The Heat Death of Civilization

CONTENTS

I. Introduction

The universe is gradually falling apart. Sometimes this is referred to as the "heat death" of the universe. Stars run out of fuel and disintegrate. Or, if massive enough, they blow themselves up in supernova explosions, strewing most of their matter into the surrounding space. New stars are being born, replacing the ones lost, but eventually the raw materials that make new stars will be exhausted. The remnants of fuel-exhausted stars - white dwarf stars, neutron stars, and black holes - will similarly die. White dwarfs will become cold, dense, Earth-sized cinders of carbon and oxygen. Neutron stars will be cold and lifeless lumps of city-sized nuclear matter. Even black holes will, over incredibly vast stretches of time, disintegrate into diffuse "Hawking radiation". It may not end there. If protons are ultimately unstable over those vast stretches of time, even the white dwarf and neutron star cinders will disappear. All that will be left is a universe of photons, growing colder and colder.

Why should this be? And why can't we arrest these processes? If we had sufficient technology, couldn't we just keep putting the pieces back together and continually restore the *status quo*? Stars convert hydrogen to helium (and other elements as they age) in their cores. When the hydrogen fuel got low in a star, we would just collect hydrogen from vast interstellar clouds and recharge the star. Or, cognizant of the fact this hydrogen, though vast, is not limitless, we might construct immense factories that reconvert the helium and other elements produced by stars back into hydrogen and use that to recharge aging stars. This would be recycling on a cosmic scale. The only problem is, it won't work, no matter how advanced the technology.

Although the statement, "it won't work", is bound to be aggravating to many a can-do-minded human, I'm afraid it's true. I once knew a handyman who was sure he could build a perfect refrigerator. He would use the heat generated by the refrigerator to run a dynamo that would then provide electricity to work the refrigerator. The energy would be continually cycled and the refrigerator would run indefinitely without being supplied with energy from an outside source. I tried to explain to him that there is the small matter of the second law of thermodynamics. I put it in as simple terms as I could, but it wasn't a lack of intelligence on his part that led him to reject my argument. He just didn't want to believe it couldn't be done. There had to be a way around this stupid law. Or, perhaps, physicists are just plain wrong.

Far from being "stupid", the second law of thermodynamics is one of the most profound concepts in physics. It is responsible for the continual change we see in ourselves and our surroundings. It is responsible for the continued integrity of our bodies, for the birth of new human bodies, for the evolution of life, and for the evolution of the entire universe. Pretty important stuff. The second law drives change. The nature of the change depends on the other laws of physics. This is such a powerful concept that some have claimed that the flow of time itself is a consequence of the second law of thermodynamics. You don't have to go that far, however, to realize, with this law, you have come into the presence of that which makes creation inevitable.

II. Exporting Disorder (Entropy)

Well, you might think, why is a law that is the impetus behind change and creation responsible for the demise of the universe? That sounds like a contradiction, but the way the second law of thermodynamics creates (in concert with the other laws of physics) is by destroying. For every ounce of order created, there is a pound of dissolution, so to speak. A creative act at one place can only occur if a larger act of destruction occurs somewhere else. This allows for the appearance of order - creation - in the universe, but at a price - a big price - the ultimate price. The order can only be temporary. The universe must eventually "die" and break down into total disorder.

You can look at the second law of thermodynamics from a merely "phenomenological" perspective. This means you observe what happens and make a generalization that doesn't include how it happens in terms of more fundamental processes. Say you see a number of processes where order decreases. You may then make the generalization that order always decreases. You see sugar cubes dissolve in a cup of hot tea. You never see a sweetened cup of tea produce a sugar cube. You acknowledge that the sugar dissolved in the tea is less ordered than the tea with the sugar cube intact. Therefore, you generalize that nature tends to greater disorder. Why, you don't know. All you know, or claim you know, is that it always happens that way.

But it apparently doesn't *always* happen that way. You place an ice-cube tray of water in the freezer and wait a couple of hours. When you open the freezer, you have a tray of ice cubes. You have learned that water is made up of molecules composed of two hydrogen atoms attached to an oxygen atom. In liquid water the molecules are (more or less) randomly distributed. (In actuality there is some short-range order in the way the molecules are distributed.) Solid water (ice), however, is highly organized as the molecules arrange themselves into a crystalline state with long-range order, sort of like house after house in a typical suburban subdivision. Isn't this the same, conceptually, as a sugar cube appearing out of a cup of sweetened tea? It looks as if order can arise from disorder after all. So much for the second law of thermodynamics!

The problem with this conclusion is that disorder has indeed increased as a result of the change of liquid water to ice. The water has increased its order by exporting disorder to its environment. And, when you take that disorder into account, it outweighs the order created. What does this disorder consist of? To freeze, the water has to give up a lot of heat. This heat does not involve a change in temperature. The water cools down to freezing (0° Celsius, also expressed as 0° centigrade), but it doesn't cease giving off heat. It continues to give off heat (about 80 heat calories per gram) as its temperature remains steady but its order increases. Heat is disorder - a form of disorder that flows from higher to lower temperature. The water increases its order by giving off this heat as it freezes into ice at 0° Celsius. In other words there is no temperature change as heat (disorder) is expelled to the freezer (the water's environment), and the liquid water gradually turns to ice, increasing the order of the water and decreasing the order in the freezer. When you measure the entire change, including not only the water turned to ice but also the heat given off, you find the total disorder has increased. So much for disrespecting the second law of thermodynamics!

The transfer of heat energy from a "system" to its environment is a way of exporting disorder. (A system can be pretty much anything consisting of interacting parts you choose, such as the molecules in a tray of water.) The freezing of the water in the above example involves other laws of physics, in particular, electrical forces. Without those forces, there would be no freezing of water to ice. (Which would be moot since, in the absence of electrical forces, there could be no water to freeze!) Without the second law of thermodynamics, you could put a tray of water in the freezer and wait until hell freezes over and still not get ice. (Of course, hell might not freeze either, for that matter.)

A consequence of the second law of thermodynamics is that spontaneous heat flow is from hot to cold and never the other way, since heat flow from hot to cold increases disorder as required by this law. Without this consequence, heat wouldn't flow only from the warmer water to the colder freezer air to produce the desired ice - it would just as likely flow the other way. You might instead get a tray of boiling water (however, this would be as unlikely as getting ice). Note this would not violate the first law of thermodynamics, which postulates the conservation of energy. The heat energy that flowed from the freezer to the water would be the same as that absorbed by the water so that no energy was created or destroyed as required by the conservation of energy.

A good physicist is never satisfied with a phenomenological observation. He or she wants to know how and why the process occurs. The physicist who gave deeper insight into the second law was Ludwig Boltzmann, who worked in the late 1800s. He believed in atomic theory - that all substances consist of atoms, or atoms combined into molecules (that is, consisting of particles that are either individual atoms or molecules). If that is true then there is an incredibly large number of ways these atoms, or molecules, can be organized with respect to each other. He made the assumption that, for a given total energy of the atoms, any of these ways, called *microstates*, are equally probable.

Consider the tray of water about to be placed into the freezer. It hardly matters to the person putting in the tray exactly where each of the water molecules is and how it is moving. Wherever they are, and whatever their individual motion in the water happens to be, the person sees a tray of water. This tray of water is termed a *macrostate*. A macrostate can consist of any of an incredibly large number of microstates. From one tiny fraction of a second to another, the tray of water will change from one microstate to another as the molecules jostle around. The tray of water has a certain temperature and a certain volume and is at atmospheric pressure (neglecting the very slight increase in pressure between the surface of the water and the bottom of the tray). The temperature, volume, and pressure determine the macrostate - what the person can measure or observe - and there is an incredibly large number of ways (microstates) the water molecules can arrange themselves, both in position and velocity, to render this particular macrostate.

It isn't hard to conclude that there is an incredibly larger number of disordered microsates than there are ordered microstates in a system. If all of these states are equally probable, than the likelyhood of a system being in a disordered state is incredibly greater than it being in an ordered state. This was what Boltzmann contended. As atoms or molecules (or even photons) randomly move around, they are far more likely to constitute a disordered rather than an ordered state. That is, it would take a mind-boggling stretch of improbability for the molecules of sugar in a cup of sweetened tea to move together and assemble themselves, by accident, into a cube. This implies that the second law of thermodynamics is, in some sense, not a real law of physics, but a statement of probability given that the universe is made up of particles - atoms, molecules, ions, photons, etc. - in constant and random motion.

Except the motion is not entirely random. Forces such as gravity and electricity cause particles to move in non-random ways. Nevertheless, there is a tremendous amount of randomness at work. Enough randomness that, on the whole, order decreases with time.

Moving on from a tray of water, consider a gold atom. Now, this particular atom was recently synthesized in some sort of nuclear reaction, possibly as a result of colliding neutron stars, and is soaring through mostly empty space. Mostly empty, that is, but for a proton with which it has a chance collision. The collision adds energy to the gold atom, putting it in what physicists call an *excited state*. This means one or more electrons in the atom have more energy than they would have in their lowest energy states. There are possibly several microstates available to the excited gold atom, all with the same energy. However, there are fantastically more microstates consisting of the gold atom back in its lowest energy state (the so-called *ground state*) and a photon (one or more) moving away from the atom, carrying off the extra energy. The number of these states is huge, because a photon can leave the atom in any direction whatsoever. If all microstates are equally likely, there is a much greater probability the excited gold atom will transition into an unexcited atom by emitting one or more photons. Of course, there are other laws of physics involved in this process, in particular electrical forces and quantum mechanics.

A process like this, where a system (here, the excited gold atom) "seeks" its lowest energy state is often referred to by saying, "Nature is lazy. It wants to be in the lowest energy state possible." However, the new state, unexcited gold plus photon(s), has the same energy as the excited gold atom. The conservation of energy says that the energy before an interaction equals that after the interaction. What has really happened is that the laws of probability have led to a more disordered situation. The second law of thermodynamics guarantees that a system, unaffected by its environment, will evolve to the state of greatest possible disorder. So, Mother Nature is not lazy, just messy.

But then you look around. Biologically, nature is complicated and ordered almost beyond belief. You see organisms with incredibly complex bodies. You see very complex plant and animal communities maintain, and even increase, their complexity. You see the ecological balance that maintains the order of vast ecosystems. You explore the past by studying fossil life and discover that, on the whole, biological complexity on the Earth has increased over time. So much for the second law of thermodynamics!

Creationists will contend that the second law of thermodynamics proves evolution could not have occurred. On the contrary, the second law of thermodynamics does not prevent the accumulation of biological order on Earth so long as there is a greater increase of disorder elsewhere. But where is this disorder? It isn't under the sea. It isn't in the atmosphere. It isn't in the solid Earth. So, where is it?

Life is truly incredible in its ability to export disorder. This is like the tray of freezing water but "infinitely" more complex. How does the tray of water export disorder? Recall it is through giving up heat to its environment. The biosphere (the sum of all life on Earth) does exactly the same thing. Where does this disorder go? Ultimately, to space. Biological processes produce heat. This heat raises the temperature of the Earth just the tiniest amount, increasing the heat flow to space. Heat, you may remember, must flow from high to low temperature and is a flow of disorder. In the case of the Earth, the flow of heat to space occurs by the emission of heat radiation (that is, thermal infrared radiation such as that you feel emitted by a hot fire in a more intense form). This heat flow exports disorder to space allowing life to be ordered on Earth. Again, the second law of thermodynamics triumphs! (Or, rather, nature triumphs by harnessing the second law.)

The details of this process are still being unraveled by scientists. After all, nature has had billions of years of trial and error to produce the ordering processes we observe, and we have just started, really, to figure all this out. Nature uses the laws of physics to create chemistry. Then she uses a particular chemistry, biochemistry, to create life. How this all has happened is a great mystery that is gradually being revealed by science. We have made great strides, such as the mapping of the human genome and the genomes of many other species. We are learning about the thousands and thousands of biological molecules and how they interact. But we are still scratching the surface. The second law of thermodynamics, however, doesn't care how the ordering is done, so long as if it is done, it is done at someone else's expense. In the case of the Earth's biosphere, the unlucky recipient of our disorder is outer space (which, as large as it is, hardly notices).

III. Calculating the Export of Entropy

To quantify disorder, you must have some sort of way of measuring and computing it. This is what the scientists Rudolf Clausius and Ludwig Boltzmann of the nineteenth century did. They each came up with a formula to quantify disorder. Even though these formulas appear to be totally different, they actually calculate the same thing. The measure of disorder is called *entropy*.

Let's look at Clausius' formula. According to this formula, the rate of the export of disorder with time (the time rate of the flow of entropy from a system to its environment) can be expressed as the heat flow from the system to its environment divided by the absolute (kelvin) temperature of the environment. (The kelvin temperature scale, named after the British scientist of the 19th century, Lord Kelvin, uses the same degrees as Celsius, but takes zero temperature to be absolute zero rather than the freezing point of water.) In general, for an environment whose temperature is changing, you have to divide the heat flow at each temperature and add these all up. However, if the environment maintains a constant temperature, you can simply divide the total heat flow by that constant temperature. This is true for the tray of freezing water in the freezer, assuming the freezer temperature remains constant at about 0° C, or 273 kelvin (written in scientific notation as 273 K).

Let's say it takes exactly one hour for the water to freeze. During this time each gram of water gives up about 80 heat calories, which comes to a heat flow rate of about 0.022 heat calories per second. We need to change our heat energy flow units to watts if we want to express the flow of disorder in scientific units, watts per kelvin (the same as "entropy per second"). The heat flow comes to 0.093 watts (0.093 W) so that the rate of disorder (the rate of entropy flow) exported by the freezing water is 0.093 W divided by 273 K (the freezing point of water in kelvin), or about 0.00034 watts per kelvin (W/K) for each gram of water. Multiply this by the number of grams of water in the tray (say 200 grams), and you get the total rate of the loss of disorder by the water, 0.068 W/K in this case. Multiply again by the number of seconds in an hour and you get the total entropy that the water has lost in units of joules (J) per kelvin. (A joule is an energy unit equal to the amount of energy in a flow of one watt in a time of one second. Therefore a 60-W bulb will use 60 J of energy every second.)

The disorder lost by the water is therefore about 250 J/K. If the freezer temperature is, say, 10 K lower than the freezing point, 263 K, then the disorder gained by the freezer will be, performing a similar calculation to that above, about 260 J/K. Note that, as the second law of thermodynamics demands, the *total* change in disorder, water plus freezer, is 260 J/K minus 250 J/K or 10 J/K. Order has decreased for the system as a whole, as required by the second law.

IV. How the Biosphere Maintains Order

The biosphere is an almost impossible highly ordered state of matter. Yet its order is actually quantifiable, as is the disorder thrown out into space, by using Clausius' formula for entropy. It is more daunting to apply this formula to the biosphere than to that tray of water. However, you can make a “back of the envelope” approximation that should at least give you an idea of the magnitude of the disorder exported to space.

To apply Clausius' formula, you need the heat flow of the biosphere to its environment (and ultimately to space) and an approximate average temperature of the biosphere's surroundings. The latter is fairly easy to estimate - a reasonable choice (close to the estimate of the Goddard Institute for Space Studies) is 290 kelvin (about 60 degrees Fahrenheit). The former is harder. The biosphere gets energy from photosynthesis, initially produced in the form of sugars, but gives off heat as it uses this energy to maintain itself. You have to calculate the heat generated by the biosphere in using the energy provided by photosynthesis and then divide by 290 kelvin to get an estimate of the disorder the biosphere exports to its environment.

A little research turns up some numbers you need to compute the amount of heat given off by the biosphere. A paper published in the journal Nature by a team led by Lisa Welp puts the average amount of carbon produced by photosynthesis on the Earth at 150 to 175 trillion kilograms a year. Assuming a value of 160 trillion kilograms for purposes of calculation and assuming the carbon is bound in the sugar glucose, this would be 400 trillion kilograms of glucose per year. A kilogram of glucose contains about 16 thousand kilojoules of energy, so the biosphere should produce something like 6.5 million trillion kilojoules of stored energy for use in maintaining itself every year; that is 210 billion kilowatts of average power collected, as a kilowatt is a kilojoule per second.

A small fraction of this energy is sequestered in sediments to form, for example, fossil fuels such as oil and coal. However, it is clear that the vast majority of it ultimately is released back into the environment as organisms live, die, decay, and turn back into carbon dioxide and water. To a very good approximation, the rate of disorder being exported to space by this decay should be, according to the formula produced by Clausius, the rate of energy released by decay (approximately equal to the rate of energy stored by photosynthesis) divided by 290 kelvin. This amounts to roughly 700 million kilowatts per kelvin.

That's a really huge number – the rate of disorder the biosphere has to get rid of to maintain itself, but what does it mean? How can you put it in perspective? Well, you can compare it to the amount of disorder human beings export to the environment (not including that due to metabolism, which is part of the biosphere already computed). This is pretty easy to compute, since the International Energy Agency estimates that humans produced an average of about 18.5 billion kilowatts of power in 2017. This is primary energy production which is what should be compared to energy captured by photosynthesis. With an environment temperature again estimated at 290 kelvin, this amounts to an outward flow of disorder around *9% of that exported by nature*. It is amazing – or maybe not so much, given our impact on the environment – that humans are producing numbers that can be compared with nature.

This energy consumption by both humans and nature will raise the Earth's temperature. (I am not talking about greenhouse gases here, which is another matter.) A calculation shows this change in temperature to be negligible: only about one-tenth of a degree Celsius for nature and less than that for humans. The difference between nature and humans is that nature uses energy from the Sun that would go to heat the planet anyway, so no net temperature change occurs. Humans mostly use fossil fuels, so this energy is extra, although quite negligible as far as raising the Earth's temperature is concerned. The non-negligible effect of greenhouse gases, on the other hand, is not due to extra energy but to how the gases change the flow of heat already in the atmosphere.

V. How Humans Create Disorder

Look at how nature works versus how humans usually do. The biosphere does not permanently disorder matter. Instead, it recycles it. Carbon dioxide and water are combined by photosynthesis to form sugar and oxygen. The sugars and oxygen go to power the biosphere, providing energy to other organisms – energy to consume other elements necessary for life, to fabricate new biological molecules, to repair damage and wear to maintain body integrity, and to propagate the species.

Ultimately, all (or almost all) this biological material that is fabricated turns once again into carbon dioxide and water and the trace elements used by living things. Nearly all the energy captured by photosynthesis is turned into disordered energy (heat) and ultimately expelled to space. Nearly all the matter is recycled, from disorder in the environment, to order in the biosphere, and back to disorder in the environment, and so on. This recycling is powered by energy captured from the Sun. If nature didn't maintain itself this way, disorder would inevitably build up on the Earth, and life could not sustain itself. (If the creationists' arguments about the second law of thermodynamics were correct, the biosphere would have collapsed long ago.)

As you know, this is not how we humans do business. We only get a fraction of our energy from so-called renewable sources. It is perhaps ironic that fossil fuels, from which most of our energy comes, contain stored solar energy. Coal used to be trees and other plants. Oil comes from the remains of organisms locked up in marine sediments. (You have a solar-powered car but may not realize it.) As far as the second law of thermodynamics goes, this energy is not a problem, because, like the energy used by the biosphere, it all eventually goes out into space as thermal radiation. Now, there may be a local problem due to, for example, hot water from a power plant being discharged into a stream, but globally everything is copacetic.

The real problem is how we humans create disorder in matter . For one thing, s***, er, human biological waste happens. Then we have landfills, strip mines, mining wastes, water and air pollution, carbon dioxide and other greenhouse gases in the atmosphere, plastics and other trash in the oceans and on beaches and roadsides, pesticides and other chemicals in waters both above and below the Earth's surface, nuclear wastes, disrupted landscapes, and on and on. All this is disordered matter, and much of it has consequences beyond the mere fact of its presence.

It is perhaps impossible to put a number on the amount of this disorder, but it is reasonable to think it may be comparable to our heat disorder, which you recall was 9% of nature's. Nature's recycling mechanisms have been able to handle a lot of it, so long as it (like human biological waste but not plastic waste) is “natural”, but nature is gradually being overwhelmed by the *concentration* of waste produced by humans. (The Gulf of Mexico “deep-horizon” oil spill is an extreme example of this. There are natural oil seeps in the sea floor of the Gulf, but they don't overwhelm the natural processes that convert them into compounds like carbon dioxide that can be used in the biosphere.)

Nature, undisturbed by humans (or asteroids), can maintain itself indefinitely, but neither nature nor we can maintain our current course. The second law of thermodynamics says so and we better take heed. With population growth, technology advancements, and rising standards of living, the amount of disordered matter exported to the environment will grow. How much can nature take? Well, she isn't handling what we are already dishing out all that well. Species are disappearing at rates only seen during “mass extinctions” in the fossil record. The ocean is acidifying. The climate is changing. We cannot continue to increase disorder on our planet and survive. Disorder is the same as unavailable energy, and we need energy to live. There is no energy crisis, but there have been and will be *available* energy crises. If things continue as they are, a breakdown is inevitable. It may not be in my or your lifetime, but it *will* happen unless humans change course.

VI. The Heat Death of Civilization

So, what do we do about this? The obvious solution is to behave like nature: get all of our energy from the Sun and recycle all our material. The problem is that solar energy is very diffuse and already contains a high degree of disorder (entropy). This is one reason why only a small percentage of it is captured by photosynthesis. Then, if we really do begin to recycle everything, we will need more energy than we are now using. We can, of course, be as efficient as possible, but there is a limit, again enforced by the second law of thermodynamics, to how great that efficiency can be. It can certainly *never* be 100%, and the first and second laws of thermodynamics, says it can't even reach a substantial fraction of that.

At some point it will be too late. There will be too many people and too much demand on our planet. The future looks gloomy without some form of abundant and clean energy. Solar energy is an unlikely source by itself. About 80 trillion kilowatts of solar power strike the Earth. (Included in this is the energy it takes to drive the weather, meaning wind energy is also part of this.) However, even photosynthesis can only harvest 210 billion kilowatts. We humans now produce 18.5 billion kilowatts of primary power, 9% (!) of what nature needs. In a "perfect" world, every person on Earth would have an economic condition equivalent to the average American. How much energy would be needed?

According to the US Energy Information Agency, the power (energy in joules per second) used per capita in the US was about 24 kilowatts in 2015. This was primary energy, which includes the energy cost of extracting fuels, transporting them, converting them into electricity, etc. The final power used per capita is about two-thirds of that or about 16.5 kilowatts. Spread that out over a population of seven and a half billion people, and we would need about 180 billion kilowatts of primary power and 120 billion kilowatts of final power. The final power consumption is close to 60% of what nature gets from the Sun!

How we would get this much power from the Sun is far from clear. Current (as of this writing) solar panel efficiencies are near 20%. Efficiencies will go up as technology advances, but we will still need to be capturing close to what nature does. Maximum theoretical efficiencies for photovoltaic cells at this time is about 33%. Even assuming 30% efficiency, it would take solar arrays adding up to a surface of something like 660 by 660 kilometers to provide 180 billion kilowatts for the Earth's population. (Heck, that would take up most of West Texas.) This does not include the inefficiencies of energy distribution. More likely something like an entire continent would have to be surfaced with photovoltaics. The only way I can see how this might be done would be for power generation to be mostly distributed rather than concentrated in solar power plants, especially when, of course, one-half the Earth is always in darkness. Energy storage for when sunlight is low or absent is also an issue.

On the other hand, if we were to divide the current energy use equally, each person on Earth would get only about one-fourth the energy an average American consumes. How would you like your standard of living to be one-fourth of what it is now? (This is a bit optimistic given the amount of energy that goes into the military, warfare, and other uses that don't help boost the standard of living. Nor does it take into account the wide gap between the wealthy and the poor.)

Improving technology can help – increased efficiency, life-cycle engineering and management of our consumer goods, improved energy generation and storage, new materials, and so on – but only if the technology takes the second law of thermodynamics into account. And the cost will go up as we will have to pay, not only for the goods, but the recycling costs as well. The dream of recycling paying for itself, as my city, Austin, seems to think is possible, is at odds with the second law. At the moment too many industries, institutions, and individuals dump this cost on someone else (typically on local, state, or federal government, aka "the taxpayer") or on the biosphere. The biosphere has to handle its own mess and can't handle our growing mess as well.

What energy sources can we tap, if not just the Sun? The unfortunate fact is that any energy generation is subject to the second law of thermodynamics, even photosynthesis. The more energy that is generated, the more disorder that will also be generated, including waste energy (heat that can't be used to generate power). To counter this, our energy sources need to be as efficient as possible and to ultimately generate disorder in the form of heat rather than disordered matter if we are not to choke on our own garbage. Heat can be expelled into space, unlike human-generated carbon dioxide, coal ash, and other by-products of fossil-fuel burning.

As a relatively clean source of energy, nuclear power comes to mind. It generates mostly heat and relatively little waste compared to fossil fuels. The most efficient nuclear fission plants are the breeder reactors, but their use is problematic due to nuclear proliferation concerns. They generate nuclear “waste” that can be reprocessed to extract the plutonium, which can be used as fuel. The problem is the danger of diversion of plutonium to nuclear weapons. This danger might be avoided by a design where the nuclear material stays in the reactor and does not need to be removed for reprocessing. A major advantage of breeder reactors is that the nuclear waste ultimately produced only takes a couple of hundred years, more or less, to lose nearly all of its radioactivity. Nuclear waste produced by most of today's reactors will stay dangerous for many thousands of years.

One particular type of reactor that probably merits some attention is the design that uses thorium for fuel rather than uranium. These reactors are safer and less susceptible to exploitation by those who would like to steal fissile material to make bombs. This type of reactor does have its drawbacks, but they might be quite suitable energy solutions in areas where other types of reactors might be considered too dangerous; for example, where there was a greater risk of earthquakes.

Thought to be an even better energy solution are nuclear fusion reactors. These should generate even less waste material than fission reactors, and the supply of fuel – deuterium from sea water – is practically endless. Contrast this to the need for dangerous uranium and/or thorium mining to supply fission plants with fuel. The problem is fusion power is decades off. The international ITER project, now underway, which will try to build a sort of prototype reactor, may clarify just what scientists and engineers have to overcome to design a production reactor. Other fusion technologies are also being explored.

As more humans inhabit the planet and as (we hope) their standards of living rise, we are facing the danger of increasing the disorder on the planet to the point it may become, ironically enough, essentially unlivable. The dangerous disorder we create is disordered matter, which often has unintended consequences, such as overloading the environment with sewage, the deterioration of the ozone layer due to man-made chemicals, damaging floods due to unwise water projects and urbanization, devastating mudslides caused by deforestation, ground subsidence resulting from groundwater and oil and gas removal, chemical and pesticide pollution (witness the environmental crisis due to the use of DDT), growing "dead zones" in the seas due to agricultural run-off, large amounts of plastics accumulating in the oceans, just to name a few.

Some of our wastes can be processed by the biosphere, but the concentration is a problem. (The old sanitary engineer saw, “The solution to pollution is dilution.” might should be, “The solution to pollution is dilution is delusion.”) The biosphere has to invest energy to do this processing, energy that would otherwise be going to maintain itself. As the biosphere is overtaxed by this increasing human load, its ability to continue to function to help maintain ecological balance, clean water, clean air, and fertile soil is diminished. What we are creating is a (usable) energy crisis for nature in addition to the one we are facing ourselves.

Very worrisome is the increase of human-generated gases in the atmosphere from numerous sources: power plants, internal combustion engines, clearing land for agriculture, deforestation, etc. Methane and carbon dioxide (and some even more powerful but less abundant greenhouse gases) are changing the climate, but they are not alone. Particulate matter in the atmosphere and land use also contribute. Carbon dioxide dissolves in sea water and increases the acidity of the ocean. Just as worrisome is the current global mass extinction of species that seems to be largely the result of habitat loss due to human land-use practices, but also due to the introduction of non-native species and pathogens.

The only practical way to minimize matter disorder is by conservation, recycling, and turning to energy sources that produce disorder in the form of heat rather than disordered matter. We really don't have an energy crisis, if you look at our situation in light of the first two laws of thermodynamics. The first law says you will *always* have the same amount of energy in the universe. The problem is how much *usable* energy you have, and that is determined by the second law of thermodynamics. What we have actually had and may have again are *usable* energy crises, not an energy crisis *per se*.

To get in step with the second law of thermodynamics, we are going to have to do some things. Don't forget, this is a *law of nature*. Congress cannot repeal it; treaties cannot do away with it. It will take cleaner energy sources (in the sense of producing less disordered matter), conservation, increased efficiency (recall the second law of thermodynamics puts limits on this, however), recycling, and life-cycle-engineered products (a sort of "cradle-to-grave-to-resurrection" plan to minimize impact on the environment). In short, it will take a radical departure from the way we are currently doing business. It's a matter of our survival.