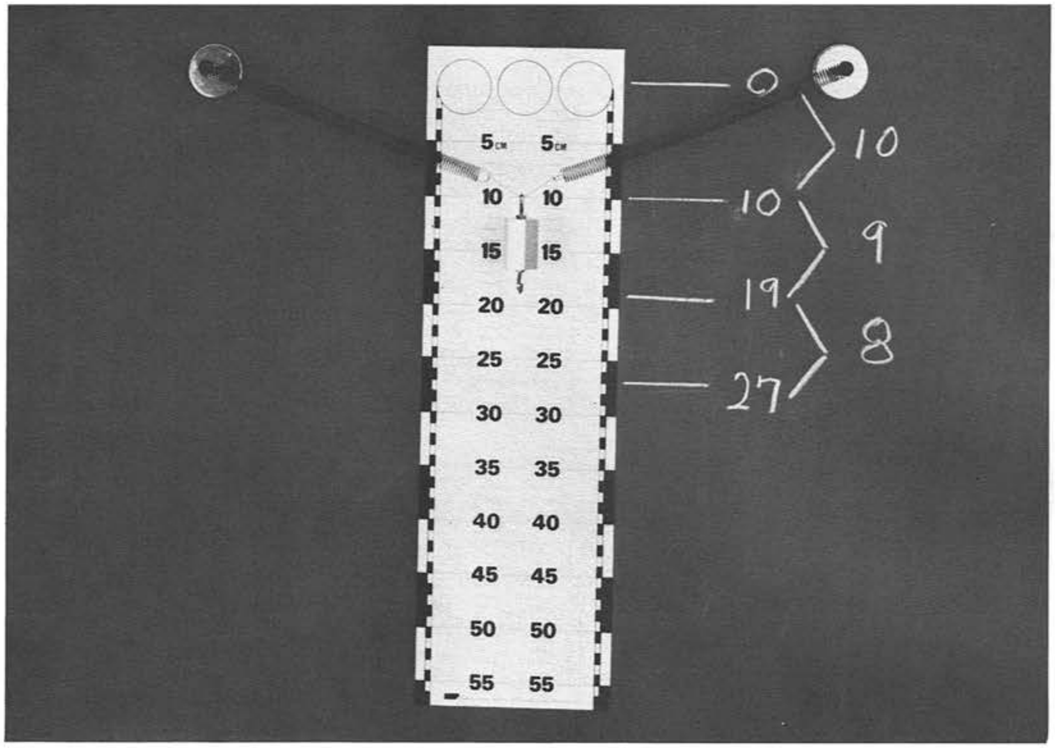



Figure 22

**Objective:** To determine the combined constant of springs placed at an angle rather than parallel to each other.

**Method:** The anchor posts are moved apart and a 1 N weight suspended on the spring clip when the angle is relatively large. Successive 1 N weights are then added and each new displacement marked on the chalkboard. The top surface of the uppermost weight is used as an index.

When the successive displacements are measured, they are found to decrease as some function of the total weight. It is suggested that this experiment be performed qualitatively. The class is asked to explain why this decrement occurs.

The answer, of course, lies in the fact that the angle between the springs decreases as more weight is added. The upward component of the force exerted by each spring therefore increases so that stretch equilibrium is reached for slightly less spring extension as each weight is added.

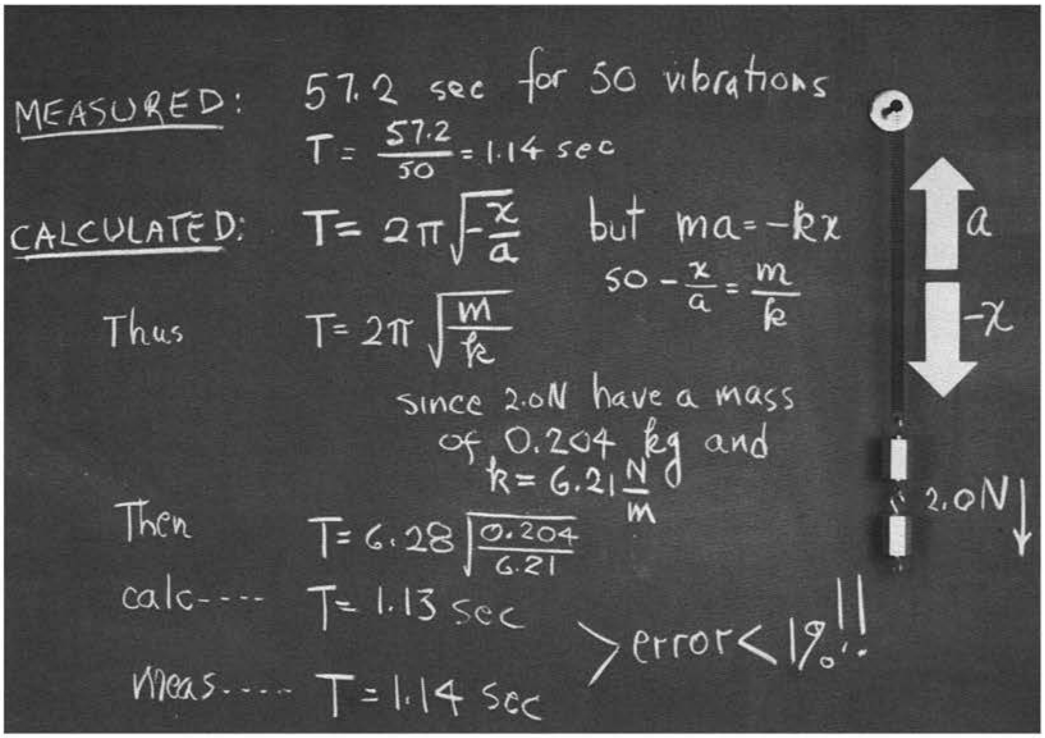



Figure 23

**Objective:** To compare the measured and calculated period of a mass vibrating on a spring with simple harmonic motion.

**Method:** The spring previously used in Experiment #21 is suspended from an anchor post high on the chalkboard. (In our experiment, this spring was shown to have a spring constant $k = -6.21$ N/m.) Two 1 N weights are then hung from the end of the spring.

The weights are drawn downward about 2 cm and released carefully so that the system begins to vibrate along a vertical line; there should be very little side-to-side motion. The time required for at least 50 complete cycles is measured with as precise a stopwatch as can be obtained and the period determined using $T = \frac{\text{Time for N vibrations}}{N}$. This should be repeated several times to obtain a reliable mean value for the period, T.

The class then calculates the period using the equation:

$$T = 2\pi\sqrt{\frac{m}{k}}$$

As indicated on the chalkboard in the photograph, the time for 50 vibrations of the 0.205 kg mass was 57 sec yielding a period T = 1.14. Using the spring constant's absolute value, 0.621 N/m in the equation above provided an answer of T = 1.13 sec as shown. The error is therefore less than 1%.

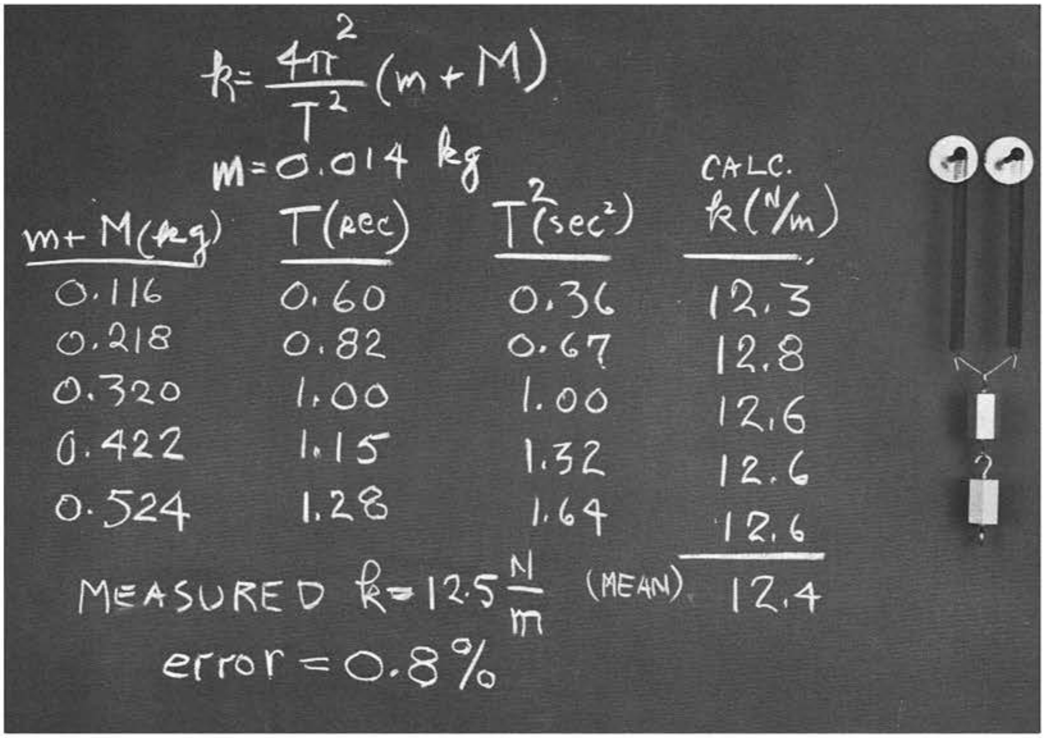



Figure 24

**Objective:** To calculate the spring constant (k) of a double-spring system from the period of the oscillation in S.H.M.

**Method:** Two of the kit springs are supported by a pair of anchor posts and a spring-clip spreader as shown in the illustration. With the bases of the posts in contact at the same level, the clip is bent until the springs hang parallel to each other. Individual 1 N weights up to a total of 5 are hung in succession from the spreader; the period of each mass is measured to the nearest hundredth of a second by counting the complete cycles over at least 50 oscillations.

For precise results, the masses of the two springs must be included in the calculations. Analysis shows that account is properly taken of the spring masses by adding 1/3 of each mass to the main mass of the system. That is:

$$T = 2\pi\sqrt{\frac{m+M}{k}} \qquad \text{- - - - - - - - - - (1)}$$

in which m = 1/3 the sum of the masses of the two springs;

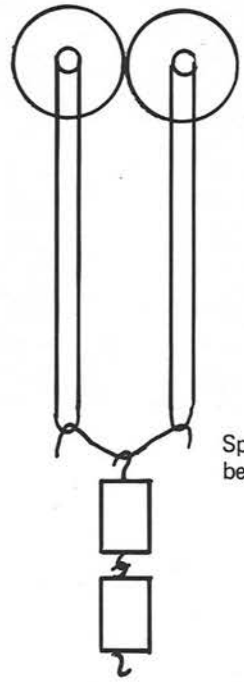
M = Total mass suspended from the springs.

In this exercise, the spring constant (k) is to be calculated for five data periods. Equation (1) converts to:

$$k = \frac{4\pi^2}{T^2}(m+M) \qquad \text{- - - - - - - - - - (2)}$$

In the test experiment, the mass of each spring was 10.5 g so that the mass of both was 21 g or 0.021 kg. Since 1/3 of 0.021 equals 0.007, this number was added to each mass in the tabulation shown on the chalkboard

To three significant digits, there is an error of 0.8% between the mean of the calculated **k**'s and the value measured by a series of extensions.




$$k = \frac{4\pi^2}{T^2} \quad (m + M)$$

m = .007 kg

| m + M (kg) | T (sec) | $T^2$ ($sec^2$) | Calc (N/m) |
|---|---|---|---|
| 0.109 | 0.59 | 0.36 | 12.3 |
| 0.211 | 0.82 | 0.67 | 12.4 |
| 0.313 | 1.00 | 1.00 | 12.4 |
| 0.415 | 1.15 | 1.32 | 12.4 |
| 0.517 | 1.28 | 1.64 | 12.4 |
| | | Mean = | 12.4 $\frac{N}{m}$ |

Measured k = 12.5 $\frac{N}{m}$

% error = 0.8%

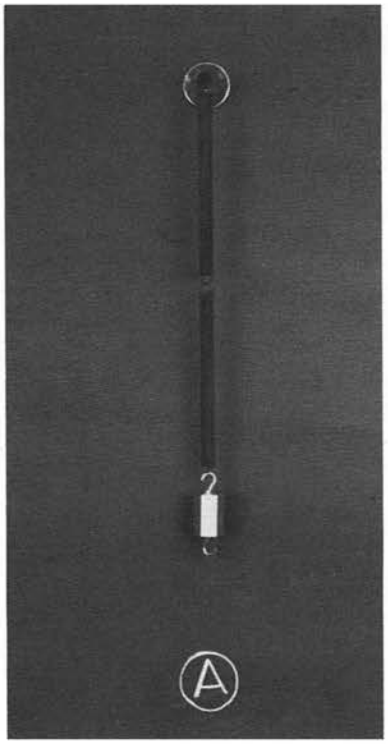


Figure 25A

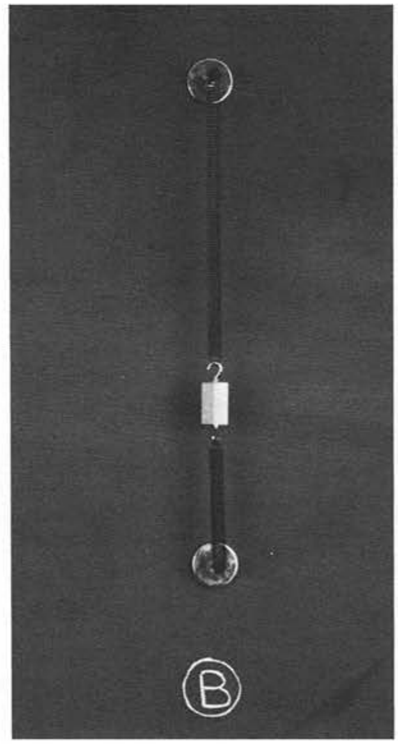


Figure 25B

**Objective:** To compare the S.H.M. period of a given mass when the oscillation is produced by (a) two identical springs fastened together and (b) the same springs used on opposite sides of the mass.

**Method:** The apparatus is set up as illustrated in Figure 25A and the period measured by finding the time required for 20 oscillations. The arrangement is then changed to that shown in Figure 25B and the period again measured in the same way.

It will be found that the period in A is twice that in B. (In the illustrated experiment, the period was 1.2 sec for A and 0.60 sec for B.)

For most levels, the explanation of this change may be couched in qualitative terms. However, for those who wish a quantitative analysis, the students must first show that:

for case A: $$T = 2\pi\sqrt{\frac{2m}{k}}$$

for case B: $$T = 2\pi\sqrt{\frac{m}{2k}}$$

By squaring both expressions and setting up the ratio of the squares of the periods, it is immediately evident that the period for case A must be twice that of case B.

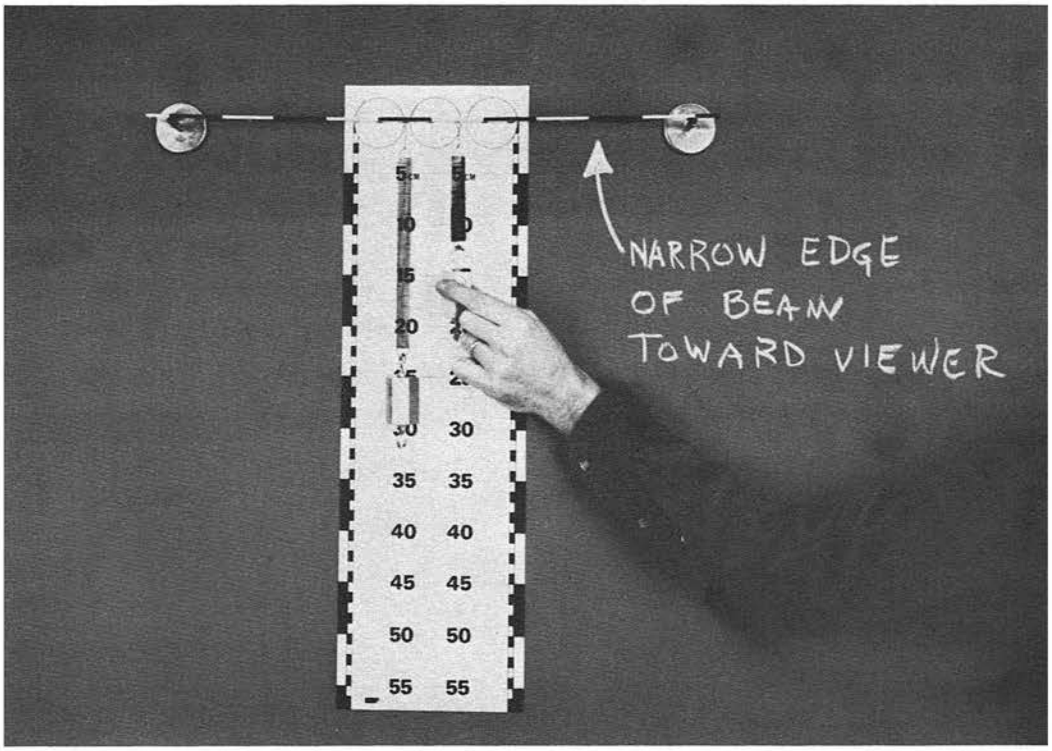



Figure 26

**Objective:** To demonstrate mechanical resonance.

**Method:** The multipurpose beam is supported with its narrow edge facing the viewer in front of the vinyl magnetic scale by a pair of anchor posts placed near its ends. Two identical springs are suspended 5 cm apart on the center of the beam by means of S-hooks as illustrated. A 1 N weight is then hung from each lower loop causing the springs to elongate equally.

The right-hand weight is then raised vertically upward by hand about 5 cm, care being exercised to see that the left-hand weight is not vibrating or swinging. When the raised weight is released it begins to move with simple harmonic motion and, in a moment or two, the weight that was initially at rest goes into oscillatory motion. The amplitude of the new motion is small at first but, in about 45 seconds, the original energy of the right-hand weight has become equally shared by the system. After about 75 seconds, virtually all of the energy resides in the weight that was initially at rest with the other weight very nearly ceasing its oscillation.

If the motion is allowed to continue, the energy passes back and forth from one to the other until the entire system comes to rest.

To show that mechanical resonance occurs only when the periods of the oscillating weights are the same, a second 1 N weight is added to right side and the steps above repeated. In this case, there is no resonance, of course; the stationary weight does not go into motion at all.

## EXPERIMENT #27

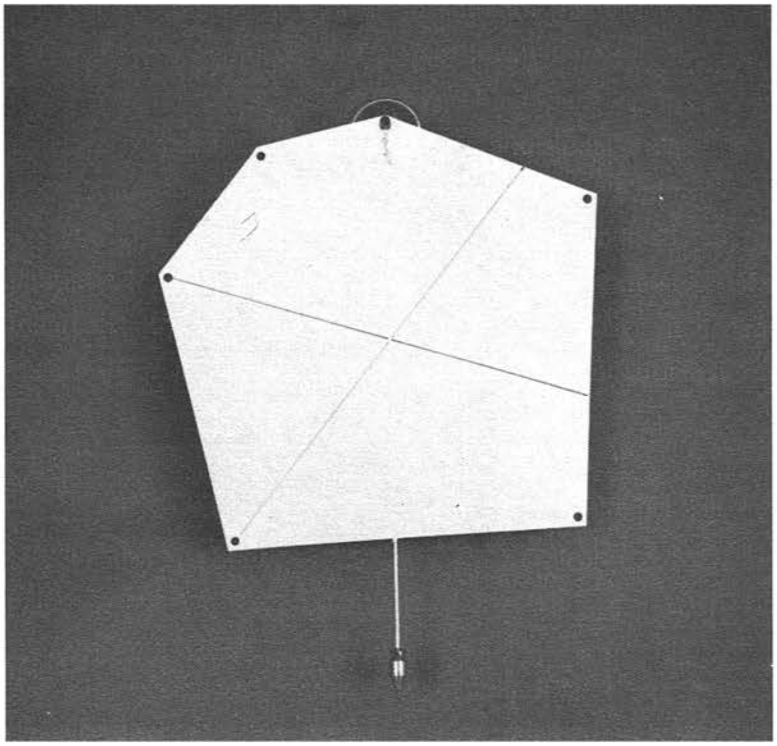


Figure 27

**Objective:** To locate the center of mass of an irregular thin, flat plate.

**Method:** The asymmetrical polystyrene plate is hung freely by slipping any one of the six holes over an anchor post high on the chalkboard. The plumb line is suspended from the same post in front of, but not touching, the polystyrene plate. The plate is then touched lightly to cause a small oscillation and then allowed to come to rest.

The experimenter now gently and carefully presses the plumb line string against the plate without shifting the position of either by grasping between thumb and forefinger. The line of suspension is marked off by placing a dot directly behind the string at two widely separated points. The plate is removed and a line drawn between the two marks with a felt-tipped pen which uses a water-soluble ink. (Parker Flair pens or Vis-a-Vis markers are suitable.)

This procedure is repeated for at least two additional holes. If reasonable care is exercised, the three or four suspension lines intersect at a single point. Although the center of mass of the plate is within the body of the polystyrene, the plate is so thin that this surface projection, for all practical purposes, may be considered to locate it satisfactorily. To test for the precision of the result, balance the plate on an unused eraser of a pencil held vertically by placing the flat end of the eraser under the intersection of the suspension lines.

EXPERIMENT #28

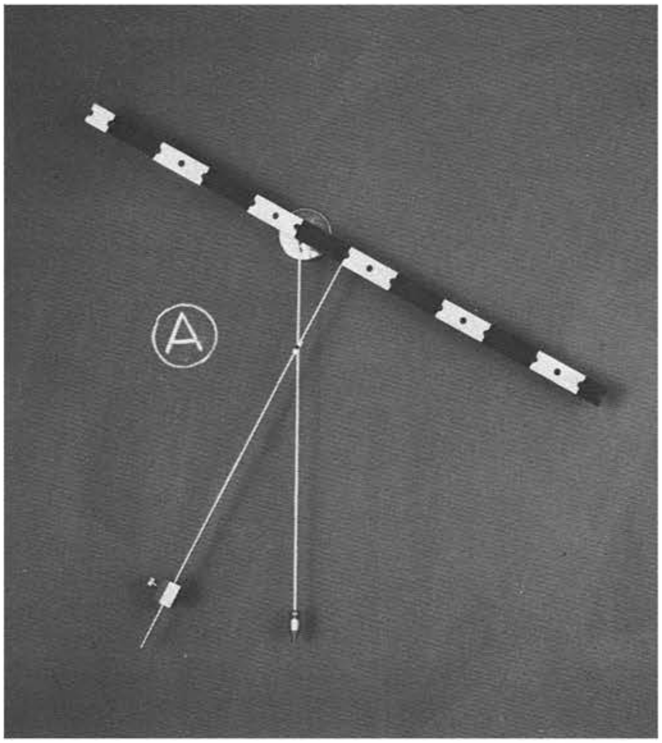



Figure 28A

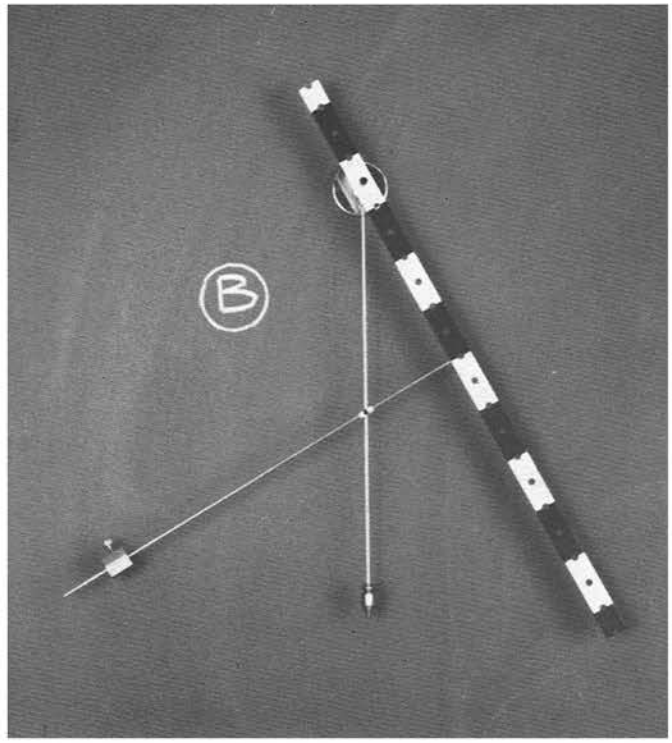



Figure 28B

**Objective:** To locate the center of mass of the multipurpose beam, beam index rod, and counterweight when set up as a single body.

**Method:** With the counterweight secured to the beam index rod near its lower end, the multi-purpose beam is slipped on to an anchor post through any hole near its center. The plumb line is then suspended from the same post.

After a small initial oscillation, the beam and plub line are allowed to come to rest. A small length of narrow masking tape is then placed on the index rod at the point of its visual intersection with the plumbline. When the beam is subsequently hung from several other holes, it is found that the same visual intersection point is obtained.

The fact that this is the center of mass of the composite body is easily checked by showing that the system balances nicely at this point. Place the assembly in a shallow notch cut in a wooden dowel stick or pencil; balance is achieved exactly or very nearly so at the center of mass obtained by successive suspensions.

EXPERIMENT #29

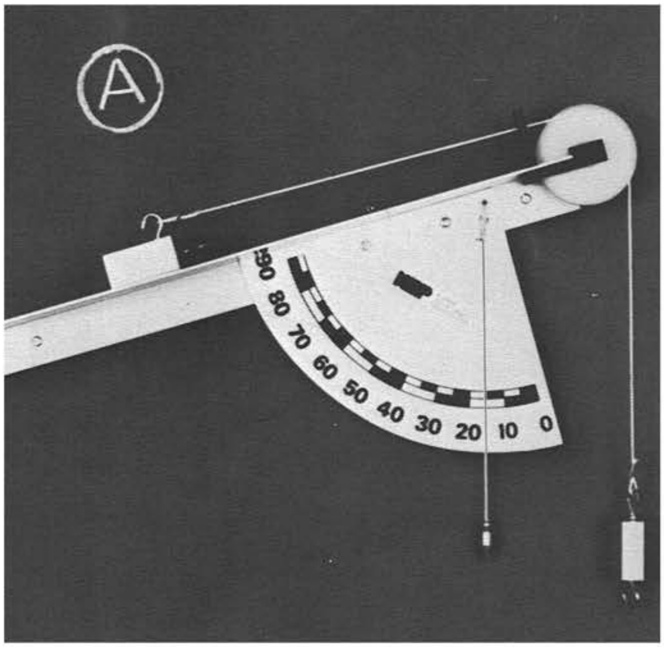



Figure 29A

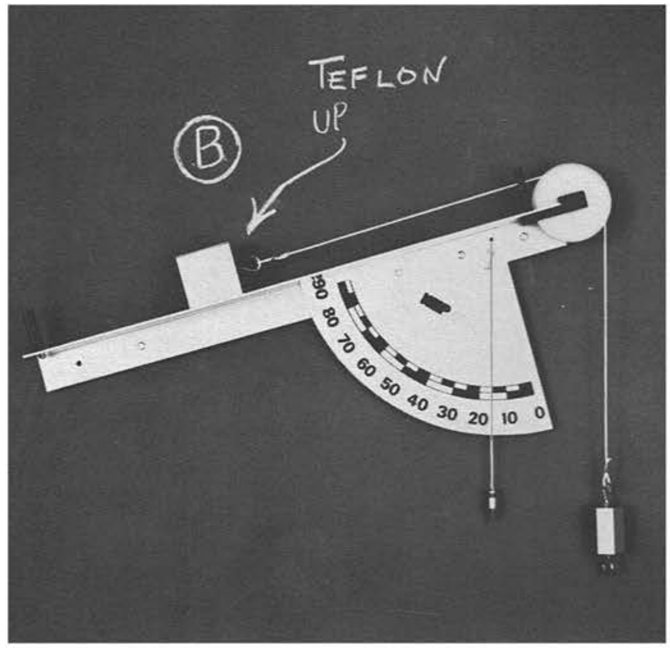



Figure 29B

**Objective:** To demonstrate that the frictional force between two sliding surfaces is independent of the area of contact.

**Method:** The plane is mounted high on the blackboard at an angle of perhaps 20°. The sliding block is placed with its large area in contact with the plane, held in position by a 1 N weight attached to a string which passes over the pulley as illustrated in Figure 29.

The left end of the plane is then slowly raised until the angle is found which permits the block to move slowly and uniformly up the plane. To insure that the string is approximately parallel to the plane, it should be looped over the hook in the large-area surface at its top.

Its motion up the plane should be observed several times and its approximate speed noted. The block is then placed on the small-area surface which does **not** have the teflon strip cemented to it. The string is then attached to the appropriate hook (to keep the string parallel to the plane). When the weight is released, the block will be seen to slide up the plane with the approximately same speed it acquired while resting on the large-area surface.

The fact that this system moves with the same speed for both surfaces of contact indicates that the retarding force of friction is the same in both cases.

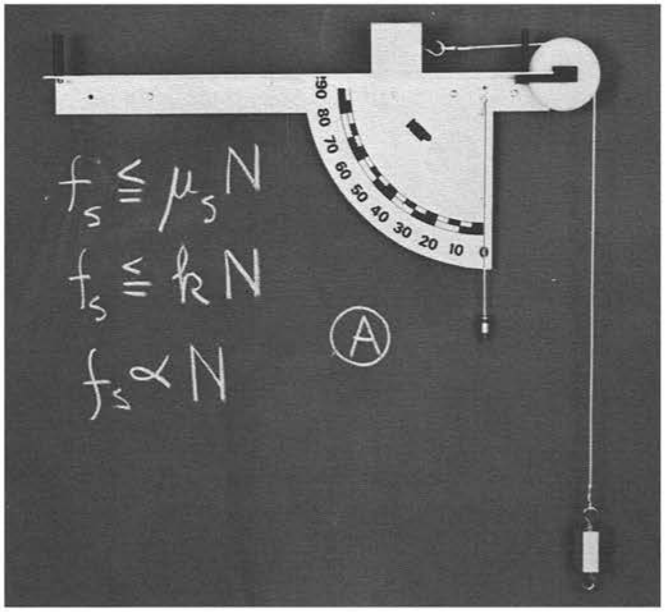


Figure 30A

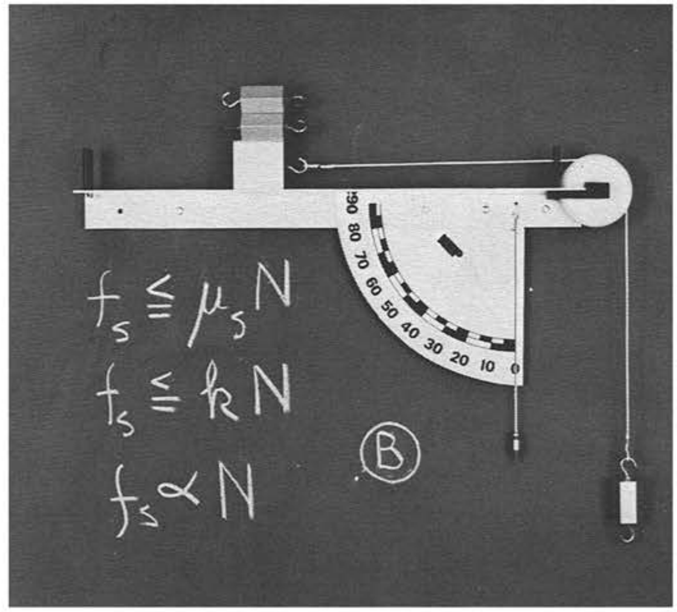


Figure 30B

**Objective:** To demonstrate that the frictional force is a function of the normal force applied by the sliding object to the plane surface.

**Method:** The plane is placed high on the blackboard and leveled by eye. The sliding block is placed on the plane resting on its small-area surface with the teflon strip **up**. A 1 N weight is then attached by string to the hook in its small-area surface while the block is held by hand to prevent sliding. When the block is released, it will accelerate at a relatively high rate indicating that the retarding force of friction is reasonably small.

Without altering the position of the plane, rest a 1 N weight on the upper surface of the block (teflon side) and again release the block from the left end of the plane. It will be seen to accelerate once more toward the right, but this time much more slowly. Add one more 1 N weight for the third trial and observe that the block remains motionless (or accelerates almost imperceptibly) for this condition.

In the relation:

$$f_s \leqq \mu_s N$$

the maximum value of the force of friction $f_s$ is nearly proportional to the normal force $N$. The factor $\mu_s$ is the coefficient of sliding friction and may be taken as constant for given frictional surfaces. The added weights in this case serve to increase the normal force, thus increasing the frictional force. As the force of friction increases, the magnitude of the unbalanced accelerating force supplied by the suspended 1 N weight decreases resulting, therefore, in a reduction of the magnitude of the acceleration.

## EXPERIMENT #31

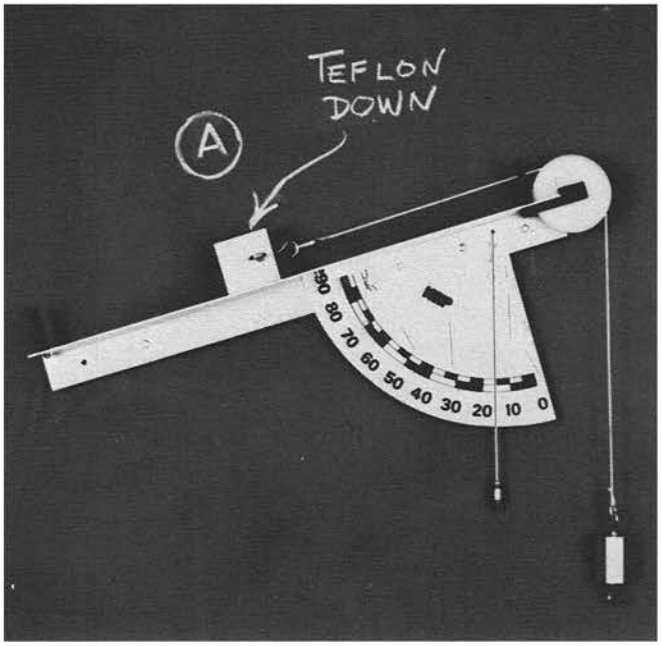



Figure 31A

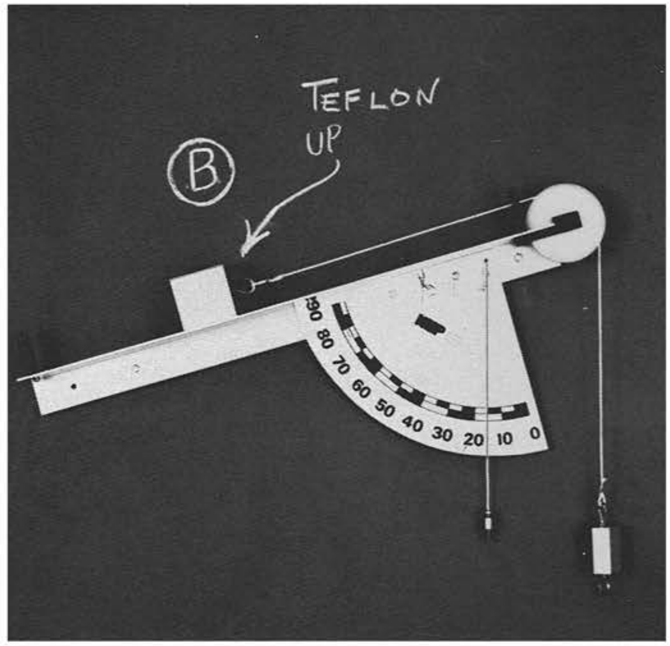



Figure 31B

**Objective:** To demonstrate the dependence of the coefficient of friction (both static and dynamic) on the nature of the sliding surfaces.

**Method:** With the plane high up on the chalkboard, adjust its angle until the sliding block resting on its small-area surface with the teflon strip **up** just begins to move after being given a slight push. Refine the adjustment so that, once in motion, the block continues to climb with uniform, slow speed.

Now invert the block so that it rests on the teflon surface and repeat the above steps without altering the plane angle or the accelerating weight. It will immediately be observed that the block now accelerates, gaining speed until it reaches the top of the plane.

Both coefficients of friction (static and dynamic) are reduced by the teflon interface. Clearly, as the coefficient decreases, the frictional force decreases in direct proportion. As this occurs, the unbalanced accelerating force due to the hanging weight also increases sufficiently to cause a significant increase in the acceleration of the block up the plane.

That is:

since $F = \mu_s N$ in which f = frictional force

$\mu_s$ = coefficient of sliding friction

$N$ = normal force

then the retarding force of friction is directly proportional to the coefficient of sliding friction.

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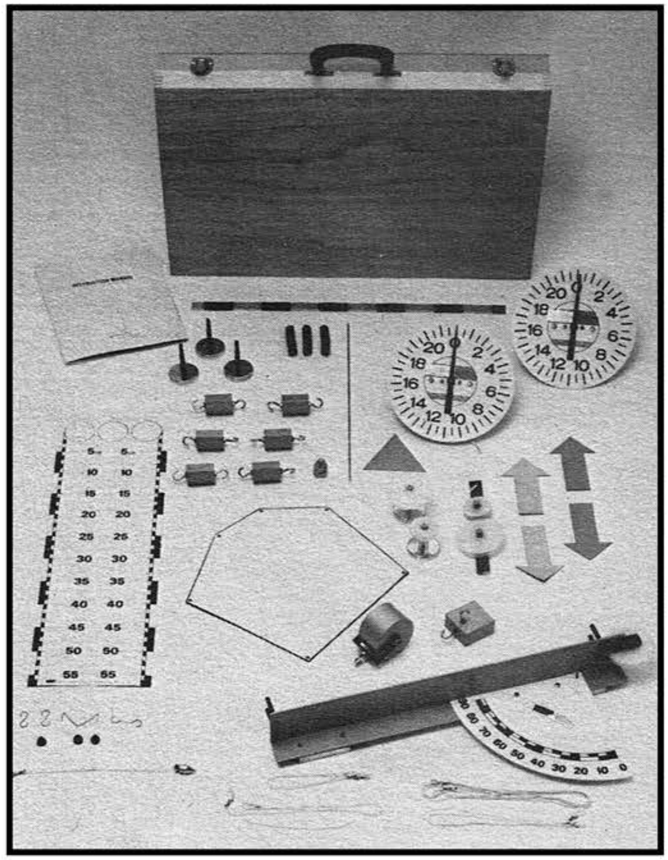

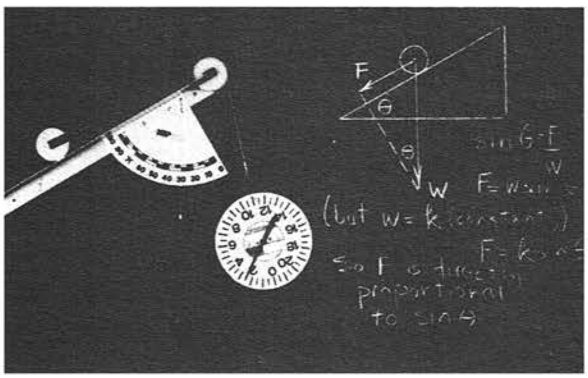

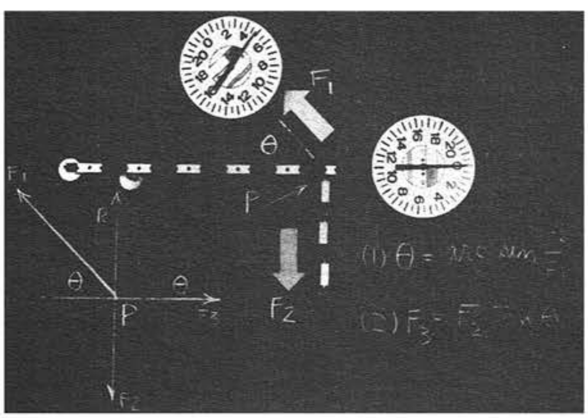

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