Chapter 2

The Cosmic Context of the Millennium Development Goals: Maximum Entropy and Sustainability

Charles H. Lineweaver[a] **and Molly Townes O'Brien**[b]
[a]*Planetary Science Institute, Research School of Astronomy and Astrophysics, Research School of Earth Sciences, Australian National University, Building 113, Mills Road, Canberra, ACT 0200, Australia*
[b]*ANU College of Law, Australian National University, Building 5, Fellows Road, Canberra, ACT 0200, Australia*
charley.lineweaver@anu.edu.au

The nations of the world are converging in health and wealth as the world grows more polluted. Navigating a path away from this unsustainable development toward sustainable development requires an understanding of the relationships between development, energy consumption, and entropy. We explore these relationships and describe the nanocosmological processes of the big bang, which are the ultimate source of the free energy that we consume. We show that the biomolecular nanotechnology of animal muscles is more efficient than internal combustion engines. We also hypothesize that an extension of the second law of thermodynamics, the maximum

Nanotechnology Toward the Sustainocene
Edited by Thomas A. Faunce

ISBN 978-981-4463-76-8 (Hardcover), 978-981-4463-77-5 (eBook)
www.panstanford.com

entropy production principle, is consistent with sustainable values for the rate of entropy production.

To see a world in a grain of sand, and a heaven in a wild flower,
Hold infinity in the palm of your hand, and eternity in an hour.
—William Blake, *Auguries of Innocence*

2.1 The Millennium Development Goals: Sustainability vs. the Other Goals

The millennium development goals (MDGs) for the year 2015, adopted by the United Nations in the year 2000 (http://mdgs.un.org), are:

1. eradicate extreme poverty and hunger;
2. achieve universal primary education;
3. promote gender equality and empower women;
4. reduce child mortality;
5. improve maternal health;
6. combat HIV/AIDS, malaria, and other diseases;
7. ensure environmental sustainability; and
8. develop a global partnership for development.

Substantial but uneven progress is being made toward these goals (United Nations, *Millennium Development Goals Report*, 2013). Economic growth has been the most effective path toward meeting the MDGs. For example, the growth of the economies of China, India, and other increasingly wealthy countries has reduced poverty and hunger for millions of people. As poverty and hunger are reduced, maternal and child health improves, female literacy increases, and this tends to stabilize population (Wardatul, 2002). However, as the wealth of this stable population increases, energy consumption and pollution increase. Thus, economic development helps achieve MDGs 1 through 6 but makes environmental sustainability (MDG 7) harder (Moran, Wachernagel, Kitzes, Goldfinger, and Boutaud, 2008; Togtokh, 2011).

As we celebrate (or mourn) the birth of the seven billionth human inhabitant of our planet (Tollefson, 2011), our most important challenge is how to promote development to avoid poverty while modifying development to avoid global pollution. We have no examples of increasing economic development without increasing energy consumption and CO_2 emissions (Rosling, 2009, 2010, 2011; Emerson, Levy, Esty, et al., 2010), so the challenge before us is an unprecedented and difficult one (Wilson, 2002). Where is the safest passage to sustainable development in a high-population world, where the use of our oceans and atmosphere as common waste sinks (Fig. 2.1) can no longer be taken for granted (Hardin, 1968, 1974; Daly, 1996, 2005)?

> The factors that have historically underpinned population health gains are now, by dint of their much increased scale, scope, and intensity, undermining sustainable good health as we exceed Earth's capacity to renew, replenish, provide, and restore. (McMichael and Butler, 2011)

Figure 2.1 Two ecospheres of different sizes (left: $\sim 10^7$ m; right: $\sim 10^{-1}$ m). Both are powered by sunlight but are otherwise self-sustaining—you never have to feed them. The larger one, on the left, is thought to be less susceptible to ecological collapse because of having more diversity in life forms. However, these life forms are constrained to live in the relatively thin surface layer, one-tenth as thick as the green line. The ecosphere on the right contains only purified seawater, algae, bacteria, and marine shrimp and has been known to last ~18 years (www.eco-sphere.com/about.html). An intermediate-sized ecosphere is described in Sagan (1990). Left image: NASA, Noon in Mozambique, 7 December, 1972.

An important policy debate is going on between neoclassical economists and ecological economists that explores whether economic life on our planet is limited. Neoclassical opinion is that "there are no . . . limits to the carrying capacity of the Earth that are likely to bind any time in the foreseeable future . . . . The idea that we should put limits on growth because of some natural limit, is a profound error . . ." (Summers, 1991; Solow, 1974; Stiglitz, 1979). Ecological economists, on the other hand, are ambitiously trying to recognize and measure the environmental overheads and weigh the trade-offs between the good and bad products of economic growth (Rees, 1992; Wackernagel and Rees, 1996; Daly, 1997a, 1997b). The argument centers around two points—which aspects of the economy are knowledge based and have no identifiable limits (or limits we haven't reached yet [Johnson, 2000]), and which aspects have thresholds beyond which growth is uneconomic and if continued will lead to ecological collapse (Rockström, Steffen, Noone et al., 2011; Diamond, 2004). Fishing is an example of the latter:

> The annual fish catch is now limited by the natural capital of fish populations in the sea and no longer by the man-made capital of fishing boats. Weak sustainability would suggest that the lack of fish can be dealt with by building more fishing boats. Strong sustainability recognizes that more fishing boats are useless if there are too few fish in the ocean and insists that catches must be limited to ensure maintenance of adequate fish populations for tomorrow's fishers. (Daly, 2005)

Forty years ago, Georgescu-Roegen (1971, 1975) introduced the concept of entropy into economics (Schneider and Sagan, 2005). There has been controversy ever since about what kinds of goods are subject to the second law of thermodynamics (Daly, 1997a, 1997b). Ecological economists, such as Daly (2005), invoke entropy as the ultimate limit on sustainability:

> [L]ack of sustainability is predicted by the first two laws of thermodynamics, namely that energy is conserved (finite) and that systems naturally go from order to disorder (from low to high entropy). Humans survive and make things by sucking useful (low-entropy) resources-fossil fuels and concentrated minerals--from the environment and converting them into useless (high-entropy) wastes. The mass of wastes continuously increases (second law) until at some point all the fuel is converted to useless detritus. (Daly, 2005)

To understand the limits of economic growth and to chart a path between the Scylla of poverty and the Charybdis of pollution, we need to understand what sets the limits on the earth's capacity to "renew, replenish, provide and restore." At what point will all the fuel be "converted to useless detritus"? It is easy to run out of fuel if you don't have a fuel gauge.

A good place to begin the task of devising a reliable fuel gauge for the planet is with the laws of thermodynamics. Daly is correct when he asserts that "at some point," all fuel will be converted to useless detritus. That is the inevitable ultimate result of the second law: $dS \geq 0$. However, the "some point" is rather far in the future. The universe will reach a heat death ~10,000 googol years (10^{104} years) from now, when there will be no more stars to shine (Egan and Lineweaver, 2010). A "lack of sustainability" is only "predicted by the first two laws of thermodynamics" on time scales longer than a billion years. There are two sources of the earth's capacity to "renew, replenish, provide and restore." For the life of the biosphere (estimated to be another billion years [Caldeira and Kasting, 1992; Lenton and von Bloh, 2001; Lovelock and Whitfield, 1982]), we can count on the fusion of hydrogen in the sun and the temperature gradient between the hot interior and the cold surface of the earth (Korenaga, 2008) to supply the earth with low-entropy energy to power winds, rain, and the biosphere and naturally recycle wastes that life forms produce. The sun provides ~300 W/m^2, while the heat of the earth's interior provides ~0.1 W/m^2 at the surface. The earth's surface and the biosphere will continue to be replenished by the supply of low-entropy free energy from these two sources—driving plate tectonics that build mountains and the hydrological cycle that erodes them down and driving volcanism that replenishes the nutrients in the soils and rains that leach the nutrients out, while providing freshwater at a given rate. That rate sets the rate of sustainable extraction. Thus, for the next billion years on the earth, the second law, $dS \geq 0$, is not the problem. The problem is much more immediate—the current rate of entropy increase is larger than a sustainable rate:

$$(dS/dt)_{\text{current}} > (dS/dt)_{\text{sustainable}} \tag{2.1}$$

We are digging up and burning fossil fuels faster than nature is burying them. We are drinking and irrigating with freshwater faster than the clouds, rivers, and aquifers can supply it (Trenberth, Smith, Qian, Dai, and Fasullo, 2007; Wada, van Beek, van Kempen, 2010), and we are mining minerals faster than plate tectonics can create new deposits.

The amount of freshwater that the earth can produce is limited by the input of free energy from the sun, which evaporates surface water and drives convection cells and winds, which carry the clouds over the land, where freshwater falls as rain, recharging the rivers, ponds, aquifers, and plants (Kleidon, 2010; Lineweaver, 2010). As is the case for the fish in the sea, the highest rate at which water can be sustainably extracted is the natural rate at which the hydrological cycle, driven by the sun, can supply it. At faster rates, aquifer water levels get lower and wells get deeper. Much of civilization (farms, desalinization plants, oil refineries, modern fisheries, and mining) is based on speeding up the natural production of food, water, and almost anything that can be made with electricity.

2.2 Energy Conservation, Entropy Increase

Understanding the role played by the first and second laws of thermodynamics can help us measure the carrying capacity of natural recycling and the price of speeding it up or overloading it (Emerson, Levy, Esty, et al., 2010). Understanding energy and entropy can help resolve the tension between development and global pollution—or at least help us think less myopically about the trade-offs. Energy conservation (first law) and entropy increase (second law) are the unifying concepts that connect gravitational collapse to nuclear fusion, fusion to sunlight, and sunlight to food, to the carrying capacity of the earth and to sustainable development. First, let's review the sources of energy.

Figure 2.2 shows the most familiar sources of energy in the universe. As mass falls into a gravitational well (Fig. 2.2A), its gravitational potential energy can be used to do work (e.g., hydroelectric power from dammed rivers and geothermal energy left over from accretion of the earth). As protons and neutrons (Fig. 2.2B) fall deeper into a nuclear potential, they release energy in the form of gamma ray photons, which emerge as visible photons from the photosphere of the sun. These photons power the hydrological cycle, ocean currents, solar cells, windmills, and phototrophic life forms. For example, in cyanobacteria and plants, solar photons excite electrons into higher-energy states, dissociating water and CO_2 to produce carbohydrates and free oxygen. We aerobic animals breathe oxygen and oxidize these high-energy electrons down into lower-energy states (ΔE in Fig. 2.2C). We live off this ΔE.

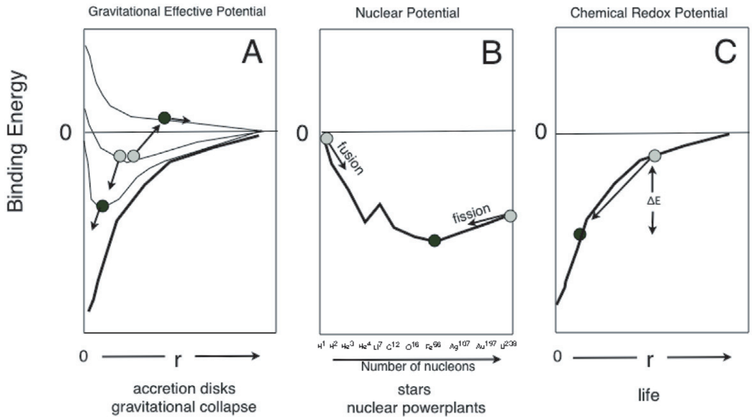

Figure 2.2 Sources of energy associated with three forces: gravity (A), the strong nuclear force (B), and electromagnetism (C). In A, gravitational binding energy is released when a particle falls deeper into the potential well. In B, nuclear potential energy is released when nuclei become more tightly bound through fusion (stars) or fission (nuclear reactors). In C, electrons release energy as they become more tightly bound into atoms and molecules (biological redox reactions).

Free energy can be extracted from the binding energies in Fig. 2.2 because the universe did not start out in a maximally bound ground state. The universe started out with potential energy. Unbound things have been able to fall into the three types of potential wells and release potential energy. For example, matter started out unclumped. As it falls and clumps into gravitational potential wells, it releases energy. Also, the hot big bang did not fuse all elements into iron. Rather, it left us with hydrogen, which can fall (fuse) into helium and eventually into iron, producing starlight.

Since energy is always conserved (first law of thermodynamics), “consuming” energy, “wasting” energy, or “saving” energy has nothing to do with the amount of energy. It has to do with consuming, wasting, and saving a specific kind of useful, low-entropy energy that is called free energy (F in Fig. 2.3). This is energy, such as the gravitational potential energy of unclumped matter or the nuclear potential energy of unfused hydrogen or the electrostatic energy of excited electrons (Fig. 2.2A–C), that can do work and has not yet been converted into waste heat (TS in Fig. 2.3).

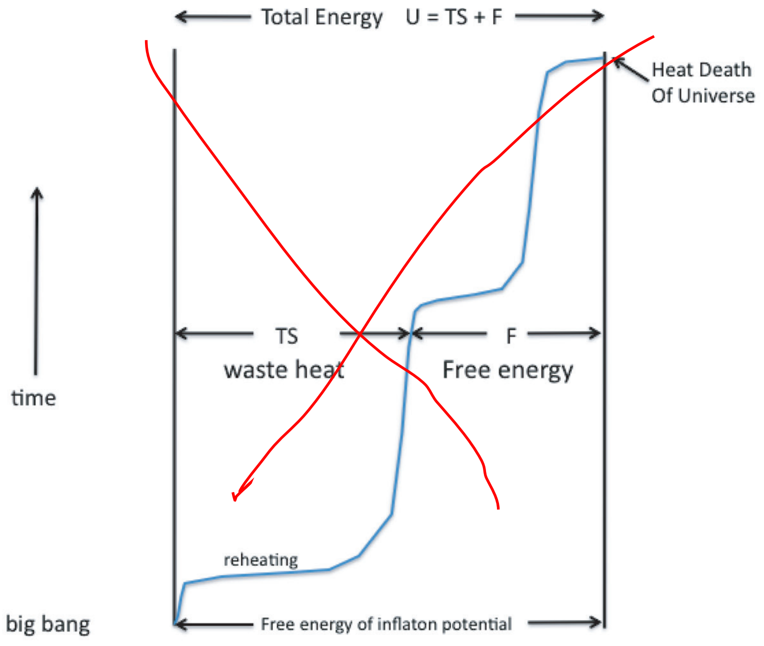

Figure 2.3 The big bang produced a low-entropy universe full of free energy (bottom of the plot). The total energy U is the sum of the waste heat TS and the free energy F. The second law ensures that with time, all of the free energy is converted into waste heat. This will occur at the heat death of the universe ~10,000 googol years from now, when there is no longer any free energy to sustain any life (Egan and Lineweaver, 2010). Figure modified from Lineweaver and Egan, 2012.

Figures 2.3 and 2.4 show how free energy is, with the passage of time, inevitably converted into waste heat or high-entropy energy. This is the unavoidable second law of thermodynamics (entropy increase $dS \geq 0$) in action. The free energy available at one level comes from the level below it. Starting at the top of Fig. 2.4, we heterotrophs (e.g., humans and pigs) depend on phototrophs (plants) for our free energy. Phototrophs get their free energy from the photons produced by the nuclear potential energy of fusion in the sun. The nuclear potential energy was made available only because of the gravitational potential energy of unclumped matter (Fig. 2.2A), which clumped and formed stars whose cores were hot enough to access the free energy of unfused hydrogen left over from the incomplete fusion of the hot big bang (Fig. 2.2B).

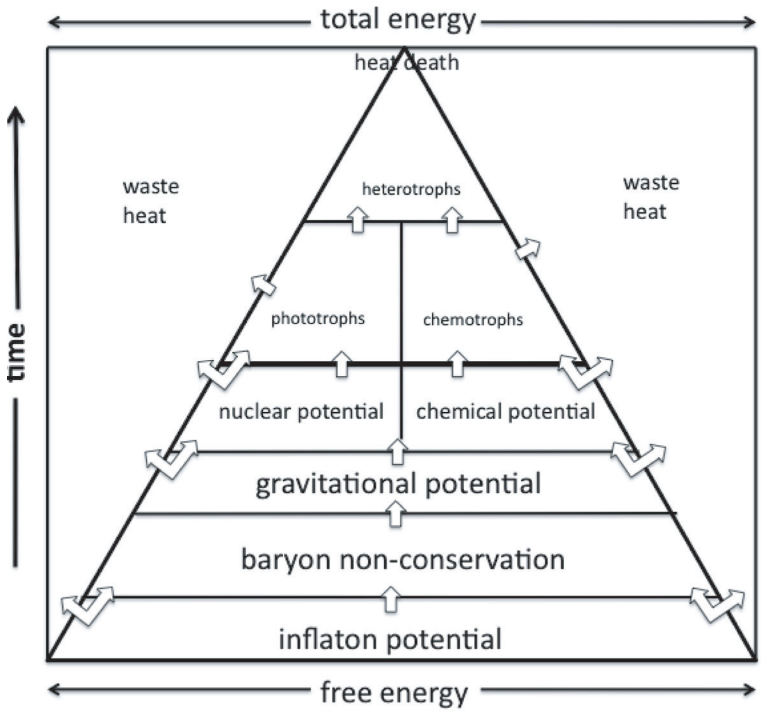

Figure 2.4 Universal trophic pyramid. The initial sources of low-entropy free energy at the bottom ("inflaton potential" and "baryon non-conservation") appeared within the first nanosecond after the big bang. The sources above them are still active today and are continually getting converted into high-entropy waste heat as their free energy drives more processes, spreading into smaller scales as waste heat is produced by dissipative structures (white arrows). The amount of free energy available narrows and disappears at the top (see also Fig. 2.3). As time goes by, free energy is converted into waste heat until the universe reaches a heat death.

The amount of free energy in unclumped matter (Fig. 2.2A) sets the amount of free energy available in gravity, represented by the width of the "gravitational potential" band of the trophic pyramid in Fig. 2.4. But what is the origin of this unclumped matter? Matter exists because of the process of baryon nonconservation non-conservation that occurred within the first nanosecond after the big bang. Baryon nonconservation non-conservation produced a one-part-in-a-billion excess of matter over antimatter (Sakharov, 1967). All the antimatter combined with matter and produced photons (which became the cosmic background radiation) and left a one-part-in-a-billion excess of matter (baryons). This excess is all the matter around us today. Without baryon nonconservation non-conservation, equal amounts of matter and antimatter would have been produced. Their mutual annihilation would have left only photons. Photons do not clump, and therefore there would be no "gravitational potential." The photons would have been maximum-entropy energy, with zero free energy, and could not have produced galaxies, stars, planets, or life (Lineweaver and Egan, 2008). Thus, baryon nonconservation non-conservation is responsible for the excess of matter and the free energy associated with this excess.

But what is responsible for there being any matter or antimatter in the first place? Our best ideas about the origin of matter and antimatter involve an epoch of rapid expansion during the early universe that happened $\sim 10^{-43}$ seconds or $\sim 10^{-35}$ seconds after the big bang (Kolb and Turner, 1990; Lyth and Liddle, 2009). Inflation took the tiny, irreducible virtual fluctuations of the vacuum and expanded them by many orders of magnitude. This is represented by the arrow on the right side of Fig. 2.5 labeled "inflation." Inflation lasted less than a nanosecond and came to an end during a process called reheating, when the energy of these inflated, formerly virtual quantum fluctuations were dumped relatively homogeneously into the universe in the form of radiation, matter, and antimatter. The level of the inflation potential above the ground state of the vacuum determined the amount of energy that was dumped into the universe, but we have very little knowledge about what set that level. Thus, we don't know what is beneath the ~~inflation~~ inflaton potential in the trophic pyramid of Fig. 2.4.

Some energy can be used to do work, while other energy cannot. The capacity of energy to do work has to do with the number of degrees of freedom over which that energy is distributed. The energy in light is distributed over the number of photons. The chemical

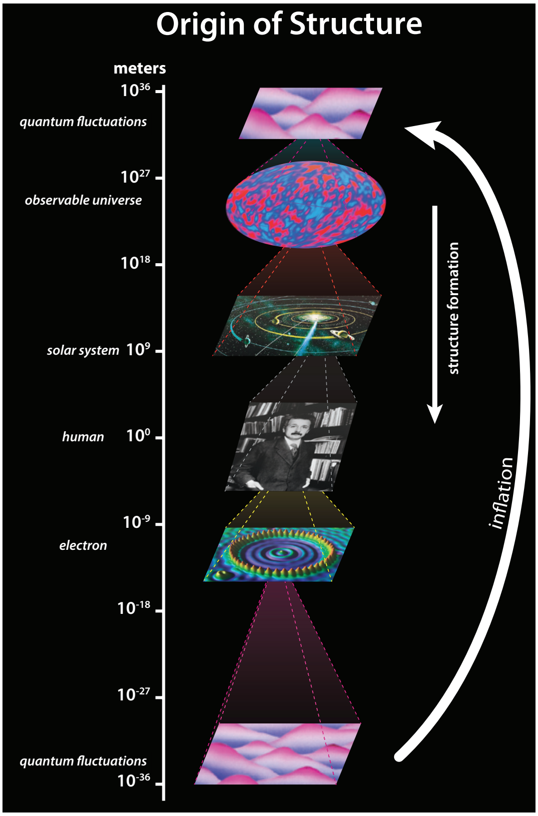

Figure 2.5 The origin of structure. The inflation of quantum fluctuations is responsible for all the structures in the universe. The tick marks on the vertical size axis are separated from each other by 9 orders of magnitude. During a brief period 10^{-43} seconds or 10^{-35} seconds after the big bang, quantum fluctuations at the Planck scale (10^{-35} m) inflated into the largest over- and underdensities of matter, currently observable as temperature fluctuations in the cosmic microwave background. The overdensities gravitationally collapsed to form large-scale structures, galaxies, stars, planetary systems, and life forms (Lineweaver and Egan, 2008). Thus, when we discovered the temperature fluctuations in the cosmic microwave background radiation (Smoot, Bennett, Kogut et al., 1992; second image from the top), we discovered Planck-scale quantum fluctuations that had been magnified by inflation to scales larger than the observable universe. Thus, we simultaneously discovered the largest and the smallest structures ever observed. This is probably the most profound and direct connection between the largest and the smallest scales in the universe.

energy in petrol is distributed over the number of molecules in the petrol. The energy in a nuclear power plant is distributed over the number of radioactive nuclei. The potential energy of water behind a dam is distributed over only one degree of freedom—the height of the water. As energy is distributed over a larger number of degrees of freedom, it becomes waste heat, incapable of providing any free energy to do work. Thus, the concept of "degrees of freedom" (Fig. 2.6) is central to understanding entropy. For example, 300,000 years after the big bang, the entire universe was filled with hot plasma, at approximately the same temperature. That was a lot of energy. But since the plasma was all at the same temperature, it was in thermal equilibrium, at maximum entropy, which means that the energy was spread over the largest possible number of degrees of freedom. No work or free energy could be extracted from all that maximally spread out, maximum-entropy energy. As the universe expanded, this cosmic background radiation expanded isentropically, so it continued to be at thermal equilibrium and unable to do work. The source of all the free energy and structure in the universe was not this background radiation but the low-entropy gravitational potential energy of unclumped matter, in Fig. 2.4 (Penrose, 2004; Lineweaver and Egan 2008, 2012). Only low-entropy energy—out of equilibrium—provides an energy gradient that can make winds blow and maintain life (Schroedinger, 1944; Lineweaver and Egan, 2008).

2.3 Plenty of Room at the Bottom

Nanotechnology is a relatively new field, primarily involved with the discovery and exploration of the properties of matter in the size range of roughly 1–100 nm (10^{-9}–10^{-7} m). In 1959, Feynman launched the field of nanotechnology with his paper "There's Plenty of Room at the Bottom." His point was that the size of the smallest parts of technological devices ($\sim 10^{-3}$ m) was much bigger than the sizes of the smallest possible parts—atoms and molecules—at the "bottom" ($\sim 10^{-10}$ m). Therefore, there was plenty of room ($\sim$7 orders of magnitude in size) between technology and nanotechnology for design miniaturization. His proof of concept was the existence of life. The nanometer-sized biomolecular machines of life continuously manipulate atoms and molecules to perform the useful work we know as metabolism. If molecular evolution could blindly design such machines, why couldn't we design them too?

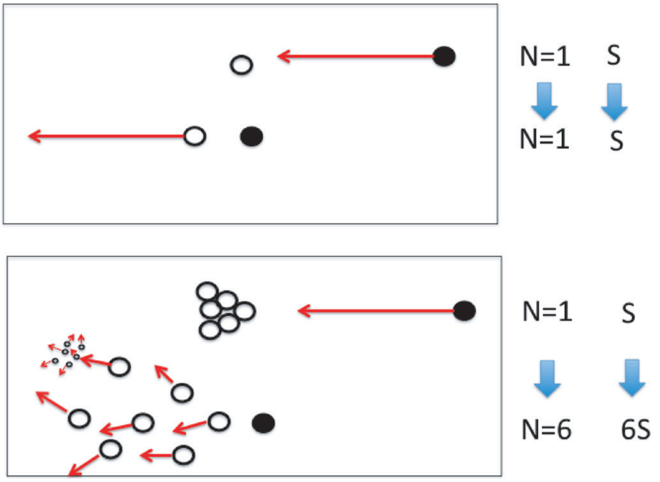

Figure 2.6 Entropy and degrees of freedom. Any increase of entropy is an increase in the number of degrees of freedom over which the given energy is distributed. In the top panel, the kinetic energy K of the black ball of mass m and velocity v is $K = 1/2\ mv^2$. The initial number of degrees of freedom is equal to the number of balls over which this energy is distributed: $N = 1$. The black ball hits the white ball, transferring all its kinetic energy but without increasing the number of degrees of freedom, which remains $N = 1$. Thus, the final entropy is equal to the initial entropy, $S_{\text{final}} = S_{\text{initial}}$. In the lower panel, when the black ball hits six white balls, $N = 1$ becomes $N = 6$ and $S_{\text{final}} = 6S_{\text{initial}}$. Entropy increases by a factor of 6 because the number of degrees of freedom increases by a factor of 6. The six smallest white balls on the left suggest that each larger white ball can begin a cascade by colliding with smaller balls, spreading the initial kinetic energy over an ever-larger number of degrees of freedom, until the energy reaches "the bottom" and becomes waste heat because it is spread over atoms and molecules—the smallest, most numerous balls. Figure modified from Lineweaver and Egan (2012).

Here, we co-opt Feynman's phrase "plenty of room at the bottom" to describe the current state of the energy of the universe. It concisely summarizes the concept that there is still plenty of room (= degrees of freedom) at the bottom for entropy to increase. The entropy of the energy of the universe started out low and has not yet reached its maximum (Fig. 2.3). The available free energy of the universe has not yet been turned into waste heat by being spread over the large number of degrees of freedom at the bottom, among the atoms and molecules or photons, as molecular waste heat or photon waste heat. Since molecular waste heat is contained in matter and matter clumps into black holes, and black holes eventually evaporate into photons, the maximum-entropy state of the energy of the universe—the "bottom"—will be after this last step, when all the energy is distributed over the maximum number of degrees of freedom as photons (Egan and Lineweaver, 2010).

The most efficient conversion of energy into work is a conversion that keeps the energy distributed over the smallest number of degrees of freedom. A heat engine converts chemical energy (with one degree of freedom per molecule of fuel) by first burning the chemical to create heat, thereby distributing its concentrated chemical energy into the more dilute kinetic energy of many molecules. For a heat engine operating between a high temperature T_{in} and a low temperature T_{out}, the maximum efficiency η is the ratio of the work out to the work in, which can be written as (Bejan, 2006):

$$\eta = 1 - T_{out}/T_{in} \tag{2.2}$$

This efficiency depends on the ratio of temperatures. For example, the temperature of an internal combustion engine $T_{in} \approx$ 800 K, while the exhaust $T_{out} \approx$ 400 K. Therefore, the efficiency with which the heat inside the cylinder is turned into work cannot be more than ~50% (= 1 – 400/800). This is the maximum efficiency of internal combustion engines because they must have T_{in} low enough to maintain the structural integrity of their cylinders and pistons. Jet engines can get efficiencies as high as ~70% by having much higher values of T_{in}.

Although a solar cell is not a heat engine, we can use Eq. 2.2 to get an idea of the maximum efficiency of a solar cell converting solar photons ($T_{in} \approx$ 6000 K) into work at the ambient temperature of the earth ($T_{out} \approx$ 300 K). We get η = 1 – 300/6000 ≈ 0.95. Thus, at the earth's surface, 95% of the energy of the solar photons can be converted to useful work.

Life has learned how to take advantage of nanotechnology, not just in its design but in its efficient energy consumption. Animal muscles are an excellent example of energy-efficient biomolecular nanotechnology. They perform work at a single temperature, so they are not heat engines driven by a temperature difference. Muscles convert chemical energy to work without high-temperature combustion. The reason muscles can access so much power so quickly is because the energy in adenosine triphosphate (ATP) can be stored—like water behind a dam—in one degree of freedom. ATP is the petrol that when oxidized supplies the muscle with free energy, and this oxidation occurs without loss of energy to a larger number of degrees of freedom. ATP is not burned. Instead, it is able to drive reactions without spreading its energy into heat first.

Recognizing that muscles must obey the second law, Jaynes (1989) generalized Eq. 2.2 to nonequilibrium situations (specifically animal muscles) by recognizing that the unit of energy E_{in} driving muscles is a single molecule of ATP. We can express E_{in} as an effective temperature with $E_{\text{in}} = 1/2\ N_{\text{in}}\ kT_{\text{in}}$, where $N_{\text{in}} = 1$ is the number of degrees of freedom over which E_{in} is distributed and k is Boltzman's constant. Thus, we have $T_{\text{in}} \approx 2E_{\text{in}}/k$. Plugging this into Eq. 2.2 yields a generalized nonequilibrium equation for maximum efficiency for extracting useful work from energy in one degree of freedom:

$$\eta = 1 - kT_{\text{out}}/(2E_{\text{in}}) \tag{2.3}$$

Just as in Eq. 2.2, the efficiency goes up if the ambient temperature T_{out} can be decreased, and the efficiency also goes up if the amount of energy E_{in}, carried in the energy molecule, goes up. Requiring an efficiency greater than zero also tells us that any biomolecule used as an energy currency must satisfy $E_{\text{in}} > (1/2)\ kT_{\text{out}}$. Inserting values into Eq. 2.3, Jaynes (1989) found that animal muscles have an efficiency of ~70%, much higher than the ~50% maximum efficiency of internal combustion engines.

2.4 Sustainable Maximum Entropy Production?

Life forms are a subset of the organized structures in the universe known as far-from-equilibrium dissipative systems (FarFEDS) (Prigogine, 1978; Schneider and Sagan, 2005; Lineweaver and Egan, 2008). FarFEDS are dissipative structures that, while maintaining their structure, convert low-entropy energy to high-entropy energy. They include galaxies, stars, convection cells, typhoons, fires, humans, and bacteria. All FarFEDS (and thus all life forms) extract free energy from the environment and turn it into waste heat faster than random processes such as diffusion would be able to do. Density, temperature, pressure, and chemical redox gradients in the environment, when steep enough, give rise to FarFEDS, which emerge spontaneously from the gradients to hasten the destruction of the gradients that spawned them. This represents a paradigm shift from “we eat food” to “food has produced us to eat it” (Lineweaver and Egan, 2008).

A growing number of researchers are investigating an extension of the second law, called the maximum entropy production principle (MEPP) (Kleidon and Lorenz, 2005; Dewar, Lineweaver, Niven, and Regenauer-Lieb, 2014 ~~2012~~). Under this principle, the terrestrial biosphere is a system that was spawned by gradients of free energy. Instead of interpreting the free-energy consumption of life’s metabolisms as an imperative of Darwinian evolution, an alternative interpretation based on the MEPP is possible: life originated like a hurricane or a convection cell in order to increase entropy by destroying the gradient that made it. Life has evolved and diversified not only to stay alive but also, quite possibly, to maximize the long-term production of entropy.

If this MEPP hypothesis is correct, one could easily imagine that the natural tendency of all life (and all FarFEDS) is to produce as much entropy as possible, as quickly as possible. Everything should just burn. However, as the fable of the tortoise and the hare shows, there is more than one way to win a race. The total amount of entropy produced during a time t is:

$$S = \int_0^t (dS/dt)\, dt \qquad (2.4)$$

Recalling Eq. 2.1, $(dS/dt)_{\text{current}} > (dS/dt)_{\text{sustainable}}$, we can insert our current unsustainable rate of entropy production into Eq. 2.4. However, because $(dS/dt)_{\text{current}}$ is unsustainable, it can only go on for some limited amount of time, t_{collapse}, until the ecosystem collapses and many (or all) of its biological components go extinct. With a sustainable dS/dt, we can integrate much longer, $t_{\text{sustainable}} >> t_{\text{collapse}}$. Thus, we obtain the simple result that a slower, sustainable level of entropy production is consistent with the MEPP:

$$S_{\text{sus}} = \int_0^{t_{\text{sustainable}}} (dS/dt)_{\text{sustainable}}\, dt > S_{\text{collapse}}$$
$$= \int_0^{t_{\text{collapse}}} (dS/dt)_{\text{current}}\, dt \tag{2.5}$$

or, in simpler form, assuming constant dS/dt:

$$t_{\text{sustainable}}\, (dS/dt)_{\text{sustainable}} > t_{\text{collapse}}\, (dS/dt)_{\text{current}} \tag{2.6}$$

Life forms, especially diverse ecosystems, unlike hurricanes and fires, allow for slower, more consistent, and continuous exploitation of free-energy gradients over time. For example, the slow and continuous oxidation of aerobic respiration can be more efficient in the long run at producing entropy than the rapid, short-lived oxidation of a forest fire. When life is present, more entropy can be produced over the long run.

Life has the ability to store low-entropy fuel for later use—for example, in the form of sugars or fat or in grain silos—which allows life to persist when low-entropy energy sources are temporarily in short supply. A forest fire that runs out of fuel will go out, but a snake may go without eating for six months at a time. Life forms have the potential to persist and continue to create entropy, when other FarFEDS would fizzle.

Life forms also have the advantage of being able to exploit a wider variety of low-entropy fuels. Life forms store and reproduce information in their DNA, which allows them to evolve to take advantage of changing environmental conditions and to live off the energy gradients created by other life forms. As one life form creates waste from a low-entropy source (e.g., as plants produce oxygen from CO_2 in the process of photosynthesis), another life form (animals) evolves to make use of that waste. Life forms have evolved into intricate systems of interdependence and diversity. Diversity contributes to life's ability to maximize entropy, by evolving catalysts to turn a larger variety of chemical redox potentials into waste heat.

If increasing entropy is the goal, life forms contribute to this goal in ways that other FarFEDS cannot. Life's ability to increase entropy depends, however, on its ability to sustain itself over time. When we life forms quickly use up the stores of low-entropy resources that have been built up over millions of years (freshwater, fossil fuels, mineral deposits, and wild fish and other game), we are behaving like a fire, and like a fire, we will go out and be replaced by less profligate life forms.

2.5 Conclusion

As the nations of the world converge in health and wealth and the human population begins to stabilize, economic development is producing pollution that is beginning to be felt on a global scale. We are burning fossil fuels to produce electricity to make stuff (Leonard, 2010), run desalinization plants to provide freshwater faster than the earth can do it, and make fertilizers to make food faster than is sustainable. Producing this electricity with fossil fuels is giving us a global problem with CO_2. Similarly, burning fossil fuel to produce electricity to run air purifiers to remove the air pollution from burning fossil fuel is a short-term solution causing long-term problems. It is like using an air conditioner to cool an apartment that is too hot because of the heat output of a refrigerator. It is solving the immediate local problem by making the long-term global problem worse. This is unsustainable development and has been described by Hardin (1968) as the tragedy of the commons (see also Buck, 1998). We are borrowing from the future and running up a debt on our children's credit cards.

The earth is not a perpetual motion machine. There are two sources of the earth's capacity to maintain the biosphere and process its pollution. The dominant source is the sun, and the secondary source is the heat of the earth's interior. Saving energy (using energy efficiently) means keeping the energy distributed over a smaller number of degrees of freedom. Animal muscle is an example of nanotechnological design and nanotechnological energy efficiency.

Life can be understood as a product of the MEPP. In this view, life evolved to produce the maximum amount of entropy. Maximum use of low-entropy energy sources over time means that the pace of exploitation of resources does not outstrip the pace of renewal, that biodiversity should be as large as possible, and that populations are kept at sustainable levels. Sustainability and the biosphere's variety of efficient metabolisms are the result of Darwinian evolution, but the origin of life and Darwinian evolution can be understood as a result of a more basic principle of entropy maximization. For the past four billion years, it is possible that the biosphere has sustainably maximized the entropy produced on the earth.

Acknowledgments

We thank Aditya Chopra for help in making Fig. 2.5. We also thank the big bang for making this research possible.

References

Bejan, A. (2006). *Advanced Engineering Thermodynamics.* Hoboken, NJ: Wiley.

Buck, S. J. (1998). *The Global Commons.* Washington, DC: Island Press.

Caldeira, K., and Kasting, J. F. (1992). The life span of the biosphere revisited. *Nature,* **360**, 721.

Daly, H. E. (1996). *Beyond Growth: The Economics of Sustainable Development.* Boston, MA: Beacon Press.

Daly, H. E. (1997a). Georgescu-Roegen versus Solow/Stiglitz. *Ecol. Econ.,* **22**, 261–266.

Daly, H. E. (1997b). Reply to Solow/Stiglitz. *Ecol. Econ.,* **22**, 271–273.

Daly, H. E. (2005). Economics in a full world. *Sci. Am.*, **293**, 3.

Dewar, R., Lineweaver, C. H., Niven, R., and Regenauer-Lieb, K. (2014). *Beyond the Second Law: Entropy Production and Non-Equilibrium Systems.* Heidelberg: Springer.

Diamond, J. (2004). *Collapse: How Societies Choose to Fail or Succeed*. New York, NY: Viking.

Egan, C. A., and Lineweaver, C. H. (2010). A larger estimate of the entropy of the universe. *Astrophys. J.*, **710**, 1825.

Emerson, J., Levy, M.A., Esty, D.C., Mara, V., Kim, C., de Sherbinin, A., Srebotnjak, T., and Jaiteh, M. (2010). *2010 Environmental Performance Index, Yale Center for Environmental Law and Policy*, http://epi.yale.edu/Files.

Feynman, R. P. (1960). There's plenty of room at the bottom: an invitation to enter a new field of physics. *CalTech's Engineering and Science Magazine*. Transcript of a lecture to the American Physical Society, Caltech, 29 December 1959.

Georgescu-Roegen, N. (1971). *The Entropy Law and the Economic Process.* Cambridge, MA: Harvard University Press.

Georgescu-Roegen, N. (1975). Energy and economic myths. *South. Econ. J.*, **41**(93), 347–381.

Hardin, G. (1968). Tragedy of the commons. *Science*, **162**, 1243–1248.

Hardin, G. (1974). Living on a lifeboat. *BioScience,* **24**(10), 561–568.

Jaynes, E. T. (1989). Clearing up mysteries: the original goal. In *Proceedings Volume Maximum Entropy and Bayesian Methods* (Skilling, J., ed.). Dordrecht, Holland: Kluwer Academic, 1–27.

Johnson, D. G. (2000). Population, food, and knowledge. *Am. Econ. Rev.* **90**(1), 1–14.

Kleidon, A. (2010). Life, hierarchy and the thermodynamics machinery of planet earth. *Phys. Life Rev.*, **7**(4), 424–460.

Kleidon, A., and Lorenz, R. D. (2005). *Non-Equillibrium Thermodynamics and the Production of Entropy: Life, Earth and Beyond.* Heidelberg, Germany: Springer.

Kolb, E., and Turner, M. S. (1990). *The Early Universe.* White Plains: NY: Addison-Wesley.

Korenaga, J. (2008). Urey ration and the structure and evolution of earth's mantle. *Rev. Geophys.*, **46**, 241.

Lenton, T. M., and von Bloh, W. (2001). Biotic feedback extends the life span of the biosphere. *Geophys. Res. Lett.,* **28**(9), 1715–1718.

Leonard, A. (2010). *The Story of Stuff*, www.youtube.com/storyofstuffproject#p/u/22/9GorqroigqM.

Lineweaver, C. H. (2010). Spreading the power: comment on "Life, hierarchy, and the thermodynamics machinery of planet earth." *Phys. Life Rev.,* **7**, 463–464.

Lineweaver, C. H., and Egan, C. A. (2008). Life, gravity and the second law of thermodynamics. *Phys. Life Rev.*, **5**, 225–242.

Lineweaver, C. H., and Egan, C. A. (2012). The initial low gravitational entropy of the universe as the origin of design in nature. In *Origins of Design in Nature: A Fresh, Interdisciplinary Look at How Design Emerges in Complex Systems, Especially Life* (Swan, L. S., Gordon, R., and Seckbach, J., ed.). Dordrecht, Netherlands: Springer.

Lovelock, J. E., and Whitfield, M. (1982). Lifespan of the biosphere. *Nature,* **296**, 561.

Lyth, D. H., and Liddle, A. R. (2009). *The Primordial Density Perturbation: Cosmology, Inflation, and the Origin of Structure.* UK: Cambridge University Press.

McMichael, A. J., and Butler, C. D. (2011). Promoting global population health while constraining the environmental footprint. *Annu. Rev. Public Health*, **32**, 179–197.

Moran, D. D., Wachernagel, M., Kitzes, J. A., Goldfinger, S. H., and Boutaud, A. (2008). Measuring sustainable development: nation by nation.

Ecol. Econ., **64**, 470–474, http://www.dcmetrosftp.org/newsletters/NL20061201.html#pop.

Penrose, R. (2004). *The Road to Reality: A Complete Guide to the Laws of the Universe.* London: Jonathan Cape.

Prigogine, I. (1978). Time, structure and fluctuations. *Science*, **201**, 777–785.

Rees, W. E. (1992). Ecological footprints and appropriated carrying capacity: what urban economics leaves out. *Environ. Urban.*, **4**(2), 121–130.

Rockström, J., Steffen, W., Noone, K., et al. (2011). A safe operating space for humanity. *Nature*, **461**, 472.

Rosling, H. (2009). *Hans Rosling: Let My Dataset Change Your Mindset*, www.ted.com/talks/hans_rosling_at_state.html.

Rosling, H. (2010). *Hans Rosling: Global Population Growth, Box by Box*, www.ted.com/talks/hans_rosling_on_global_population_growth.html.

Rosling, H. (2011). *Hans Rosling: The Magic Washing Machine,* www.ted.com/talks/hans_rosling_and_the_magic_washing_machine.html.

Sagan, D. (1990). *Biospheres: Reproducing Planet Earth*. New York: NY: Bantam Books.

Sakharov, A. D. (1967). Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe. *J. Exp. Theor. Phys. Lett.*, **5**, 24–27.

Schneider, E. D., and Sagan, D. (2005). *Into the Cool: Energy Flow, Thermodynamics and Life.* Chicago, IL: University of Chicago Press.

Schroedinger, E. (1944). Cambridge, UK:Cambridge University Press.

Smoot, G. F., Bennett, C. L., Kogut, A., et al. (1992). Structure in the COBE differential microwave radiometer first-year maps. *Astrophys. J.,* **396**, L1–L5.

Solow, R. (1974). The economics of resources or the resources of economics. *Am. Econ. Rev.,* **64**(2), 1–14.

Stiglitz, J. E. (1979). A neoclassical analysis of the economics of natural resources. In *Scarcity and Growth Reconsidered* (Smith, V. K., ed.). Baltimore, MD: RFF and Johns Hopkins Press.

Summers, L. (1991). In an interview cited in Rees, W. E. (6 April 2006). Footprints to sustainability. *UBC Rep.*, **52**(4). University of British Columbia.

Tollefson, J. (2011). Seven billion and counting. *Nature*, **478**, 300.

Trenberth, K. E., Smith, L., Qian, T., Dai, A., and Fasullo, J. (2007). Estimates of the global water budget and its annual cycle using observational and model data. *J. Hydrometeorol.: Spec. Section*, **8**, 758–769.

Togtokh, C. (2011). Time to stop celebrating the polluters. *Nature*, **479**, 269.

United Nations (2013). *Millenium Development Goals Report*, http://mdgs.un.org/unsd/mdg/News.aspx?ArticleId=75.

Wackernagel, M., and Rees, W. (1996). *Our Ecological Footprint: Reducing Human Impact on the Earth.* Gabriola Island, British Columbia, Canada: New Society Publishers.

Wada Y., van Beek, L. P. H., van Kempen, C. M., et al. (2010). Global depletion of groundwater resources. *Geophys. Res. Lett.*, **37**, L20402.

Wardatul, A. (2002). Women's education and fertility rates in developing countries, with special reference to Bangladesh. *Eubios J. Asian Int. Bioeth.,* **12**, 138–143, http://www.eubios.info/EJ124/ej124i.htm.

Wilson, E. O. (2002). The solution. In *The Future of Life*. UK: Little Brown.