Chapter 2
Thesis

In the very beginning, there was only pure energy—neither particles nor photons—and the laws of physics. As the energy has cooled and dissipated, an immense diversity of particles, elements, chemicals, organisms and structures, has been created (and also destroyed) by the blind functioning of those laws. Wealth in nature consists of complex structures of condensed ("frozen") energy, as long-lived mass. Wealth in human society is the result of conscious and deliberate reformulation and dissipation of energy and materials, consisting of frozen energy, for human purposes. This book is about both natural and human wealth creation, preservation and maximization. Knowledge is a new sort of immaterial wealth that enables us to dissipate—and utilize—that natural wealth more and more effectively for human purposes. Can the new immaterial wealth of ideas and knowledge ultimately compensate for the dissipation of natural wealth? This is the question.

During the first expansion (and cooling) of the universe, mass was distinguished from radiation by an interaction not yet well understood, but thought to be driven by the so-called "Higgs field" which (supposedly) permeates everything. All of the (several dozen) "known" elementary particles were created by what physicists call "symmetry breaking", which cannot be explained in a paragraph or even a whole chapter. (But if you are interested, look at the "Afterword" of Steven Weinberg's marvelous book, especially pp. 158–160 (Weinberg 1977). However it is clear that most particles were annihilated by anti-particles as quickly as they emerged from the "vacuum" (physics-speak for "nothingness"). So the analog of Darwinian "fitness" for elementary particles was stability and long lifetime. But, for a very, very short time (called "inflation") the baby universe expanded so fast—much faster than the speed of light—that causal linkages between particle-antiparticle pairs were broken. A few elementary particles– the electrons and protons (and the neutrons were unbound) constituting ordinary matter as we know it—survived. They are the building blocks of everything.

When the universe was about 700,000 years old it consisted of a hot, homogeneous "plasma" (~3000 K) consisting of photons, electrons, protons, neutrons and neutrinos (Weinberg 1977). That plasma was the origin of the microwave

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"background" radiation, discovered in 1965, that provided the first real evidence of the Big Bang (BB). Quantum fluctuations appeared as infinitesimal density and temperature variations in the plasma. In fact, that plasma was very smooth and uniform, homogeneous and isotropic. But those quantum fluctuations grew over time.

The next phase (as expansion continued) started with the synthesis of hydrogen and helium atoms in the hot plasma. Hydrogen atoms consist of one proton and one electron, dancing together (but at some distance) and held by electromagnetic forces. As temperatures cooled, more and more of the free electrons and free protons decided to "get hitched", as it were. But some of the free protons met and were attracted by neutrons, resulting in deuterons. The deuterons also grabbed electrons, becoming deuterium ("heavy hydrogen"). Some deuterons decided to merge with hydrogen atoms, becoming helium 3. And some of the helium 3 grabbed another neutron while other pairs of deuterons also got married, as it were, creating helium 4. *Each of these mergers took place in order to increase their "binding energy"—a kind of measure of love among the elementary particles.*

As the expansion continued and the temperature continued to drop, the free electrons and protons were "used up" and the substance of the universe became a cloud of atomic hydrogen and atomic helium. Tiny density and temperature fluctuations in the cloud, were gravitationally unstable. The symmetry of homogeneity was broken as the denser regions attracted each other gravitationally. The dense regions got still denser (as the rich nowadays get richer). This "cloud condensation" process resulted in the creation of the stars and galaxies.

As the densest central cores of the proto-stars heated up under extreme pressure, they became nuclear fusion machines. The same process of binding particles into nuclei (by irreversibly converting mass into energy) that made hydrogen atoms and atoms, carried on to form helium, boron, neon, carbon, nitrogen, chlorine, oxygen, silicon and other elements—up to iron, with atomic weight 56. All this took place in young stars. That "nucleo-synthesis" process produced light and made the stars "shine". *But it also resulted in increasing the complexity and diversity of matter. Complexity is a form of natural wealth.*

As the stars used up their fuel (i.e. hydrogen) they also got cooler and denser. The delicate balance between gravity and radiation pressure broke, and the smaller stars became very dense "white dwarves". The bigger stars, especially the ones several times as massive as our sun, collapsed into neutron stars or (maybe) "black holes". The most violent collapses of the biggest stars resulted in "supernovae", which emitted huge amounts of energy almost all at once, by galactic standards. These explosions created heavier-than iron elements by endothermic fusion, and scattered their mass all over their galaxies. Our galaxy (the "Milky Way"), which incorporates about a 100 billion stars, experiences a supernova once or twice every 100 years. When small stars die, they become white, brown and finally black dwarfs Nothing happens to them after that. *It was the catastrophic collapse—call it creative destruction—of big stars, resulting in supernovae, that made life itself and everything we care about possible.*

Some of that scattered mass of nuclei and atoms (together with fresh hydrogen) formed into new "second generation" stars. Our sun is one of those. The inner planets, including Earth, have iron cores and large stocks of all the elements, including carbon, oxygen, nitrogen and others that are essential to life. That endowment was left over from a supernova explosion that occurred about 5 billion years ago. The entire evolutionary process from the Big Bang to the creation of our sun was driven by *exergy destruction* (i.e. the second law of thermodynamics). Yet the cooling also resulted in the creation of physical structures with compartments separated by boundaries and gradients. *The process can be characterized roughly as the "condensation" of useful energy (exergy) into useful mass and massive planets, such as Earth.*

In the Earth the elements that were created in stars and supernovae have undergone gravitational condensation and separation by weight, which is why iron and nickel are predominant in the core while aluminum, silicon are concentrated in the mantle while and calcium, carbon, oxygen and other light elements are more concentrated in the crust. There are also endothermal chemical reactions powered by heat from radioactive decay of the heaviest elements. Those processes have created a variety of mineral concentrations ("ores") that can be differentiated by composition (Ringwood 1969). Our planet has also acquired a lot of water since the beginning, mostly from space, via comets and meteorites (Frank 1990). (The original endowment would have mostly boiled off, when the Earth was hot, as it did from Mars and our Moon.)

Water has an extra-ordinarily useful property: unlike most other substances, the solid phase (ice) is less dense than the liquid phase. So ice floats on top. If it sank to the bottom, the pressure would keep it solid forever. Hence, our blue planet remains liquid on the surface. water is also the "universal solvent". Not quite universal, of course, but it has been essential for the creation and spread of life.

Chemical "monomers" (small molecules), were formed as temperatures dropped, starting with molecular hydrogen, H_2. This was followed by combinations of atomic H atoms with other light elements such as C, O, N. These small molecules were synthesized, both in space (e.g. dust clouds or comets) and on Earth. It was the same process—maximization of stability as binding energy (love among the elementary particles) that accounted for the nucleosynthesis of heavier elements in the stars. As time went on, some of the light elements combined to make small molecules like CO, CO_2, HCN, H_2O, NH_3, CH_2—and so on. And these molecules began to combine with each other. This took place, mostly on the surfaces of silica dust particles in space, but partly in the early oceans.

The combinations of small molecules (monomers) was assisted by catalytic properties of the dust or rock surfaces. At a later stage, more complex molecules were able to assist in the formation of others like themselves (this is called autocatalysis). Finally polymers, consisting of long chains of simple monomers appeared. Thanks to the propensity of carbon atoms to attach to hydrogen atoms, and to each other, the most common polymers were formed from hydrocarbons and carbohydrates. Among the most important early polymers were "lipids" (fats and fatty acids). Some of these attached to phosphate (PO_4) monomers. (There was more reactive phosphorus in the oceans at the time than there is now.) Stable phospho-lipid polymers—formed by as yet unknown micro-processes—enabled the creation of protective cells with “skin”. Life was on the verge.

Protected by cell walls, more complex chemical species, such as amino acids and nucleotide bases were able to survive. One of those autocatalytic chains was ribonucleic acid (RNA). Auto-catalysis made chemical replication possible. The first living (metabolizing) cells appeared on Earth around 3.5 billion years ago. At first they were energized by chemical gradients, especially involving the oxidation of iron and sulfur. There wasn’t much “free” (atomic or molecular) oxygen around in the early oceans, but there must have been a little, perhaps due to decomposition of some oxides by ultraviolet radiation. Darwinian evolution of species began. It seems to have been promoted near environmental gradients, such as undersea volcanic vents.

The next stage was the “invention”—excuse the word—of *oxygen photosynthesis*, and the protein molecule (chlorophyll) that does the job. This was almost miraculous, since it involved combining two distinct metabolic process into a single one (Lenton and Watson 2011). The result was the emergence of “blue-green algae”. Those algae used energetic photons from sunlight to convert carbon dioxide and water molecules into glucose (a simple sugar) plus oxygen. Oxygen was the waste product of photosynthesis. It is also very reactive, chemically. Consequently oxygen is toxic to anaerobic organisms.

The blue-green algae soon took over the oceans, spewing oxygen as they spread. As oxidizable compounds were used up, toxic oxygen accumulated in the atmosphere. That buildup was a time-bomb. Had it continued, life on Earth would have died out due to poisoning by its own waste products.

A lucky mutation (*respiration*) saved the day. It did two things. First, it provided metabolic energy no less than 18 times more efficiently than the prior fermentation process (still used by yeasts). And secondly, it used up some of the oxygen. To us, oxygen is necessary. In fact, it is probably a precondition for the development of intelligent life (Lenton and Watson 2011, pp. 296 et seq). But to the first living cells it was poison.[1] Evidently maximization of life on earth is inconsistent with maximization of chlorophyll. A certain amount of that green stuff needs to be metabolized by oxygen breathers, to keep the plants from dying of their own waste product. And, conversely, the oxygen breathers can’t survive without the glucose produced by the plants. That balance is critical.

Thanks to the more efficient energy metabolism enabled by respiration, living organisms became mobile. Some single-celled organisms attached themselves symbiotically to others. Eventually some of those symbiotes “merged” with each

[1] People who worry about cancer will have heard of “free radicals” and the dietary components of some fruits and vegetables called “anti-oxidants” that combine with and neutralize those free radicals. Free radicals are chemical compounds that have an attached oxygen atom with a spare “hook” (excuse the metaphor) eager to combine with something—almost anything—else. When that happens, functions essential to life are degraded. Aging is thought to be largely attributable to free radicals.

other, as a cell might become the nucleus of another cell. DNA arose. Multicellularity appeared. Species competed for resources (light, space, nutrients). Some of them began to attack others for food. "Fight or flight" appeared. New territories were invaded (especially land). New niches were invaded, and new species appeared. Complexity and diversity increased.

While the cooling of the universe is irreversible, it led to the formation of the different elements and later, of chemicals. After life appeared, the process of differentiation and complexification accelerated. Darwinian evolution is also irreversible in the sense of continuously increasing complexity and "fitness". Because all organisms depend on "food" in the sense of exergy flux, Darwinian evolution can be characterized as increasing exergetic efficiency at the individual and species levels.

Biomass and complexity increased, as did the exergy "consumption" of the survivors. Living organisms became more and more diverse. There were several "great extinctions" followed by recoveries that enabled new "winners" to dominate—for a while. Atmospheric oxygen increased as plant life flourished in the "Carboniferous" age. Bones appeared, followed by spines and skulls. Teeth appeared. Fish appeared in the oceans. Biomass on land was buried and converted into coal and oil. Dinosaurs came and went. Homeostasis (warm blood) provided an advantage. Birds appeared. Sensory organs evolved. Central nervous systems and brains evolved. Mammals with four legs and tails occupied many "niches" (along with six-legged insects and eight-legged arthropods).

Some mammals climbed trees and developed hands with thumbs for gripping. They came down from the trees and became bipedal. They communicated with each other and used tools, and weapons. Their brains got bigger, allowing greater intelligence. They tamed fire and animals. They organized. They learned to transmit knowledge. They took over the world. They may destroy it.

The "wealth of the world" 10,000 years ago—at the end of the last ice age—consisted of natural resources. There were rich soils, great forests and grasslands, streams and springs delivering clean water, useful and tame-able animals (such as horses, oxen, sheep, cattle and dogs) and visible and extractable concentrations of metals, clay and stone. The environment had other beneficial characteristics that were not noticed or needed 10,000 years ago, notably a benign climate and the innate ability to absorb and recycle wastes.

Humans started multiplying and using up those stored natural resources—both organic and mineral—partly for useful material properties and partly for their stored exergy. Humans are spending our inheritance, like children with no idea of saving or investment. This happened slowly at first, but faster and faster. As natural resources have been used, and abused, much of that original endowment have been used up or damaged. Resource exhaustion in human civilization bears a certain resemblance to the process that led to supernovae explosions. The explosion creates a bright but brief light, and what follows is devastation.

Or, is there another way to go? Luckily another "resource" has emerged. It is knowledge, embodied in brains and books and (more importantly) in organization and societal institutions. Those "new" resources have enabled humans to greatly extend the life of our original material resource inheritance. We can find and mine metal ores far less concentrated than those our ancestors exploited. We can see better and dig much deeper wells and mines. We can plow, plant and fertilize soils that our ancestors could not. We can multiply the muscle power of animals—and ourselves—by enormous factors. We can fly. We have, thanks to fossil fuels and flowing water—in the words of Reiner Kümmel—"energy slaves" of great flexibility and power (Kuemmel 2011). Not only that, our energy slaves are "smarter" and less material-intensive as our knowledge base grows.

The evolution of human civilization has been Darwinian, in the sense that it was based on competition for resources (including mates). It has also been irreversible in the sense that the "winners" in every niche are able to capture and exploit more exergy and use it more efficiently than the "losers". The winners survive, the losers disappear. (The vast majority of species that once thrived on Earth are long gone. Even if they could be re-created, dinosaurs could not survive in the wild today. Their eggs would never even hatch.) The rule applies to societies: there is no way a society of primitive hunters or self-sufficient peasant farmers can compete with an industrial society.

This irreversible "progress" depends essentially on selection within increasing diversity and complexity. It may, or may not, be a direct consequence of the second law of thermodynamics (the "entropy law"). After all, one's intuitive understanding of the entropy law is that things degrade, wear out, fall apart, and gradients disappear. But there seems to be a general "law of irreversibility" affecting all dynamical interactions between entities, from atoms to molecules, to living organisms. Each successful evolutionary innovation increases complexity and organization, increases information content of structures, increases both exergy consumption for maintenance and also increases exergy efficiency. It applies to nuclear reactions and chemical reactions. It applies to biological interactions. It also applies to competition between human individuals (as they grow and learn), and to societies, corporations and nations. The attractive "binding energy" applies to humans, not just in marriage or families, but in tribes, enterprises, and nations.

Evolutionary innovations often occur as a result of "creative destruction" (Schumpeter's phrase). Examples range from the collapse of a star that has burned all its fuel, to a planetary collision (such as the one that gave us our Moon), the "snowball Earth" episodes, and the asteroid strike that killed off the dinosaurs. Those were episodes of creative destruction. Glaciation also qualifies. Others were "Noah's flood" (probably due to the post-glacial rise in sea level that re-connected the Mediterranean Sea with the Black Sea), the volcanic explosion of Santoro that ended the Cretan dominance of the Aegean Sea, another (unnamed) volcanic outburst that occurred in Indonesia in 550 AD. That eruption may have shifted a balance of power in the steppes of Asia and indirectly kicked off a series of westward migrations, from Attila the Hun to Genghis Khan (Keys 1999). A more recent example was the spread of the "black death" in the fourteenth century. It caused a labor scarcity that shifted the power balance between towns and castles.

More pertinent to the problems of today was the more gradual, but equally important consequence of deforestation of England in the sixteenth and seventeenth centuries. That deforestation caused the price of charcoal to rise dramatically and accelerated the use of coal. But, of course, the great human innovation was the use of coking as a way to utilize coal (instead of charcoal) for iron-smelting. That discovery-innovation, in the early eighteenth century, arguably maximized wealth (by making coal into a substitute for charcoal, thus increasing available exergy reserves) and kicked off the industrial revolution. The need to dig deeper coal mines, in turn, led to mine flooding. The creative response to mine floods was the development of the steam engine, by Newcomen and Watt, followed by steam-powered railways and much else. During that industrial development, which fed on coal, exergy consumption, *per capita*, rose enormously.

Another resource-related problem was the near extinction of sperm whales (whose spermaceti was the source of whale-oil for lamps) in the nineteenth century. That scarcity—signaled by rising prices—triggered the search for "rock oil" in Pennsylvania and its active exploitation where it was already well-known, in Azerbaijan. The petroleum industry and its "children"—automobiles, aircraft and plastics—followed quickly. Moreover, the profits (derived from economic surplus) of that resource discovery financed a great deal of the industrialization of Europe and the USA. It also drove exergy consumption and resource destruction, *per capita*, still higher.

The acceleration of material resource consumption and wealth creation has been accompanied—and arguably caused, at least in part—by social changes. The formalization of coinage and the rise of markets and long-distance trading were important. The spread of literacy, numeracy, and education were important. The end of feudalism, slavery and the "divine rights" of hereditary monarchs, replaced by ideas of free association, freedom of religion, free speech and other freedoms, were critical. The Protestant Reformation and the rise of capitalism and fractional reserve banking were crucial. All of this history is recounted, very briefly, in Part II of this book.

The unprecedented natural resource destruction, in the form of deforestation, environmental pollution, fossil fuel combustion and atmospheric buildup of greenhouse gases (GHGs), now in progress, may also be the stimulus for a new round of technological and social innovation. We must hope that it will be so.

Today an increasing fraction (albeit still only a fraction) of all competitive human interactions occur non-violently, whether in families or in markets. The days of competition for land by fighting or military conquest are largely (if not quite entirely) past. Capitalism and the production and exchange of goods and services in markets have proven to be more efficient ways of acquiring—and creating—wealth. That is the good news.

There is also bad news. Part of it is the fact that our economy is now "addicted" to economic growth, whereas the natural resources that enabled that growth since the eighteenth century are becoming harder to find and utilize. Moreover, economic growth in recent years is much less beneficial to society as a whole than it was two centuries ago. It is increasingly a sequence of "bubbles" that leave devastation in their wake. Another part of the bad news is the growing inequality between those with access to natural resources, or the capital created by earlier access, and those without it. A conflict is already brewing between inconsistent “rights”: notably the property rights of those few who own the material and financial assets of our planet versus the supposed right to equal opportunity for the rest of the population.

In short, *wealth maximization, as a strategy, is not yet what human governments do, or know how do*. That needs to change. Economics is the science that attempts to explain these dynamical interactions and help to manipulate their outcomes. The creation and preservation of wealth—meaning both productive and consumptive assets—is an explicit subject within the domain of economics. But so far, it is being applied only in the realm of finance and technology.

Physical capital (machines, houses, infrastructure) are useless—unproductive—unless they are activated by exergy flows. Motors need electricity. Engines need fuel. Horses must be fed. The same is true of human workers. Exergy is what “makes things go” but knowledge is needed to optimize and control exergy flows and material transformations, as well as social activities and institutions. Knowledge enables us to do more with less. Knowledge in a book is not wealth—or is it?—but applied knowledge certainly creates wealth. Economic growth, per capita, is not driven by capital accumulation *per se*, but by exergy availability and knowledge. That is what Part III of this book is about.

In summary, the history of the universe until humans appeared on Earth was the history of material differentiation and increasing diversity and complexity. The history of Man until now, has been the history of converting materials into “things”. The history of the future may be a history of wealth creation by knowledge accumulation, de-materialization and institutional innovation. That history will be subject, of course, to the laws of physics—especially the laws of thermodynamics.

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