# 12. The Law of Increasing Disorder

Before proceeding further, we need to discuss one additional universal law: the Law of Increasing Disorder. Although more subtle than the laws previously described, this law is just as important because it significantly limits our actions and capabilities. For example, proposed solutions to problems involving environmental pollution and the use of energy must take this law into account. The Law of Increasing Disorder explains impossibilities in some proposed solutions that otherwise seem possible.

## Irreversible Processes

Almost all of the spontaneous processes in nature proceed only in one direction; the reverse process does not occur if outside influences do not interfere. For example, an ice cube melts in a glass of warm water (Fig. 12.1). A rolling ball comes to rest. A ripe apple gradually decays. We never see an ice cube spontaneously form in a glass of warm water, a ball suddenly start rolling by itself, or a rotten apple become wholesome.

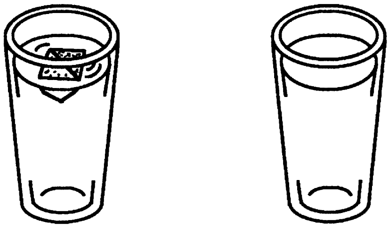

Figure 12.1. An ice cube in a glass of warm water. Which event occurs first if the system is left to itself? Why could the other not have been first?

Processes that spontaneously occur in one way but never in exactly the reverse way are called **irreversible** processes. A simple test of whether a process is irreversible is to imagine a movie of the process (Fig. 12.2). When the movie is run forward, the process is shown in the way that it actually occurs in nature. When the movie is run backward, however, the reverse process is shown. If running the movie backward shows a process that could not happen spontaneously, the original process is irreversible.

Irreversible processes present us with a puzzle. Why can they occur in one direction as time changes but not in the reverse direction? Some fundamental law must prevent such processes from reversing themselves.

Nothing in the laws we have discussed to this point explains why some events are irreversible. The laws of motion apply equally well to the reverse processes as they do to the originals. Energy could be conserved both ways. A melting ice cube cools the water in which it is placed. If the ice were to form again spontaneously, energy would be conserved by the remaining water becoming warmer, returning to its original temperature. In the case of the ball, the kinetic energy of the rolling ball is dissipated to thermal energy as the ball slows and eventually stops. The ball and the surface it rolls on are both warmer than before. If the ball were suddenly to start rolling again, its kinetic energy could presumably come from this thermal energy, the ball and surface becoming cooler as the ball rolls faster. All the other laws and principles can be accommodated in about the same way. None of them prevents any process from reversing itself. According to the laws we have studied, all processes should be reversible, yet most are not.

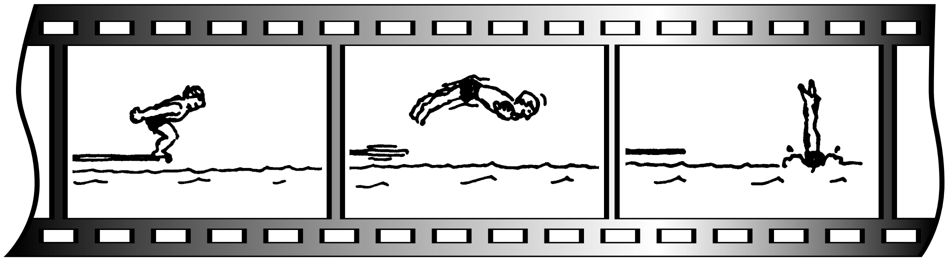

Figure 12.2. Which way does the film run forward? How do you know?

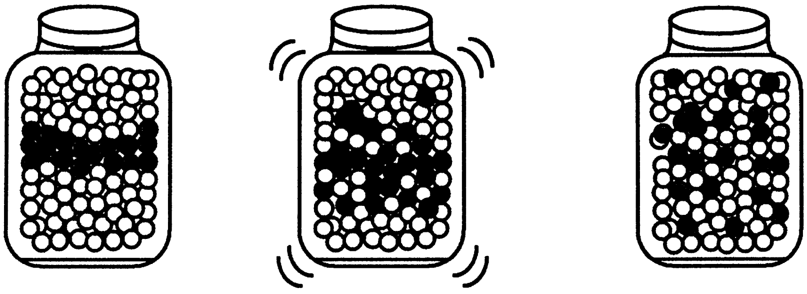

Figure 12.3. Shaking the bottle destroys the original order. How long must you shake before you restore order?

## Order and Disorder

An important clue regarding irreversible processes comes from consideration of the following example. Imagine a bottle partly filled with red and white sand that is separated into two distinct layers (Fig. 12.3). Suppose that someone shakes the bottle and mixes the colored sand. The boundary between the two colors disappears; the original ordered arrangement is destroyed and is replaced by a completely disorganized, random arrangement of sand grains. Further, no amount of shaking restores the sand to its original ordered arrangement. The process by which the sand is mixed is an irreversible process.

Why can't the sand be shaken back to its original configuration? One answer is that "order" has been lost and has been replaced by "disorder." Somehow the disorder of this system has been increased and cannot be reduced by more shaking. All irreversible processes have this same characteristic—disorder increases as the process occurs. Order never spontaneously increases in isolated systems. This suggests a fundamental law of nature that might appropriately be called the **Law of Increasing Disorder:**

> Changes occurring in natural systems always proceed in such a way that the total amount of disorder in the universe is either unchanged or increased. If total disorder is increased, the process is irreversible.

This law is usually known as the Second Law of Thermodynamics. (The Law of Conservation of Energy is known as the First Law of Thermodynamics.)

We can illustrate this law by considering once again the examples of irreversible processes we began this discussion with (Fig. 12.4). The loss of order that occurs in the decaying apple seems obvious. The molecules of which the apple is composed were originally arranged in an orderly array. The later arrangement seems disorganized, particularly in the last stages of decay when the materials are actually dispersed in the earth and atmosphere. Significant changes also occur on the molecular level—the complicated and highly organized carbohydrate molecules of the healthy apple break down into the simpler molecules of water and carbon dioxide.

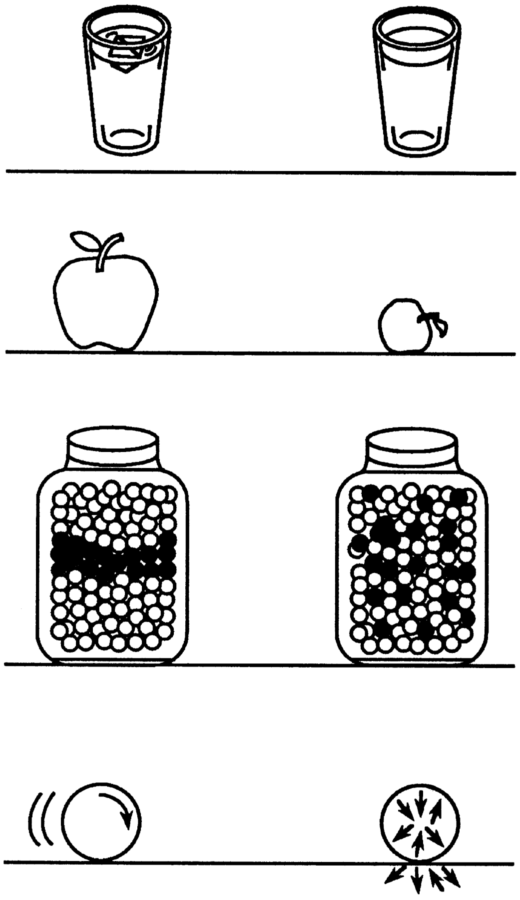

Figure 12.4. How is one arrangement in each case more organized than the other?

Sometimes we have to look more carefully to discern that the relative order and disorder in a system are changing. Consider once again the ice cube in a glass of warm water. The important clue here is the organization of energy in the system. The main difference between the ice and the water is that the molecules in the ice have less average energy than the molecules in the water. Thus, the energy in the ice and water combination is "organized" so that the molecules with less energy are mainly in one place (the ice cube) and the more energetic molecules are elsewhere (the water). As the melting proceeds, the molecules are mixed; fast and slow molecules are distributed throughout the system. The average energy is less than the average energy in the original water (but greater than in the ice cube), so the temperature of the water is cooler than before the ice melted. The original organization has been lost and cannot be put back together again. In some ways the ice cube and water are much like the layers of colored sand, except that the water molecules were originally separated on the basis of energy rather than color.

The organization associated with a ball rolling on a table is even more subtle. As the ball rolls, the velocities of its various parts are organized in a specific way. Each piece of matter revolves about the center of the ball in a regular, organized motion. After the ball stops, the total energy is the same as before. The pieces of the ball (and the table) are still moving, but the directions of the motion are random. Instead of being organized as before, the particles are moving in the completely disorganized patterns characteristic of thermal energy. Again, disorganization increases as the ball moves more slowly and eventually stops.

Scientists use a quantity called **entropy** to measure disorder. Elaborate rules for calculating and measuring entropy are available. Simply stated, high entropy implies a high state of disorder; low entropy implies a low state of disorder. In terms of entropy, the Law of Increasing Disorder may be stated as follows:

> Total entropy never decreases. It increases in irreversible processes and remains unchanged in reversible processes.

### Order and Energy

The study of the Law of Increasing Disorder was initiated by those interested in energy use in industry and transportation. They wondered why their steam engines, for example, had such low efficiency (about 10 percent). Why was it not possible to convert all of the internal energy of the steam into useful energy?

The answer is that forms of energy differ in the degree to which they are organized. We have already seen some examples of this. The energy in the rolling ball had more organization than the same amount of thermal energy that was present after the ball had stopped. The thermal energy associated with the ice cube and warm water had more order than did the same amount of energy after the ice cube had melted. There is a change in disorder in each case even though the amount of energy does not change.

Figure 11.5 shows the degree to which the various kinds of energy are organized. The macroscopic forms of energy—kinetic energy, gravitational potential energy, and electromagnetic potential energy—tend to be highly organized (or high-quality) forms of energy. Any of these can be transformed completely into one another or into one of the other energy forms. At the other extreme, most processes end up as thermal energy at a temperature about the same as the surroundings. Thus, ambient temperature thermal energy must be the most disorganized (or lowest-quality) form of energy. In reality even thermal energy can be partly organized if there are differences in temperature between parts of a system, but the level of organization is still lower than any of the other forms of internal energy.

Internal energy associated with chemical bonds, excited atoms and molecules, and the physical states of matter is more organized than thermal energy. The exact degree of organization depends on the physical and chemical state of the material. All physical and chemical changes decrease the overall organization of the system and its surroundings.

Finally, nuclear potential energy is the most organized of the internal forms of energy. Once again, there are differences in organization that depend on the exact form of nuclear configuration.

It is useful to make a rough listing of these kinds of energy according to the degree of order they tend to represent. If we list them with the most ordered at the top and the most disordered at the bottom, the Law of Increasing Disorder dictates that a form of energy cannot be totally converted to a form which is above it on the list. Equivalently, processes in nature that follow the direction of the arrow of time will be processes which accompany an overall trickling of energy downward through the list. We can make such a list, realizing that in some specific circumstances the order may be different.

1. Macroscopic kinetic and gravitational potential energy
2. Nuclear potential energy
3. Electrical potential energy
4. Chemical potential energy
5. Ambient temperature thermal energy

Stars obtain the energy to shine from a release of nuclear potential energy. The energy is transmitted as sunlight, part of which is taken up by plants in photosynthesis to become chemical potential energy. When the plant dies, the decay process passes the energy to the environment as part of the random molecular motion (thermal energy) of the ambient temperature. The trickle of energy flows naturally with the arrow of time from the top of the list to the bottom, from order to disorder.

The dependence of disorder on the chemical form of energy has some interesting and important consequences. For example, the disorder associated with hydrocarbons (e.g., gasoline) and atmospheric oxygen is fairly low. These can combine chemically when gasoline burns to yield carbon dioxide, water vapor, and considerable thermal energy. All of these are more disorganized than the original materials, so the process is irreversible. Disorder associated with various chemical combinations is one of the important properties that chemists study. Here, however, our intuitive ideas about measuring order and disorder are not adequate. The more sophisticated term “entropy” is used in this work.

### Ways to Increase Order

At this point, we are ready to consider the circumstances under which things become more organized. Such events seem to happen all around us. After all, an apple tree can organize an apple from seemingly disorganized materials; the ice cube in a glass of water was once water itself; every rolling ball was caused to roll. Are these not violations of the Law of Increasing Disorder?

Such a question permits us to emphasize the word *total*, which appears in our formal statements of the Law of Increasing Disorder. It is total disorganization that is required to increase in any irreversible process. It is perfectly legitimate for the disorder of one part of a system to decrease as long as disorder increases even more somewhere else. The total disorder would then increase in harmony with the requirement imposed by the law.

Efficiency of a car, for example, is limited in this way. Gasoline, a substance with moderately organized chemical potential energy, burns in the cylinders to yield the high-temperature internal energy associated with the

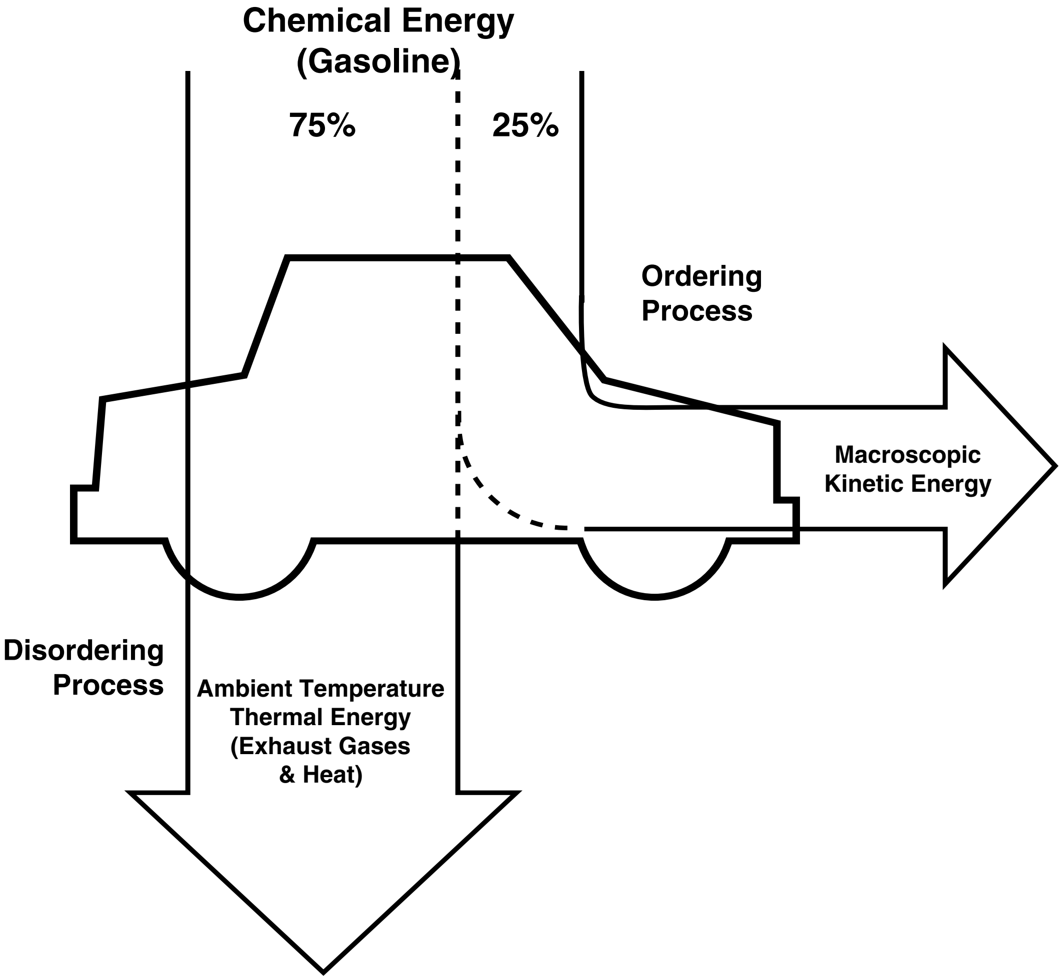

Figure 12.5. Energy changes in a car when chemical potential energy in gasoline is converted into macroscopic kinetic energy and low-temperature thermal energy. Notice that the total energy is conserved, but that total disorganization increases even though some of the energy is changed to kinetic energy.

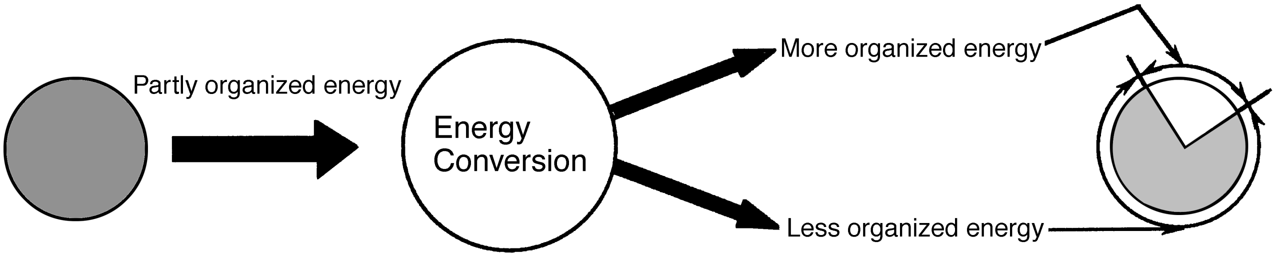

Figure 12.6. Any energy-organizing device divides energy into two parts, one more organized and the other less organized than before. The total organization cannot increase.

hot gases that drive the pistons. The disorder is now significantly higher than in the unburned gasoline, so considerable degradation has already occurred in the "quality" of the available energy. However, this moderate-order chemical potential energy also produces energy with the most order of all—kinetic energy of the moving car. If all the energy of the hot gases were converted to kinetic energy, overall increase in organization would be significant. On the other hand, if the hot gases were allowed to cool to the ambient temperature of the engine, the organization would decrease. The key is to combine these two processes. Some of the energy can be converted to kinetic energy, thereby increasing its order. If the rest of the energy becomes thermal energy at the lower temperature, the disorder of that portion is increased. The process works because the increased disorder at least balances the increased order so that the overall disorder does not decrease (see Fig. 12.5). The "efficiency" of the automobile engine is the fraction of the input energy that the engine converts to its primary purpose of providing macroscopic kinetic energy. Automobile engines are constrained by the Law of Increasing Disorder to an efficiency of about 25-30 percent.

The operation of refrigerators, air conditioners, and heat pumps illustrates this principle in a slightly different way. The function of such devices is to "pump" thermal energy from a low-temperature region (the inside of the refrigerator) to a higher temperature region (the space outside the refrigerator). The order associated with this energy is thereby increased. If the refrigerator were able to accomplish this transfer of energy without outside influence, it would violate the Law of Increasing Disorder. No one has ever successfully constructed a device that could do this.

All cooling devices of this kind require a source of high-quality, organized energy, such as electricity or natural gas. This energy becomes room-temperature thermal energy as the device operates, with a corresponding increase in its disorder. (The refrigerator actually emits more thermal energy into the room than it removes from the cold box.) This increased disorder more than balances the decrease associated with the thermal energy transferred from the cooled region, so that the total disorder of the system (refrigerator, surroundings, and input energy source) increases in accord with the Law of Increasing Disorder.

All "organizing" processes in nature have these same characteristics. If something is organized, something else must become even more disorganized so that total disorder is increased (Fig. 12.6).

### The "Energy" Crisis

There is much discussion these days about energy "conservation." The term itself is misapplied. Energy is conserved automatically in nature. We can do nothing either to create more energy or to do away with any that is already here. In fact, we do not have a shortage of energy. The thermal energy in the oceans and solid earth is more than we could ever use in any technology.

The problem we face is nonetheless real; however, it is a problem of disorder rather than one of energy. The vast amount of thermal energy in the materials around us is not useful, because its disorder is already at almost the maximum level permitted by the earth's temperature. Our fossil fuel supply is important because it provides our best supply of highly ordered energy. When we burn it, we do not lose its energy—we lose its order. We do not have an "energy crisis"; what we have is a "disorder crisis" or, more precisely, an "entropy crisis."

### The Efficiency of Energy Conversion

The Law of Increasing Disorder significantly limits the efficiency of the various processes and machines that convert energy from one form to another. We already have seen how automobile engines are limited to efficiencies in the range of 25 percent. Steam power plants, which generate electricity by burning coal or natural gas, and modern diesel engines both have efficiencies around 40 percent. Electric motors and generators, on the other hand, both have efficiencies exceeding 90 percent, since these use high-quality (highly organized) energy as input.

The important point here is that these efficiencies are limits that a fundamental law of nature imposes.

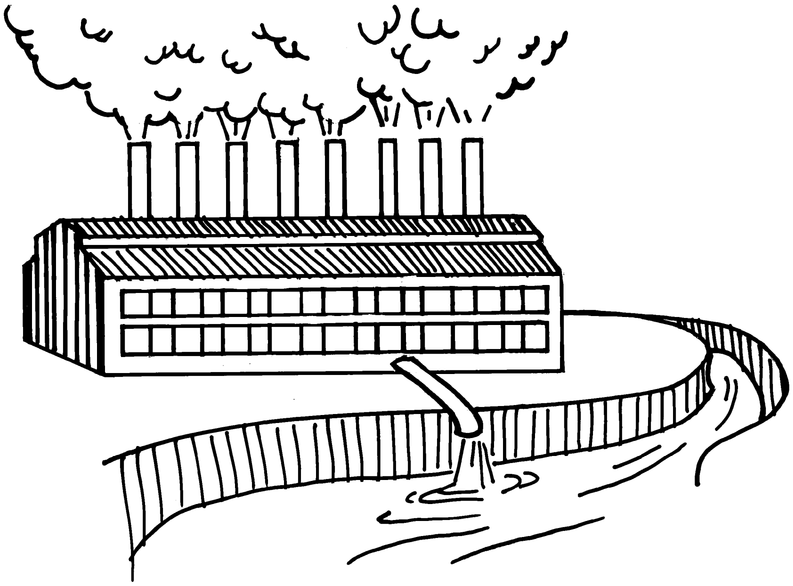

Figure 12.7. Why must energy be used if we are to control pollution?

They are not a penalty for poor engineering, nor can they be improved much by better design of existing types of machines.

### Pollution

The problem of industrial pollution is also partly a problem of increasing disorder. Pollution itself usually results from the dispersed by-products of industrial activity. The problem of control is basically one of organizing these randomly dispersed materials so that they are no longer bothersome or dangerous. Of course, as one component of our environment becomes more organized, another must become more disorganized. So to control pollution we usually must expend more of our high-order energy sources (Fig. 12.7).

Industrialists have been trying to tell us for some time that industrial processes involving pollution control require more highly organized energy than those that do not require such control. We must realize that these processes are limited by the Law of Increasing Disorder. There is no way to have more pollution control with less energy degradation. Only two ways exist to have less pollution and simultaneously use less high-quality energy: one is to continue increasing the efficiencies of industrial processes until they reach their theoretical limit and the other is to reduce the level of industrial production. The latter may be an appropriate choice, but at least we ought to evaluate realistically the various possibilities that are consistent with the fundamental laws of nature.

On the other hand, pollutants would seem to be most easily controlled when they are most organized—that is, at the point where they are produced. Once they leave their source they become even more disorganized as they disperse throughout the environment. They then require even more useful energy for control than would be required earlier.

### Equilibrium

When an isolated system reaches its state of maximum disorder, it is said to have reached **thermodynamic equilibrium.** If left to themselves, natural systems approach equilibrium. A rolling ball, which slows and finally stops, is an example. In such cases, the system changes so that its disorder continuously increases until it reaches a maximum. No further change occurs because disorder cannot decrease spontaneously.

Equilibrium arrangements of many systems can be changed by introducing outside influences. For example, the equilibrium reached after ice has melted in a glass of water can be shifted the other way by placing the glass in a freezer. Most of our technology depends on our ability to control equilibriums by introducing highly organized energy into a system.

The universe as a whole seems to be following the Law of Increasing Disorder and eventual equilibrium. Highly organized forms of energy convert to more disorganized forms. Hot regions become cooler, while cold regions are becoming warmer. Planets and stars gradually become run-down, their kinetic energy being converted to thermal energy by tidal effects. The equilibrium universe seems to be a situation in which everything is at the same temperature, and all forms of energy are converted to internal energy. No further energy-changing processes of which we know would then be possible. The equilibrium universe would be a dead universe.

## Summary

Disorder may seem abstract at this point, but it is a real and important entity in nature. Without disorder (and its mathematical expression, entropy), our description of the physical universe would be incomplete because it should be evident that the Law of Increasing Disorder is one of the important, far-reaching laws required to understand the universe. It limits and controls our actions and the processes that occur around us just as much as the laws of motion, the laws of force, or the laws of conservation.

The Law of Increasing Disorder (also known as the Second Law of Thermodynamics) states that the total amount of disorder in the universe always increases in physical changes, thus creating a direction to time. The real processes of our everyday experience are invariably irreversible processes. They occur one way in time but never exactly in the reversed way.

The disorder of molecular systems is a measure of the degree of randomness of motion of the molecules, the degree of mixing of species, or the degree to which temperature differences have been eliminated by randomizing the energy among the molecules. In general, in chemical reactions disorder is increased as the number of independent molecules is increased as a result of the reaction.

In a rough way, forms of energy can be classified according to their likely degree of order. Macroscopic kinetic energy represents coherent motion of very large numbers of molecules and is, therefore, highly ordered. In contrast, ambient temperature thermal energy represents completely random motion of very large numbers of molecules and is highly disorganized. In naturally occurring and spontaneous processes, energy is transformed from the ordered forms to the disordered forms.

It is important to understand that all the Law of Increasing Disorder requires is that the *total* disorder of the universe increase. Thus, order may be created in a subsystem of the universe if a more than compensating amount of disorder is created elsewhere. The operation of engines and refrigerators illustrates this important point.

If left to themselves, natural systems tend to a state of maximum disorder. This state is called “equilibrium.” When equilibrium is reached, no further energy processes are possible. The universe as a whole seems to be tending toward such an equilibrium state.

## Historical Perspectives

The Industrial Revolution promised to put engines to work to produce goods and stimulate commerce on a scale never before possible. In particular, the new steam engine patented by James Watt in England in 1789 made steam the servant of the human will.

The French physicist and engineer, Sadi Carnot (1796-1832), went to work on the fundamental question of determining how much motive power one could actually get out of a steam engine which was running in a cycle of operations. Is the efficiency of an engine limited and, if so, how is it limited? Although Carnot died of cholera at a relatively young age and, although he actually published but one work in his brief career, we credit him with discovering, in 1824, the unexpected limitation on the efficiency of engines which we now call the Second Law of Thermodynamics. The law was independently established by Rudolf Clausius in 1850, but it was not until 1852 that it was publicized by William Thomson (Lord Kelvin). In 1852 the German, Hermann von Helmholtz, pointed out another very unexpected consequence: The universe was using up all its available useful energy. Within a finite time all changes must cease, and the universe, with all its life, would perish in what came to be called the “heat death.” It was a disturbing thought. Would all of man’s achievement and progress come to naught in a new *Goetterdaemerung*, albeit one far removed into the future?

Isaac Newton’s legacy was a clockwork world which operated according to law. Newton himself, however, saw God as the author and continual preserver of the original forces and moving powers of the world. He wrote that the world is

> not a diminution, but the true glory of His workmanship, that nothing is done without his continual government and inspection. The notion of the world’s being a great machine, going on without the interposition of God, as a clock continued to go without the assistance of a clockmaker, is the notion of materialism and fate, and tends (under pretence of making God a *supramundane* intelligence) to exclude providence and God’s government in reality out of the world. (Quoted by Gerald Holton in *Introduction to Concepts and Theories in Physical Science*, p. 284.)

But now the clockwork was discovered to be running down! Where some people interpreted Brownian Motion as evidence of some vital life force in matter, the behavior of the world was increasingly being interpreted—and often very successfully—as atoms in motion. In 1830 Charles Lyell (1797-1875) published his influential *Principles of Geology*, which held that the earth had evolved over a long period of time and had been shaped by quite natural processes of erosion. In 1859 Charles Darwin (1809-1882) published his *Origin of Species*, which again invoked natural processes to explain the variety of life on the earth. The entire edition of 1250 copies was sold on the day of issue, and a storm of controversy arose over the book.

The march of materialism was disturbing. T. H. Huxley, who defended Darwin's right to be heard, expressed his dismay in 1868:

> The consciousness of this great truth weighs like a nightmare, I believe, upon many of the best minds of these days. They watch what they conceive to be the progress of materialism, in such fear and powerless anger as a savage feels when, during an eclipse, the great shadow creeps over the face of the sun. The advancing tide of matter threatens to drown their souls; the tightening grasp of law impedes their freedom; they are alarmed lest man's moral nature be debased by the increase of his wisdom. (From the *Collected Essays* of T. H. Huxley, quoted in Dietrich Schroeer, *Physics and its Fifth Dimension: Society*, Addison Wesley, 1972, p. 127.)

The Second Law of Thermodynamics was, in fact, enlisted in the war against the evolutionists who envisioned, with Darwin, that "man in the distant future will be a far more perfect creature than he now is." In contrast, the Second Law argued for decay and degradation and a dismal future for achievement and progress.

The debate continues to this day. Some, like Bertrand Russell in 1903, simply conceded to the demonstrations of science and adopted a materialistic philosophy that tried to find a ground for ethics in a purposeless world. Others took the view that the Second Law meant that God must be "wholly other" than the world, a Being out of time and space and, hence, free of the Second Law. But most people probably just ignored the whole thing and weeded their gardens.

But Huxley's statement above brings into focus why religious leaders have grown very anxious about the role of science in the world. There is, indeed, a tension between the two that has its roots in the ways of discovering truth. Science places its faith in sensory perception, the reasoned argument, and the controlled and repeatable experiment. With these tools it has been strikingly successful in understanding the physical world. Religion, on the other hand, particularly values authority and revelation. With these, it has given meaning and purpose to life and stirs feelings within the soul of man, which science does not explain.

Finding the truth about the world is much like putting together a very complex picture puzzle: some pieces fit together quite nicely; others do not. Some pieces may not yet be on the table. George Will once observed that we know next to nothing about almost everything. It behooves us to be a little tentative about those things that time will yet unveil in ways we probably cannot anticipate.

## STUDY GUIDE
## Chapter 12: The Law of Increasing Disorder

A. FUNDAMENTAL PRINCIPLES

1. **The Law of Increasing Disorder** (also the **Second Law of Thermodynamics):** Changes occurring in natural systems always proceed in such a way that the total amount of disorder in the universe is either unchanged or increased. If total disorder is increased, the process is irreversible.

B. MODELS, IDEAS, QUESTIONS, OR APPLICATIONS

1. Does nature run forward and backward in time equally well? What are reversible and irreversible processes?
2. Do the laws of force and motion give an adequate answer to question 1?
3. What happens to order and disorder in nature over time?
4. What is the relationship between order and the accessibility of energy?
5. Are there ways order can be increased?
6. Is there an energy crisis?
7. Is it easy to eliminate pollution?

C. GLOSSARY

1. **Ambient Temperature Thermal Energy:** The energy associated with random, disordered motion of molecules at a particular temperature.
2. **Disorder:** For molecules, disorder is associated with the mixing of molecules such as to destroy separation by species or by internal energy content. Entropy is a technical name for disorder.
3. **Entropy:** The name given to the technical, quantitative measure of disorder.
4. **Equilibrium:** In the context of the Law of Increasing Disorder, equilibrium is that state of an isolated (from energy input or output) system when it has achieved the maximum disorder possible.
5. **Irreversible Processes:** Energy-changing processes which occur spontaneously in one way, but never in exactly the reverse way. An ice cube melts in a glass of water, but never spontaneously reappears.
6. **Order:** A system of molecules possesses order if the molecules are physically separated by species or by internal energy content. The refining of ore to separate molecules of lead, silver, and zinc is an order-increasing process. The melting of an ice cube to remove the distinction of water molecules (some ice, other liquid) is a disorder-increasing process.
7. **Reversible Processes:** An energy-changing process which can happen spontaneously and completely either forward or backward in time. Such a

process does not change the amount of disorder of the universe. If a ball were thrown upwards in a perfect vacuum, kinetic energy would be converted completely to gravitational potential energy, then back again.

D. FOCUS QUESTIONS

1. For each of the following situations:
   a. Describe what would happen to the system.
   b Name and state in your own words the fundamental principle that could explain what would be observed.
   c. Explain what would happen to the order of the system in terms of the fundamental principle. Be sure to describe the order at the beginning and how it changes with time.
      (1) A car is moving along a flat highway. The engine is off and the car coasts to a stop.
      (2) A drop of ink is released into a large flask of water.
      (3) An ice cube is placed into a pan of warm water.
2. State both the Law of Conservation of Energy and the Law of Increasing Disorder. What happens to the energy and to the order when:
   a. Fossil fuel is burned.
   b. Water from behind a dam is used to make electric current and the electric current is used to operate a toaster.
3. Finding useful energy and eliminating pollution are major social problems. State the problems accurately in terms of fundamental principles and describe limitations these principles impose in working toward solutions of the problems.

E. EXERCISES

12.1. When a hot and a cold object are in contact, heat flow always occurs so that both become warm. Explain how there is more "order" in the beginning and more "disorder" at the end of this process.

12.2. An object slides across a table and comes to rest because of friction. Explain how there is more "order" in the beginning and more "disorder" at the end of this process.

12.3. Why do ice cubes always melt in warm water? Why don't the ice cubes get larger? Why doesn't the water get warmer? Would the Law of Conservation of Energy be violated if they did?

12.4. What is an irreversible process? Why are such processes not reversible?

12.5. State the Law of Increasing Disorder in your own words.

12.6. Illustrate the Law of Increasing Disorder by describing an irreversible process.

12.7. What is the First Law of Thermodynamics?

12.8. What is the Second Law of Thermodynamics?

12.9. Explain the meaning of the word "entropy."

12.10. Is it possible to use the energy involved in the random motion of molecules (internal energy) for doing work? A device for doing this would be called a heat engine. If your answer is yes, give an example or two; if no, explain why not.

12.11. What conditions must be satisfied in the design of a heat engine if it is to work?

12.12. No process can occur in which the total effect is heat flow from one object to a hotter one. Why?

12.13. Isn't the kind of engine or motor described in Exercise 12.10 forbidden by the Law of Increasing Disorder?

12.14. What conditions must be satisfied in the design of a refrigerator if it is to work?

12.15. Use the table of relative entropy values to show that each step in the hydrocarbon cycle (solar energy, sunlight, plant growth, gasoline formation, gasoline burning, thermal energy) is associated with increasing entropy.

12.16. Discuss the problem of mining and refining metals (e.g., copper or iron) in terms of the Law of Increasing Disorder. Why must energy be used in such processes?

12.17. Many coastal regions of the earth (Los Angeles and New York are good examples) often experience shortages of water even though they are adjacent to oceans. Discuss their desalination problems in terms of disorder. Why must energy be used in any desalination process?

12.18. Why has no one invented a gasoline engine with 100 percent efficiency?

12.19. Imagine a ship in the middle of an ocean. There is plenty of thermal energy in the water by which it is surrounded. Why cannot this be used to propel the ship? Why must the ship carry its own fuel?

12.20. Imagine a hot stove in the middle of a room. What is the equilibrium arrangement in this situation? Does equilibrium in this case mean that everything is at rest? Does it mean that no further changes are taking place? Explain your answers.

12.21. Why must energy be used if we wish to control pollution?

12.22. Overall disorder is unchanged in
(a) chemical processes
(b) mechanical processes
(c) irreversible processes
(d) reversible processes
(e) nuclear power generation.