Mechanism and Innovation

(Machines and Their Evolution – An Analytical Approach)

Do the Mechanism-Innovation Moodle Quiz on http://thinkproblemsolving.org
There is an assignment in the Pendulum_Clock.doc

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1 You Already Know Much More Than You Think You Know (Recall)

1.1 Recall from Science Classes – Fundamental Machines... Make up a System

You should recall from science class that there are several classic and basic kinds of machines – levers, pulleys, wheel and axle, inclined planes, screws and gears. A machine is any device that helps us do work. For example, a motor vehicle is a very complex machine that can be used to move people or goods from point 'a' to point 'b'. The motor vehicle is composed of many smaller machines that all work together to form a system which gets that transport job done. Each smaller machine within the system has its own function or purpose in the overall context of fulfilling the design goals. In general, a system is made up of sub-systems which all mesh together in order to achieve something.

Think About It --

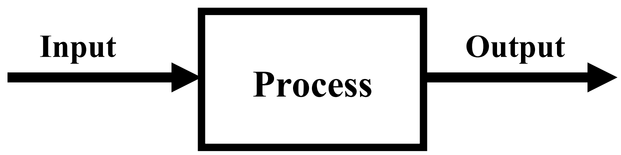
What do a screw, propeller and wedge have in common?
What do a pulley, gear, wheel and axle and block and tackle have in common?
How can you represent these two families of simple machines in a simple visual diagram?

1.2 Review from 13 Fundamental Concepts

1. What is a mechanism?
   a. A definition derived from the curriculum document is "*An arrangement of connected parts that allows a component, product or system to work or function*."
   b. Now translate this definition into your own words -- preserving the meaning.

1.3 The Essence of a Machine (Fundamental Knowledge)

The teacher will lead a class discussion and analysis of simple machines beginning with the familiar Input – Process – Output model of a system.



A machine is a process or, rather, a processor. The machine takes input and does something to it. The machine gives output that is more useful to the system users (in a particular context) than was the original input. The output of the machine is "*the good thing that we want it to do*" – ie the "function"` or purpose of the machine such as lifting a heavy load of bricks.

In the case of a general machine, inputs can include materials that are transformed or converted by the machine (eg a planer) into different shapes for example. A machine can be primarily an information converter (eg printing press, telephone, radio, computer). Still other machines can be classified as energy conversion machines (eg bicycle, electric motor, internal combustion engine).

However most of our discussion in this document will generally be limited to simple machines that:
- "modify" a force or
- "modify" a displacement (ie the position of some object (the load) or the direction of motion of the object).

Such a simple machine could be used in some way within a more complex energy processing machine, in a materials processing machine or in an information processing machine.

1.3.1 Connection with Energy – A Required Input to all Machines

For all machines, one of the inputs must be energy. Energy is the capacity to do work, or in the most general case, the "***capacity to have an effect***". The output from the machine is the work or effect that we desire – *the good thing that we want to have happen*. There will be energy losses within the machine due to friction – one part rubbing on another. Hence the ratio of output energy to input energy – the machine`s efficiency – is less than 1.

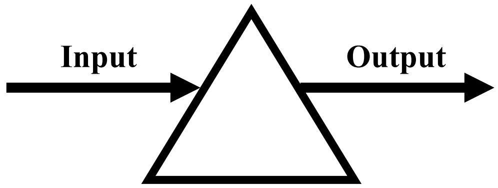
An energy processing machine typically has one of three main purposes. In the following examples, please notice that an energy processing machine can be very complex or it can be extremely simple.

Machine / Mechanism	Input	Output / Notes
Alternator	Mechanical energy (rotation of a shaft)	Electrical energy (Change the form of the energy)
Gasoline engine	Chemical energy	Mechanical energy (rotation of the crankshaft) (Change the form of the energy)
Single Pulley	Force (Effort) acting through a distance	Same force magnitude (Load), acting in opposite direction through the same distance (no change in power) (Change the direction of the energy) (Mechanical advantage = 1.0)
Elevator	Electrical energy	Lift a load vertically (linear motion) (Change the form of the energy)
Hay mower	Rotational mechanical energy (early mowers were powered by the turning of the wheels)	Reciprocating motion (Change the direction of the energy)
Motor vehicle transmission	Rotational energy coming off the crankshaft of the engine	Rotational energy at the drive-shaft of the vehicle (Depending on the gearing, may be an increase in rotational speed / decrease in torque OR an increase in torque / decrease in rotational speed) That is, this machine simply moves energy from one point to another within a system with a change in torque / speed in one way or another
Second class lever	Force (Effort) in upward direction moving though a distance x	Load greater than the Effort is lifted a distance less than x in upward direction Positive mechanical advantage – force multiplier
Coal Furnace	Chemical energy	Heat distributed to a home. Early home heating relied on only convection to “lift” the warmed air to upper storeys of the house.
Pendulum Clock	Slowly falling weights	A display of elapsed time based on scientific observations in relation to periodic motion of a mass falling and swinging in a gravitational field.

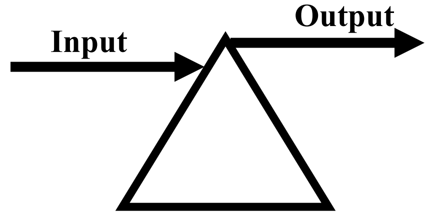
1.4 Black Box Modelling – Simplify for Better Understanding

The first trick to understanding a system is to simplify. Consider a machine to be a black box. You don`t know what is inside the black box and you don`t know how the box works. In this Black Box modelling strategy, you only know that you have inputs to the black box (eg magnitude and direction of a force) and you have outputs from the black box (eg magnitude and direction). Ignore the losses inside the black box – you can make the simplifying assumption that the losses are zero. Keep in mind that the main purpose of making an assumption is to simplify a problem – such that you will have a better chance of understanding the problem.

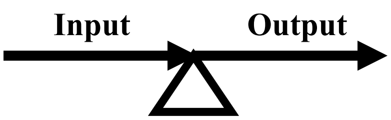
If you don`t know what`s in the black box, you can represent the model visually any way you want. Let`s model it using this visual.



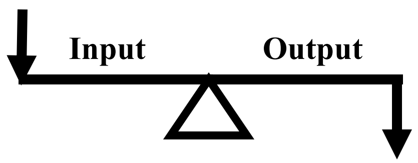
or like this



or why not like this



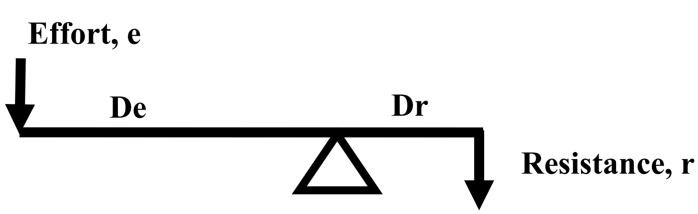
or maybe even this



The visual model in the bottom right is beginning to look familiar. You already know from science class that a lever involves an effort, a rigid beam, a fulcrum and a load or resistance. The downward application of the effort is the input and the movement of the load up a certain distance is the output. Our simple black box model (that we did not want to look inside) has now actually become a white box model revealing almost exactly how our machine works. The peak of the triangle is the fulcrum and the horizontal line is a long slender but rigid body that does not deform during use (ie a beam).

1.5 White Box Modelling – What`s Going On Inside? – How`s It Work?

Let`s make one more change to our visual model to make it more of a white box than a black box model.



Now in our white box model, we can see almost exactly how our machine works. The system is in balance, meaning that the system is neither moving left nor right nor up nor down, nor is it spinning around (out of control or at some constant rate). You recall the law of the lever from science class....

> The effort (say in Newtons) times the distance from the point of application of the effort to the fulcrum (say in metres) is equivalent to the resistance or load (in Newtons) times the distance from the point of application of the load to the fulcrum (metres).

This long statement is difficult to comprehend by itself. Let`s translate the statement into something we can more easily understand.

1.5.1 Translate into a Simple Mathematical Form (Tools of Math)

Now translate the very cumbersome English statement above into a more convenient and useful form – a simple mathematical equation.

e * De = r * Dr	Law of the lever.
e = r * Dr / De	Multiply both sides by 1/De to solve for the Effort
e / r = Dr / De	Multiply both sides by1/r to find two equivalent ratios

This machine has been designed to allow you to lift a heavy load using a small effort, in the ratio of Dr/De which is equivalent to the ratio, effort / resistance. The ratio of output force to input force (r/e) is called "*Mechanical Advantage*" (more precisely, the "actual mechanical advantage"). The distances to the fulcrum, De and Dr, are called "moment arms". The product, e * De, is the applied torque – or the "*moment of a force*".

Notice that to achieve a mechanical advantage, you must move your effort, e, through a greater distance.

1.6 Making Connections – Mechanism and the Conservation of Energy

You have already made the simplifying assumption that the energy losses in our machine are zero (we assumed zero friction inside our machine). You already know then that Energy In = Energy Out, ie the efficiency is 1.0. And you already know that Energy is the capacity to do work and that an amount of work is a force moving through a distance, E = F*d (not the same as 'e' and not the same as 'D' above).

In your lever model above, your effort (the Input force) pushes down on one end of the rigid part, moving through a relatively vertical distance d_e and the resistance is lifted up through the relatively vertical distance d_r .

Energy In = Energy Out	You already know about the law of conservation of energy
$e * d_e = r * d_r$	Energy is work and work is the product of a force times the distance moved

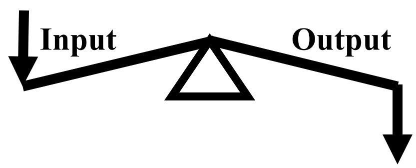
The ratio of the two distances moved is identical to the ratio of the two forces. If the friction is indeed zero, the efficiency is 1.0. We thus have an ideal machine and the corresponding ratio of output force to input force is the Ideal Mechanical Advantage. In reality, there is always some friction and the Actual Mechanical Advantage is less desirable than the Ideal Mechanical Advantage.

The major feature of a lever is that, depending on the relative lengths of the moment arms in your machine design, you can either:

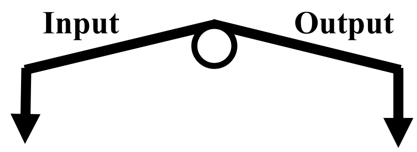
- use a small input force to obtain a large output force
- use a small input displacement to obtain a larger output displacement

1.7 Re-Design the White Box Model – Connection With Material

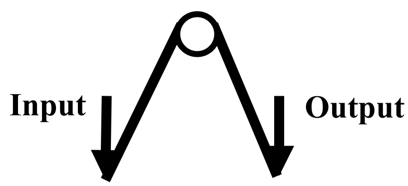
What if we drew our model like this?
(Does it still work the same?)



Or how `bout like this?
(Still the same, right?)

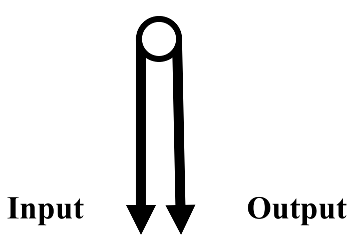


Or why not like this?



Our original ideal machine, the lever, had one long horizontal member – a beam -- that did not deform when in use. In other words, the lever`s beam did not bend appreciably under loading. Bending is a combination of compression and tension. In the three `kinked beam` models above, the beam is kinked around the fulcrum but it is still a continuous and rigid beam nonetheless.

Now let`s change the material – change the rigid kinked beam to a flexible rope. A rope only resists a tension loading. Our model can then be changed to this.

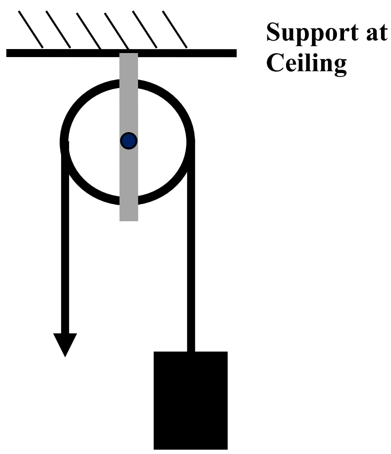


This model should look familiar. Our lever has now become a pulley where the features of our "new" machine are as follows:

- The effort is a pull down on the rope (input force moves the end of the rope a certain distance)
- The resistance is the weight of an object (the force of gravity acting on the mass of the object)
- The object tied to the end of the rope moves upwards (output) the exact same distance that the effort pulls the other end of the rope downwards (input)
- The fulcrum is the centre pin that holds the pulley wheel in one location – the pulley wheel spins freely around the centre pin – we again assume zero friction as the machine operates
- The moment arm of the input force (effort) is the radius of the pulley wheel
- The moment arm of the output force (gravity acting on the object) is also the radius of the pulley wheel
- This machine changes the direction of the displacement (effort moves rope down while the object is moved up the same distance). Notice our assumption that the rope does not stretch.
- Only one force is lifting on the object
- The magnitude of the effort is equal to the weight of the object

- The ideal mechanical advantage = 1.0

Our model above is a very simple representation – we had derived that model to show that a pulley is just a lever with a change in material from rigid beam to flexible rope. Let's re-draw the model showing the object to be lifted as well as a symbol to show that the pulley is attached to the ceiling.

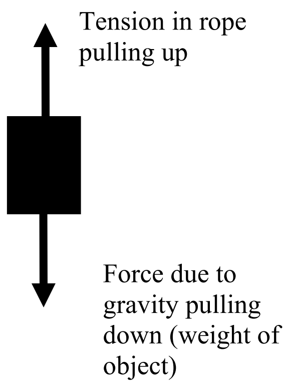


Think About It --

If the object weights 100 pounds, what pull force on the other end of the rope is required to just lift the object off the floor?
How many forces are acting on the object? Is the object connected to anything else that you can use to actually re-define the object – or re-define the system?
When the object is just lifted off the floor using the pulley and rope, what is the load on the bracket holding the pulley to the ceiling?

1.8 A New Tool – Free Body Diagrams

We can draw a different model of our system above, but this time focusing only on the forces that act on our object – the weight that we want to lift. This is called a free body diagram. Below is the free body diagram of the object above.



Think About it… Draw It --

Consider the pulley in the above diagram. How many forces are acting on it? What is the direction of each of those forces?

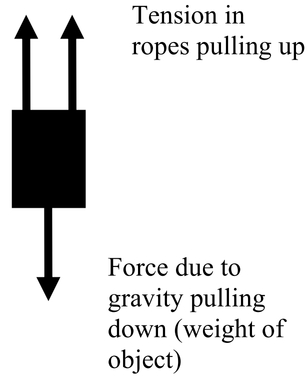
Make a free body diagram for the pulley in the system above.

The above machine just lifts a weight in a direction opposite to the pull force. It gives no mechanical advantage. Now let`s design a machine that will do the same -- but with some mechanical advantage.

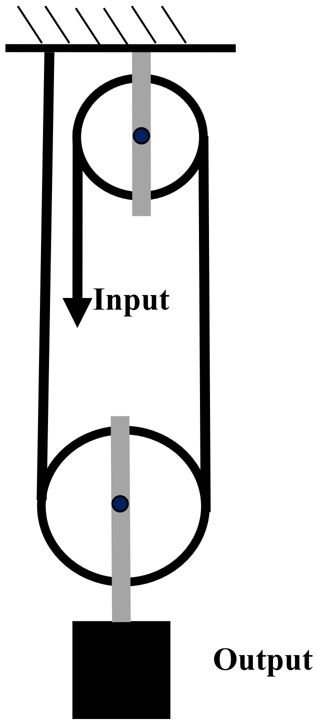
1.9 Innovation – Making a Better Machine

To innovate is to make something better. This takes both critical and creative thinking. The critical thinking is necessary to be sure that you understand and appreciate the (presumably) simpler technology that you began with – the thing that you want to make better. This is what we've been doing so far in this document. This is also one aspect of what is generally called "analysis".

What if we pulled up on our object using two ropes instead of one? Here is the free body diagram. Assuming that our system isn't accelerating upwards or falling downwards, the sum of the two forces pulling up must be equal to the weight of the object (gravity pulling down.) In this free body diagram, we can see that the tension force in each rope has been halved.



So, let's innovate. How can we use this idea to enable us to lift a heavy load using a much smaller effort?



You may be tempted to say that the object is only acted upon by two forces, as in the previous model – gravity pulling down and the bracket pulling it up. However, you can state your assumption that the object and lower pulley are connected to each other such that they become another object --- another free body. And it could very well be that the weight of the lower pulley / bracket is very small compared to the weight of the object load.

Because the input force is now only half of the object's weight, the Mechanical Advantage is 2.0.

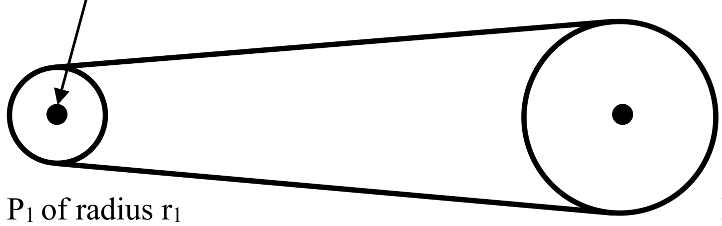
Think About It --

Find a simple way to determine the mechanical advantage of a pulley system with any number of pulleys contributing to the work of lifting a load. What name has been given to such a machine made up of multiple pulleys? Where are these machines used – what modern applications are there for these machines?

1.10 Derive a Whole New Family of Machines from the Fundamental Machine

Many modern machines use another mechanism that is also derived from the simple lever – the wheel and axle, a simple fixed arrangement of 2 concentric circles of different diameters.

First consider only the pulley on the right side of the diagram below. The centres of the two circles (the outer circle and the inner black shaft) are coincident. The rigid connection between the shaft and the wheel can be an extremely tight press fit or a keyway / key. A relatively small force (the tension in the belt) acting on the outer diameter of the pulley wheel will cause the axle or shaft to turn its load with a much larger force. But you have to move your applied force much farther to get this mechanical advantage. A wheel / axle or pulley / shaft may not look like a lever in action, but it fundamentally is – it is all about the balance of two forces acting at different distances from a common point, the fulcrum. Torque is the name given to a force that turns something at a distance – also called the Moment of a Force.



The above mechanical drive system has 2 pulleys (P_1 is driving and P_2 is being driven) and a flexible drive belt which is strong in tension. Suppose the radius of P_1 is r_1 centimeters and the radius of P_2 is $r_2 = 2r_1$ centimeters. If P_1 rotates one revolution, then a length of belt equal to its circumference ($\pi 2r_1$) cm has been moved. This same length of belt, $\pi 2r_1$ is only half of the circumference of pulley P_2. So P_2 has only rotated half a revolution. This system of pulleys (wheel / axle) has reduced the speed of the driven shaft by half.

Now suppose a gasoline engine is driving P_1 on its shaft of radius r_0. If the force of the engine acting on the outer edge of the shaft causing it to turn is F_0 then the torque or moment of force F_0 acting on the shaft is $F_0 * r_0$. This is identical to the situation on one side of a lever. As with a simple lever, the torques acting on the system must be in balance, ie equivalent. This is the law of the lever. The centre of the pulley / shaft is the fulcrum. Thus, the law of the lever says that:

$F_0 * r_0 = F_1 * r_1$

where F_1 is the force being transmitted at the outside edge of wheel P_1 having radius r_1. This force F_1 is the tension in the belt which connects the P_1 wheel /axle to the P_2 wheel / axle. This tension is transmitted along the belt to act on the outer edge of P_2. The torque on P_2 is thus $F_1 * r_2$ which is twice r_1. By cutting the speed of rotation in half, we have doubled the torque on the driven pulley.

The wheel and axle provides us with another way to optimize power and speed for our particular design situation.

1.11 Inclined Plane – The Second Elementary Machine

The screw, propeller, wedge, axe are all inclined planes. Any inclined plane also has a mechanical advantage – reducing the required effort by moving the load a greater distance. Depending on the nature of the surfaces in contact, friction losses are typically greater in an inclined plane than in a pulley system with well lubricated and finely finished roller or ball bearings.

Think About It --

Is the friction in a screw a good thing?

Is a 'cam' a lever or an inclined plane? Explain. Take a look inside a small engine.

1.12 Innovation – A Brilliantly Simple Automatic Transmission

Think About It –

Think about how a belt-drive system with two pulleys can be modified to become an "automatic transmission", starting with high torque / low speed at low rpm and "ramping up" to low power / high speed at high rpm. Consider what you learned in science about rotational energy. "Synthesize" (or create) your conceptual plan for such an "automatic transmission". Only after seriously thinking analytically about this idea, should you do a search on the internet or in the library.

2 Self and Peer Assessment

2.1 Inputs / Knowledge / Understanding I Still Need For This Module

Give each issue a number for future reference:

1

2

3

2.2 Peer Assessment

NOTE: In the feedback, the Assessor must "make the student think" – not give the student the answer! Be sure to include comments justifying the mark that you are giving.

Date _______________ Portfolio For (Name) ________________________________ Page ____

Assessor's Name and Additional Notes: