California Physics Standard 3a

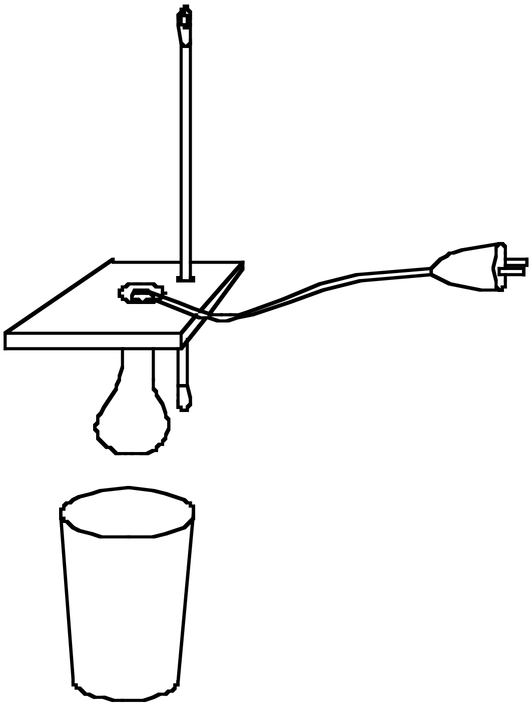
Energy cannot be created or destroyed although in many processes energy is transferred to the environment as heat. As a basis for understanding this concept: **3a. Students know heat flow and work are two forms of energy transfer between systems**.

Rubbing hands together as an example of work to heat:
The following great old activity should not be overlooked even though it was discussed in the Framework as early as in grade three. Have the students rub their hands together. First with little or no pressure applied between their hands. Next by pressing their hands together with great force. In the first case little work is done and little heat evolves. In the second case it is apparent that continued rubbing can get you tired and your hands will certainly heat up.

Activity to measure the relationship between work and heat:

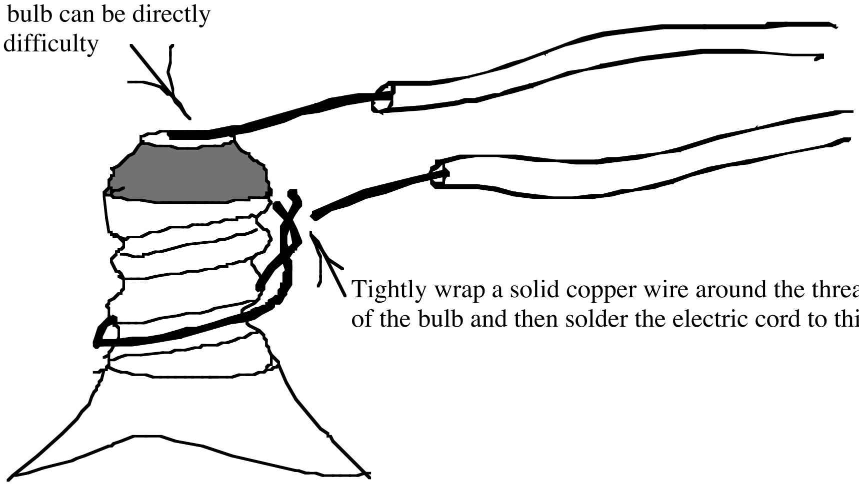
Commercial apparatus is available to reproduce Joule's determination of the mechanical equivalent of heat, but a fairly simple and inexpensive duplicate of this experiment can be made using a standard 60-watt light bulb.

The basic apparatus is a 60 watt light bulb that has been attached to a line cord through a hole in a piece of ¾" soft wood. (Details on how to attach the cord below.) Using silicon calking, the base of the bulb is glued to the wood and covers the electrical attachment to the bulb. A hole through the wood allows a thermometer to be pass through it. Using a Styrofoam cup large enough to accommodate the bulb, an amount of water is filled in the cup to completely submerge the bulb when lowered into the cup. (Do not plug in the bulb until it is completely submerged in the water.) The idea behind the experiment is to carefully time how long the bulb is on while submerged in the water. The temperature change is recorded during the time the bulb is on. Multiplying the power of the bulb times the seconds it was on would give the joules of energy put into the bulb. The mass of the water times the temperature change will give the amount of heat delivered to the water.



One error in this experiment will be the energy loss as visible light through the sides of the cup. Lining the cup with aluminum foil can minimize this. Also, to minimize the effect of loss heat through the walls of the cup, one could start the experiment with the temperature below room temperature and heat it to the same temperature above room temperature.

Below is an illustration of how to attach the line cord to the light bulb. A socket can be used but this method is less expensive. If the entire base of the bulb, below and above the wood is covered with silicon calk, the apparatus will be quite safe.



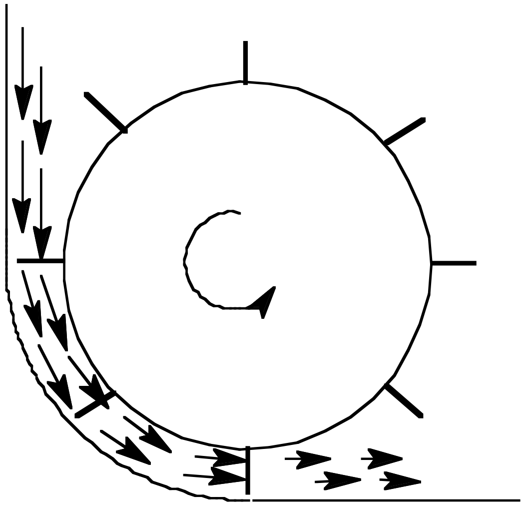
The center of the bulb can be directly soldered with no difficulty

Tightly wrap a solid copper wire around the threaded base of the bulb and then solder the electric cord to this wire.

California Physics Standard 3b

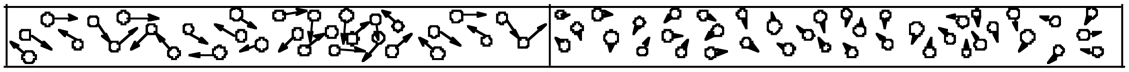
Energy cannot be created or destroyed although in many processes energy is transferred to the environment as heat. As a basis for understanding this concept:
3b. Students know the work done by a heat engine that is working in a cycle is the difference between the heat flow into the engine at high temperature and the heat flow out at a lower temperature (First Law of Thermodynamics) and that this is an example of the law of conservation of energy.

Models of the kind of engines used in automobiles:
This standard seems to be approaching the first law of thermodynamics with a specific intent to discuss heat engines. Students would probably appreciate this more if they could learn about practical heat engines like the internal combustion engines they encounter every day in their cars. Since auto shops are less common in today's schools, working models of such engines are hard to find. The least expensive I have found can be had from Cynmar Scientific (www.cynmar.com). Go to their webpage and in the search window type: 022-39329 for a "Petrol Engine Model" and/or 022-39327 for a "Diesel Engine Model". Students can learn a lot by turning the crank on these models and coming to a better understanding of what is going on under the hood of their car.



The flow of heat and the basics of heat engines: The Framework is very careful to caution against any instruction that might give students the idea that heat is a fluid. (The fact that this was a common misconception with early scientists suggests that the idea must be quite compelling.) In order to help students understand the basics of how heat engines work, we suggest beginning with an analogy to how a water wheel extracts energy from a waterfall. The water strikes the wheel at a high-energy state, transfers some of this energy to turning the wheel and then passes water out from the wheel at a lower energy state. The maximum energy that the wheel can extract in this process is the difference between the energy of the water that initially struck the wheel and the lower energy water that is exhausted from the wheel.

The problem with the water wheel analogy and a suggested solution:
If, as the Framework suggests, it is important that students do not get the idea that heat is a fluid, the problem with the above water wheel analogy should be obvious. It is good at suggesting how the difference between the energy in and out of the wheel should correspond to the energy obtained by the wheel but it definitely suggest that something material (water) had to flow through the wheel. It is perfectly fine if students understand that heat "flows" as long as they don't think heat is a fluid like water or air. Heat energy can flow without necessarily having any material flow. Here is a thought experiment that should be computer animated but no such animation has been found by me yet:



Imagine a long horizontal tube with a partition in the middle. On the left side of the partition are rapidly moving molecules. On the right side of the partition are slow moving molecules. The partition is removed and the resulting collisions, particularly near the interface between the rapidly and slowly moving molecules, result in having the fast ones slow down and the slow ones speed up. After many such collisions, the tube is now filled with molecules moving at a speed that, on average, represents a kinetic energy that is the mean between the original two different kinetic energies. The concept to stress is that even though there has been no overall flow of the molecules in either direction, there has been a flow of kinetic energy from the left side of the tube to the right side of the tube.

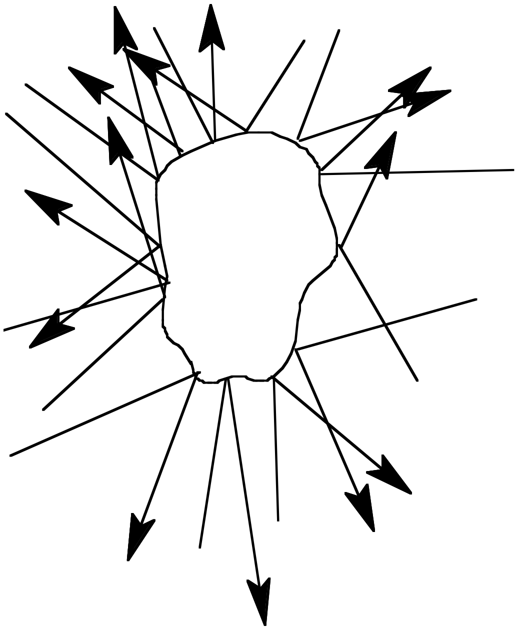
The waterwheel analogy together with the image of the molecules in the tube might help students to understand how a heat engine extracts heat energy from the high temperature source, converts the energy from this heat into work, and then exhausts much of this energy to the low temperature source.

California Physics Standard 3c

Energy cannot be created or destroyed although in many processes energy is transferred to the environment as heat. As a basis for understanding this concept:
3c. Students know the internal energy of an object includes the energy of random motion of the object's atoms and molecules, often referred to as thermal energy. The greater the temperature of the object, the greater the energy of motion of the atoms and molecules that make up the object.

The idea of atoms is very old and often originally attributed to Democritus (c.460—370 B.C.) Perhaps because these ideas are so old, students seem willing to accept the basic concepts related to atomic motion all too easily. As late as the 19th century, scientists vigorously debated the reality of atoms. An observation made by the botanist Robert Brown in 1897 and finally explained by Einstein in 1905 can serve as macroscopic proof of the motion of microscopic atoms. The observation made by Brown was that microscopic pollen grains were observed to display random motion under a microscope even though they were definitely not alive.

The argument presented by Einstein suggested that even though the pollen grain was massive compared to atoms, their rapid random motion could occasionally cause a larger force on one side of the grain than on the other giving it a small acceleration in one particular direction. Later, the random motion would cause acceleration in a different direction, which would cause the grain to jiggle around. On average, the net force would be zero and the larger the grain, the less would be the jiggling. However, if the grain were small enough, the slight difference that randomly developed on one side of the grain would be large enough to move the drop. The prediction was that the smaller the grain, the more noticeable the motion. The viscosity of the surrounding fluid as well as its temperature could influence the random motion of the grain. An excellent movie of this effect can be found on the web at: http://www.physics.emory.edu/~weeks/squishy/BrownianMotionLab.html



This movie shows different sized grains in different concentration of glycerol and water that clearly demonstrates the effects of Brownian motion. Another web page suggests an experiment that could be done with grains of India ink under a microscope that should be easily repeated by a student: http://www.science-projects.com/Diffuz.htm
The instructions seem simple and are copied below:

Student activity to illustrate Brownian motion:

1. Take a drop of real "India Ink" (not just any black ink), and dilute it in half with distilled water.
2. Place a drop of this "solution" onto a slide and cover it with cover slip.
3. Under a light microscope, you should see small black specks that are jiggling around.

THAT is "Brownian Motion." It is the basis of diffusion.

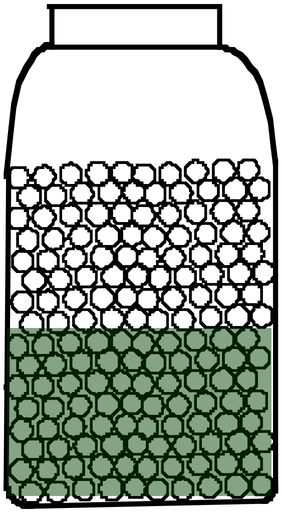
This experiment might give a student an opportunity to experiment with different fluid concentrations and perhaps even the temperature of the fluid.

California Physics Standard 3d

Energy cannot be created or destroyed, although in many processes energy is transferred to the environment as heat. As a basis for understanding this concept, **3d. Students know most processes tend to decrease the order of a system over time, and energy levels are eventually distributed uniformly.**

Students are no doubt familiar that a deck of cards that has been completely organized into suits by number will begin to randomize in a single shuffle. Repeated shuffling will only end in other random organizations. Students are easily convinced that no amount of further shuffling would end in having the cards reorganize into the original arrangement. A related classroom demonstration is to take a large clear jar filled with marbles of equal size but of two different colors. Black and white beans work well for this demonstration.

After carefully filling the jar half full with one color bean, fill the rest of the jar with the other color. Show this to the class and ask what will happen if you shake the jar. They will correctly assert that the beans will get mixed up. You confirm their assertions by shaking the jar and mixing the beans. Now ask, how long will I have to shake the jar to return the beans to their original configuration? They probably will suggest that this can never happen. The discussion that follows should help them to realize that the original arrangement <u>is</u> one of the possible configurations but that there are so many other possible configurations that lead to mixing that returning the beans to the original configuration is, although possible, highly improbable.



Just as the beans tend to go from a highly organized state to a more mixed up state, a conductor which is hot on one end and cold on the other will, if left for some time, come to an equilibrium temperature. The collisions of the rapid moving molecules on one end with the slower moving molecules on the other with cause the heat energy to transfer in such a way that most of the molecules will end up moving at median velocity.

Hint to help make it possible to repeat this demonstration in a later class:

How do you get the beans back to the original configuration for the next class? You can turn this into good-natured fun if some student who needs a little extra "attention" is called upon to return the beans to the original configuration. You can then discuss that although this act is returning the beans to their original configuration, it takes energy for the student to do it. When viewed from a larger picture, the biological processes involved as the student sorts the beans causes the universe as a whole to become more disorganized.

California Physics Standard 3e

Energy cannot be created or destroyed, although in many processes energy is transferred to the environment as heat. As a basis for understanding this concept:
e. Students know entropy is a quantity that measures the order or disorder of a system, and is larger for a more disordered system.

This standard seems to be best appreciated as an effort to have the students begin to get a qualitative understanding of entropy. Most students find it quite intuitive to learn that most processes will lead to an overall increase in disorder. It takes a little learning to identify increasing disorder with "increasing entropy". It also takes some adjustment to understand that although many important quantities in nature like energy and momentum are conserved, entropy is only conserved in special situations and in general, entropy always increases.

The framework discusses how a system at constant temperature that has heat flowing in or out of it, such as the melting or freezing of ice, has a change in entropy ΔS described by:

$$\Delta S = \Delta Q/T$$

where ΔQ is the heat that enters or leaves the system and T is the absolute temperature. This relationship should serve to introduce students to a quantitative definition of entropy and start them to appreciating that the units of entropy are joules/K. If just the melting or freezing ice cube is considered, it might seem that entropy could decrease during freezing since energy must be extracted from the system. However, when considering the "entire universe" it will be appreciated that a refrigerator that could extract the energy from the ice cube would require an energy input to operate and the entropy in the overall universe must increase.

Since the statistical mechanics required to develop the relationship between temperature and disorder is quite complex, this standard should be appreciated as a way to start students to thinking about the concept of entropy, how it can be defined and the units used to measure it. A discussion of how the second law of thermodynamics can be cast in terms of entropy should be given that relates heat flow from a high temperature to a low temperature source with an increase in the disorder of the system

California Physics Standard 3f*

Energy cannot be created or destroyed, although in many processes, energy is transferred to the environment as heat. As a basis for understanding this concept:
f* Students know the statement "Entropy tends to increase" is a law of statistical probability that governs all closed systems (second law of thermodynamics).

Often, the initial statement of the Second Law of Thermodynamics students learn is: Heat flows spontaneously from a high temperature source to a low temperature source. The objective of Standard 3f* is to expand the 2nd law to a more general entropy and probability statement. The discussion of the jar with two different colored beans discussed in standard 3d. should again remind students how order naturally moves to chaos. Reminding them that when a hot piece of metal is brought into contact with a cold piece of metal, the interaction between the rapidly moving molecules in the hot metal with the slower moving molecules in the cold metal will eventually lead to most molecules moving at an intermediate speed. This is analogous to the different colored beans becoming so uniformly mixed that no amount of additional mixing will return them to the original separated state.

Standard 3 g* will discuss how all heat engines operate by extracting work from energy as it transfers from a high temperature source to a lower temperature source. The first law of thermodynamics demands that the total heat energy put into the engine must equal the total work extracted from the engine, plus the amount of heat energy transferred to the low temperature source. The first law demands that energy must be conserved. However, after the energy has been transferred, although it is conserved, the energy is now in a less useful state. The second law demands that all processes involving energy transfer will result in moving the energy to a less useful state.

At this point it might be well to be reminded that it was less than two centuries ago before it was finally appreciated that heat was <u>not</u> a fluid and even as late as about one century ago leading, physicists were debating the validity of the kinetic molecular theory. Hopefully these two historical facts will justify our stating that although the mathematics is probably beyond most high school students, arguments involving probability and atomic theory can be used to relate entropy to a natural movement of molecules from a highly improbable configuration to a more probable configuration. This is realized in the most elemental way when a hot piece of metal is placed in contact with a cold piece of metal and, after some time, the combination comes to an intermediate temperature. The original organization has moved to a more chaotic state. All processes in nature move in this direction. Something as highly complex as life will always originate at the expense of an even more highly organized state of matter and energy. Energy from the sun, on its way to the colder earth below passes through a leaf and through the process of photosynthesis a seemingly more complex plant cell is formed. However, the loss in organization of the transfer of energy from the sun to earth is greater than the organization of the matter in the leaf into a plant cell.

Three common statements of the Second Law of thermodynamics are:

1. Heat flows spontaneously from a high temperature source to a low temperature source.

2, All process move spontaneously from a less probable to a more probable state.

3, Entropy tends to increase.

Each of these statements can be interpreted as meaning the same thing.

California Physics Standard 3g*

Energy cannot be created or destroyed, although in many processes energy is transferred to the environment as heat. As a basis for understanding this concept:
3. g* Students know how to solve problems involving heat flow, work, and efficiency in a heat engine and know that all real engines lose some heat to their surroundings.

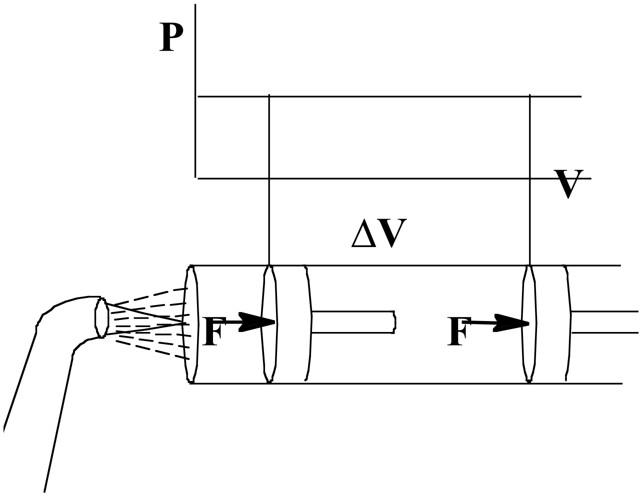
Introduction to real heat engines.

As stated in Standard 3b, a good way to begin a study of heat engines is to discuss examples of actual engines. Models like those that can be obtained from Cynmar (Petrol 022-39327 and Diesel 022-39329 www.cynmar.com) could help the discussion. Even discussing a steam turbine would give a real reference to how work can be extracted from a heat engine as the heat flows from a high temperature source to a low temperature source.

Understanding he meaning of the area under a pressure vs. volume graph.

Although not specified in the statement of the standards, much of the physics of how heat engines work requires an appreciation that the area under a pressure vs. volume graph is work. A simple discussion of what happens when a piston confining a volume of gas moves outward under the force exerted by the pressure of the gas can help to understand this concept.

The piston shown on the right confines a volume of air inside of a cylinder under pressure, P. The air is heated in such a way as to cause the piston to move to the right and for simplicity, the pressure is kept constant as the piston moves. The area of the piston is A and from the definition of pressure, the force exerted on the piston by the air is F = PA. As the piston moves in the cylinder it sweeps out a volume ΔV = A d where d is the distance the piston moves. Since work equals F d = PA d = P ΔV we can see that the work done in moving the piston

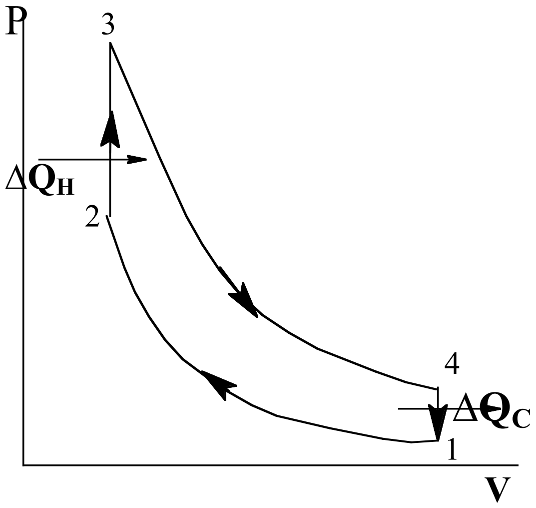


can be represented on the pressure vs. volume graph illustrated above as the area under the graph. We have chosen to use a graph for which the pressure remains constant, however, the area under <u>any</u> graph of pressure vs. volume (which can be approximated by a large sum of $P\,\Delta V$ rectangles) will <u>always</u> equal work or energy. If pressure is measured in N/m^2 (or Pascal) and volume is measured in m^3 the product of pressure and volume will be Nm, which, as we already know, is a joule, the unit of work or energy.

Real engines and the PV graph.
If you do not have a model of an internal combustion engine to use to demonstrate with your class, a good animation can be obtained at:

http://auto.howstuffworks.com/engine1.htm&usg

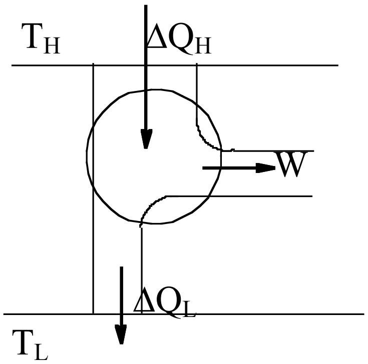
Although there are several steps to the cycle, students can be brought to understand what is going on inside of their car's engine and usually find it quite interesting. This introduction to a real engine seems to be a good point of departure for the more abstract discussion that follows. First, consider the Pressure -Volume graph of the engine cycle:



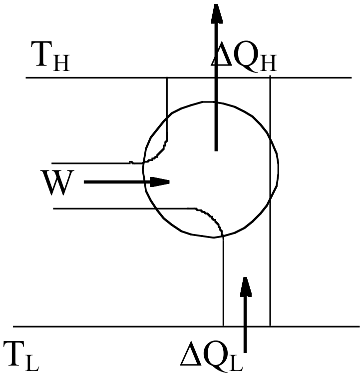
The cycle begins at 1 when the fuel air mixture is compressed to 2. At this point the fuel air mixture is ignited introducing a large amount of heat, ΔQ_H into the cylinder with a corresponding large increase in pressure to 3. From 3 to 4 the high pressure heated combustion products are allowed to expand against the piston delivering work to the crankshaft of the engine. From 4 to 1 the exhaust valve opens and any excess heat ΔQ_c leaves the cylinder and the pressure is returned to the original atmospheric pressure. The area inside of this closed curve equals the work done by the engine. ΔQ_H is the heat that enters the engine and ΔQ_C represents the heat that the engine. As with all heat engines, the first law of thermodynamics says that the difference between ΔQ_H and ΔQ_C will equal the work extracted from the engine. The second law of thermodynamics demands that the engine will only operate if heat flows from a high temperature source (the exploding fuel air mixture) to a low temperature source (the exhaust into the environment.)

What makes the most efficient engine?

The efficiency of any heat engine will be the work produced by the engine, **W,** divided by the heat introduced into the engine from the high temperature source, **ΔQ_H.** Since ΔQ_C is lost to the environment, only ΔQ_H is of interest. Designing the most efficient engine requires an understanding of how to get the most out of the heat put into the engine and minimizing the heat that must be wasted in the exhaust. It would be nice if we could design an engine that would not waste any energy in the exhaust. But the second law of thermodynamics demands that we can't have heat flow through the engine unless we have a lower temperature sink to which the heat energy can flow. So the question of engine efficiency reduces to: What is the maximum work that can be extracted from an engine operating between a given high temperature source and low temperature sink? Historically it is surprising to learn that this problem was solved before James Watt improved the efficiency of the steam engine and even before the kinetic molecular theory was understood. In 1824 Sadi Carnot published an abstract paper that addressed this problem without even considering the mechanical details of the steam engines of his day. His answer (that had to be rediscovered almost a half a century later) was that the most efficient engine must be a <u>reversible</u> engine. That is, given heat sources of two different temperatures, the most efficient engine operating between these two sources could equally well work as a refrigerator operating between these two sources. Let's take an abstract look at an engine and a refrigerator:

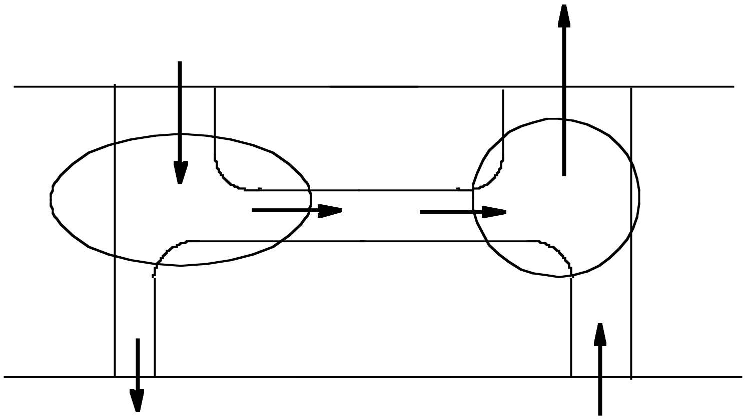


In the diagram on the left the circle represents an engine and on the right the circle represents a refrigerator. In the engine the heat flows in from the high temperature source, work goes out and the heat left over flows into the low temperature source.



With the refrigerator, work is put into it and it drives heat from the low temperature source to the high temperature source. (Students find the details on how a refrigerator works to be very interesting. These details can be found on the web or in any good college physics text.) The first law of thermodynamics demands that the difference between the heat extracted from the high temperature source and the heat rejected to the low temperature source will exactly equal the work output from the engine. A <u>reversible</u> engine could be operated as a refrigerator. The perfectly reversible engine, when operated as a refrigerator, would require the same amount of work put into the refrigerator to pump the same heat difference from the low temperature source to the high temperature source. That is, run frontward or backward, as an engine or a refrigerator, the same heat difference would produce the same work <u>output</u> when run as an engine <u>or</u> require the same work <u>input</u> when run as a refrigerator.

At last we get to the argument that says the most efficient possible engine operating between two given temperatures must be a perfectly reversible engine. First imagine there is an engine that is even <u>more</u> efficient than a perfectly reversible engine.



This super engine is represented with the oval in the diagram on the right. Since the super engine is more efficient than the reversible engine, (now operating as a refrigerator), less heat will be extracted from the high temperature source by the super engine to produce the same amount of work output to run the refrigerator. This means less heat will pass from the high temperature source through the super engine than will be driven from the low temperature source to the high temperature source by the "less efficient" reversible engine. However, this would violate the second law of thermodynamics! The overall heat transfer would be from low temperature to high temperature, entropy would be decreased. Since this violates a basic law of physics, the super engine is impossible!

Computing the greatest possible energy that can be extracted between two different temperature sources.

Now that we know that the most efficient engine operating between two different temperatures is a reversible engine, we can compute the maximum possible efficiency we can expect from any engine operating between these two temperatures. When a reversible engine completes a cycle, the change in entropy is zero. (More details on how such an ideal engine, called a Carnot engine, operates, will not be discussed here but again, such details can be found on the web or in any introductory college physics text.)

Since entropy does not change, $\mathbf{Q_H/T_H = Q_L/T_L}$ or $\mathbf{Q_H/Q_L = T_H/T_L}$

The efficiency will be the work produced by the engine divided by the heat removed from the high temperature source, or efficiency = $\mathbf{W/Q_H}$

The work produced by the engine must be the difference between the heat extracted from the high temperature source and the heat delivered to the low temperature sink, or:

$\mathbf{W = Q_H - Q_L}$ so efficiency = $\mathbf{(Q_H - Q_L)/Q_H = 1 - Q_L/Q_H}$

Since the engine is reversible in one complete cycle entropy will be same so we can use the first equation above and the maximum possible efficiency of any engine operating between two different temperatures will be:

Efficiency = $\mathbf{1 - T_L/T_H}$ or as a percent: = $(100)\mathbf{(1 - T_L/T_H)}$

The above equations describe the maximum possible efficiency of any heat engine. Since a perfectly reversible heat engine can never be achieved in practice, all heat engines will have less efficiency than will be computed in the above equations. Notice also, that the greater the difference in temperature between the high temperature source and the low temperature sink, the greater the efficiency of the engine. Many practical engines such as the gasoline engine in a modern automobile will rarely have an efficiency of greater than 20%. Some of the most efficient steam turbines used in electrical generating plants will have efficiencies of around 40%.

Finally, students often confuse efficiency with power. An engine can be very efficient yet not powerful and vice versa. Efficiency is the ratio of the work the engine puts out to the energy introduced into the engine from the high temperature source (such as the exploding gasoline air mixture in a gasoline engine). Power is the work the engine can produce in a given amount of time. Efficiency is usually measured as a percent. Power can be measured in watts, kilowatts, horsepower, etc.

In the future, the most efficient engines will probably operate between very high temperature differences and will seem more like engines that could be operated backward as refrigerators.