

## ENERGY IV

### EFFICIENCY OF HEAT ENGINES

#### HEAT ENGINES

A heat engine is a device that converts thermal energy, or “heat”, to mechanical energy. While mechanical energy can be completely converted to thermal energy, the reverse is not true. While experience indicates, as we have said, that energy is neither gained or lost when change occurs (energy is *conserved*), there is a “directionality” to change that favors conversion to thermal energy.

#### *Evidence for directionality*

We see in our everyday life lots of evidence for directionality. Consider those old movies of early attempts to fly. The device lumbers along, maybe gets off the ground, and then falls and smashes into a million pieces. We can easily tell whether the movie is being run in the forward direction or in the reverse direction. We can immediately sense the “directionality” of the change. Race cars do not unburn and unsmash and then race around the track, backwards.

#### *Cause of directionality*

The common feature of directional processes is the conversion of ordered, *coherent*, energy into disordered, or *incoherent*, energy. While the total energy is conserved, the nature of some of the energy has changed from coherent to incoherent. This is easy to see in the everyday examples of change just presented, but it is not so obvious when the changes take place at the atomic and molecular level. Nevertheless, when we realize that “heat”, or thermal energy, is the outward manifestation of the random, disordered, or incoherent motion of atoms and molecules we can understand why heat cannot be *completely* converted into coherent energy. Just as the airplane and the race cars cannot reassemble themselves, so heat cannot completely reorganize itself into coherent energy.

#### **Efficiency of a heat engine**

As we said, a heat engine is a device that converts thermal energy to mechanical energy. To be *useful*, a heat engine must be self-sufficient; a heat engine cannot require energy from another source. Whatever a heat engine does must be done entirely with and by the heat that is put into it. Being self-sufficient, then, a heat engine must use some of the incoherent heat energy that is put into it to convert the rest of the incoherent energy to coherent

mechanical energy. The heat put in cannot be *completely* converted to mechanical energy. Only a fraction of the heat put in can be converted to mechanical energy by the heat engine. This fraction is called the *efficiency* of the heat engine.

At this point we know that the fraction will be less than 1; the efficiency will be less than 100%.

*What determines the efficiency of a heat engine?*

The French engineer Sadi Carnot has been given the credit for first answering this question. Mendoza describes the situation in this way.

*“The problem occupying Carnot was how to design good steam engines. Steam power already had many uses - draining water from mines, excavating ports, forging iron, grinding grain, and spinning and weaving cloth - but it was inefficient. The import into France of advanced engines after the war with Britain showed Carnot how far French design had fallen behind. It irked him particularly that the British had progressed so far through the genius of a few engineers who lacked formal scientific education. British engineers had also accumulated and published reliable data about the efficiency of many types of engines under actual running conditions; and they vigorously argued the merits of low- and high-pressure engines and of single-cylinder and multi-cylinder engines.”*

*Setting the stage*

We have said many times that the presence of energy is indicated by the ability to make something move, or the ability to do *work*. More recently we have identified “heat” with thermal energy. There are, then, only two ways by which the energy of something can be increased: by doing work on it or by adding heat to it. Similarly, there are only two ways by which the energy of something can be decreased: by having it do work on something else, or by allowing it to lose heat.

Applying these ideas to the steam of a steam engine we can say:

*“There are only two ways by which the energy of steam can be increased: by doing work on it or by adding heat. Similarly, there are only two ways by which the energy of steam can be decreased: by having it do work on something else, or by allowing it to lose heat.”*

*Behavior of gases*

Before we continue we need to remind ourselves of some of the ways in which

gases behave. For example, gases get hot when they are compressed. Remember how the hand pump for your bicycle tire got hot after you pumped a few strokes. You put work into the gas when you compressed it, and some of the work shows up as heat.

The reverse of is also true. Gases cool when they expand. That's why when humid air is blown over the mountain it rains on the other side. The air rises as it is pushed against the mountain; the pressure becomes less as the air goes up and so the air expands and cools; the water vapor condenses; it rains.

### *An analogy*

There is an analogy between determining the height of a building and determining the efficiency of a heat engine. So long as the method is not mistaken it does not matter what method is used; the answer is independent of the method. Although Carnot's example is that of a specific steam engine, the result is universally true. The Carnot efficiency is the best that can be achieved with any heat engine.

### *Carnot's analysis of a steam engine*

There are two halves to the Carnot process. The first half is the part where the engine does work, where the engine does the "pushing" for which it was built. The second half is the part during which the engine gets back to the state from which it started its push. The engine thus works on a *cycle*. The first part of the cycle is the work stroke, and the second part of the cycle is the recovery stroke. In order for an engine to be useful it must be capable of delivering repeated pushes; a useful engine operates on a cycle.

### *The work stroke*

For Carnot the work stroke consists of two parts.

In the first part of the work stroke the steam expands and delivers its push; the steam does work. In order that the temperature of the expanding steam not fall heat energy is delivered to the steam in such a way that the temperature of the expanding steam is maintained at its initial, "high" temperature.

In the second part of the work stroke the steam continues to expand and to deliver more of its push, but the temperature, and thus the pressure, of the steam is allowed to fall. When the temperature of the steam has fallen to the "low" temperature, the work stroke is done. It is now time for the recovery stroke.

### *The recovery stroke*

The recovery stroke *cannot* be merely the reverse of the work stroke. If the recovery stroke were the reverse of the work stroke the recovery stroke would undo the effect of the work stroke. Nothing would have been accomplished. The first part of the recovery stroke is, instead, compression of the steam at the “low” temperature in such a way that the temperature of the steam undergoing compression does not rise; heat must be removed from the steam during this compression.

The second part of the recovery stroke is further compression to the initial pressure of the steam. Heat is not removed during this compression and the temperature of the steam rises to the original, “high” temperature. The steam is now ready for a second cycle.

When the recompression is done at the lower temperature less energy is used for compression than was delivered in expansion. There will be a net gain in work done by the engine, which is the whole point of building an engine.

### *The efficiency of a heat engine*

Carnot showed for his heat engine, and therefore for any heat engine, that the maximum possible work that can be gotten from a given amount of fuel depends *only* upon the “high” and “low” temperatures.

$$\text{maximum possible efficiency} = \frac{\text{work}_{\text{out}}}{\text{fuel}_{\text{in}}} = \frac{T_{\text{high}} - T_{\text{low}}}{T_{\text{high}}}$$

Carnot saw a heat engine as analogous to a waterfall. In a heat engine the “heat”, or “caloric”, or “igneous fluid”, falls from a high temperature to a low temperature, the engine capturing work as the heat falls, just as a paddle wheel captures work as the water falls.

In analogy to a waterfall Carnot correctly saw that the larger the difference in temperatures, the larger the “heat fall”, the more work could be done. Carnot did not realize, as we realize, that there is less heat at the bottom of the “heat fall” because some of the heat has been converted to work.

When the temperatures are expressed as absolute temperatures, in Kelvins, a modern expression of the Carnot efficiency of a heat engine could be this.

$$\text{maximum possible efficiency} = \frac{\text{work}_{\text{out}}}{\text{heat}_{\text{in}}} = \frac{K_{\text{high}} - K_{\text{low}}}{K_{\text{high}}}$$

*Comments on the Carnot efficiency*

First, it is quite clear that the *greater the difference* between the “high” and “low” temperatures the greater will be the efficiency of the heat engine.

What is equally true, but not so obvious, is that *for a given difference* between “high” and “low” temperatures the *lower* the “high” temperature the greater will be the efficiency of the heat engine.

For example, a heat engine operating between 600 K and 300 K will have an efficiency of  $(600 - 300)/600 = 0.50$ , or 50%, while a heat engine operating between 500 K and 200 K will have an efficiency of  $(500 - 200)/500 = 0.60$ , or 60%. It is as if a 100 foot waterfall at sea level will produce more work than a 100 foot waterfall up in the mountains! We will return to this phenomenon later.

You can also see that the efficiency with which heat is turned into work can approach 1 only as the “low” temperature approaches absolute zero, a possibility unattainable in practice. You can also see that if the “high” and “low” temperatures are the same no heat will be converted to work. Finally, the efficiency of a heat engine is *independent* of the identity of the working fluid, be it steam, air, or any other vapor or gas, and the efficiency is also *independent* of the type of engine, whether it involves pistons or turbines. The efficiency of a heat engine depends *only* upon the “high” and “low” temperatures.

*One more time*

The efficiency of a heat engine is the fractional part of the heat put into the heat engine that is converted to work. The part of the heat put into the heat engine that is *not* converted to work is the heat that is removed during the return stroke, or recompression.

This heat is removed so as to keep the temperature from rising during the recompression. If this heat is not removed, the recovery stroke will simply undo the effect of the work stroke.

Carnot showed that the maximum possible value of this fraction is completely determined by the temperature of the source of high temperature heat, and the temperature of the sink into which the low temperature heat is discharged.

Carnot published his work on this subject as a book in 1824. The title of the book, in translation, was Reflections on the Motive Power of Fire, and on Machines Fitted to Develop that Power.

### *Electrical generating plants*

The typical electrical generating station in the US is a steam plant. The steam is generated and kept hot by heat produced from either the burning of coal, the burning of oil, the burning of natural gas, or from the fission of U-235.

Other than differing in the source of heat, all these power plants work in the same way. The superheated steam at high pressure is passed into a series of turbines, and as the steam rotates the turbines, producing work, the steam expands and cools.

At the exit of the “low pressure turbine” the steam is condensed to water. Two important things are accomplished by condensation of the steam vapor to liquid water. First, the exit pressure of the low pressure turbine is reduced, thus increasing the efficiency of the low pressure turbine. Second, the “working fluid”, steam, is greatly reduced in volume; it has, in effect, been compressed. It is now ready to be reheated by the boiler to superheated steam at high pressure.

### *The energy trail*

The operation of an electric generating station can be summarized by following the “energy trail.” The original chemical energy of the fossil fuel, or the nuclear energy of the U-235, is converted to the thermal energy of the steam.

Some of the thermal energy of the steam is then converted to the mechanical energy of the turbine and then to electrical energy by the generator. More thermal energy of the steam is then removed by condensation of the steam to water, which has the effect of compressing the working fluid.

The circulating cold water that cools and condenses the steam is, of course, warmed. If the circulating water has been drawn from a river it is then returned, warm, to the river, downstream from where it was taken in from the river.

Sometimes “cooling towers” are used to cool the circulating water so that the circulating water can be reused. The cooling towers work by evaporative cooling with still another portion of water. We will return later to evaporative cooling.

Overall, as we will see next, less than half of the chemical energy that enters the generating station is converted to electrical energy. More than half of the

chemical energy that enters the generating plant leaves as heat.

*The Carnot efficiency of an electrical generating plant*

The “Carnot efficiency” is the maximum possible efficiency for a heat engine. The Carnot efficiency is for an “ideal” or “perfectly designed” heat engine that is operated under impractically ideal conditions. All real heat engines, therefore, will have an actual efficiency that is less than the ideal efficiency. It is useful, however, to estimate this impossible standard. This can be done by estimating the “high” and “low” temperatures between which the heat engine is working.

The temperature of the superheated steam of a coal-fired electrical generating plant is about 1000 °F, or about 550 °C, or about 823 K. The temperature to which the steam can be cooled is about 95 °F, or 35 °C, or 308 K. The Carnot efficiency of the coal plant would then be about 63%

$$\text{Carnot efficiency, coal} = \frac{\text{work}_{\text{out}}}{\text{heat}_{\text{in}}} = \frac{823 \text{ K} - 308 \text{ K}}{823 \text{ K}} = \frac{515 \text{ K}}{823 \text{ K}} = 0.63$$

In a nuclear powered electrical generating plant the temperature of the steam is only about 570 °F, or 300 °C, or 573 K since superheating is not allowed in a nuclear steam generating plant. We can estimate that the corresponding Carnot efficiency of the nuclear plant would be about 46%.

$$\text{Carnot efficiency, nuclear} = \frac{\text{work}_{\text{out}}}{\text{heat}_{\text{in}}} = \frac{573 \text{ K} - 308 \text{ K}}{573 \text{ K}} = \frac{262 \text{ K}}{573 \text{ K}} = 0.46$$

*The overall efficiency of an electrical generating plant*

The actual efficiency of an electrical generating plant will be less than the ideal, or Carnot, efficiency. Fossil fuel plants can achieve 36-38% efficiency, and nuclear plants can reach 34-36% efficiency. Thus only a little more than one third of the heat energy put in is converted to electrical energy for distribution, assuming 100% efficiency of the generators. Almost two thirds of the heat energy put in is passed through and lost.

*How can efficiency be improved?*

Since the Carnot efficiency is determined by the “high” and “low” temperatures, the Carnot efficiency can be improved either by raising the “high” temperature or by reducing the “low” temperature. Elevation of the “high” temperature is limited by the properties and strengths of materials. Reduction of the “low” temperature is limited by the local climatic conditions.

## REFRIGERATORS

A refrigerator is device that moves heat from something cold to something hot. A refrigerator is a heat engine run in reverse, just as an electric generator is an electric motor run in reverse.

### *Evaporative cooling*

The crucial effect needed for an effective and practical refrigerator is absorption of heat energy by evaporation of a liquid, or *evaporative cooling*. Anyone who steps out of the shower or out of a swimming pool experiences evaporative cooling. When water evaporates from your skin it is the faster water molecules that escape into the air. If the faster molecules are selectively lost the remaining molecules are, on the average, slower and therefore of lower kinetic energy. We sense this loss of thermal energy of the water on our skin as a cooling effect. The temperature of the remaining water is, in fact, lowered by evaporation.

Evaporative cooling is also the mechanism by which water kept in unglazed clay pots or canvas bags is cooled. The water that leaks through evaporates, and the water that remains is thus cooled.

### *It's not the heat; its the humidity*

We are normally cooled by evaporation of water from our skin. Evaporative cooling actually operates all the time, not just after a shower or a swim. In order for net evaporation to take place, and thus for cooling to occur, the reverse process, *condensation*, must be relatively slow. If the air is “dry”, that is, if the water vapor content of the air is low, if the *humidity* of the air is low, evaporative cooling is effective. This is why we are more comfortable when the humidity is low.

On the other hand, when the humidity is high, the rate of condensation of water vapor onto our skin is pretty close to the rate of evaporation; the net rate of evaporation is small, and the cooling effect is small. No matter that we sweat, evaporation is slow. We go inside, where the humidity, as well as the temperature, is lower.

We use the opposite of this effect to our advantage in the winter. When we humidify the air in our house in the winter we feel warmer at the same temperature because the evaporative cooling of our skin is less at higher humidity.

### *Refrigerators*

A refrigerator, as well as a heat engine, works on a cycle. The first part of the cycle takes place inside the refrigerator. The first part is evaporation and expansion of the refrigerant, the “working fluid”. Both vaporization and expansion cool the refrigerant, and the cold vapors of the refrigerant circulate through coils inside the freezing compartment of the refrigerator. As heat is absorbed by the cold vapors of the refrigerant the air inside the refrigerator and the vapors of the refrigerant come to the same temperature, the temperature of the inside of the refrigerator.

The now relatively “warm” vapors of the refrigerant pass outside the refrigerator to the compressor where the vapors are compressed and liquefied. Compression, as we have mentioned before, will raise the temperature of the vapors, but the pressure after compression is high enough to force the vapors to condense even though they are hot. The heat released by compression and condensation is transferred to the room. The “cold” liquid refrigerant now reenters the freezing compartment of the refrigerator, starting a new cycle.

### *More about refrigerators*

A practical refrigerant must have special qualities. It must have a high “latent heat of vaporization”, so that it can absorb lots of heat as it evaporates, and release lots of heat as it condenses.

The refrigerant must also undergo liquefaction under moderate pressure even when the temperature is well above room temperature.

Ammonia gas is an excellent refrigerant, but ammonia is also toxic. The incidence of fatal accidents from failures of ammonia refrigerators was one of the motivations to develop non-toxic refrigerants such as the R12 refrigerant, dichlorodifluoromethane.

The noise you hear when the refrigerator is “on” is from the compressor.

### *Air conditioning*

An air conditioner is a “refrigerator” that operates between a room and the out-of-doors. As the air of the room is drawn over the cooling coils of the air conditioner the air is cooled to a temperature below the *dew point* of the air, the temperature at which the relative humidity of the air is 100%. Air below the dew point is supersaturated with water vapor, and when the temperature of the air is below the dew point liquid water will condense from the air. When the cooled air is returned to the room both its temperature and its humidity will be less than that of the air in the room.

### *Efficiency of refrigeration and air conditioning*

Refrigerators and air conditioners move heat from a cooler place to a hotter place. The refrigerator moves heat from the inside of the refrigerator to the room. The air conditioner moves heat from the room to the out-of-doors. In both cases the heat released to the hotter place is the sum of the heat removed from the cooler place plus the heat equivalent of the work done by the compressor. Thus, overall, there is an increase in thermal energy that accompanies refrigeration and air conditioning.

The *efficiency* of a refrigerator or an air conditioner can be expressed as the fraction that the heat removed from the colder place bears to the total heat released to the hotter place, or the surroundings. The heat released to the surroundings will be the sum of the heat removed plus the heat equivalent of the work done by the compressor. The efficiency will be less than 1.

$$\text{refrigerator efficiency} = \frac{\text{heat}_{\text{removed}}}{\text{heat}_{\text{released}}}$$

*Which way does heat “flow”?*

We’re told that heat flows from something hotter to something cooler. Is that still true for refrigerators and air conditioners? Yes, it is still true for refrigerators and air conditioners.

For the refrigerator, the vaporized and expanding refrigerant is colder than the inside of the refrigerator. Heat flows from the inside of the refrigerator into the refrigerant. For the refrigerator, the compressed and liquefied refrigerant is hotter than the room. Heat flows from the compressed and liquefied refrigerant into the room.

For the air conditioner, the vaporized and expanding refrigerant is colder than the room, and, for the air conditioner, the compressed and liquefied refrigerant is hotter than the out-of-doors. Heat flows first from the room into the refrigerant and then from the refrigerant into the out-of-doors.

### **Science**

Science is figuring out the rules of Nature. The great advances of science are the discoveries of new rules of great generality.

*Observational rules*

Some rules are summaries of observed behavior. The rules for planets are rules of this type. Johannes Kepler is given the credit for “discovering” these rules. The planets were following the rules all the time, but we did not know it until Kepler pointed it out.

The first rule is: each planet appears to follow an elliptical orbit.

The second rule is: the imaginary line that connects the planet to the sun appears to sweep out the same area during the same period of time. That is, the planets appear to move a little more slowly when they are a little farther from the sun. The third rule is that the time required for each planet to go around once depends upon the distance of the planet from the sun. The farther away the longer it takes.

There was a tiny discrepancy, but these are the general rules.

### *Explanatory rules*

Other rules are explanations conceived to account for, or “explain”, observed behavior. Isaac Newton had the genius to propose that whatever it is that pulls the apple toward the earth keeps the moon and the planets in their orbits. He proposed that a “gravitational” force exists between all massive bodies, a force that is proportional to the product of the masses of the bodies, and inversely proportional to the square of the distance of their separation. Although we cannot “observe” gravity we know gravity by its effect.

### *Alternative explanations*

Frequently, even typically, more than one explanation is offered, and then there arises the problem of *choice*. In general, given equal explanatory power, the explanation that leads to the best predictions finally endures. This “method” is sometimes called the “destructive testing of hypotheses”, or “guess and test”, or, by Peter Medawar “conjecture and refutation”.

### *The rules of chemistry*

The two examples of scientific rules just given are from the realm of physics. Chemistry also has its rules, and it is the job of chemists to find them.

One of the most basic rules of chemistry is that matter cannot be subdivided indefinitely. There is a least amount of matter. There is an “uncuttable” amount of matter. Matter exists as atoms. Matter is quantized.

Chemistry is interesting because there is quite a variety of atoms. Ninety one different kinds occur in Nature (element number 43 does not), and most

elements occur in more than one form, as a mixture of isotopes.

Why do we believe that this is a rule of Nature? Richard Feynman knows. “How do we *know* there are atoms? By one of the tricks mentioned earlier: we make the *hypothesis* that there are atoms, and one after another results come out the way we predict, as they ought to if things *are* made of atoms.”

### **The Rules of Energy**

We have seen the two most important rules of energy (there is a third). These rules are very general; they appear to apply to everything.

#### *The first rule of energy*

The first rule of energy is that *energy is conserved*. Energy never disappears; energy just changes form. This implies that the total energy of the universe is constant.

Another way to say the same thing is to say that a certain amount of heat is equivalent to a certain amount of work. If this were not so there could be an endless source of heat, and total energy of the universe could increase.

Yet another way to say the same thing is to say that there are only two ways to increase the energy of something: do work on it or warm it. As this is done the energy of the donor of the work or heat will decrease by the exactly the same amount. There will be no change in the total amount of energy.

#### *The second rule of energy*

The second rule of energy is that all other forms of energy eventually turn into thermal energy. While energy only changes form, less coherent forms are always favored.

These two rules are observational rules. They are based on experience. Experience has been completely consistent. There have been no exceptions.

At this time the United States Patent and Trademark Office refuses to consider a patent application for a perpetual motion machine without submission of a working model.

*“With the exception of cases involving perpetual motion, a model is not ordinarily required by the Office to demonstrate the operability of a device. If operability of a device is questioned, the applicant must establish it to the satisfaction of the examiner....”*

A device that breaks the first rule is called a perpetual motion machine of the first kind. A device that breaks the second rule is called a perpetual motion machine of the second kind.

### *Rudolph Clausius*

The most famous statements of these two rules were made by Rudolf Clausius in 1865. He reached these conclusions from his consideration of Carnot's analysis of heat engines:

*“Die Energie der Welt ist Konstant. Die Entropie der Welt strebt einem Maximum zu.”*

*“The energy of the world is constant. The entropy of the world tends toward a maximum.”*

The first sentence recognizes the conservation of energy. The second sentence recognizes the directionality of change.

### *Entropy*

Entropy, joules per kelvin, changes when heat is produced or transferred. The change in entropy depends upon the amount of heat that is produced or transferred, and the temperature at which the production or transfer takes place.

If, say, 6,000 joules of heat are transferred at 600 K, the change in entropy is 6,000 joules divided by 600 K, or 10 joules per kelvin, or 10 entropy units. The acceptor of the heat will gain 10 entropy units, and the donor of the heat will lose 10 entropy units.

If, say, 3,000 joules of heat are transferred at 300 K, the change in entropy is also 10 entropy units: 3,000 joules divided by 300 K equals 10 entropy units.

### *Entropy changes in a Carnot engine*

In a Carnot engine the transfers of heat take place during the first half of the work stroke and during the first half of the recovery stroke.

Let's suppose the engine absorbs 6,000 joules of heat from a source of heat at 600 K. The engine thus gains 10 entropy units, and the heat source at 600 K loses 10 entropy units. The second half of the work stroke does not involve the transfer of heat and so there is no change in entropy during this expansion.

We could say that during the work stroke the engine has “borrowed” 10 entropy units from the surroundings. Since to be useful the engine must operate in a cycle, and so this entropy debt must be repaid during some other part of the cycle.

The entropy debt is repaid during the first half of the recovery stroke of the engine. This time the transfer of heat takes place at, say, 300 K. However, at 300 K only 3,000 joules of energy need be transferred from the engine to the surroundings to pay off the entire debt: 3,000 joules divided by 300 K is 10 entropy units! Thus if the engine is able to convert 3,000 joules of the 6,000 joules of heat absorbed at 600 K to work the engine will still have enough heat to repay the debt at 300 K. This corresponds to an efficiency of 50% for the conversion of heat absorbed to work performed.

If the debt had been repaid at 1 K, the repayment would have been only 10 joules. The efficiency would then have been 99.8%.

### *Higher Carnot efficiency for a lower “high” temperature*

We can now see why for a *given difference in temperature* the Carnot efficiency will be higher for a lower “high” temperature.

Imagine a second Carnot engine, this one operating between 500 K and 200 K. The second engine absorbs 5,000 joules at 500 K, or “borrows” 10 entropy units at 500K. It then repays this entropy debt at 200 K, needing only 2,000 joules to do so. That means that 3,000 joules of the original 5,000 joules could have been converted to work in the second engine; an efficiency of 60%.

### *Why do we need entropy?*

We need entropy to understand directionality.

The first rule of energy says that only those processes in which energy is conserved can *possibly* occur.

The second rule of energy says that of those possible processes only those that are accompanied by an increase in entropy can *actually* occur.

### *An example*

We would not be surprised to see an ice cube melt after it is dropped into a cup of water at, say 5 °C, all of this happening in a perfectly insulated container.

We would, however, be surprised to see the reverse of this. If the container

really is perfectly insulated the first rule of energy will be followed whether the ice cube melts or forms. So what is it that accounts for the directionality of this change? The answer is that the melting direction is the direction of increasing entropy. Melting of the ice cube is more likely than freezing of some of the water.

### *The explanation of directionality*

Directionality is related to probability. If all possible outcomes are equal in energy, the most probable outcomes will predominate.

### *Another example*

Consider two dice. Place them on the table so that the two have the same face up. Now pick them up and throw them out on the table. If the table is flat, each of the 36 possible outcomes will be equal in energy. Probability, however, favors an outcome in which the faces on the two dice are different. There are 6 ways to have the two faces the same, but 30 ways to have them different.

Do the other experiment. Place the two dice on the table with different faces up. Pick them up and throw them back onto the table. Probability, again, favors an outcome in which the faces on the two dice are different. It doesn't matter where you start; the probabilities of the outcomes are the same.

### *Back to the ice cube experiment*

In the ice cube experiment it is overwhelmingly more probable that the ice cube will melt than that water at, say, 1 °C, will produce an ice cube as it warms to 5 °C. Remember, the energy remains constant because the entire process, whichever it is, takes place in a perfectly insulated container.

### *Statistical mechanics*

Statistical mechanics is the scientific specialty that considers the question of directionality. The approach, in general, is to consider the energetic possibilities, usually determined by the methods of quantum mechanics, and then to determine the relative probabilities of these energetic possibilities. This combination of energy factors and probability factors determines the outcome of any process.

Statistical mechanics and quantum mechanics are without a doubt two of the greatest conceptions of the human mind. James Clerk Maxwell (1831), Ludwig Boltzmann (1844), and, independently, the American physical chemist J. Willard Gibbs (1839) were among the most important developers

of statistical mechanics.

Max Born (1882), Werner Heisenberg (1901), P. A. M. Dirac (1902), and Erwin Schrödinger (1887), were among the most important developers of quantum mechanics

*But what about Einstein?*

I expect that more than once you've wondered "But what about Einstein?" Didn't he have something to say about, for example, the conservation of energy? Yes, he did. He went much further, saying that energy and mass are different forms of the same thing, and that it is the total of mass plus energy that is conserved.

In all processes that we have considered that do not involve nuclear changes the change in mass is insignificant and undetectable. For example, in the chemical reaction of 2 grams of hydrogen with 8 grams of oxygen to give 10 grams of water and 241 750 joules of energy we rightfully neglect the 0.000 000 003 2 grams of mass that are "lost".

In nuclear processes, however, the fraction of the starting mass that is converted to energy can be ten million times greater. Thus for 10 grams of starting material for a nuclear reaction the mass that is converted to energy could be as much as 0.032 grams.

*Einstein and Newton*

Einstein also went far beyond Newton. Newton assumed, as we do in everyday life, that space and time are different. Einstein's theory of relativity treats the three dimensions of space and the one dimension of time as four views of the same thing. In this way Einstein accounts for the measured speed of light in a vacuum being the highest speed possible and the same for all observers, no matter what their relative velocities might be.

The assertion that nothing can go faster than the speed of light in a vacuum is accounted for by saying that as the moving body is pushed to go faster and faster its kinetic energy increases. This increase in energy shows up, however, as an increase in mass. As the velocity of the moving body approaches that of the speed of light in a vacuum its mass increases to the point that the accelerating force can't make it go any faster; it's going as fast as it can; it's going at the speed of light.

This is another manifestation of an equivalence between mass and energy.

*Can anything ever go "faster than the speed of light"?*

It is interesting to know that it is possible for something to “go faster than the speed of light”. The speed of light in water is only about 3/4 of the speed of light in a vacuum, so there is plenty of “room” for something to go faster than the speed of light in water but not faster than the speed of light in a vacuum.

### *Cherenkov radiation*

One manifestation of this is the blue glow that can be seen around spent fuel rods from nuclear reactors when the fuel rods are stored in water. Some of the  $\beta$  particles, electrons, emitted by nuclei of the fission products in the spent fuel rods come out of the nucleus at a speed greater than the speed of light in water. As the electrons are slowed by water some of the energy lost by the electrons shows up as light in the “blue” end of the electromagnetic spectrum. The blue glow is called *Cherenkov radiation*.

### *Relativity in everyday life*

Newton’s concept of universal gravitation accounts for all the features of planetary motion, except for one: a portion of the “advance of the perihelion of Mercury” equal to 0.43 second of arc per century. At the end of his paper on relativity Einstein writes:

*“Calculation gives for the planet Mercury a rotation of the orbit of 43 seconds of arc per century, corresponding exactly to the astronomical observation ...; for the astronomers have discovered in the motions of the perihelion of this planet, after allowing for disturbances by the other planets, an inexplicable remainder of this magnitude.”*

The fact that Einstein’s concept of relativity was able to account for this “discrepancy” was a persuasive indication of its validity.

The other persuasive indicator was confirmation of a prediction concerning the ability of the sun to “bend” light.

When it comes to everyday life, however, including the exploration of “space”, Newtonian mechanics are entirely satisfactory. Just as we can ignore the mass changes that accompany chemical reactions we can also ignore relativistic corrections for the motions of large objects.

### *Relativity in atomic life*

But it is also true at the atomic and sub-atomic scale that “relativistic effects” cannot be ignored.

### *The rules of energy in everyday life*

The rules of energy apply to everything in everyday life. The most common examples are those in which potential energy turns into kinetic energy. Something falls; something is pushed. One kind of energy turns into another. But eventually the motion stops, or appears to stop. Where did the energy go? It has turned into heat, thermal energy, the unseen, random, incoherent motion of atoms and molecules. This change can never undo itself.

For something to happen there must be, overall, an accompanying increase in entropy.

### *Entropy and life*

Before we end, here is a brief comment about the “natural processes” of life. The way that the low entropy of a living system is maintained is for the living system to take in materials of low entropy (food) and to convert these to products of high entropy. Thus, for the universe as a whole, the natural processes of life are accompanied by an increase in entropy. It is as if a heavy weight is being used in a pulley system to raise a lighter weight; the entropy producing metabolism of food pulls along all of the entropy consuming processes of life.

This has been said far more eloquently by Szent-Gyorgyi:

*“It is common knowledge that the ultimate source of all our energy and negative entropy is the radiation of the sun. When a photon interacts with a material particle on our globe it lifts one electron from an electron pair to a higher level. This excited state as a rule has but a short lifetime and the electron drops back within  $10^{-7}$  or  $10^{-8}$  seconds to the ground state giving off its excess energy in one way or another. Life has learned to catch the electron in the excited state, uncouple it from its partner and let it drop back to the ground state through its biological machinery utilizing its excess energy for life processes.”*

## **Summary of Energy IV: Efficiency of Heat Engines**

### **Heat engines**

- A heat engine is a device that converts heat energy to mechanical energy
- The efficiency of a heat engine is less than 100%.
- The efficiency of a heat engine is the fraction of the heat absorbed that is converted to work.

- The maximum possible efficiency of a heat engine is determined by the temperature at which heat is absorbed, and the temperature at which heat is released
- The maximum possible efficiency of a heat engine is independent of the working fluid

### **Refrigerators**

- A refrigerator is a device that moves heat from something cold to something hot
- Evaporative cooling
- Refrigerators
- Air conditioning
- Efficiency of refrigeration and air conditioning

### **Science**

- Science is discovering the rules of nature
- Rules of nature: observational rules; explanatory rules
- The rules of chemistry
- The rules of energy: the first rule of energy; the second rule of energy
- The first rule of energy: energy is conserved
- The second rule of energy: directionality; thermal energy increases; entropy increases
- Entropy: energy per kelvin
- The most probable outcome will be the actual outcome
- The calculation of probabilities is done by statistical mechanics
- Entropy and life