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Determining the Force of Friction in a Simple Machine

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ARTICLES

Determining the Force of Friction in a Simple Machine

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Too often a science unit on simple machines consists of a discussion of ideal mechanical advantage (I.M.A.) and actual mechanical advantage (A.M.A.) in pulley systems and inclined planes, without really emphasizing the role of friction. Texts and laboratory manuals generally state that the A.M.A. is the ratio of the resistance force (R) to the actual effort force (E), that is:

$$\text{A.M.A.} = R/E \qquad (1)$$

and that the I.M.A. is the ratio of the distance the effort moves (D_e) to the corresponding distance the resistance moves (D_r), that is:

$$\text{I.M.A.} = D_e/D_r \qquad (2)$$

In the experimental situation, R, E, D_e, and D_r yield values that when "plugged" into the two expressions above show that I.M.A. > A.M.A. Generally the students are asked to make at least one more calculation which results in obtaining the efficiency of the machine (Eff) defined as:

$$\text{Eff} = \frac{R/E}{D_e/D_r} \times 100\% = \frac{\text{A.M.A.}}{\text{I.M.A.}} \times 100\% \qquad (3)$$

An alternate method of calculating the efficiency of a machine is:

$$\text{Eff} = \frac{R \times D_r}{E \times D_e} \times 100\% = \frac{\text{Work out}}{\text{Work in}} \times 100\% \qquad (4)$$

Obviously equations (3) and (4) are identical and this may be verified by the students. Thus in any actual machine the efficiency will be less than 100%.

Unfortunately the laboratory exercise often ends here, and this is where it really should begin. The students should feel a certain incompleteness about the relationship of A.M.A. to I.M.A. or Work out to Work in. The instructor too often will explain that the difference between the two quantities is due to friction and the subject is dropped there. Unfortunately many students accept this totally unsatisfactory answer to an important question and passively move on to the next activity. This subsequent activity may involve measuring the force of friction (F_f) of a sliding block which does little to clarify the mystery of the friction in the machine.

The alert teacher may encourage his pupils at this point, rather than letting the subject drop, by asking them two questions:

(a) How is F_f related to I.M.A. and A.M.A.?

(b) How may F_f be determined experimentally for a simple machine?

These two questions should challenge the best of students and in the process of answering them, the students will gain a more complete understanding of the physical situation and the relationships.

In the process of solving the two problems above, the thinking of the students may proceed in the following manner: Since R, D_e, and D_r would have the same values whether the machine was ideal or actual, F_f must be involved in E. Thus by experimental observation, the idealized frictionless effort (E*) must be related to the actual effort (E) and F_f in the following manner (See Figure 1):

$$E^* = E - F_f \qquad (5)$$

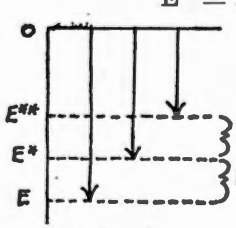

Figure 1.

Figure 1 (left): Diagram (not a graph) illustrates the relationships of E, E*, and E** to F_f. Vector representations are

displaced horizontally for the sake of clarity.

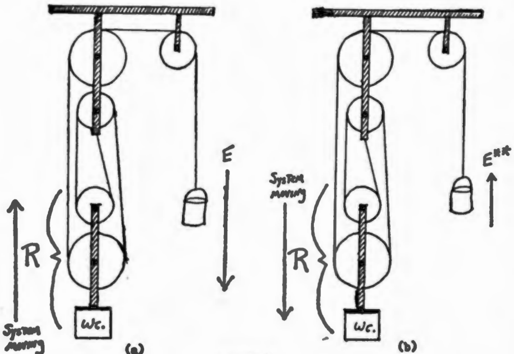

Figure 2.

Figure 2 (above): Figure 2(a) illustrates a pulley system design for measuring E. Note that R (which includes the attached weight and the weight of the lower block of pulleys) will move upward. Figure 2(b) illustrates the same pulley system for measuring E**. R, in this case, will move downward. In making both measurements, the system must move with a constant velocity. The single pulley to the right in each illustration serves to keep the sand pail from coming into physical contact with the main part of the system. It will not change the mechanical advantage of the pulley system, but it will add to the friction.

But experimentally as mathematically, E* cannot apparently be determined unless F_f is known and this is the very quantity the students are attempting to determine. To solve for F_f, equation (5) may be rearranged to:

$$F_f = E - E^* \qquad (6)$$

However, this would require the knowledge of E*, the idealized effort. The situation at this point certainly seems hopeless unless alert students recall that F_f is the force that opposes motion in a direction opposite to that motion. In a simple machine, motion is in either of two directions, up or down. Now E is the downward force that moves R upward (See Figure 2[a]). There is, however, another effort force (E**) which moves upward while R moves downward (See Figure 2[b]). Necessarily $E^{**} < E$, and in essence E** plays the role of a resistance while R serves as the effort in reversing the sense in which the machine is used. It should be apparent then that:

$$E^* = E^{**} + F_f \qquad (7)$$

or that:

$$F_f = E^* - E^{**} \qquad (8)$$

This suggests that by adding equations (6) and (8), a relationship results in which the idealized effort (E*), which cannot be directly determined experimentally, may be eliminated:

$$F_f + F_f = (E - E^*) + (E^* - E^{**})$$

$$2F_f = E - E^{**}$$

$$F_f = \frac{E - E^{**}}{2} \qquad (9)$$

Since E and E** are both experimentally measurable, the F_f of the machine may now be calculated from equation (9).

E may be very accurately measured by using a small pail (such as a small tomato paste tin adapted with a wire handle) to which sand is added until the pail moves steadily downward (and thus R upward) with a constant velocity. E** may likewise be very accurately measured by removing sand from the pail (after it has been weighed and the value of E recorded) until the pail moves upward (and thus R downward) with a constant velocity. Allowing the pail to accelerate in either case would amount to adding an unbalanced force and thus should be avoided. The students may wish to investigate the significance of this.

Having determined E and E**, F_f and E* may now be calculated by equations (9) and (7) or (5) respectively. It may further be noted that since the F_f is equal in either direction,, E* is really the average value

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Vandruff's Island about three miles from Davenport, Iowa. Several weeks before the trip permission had been obtained from Mr. Wood, official of the quarry. The quarry geologist sent the school the diagram of the quarry wall (fig. 1) and Mr. Wood briefly outlined the high points of the trip. Students studied the diagrams at school and carried them as vertical maps in their trip to the quarry.

At the quarry Mr. Wood and the geologist gave about ten minutes of added explanation and for the remainder of the hour answered the individual problems of the students. In addition to facts, the students gained much respect for geologists from those two learned and kindly men.

One could sense knowledge of facts evolving into understanding from the remarks and enthusiasm of the class. The "petroliferous" layer smelled oily! And fossils actually did exist, and in unbelievable abundance. "Concretion" became a word with meaning after students had dug a good number of the "chocolate pieces" from the walls of the quarry. As they looked at the walls from a distance, different ones would turn to their teacher, "Oh, **that's** what you mean?" when they suddenly realized what is meant by a sedimentary rock being formed in place. Others found pieces of gravel, washed into Allied Quarry at flood-time from a neighboring gravel pit. They contrasted the rounded basalt and granite with the limestone of the quarry, and were awed as for the first time the effect of the glacier "grinding and rounding" rocks made sense to them. They could see the marks of glacial striations on the big gravel and the contrast with the angular pieces of limestone. More questions led them to realize that the glacial deposits of gravel would have come long after the stone of the quarry had been laid down.

Each group was at the quarry for an hour; no one was ready to leave, and not even the liveliest of the youngsters did anything with the rocks except to study, explore, and study them more. They were asked to bring back to school and indentify at least one rock (limestone!). They brought many rocks, especially many fossils, and spent all extra time indoors the next week identifying their prizes.

In their independent evaluations of the course 75 of the 79 students listed the trip to Allied Quarry as the most valuable part of their geology study because, as one boy bluntly stated, "(The quarry) . . . made sense out of all that stuff about faults and folds, formations and strata!"

Suggested sources of information:
Iowa Geologic Survey
State University of Iowa, Iowa City
American Geological Institute
Office of Education
2101 Constitution Avenue, N.W.
Washington 25, D.C.

FORCE OF FRICTION

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of E and E**, that is:

$$E^* = \frac{E + E^{**}}{2} \qquad (10)$$

and thus it could be determined without the knowledge of F_f.

Physically, it is apparent, that lubricating the machine will decrease F_f. Equation (9) indicates that the difference between E and E** will become smaller if the F_f is made smaller. Ideally then, it may be imagined that the difference between E and E** could become zero if there were a lubricant so efficient that all frictional force was eliminated. In other words, if $F_f = 0$, then $E = E^* = E^{**}$.

In an opposite sense, the student may imagine pouring sand or some other abrasive into the bearings of the machine until the system "locks". In this case E and E** would become infinite and from equations (9) and (10), so would E* and F_f.