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Robert Ayres

ENERGY, COMPLEXITY AND WEALTH MAXIMIZATION

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Praise for *Energy, Complexity and Wealth Maximization*

"Economists and physicists, like oil and water, resist mixing, sadly to the detriment of useful human knowledge. Bob Ayres is the rare combination of a physicist and a resource economist, giving him a unique understanding of the importance of useful energy services to all of life. This unique understanding is critical to the massive challenge human kind now faces – how to 'power' continued wealth creation without destroying the planet we call home. This book will almost certainly alter the way we approach this great challenge."

Thomas R. Casten, Chair, Recycled Energy Development LLC

"This is a must read for those who wish to understand what we've got wrong in our contemporary development paradigm and how we can fix it. By far the most important book in years that will reshape physics the way Darwin and Einstein have done, and will hopefully reshape economics too!"

Dr. Stefanos Fotiou, Director of the Environment and Development Division, UNEP

"The fact that the world's nominal GDP shrank last year by 4.9%, while the planet experienced no financial crash, no earthquake, and no sovereign default, remains impossible to understand unless one acknowledges the dependency of our economies on finite natural resources. Bob Ayres is among the pioneers of this biophysical approach to economics, which may prove to be the most fruitful innovation in economics since Keynes. This extraordinary book crosses disciplinary boundaries to takes a broad, evolutionary perspective on human societies as thermodynamical dissipative structures. As natural resources become scarce and quality declines, knowledge is the one ingredient that may save us from following a path analogous to supernovae explosions. At a time when most economists confine themselves to partial and local micro-explanations, Ayres provides a big-picture understanding of the forces that underlie our current economic paradoxes."

Gaël Giraud, Professor of Economics, Ecole Normale Superieur (Paris), and chief economist, Agence Francais pour Developpement

"The energy system of the world has gone through several changes in recent decades, and it is expected that with current global developments and the Paris agreement on climate change, major changes in global energy developments and wealth need to be assessed in depth with the revolutionary changes that are likely to occur. No one better than Prof. Robert Ayres, who understands the industrial metabolism of the world and the role of energy globally, could attempt the analysis presented in this book. This analytical study combines science, economics and technology issues in a remarkable manner to provide rare insights into where the world is heading and why. The book is a must read for concerned citizens and decision makers across the globe."

R K Pachauri, Founder and Executive Vice Chairman, The Energy and Resources Institute (TERI) and ex-chair, International Panel on Climate Change (IPCC)

"This magisterial synthesis traces the evolution of order and complexity from the Big Bang to Big Data to Big Dangers ahead. The book delineates the urgent collective challenge of making the 'great transition' from an economy that squanders nature's wealth to a new paradigm rooted in a knowledge-based wealth."

Dr. Paul Raskin, Founder and President Tellus Institute

"Robert Ayres' new book is a historic, a contemporary, and a future oriented work of immense depth of thought, written by an author of incredible knowledge and wisdom, and encompassing views and concepts of both social and natural sciences. It is theoretically interesting, empirically relevant and timely regarding integrated assessments of social and natural systems. I think the work is a seminal contribution to looking at the co-evolution of human (economic and social) development and the Earth system, and will especially help to comprehend the new geological era – the 'Anthropocene.'"

Udo E. Simonis, Professor emeritus for Environmental Policy at the Berlin Social Science Center (WZB)

"Recommending this book is done best by stating a fact and making a wish. The fact: most people who run the modern world (politicians, economists and lawyers) have a very poor grasp of how it really works because they do not understand the fundamentals of energy, exergy and entropy. The wish: to change the ways of thinking of all those decision-makers, who would greatly benefit from reading this book. But so would scientists and engineers who may be familiar with its basic messages. They would profit from Bob's life-long examination of fundamental ideas and from their lucid distillation and synthesis: an important book, indeed."

Vaclav Smil, Distinguished Professor Emeritus, University of Manitoba, Canada

"Bob Ayres, the doyen of the intellectual universe encompassing physics and economics, has hit again. Beginning, of course, at the origin of the physical universe, he traverses galaxies, stars, planets and then our own planet's history. He then concentrates on human history and offers explanations for the dynamics of natural wealth creation that must become our new paradigm after conventional 'progress' has destroyed so much of natural wealth. And it is knowledge, rather than Gigabytes of 'information,' that can lead humanity into a better future. A grandiose design; impressive; worth reading and reflecting!"

Dr. Professor **Ernst Ulrich von Weizäcker**, Founder of Wuppertal Institute; Co-President of the Club of Rome, Former Member of the German Bundestag, co-chair of the UN's Resource Panel.

"In an age of sustainable development goals, there is no more urgent need for the policy makers and the public alike than to have a clear understanding of the complex linkages among energy, innovation, and wealth. Bob Ayres' book has done a superb job, weaving back and forth between physics and economics seamlessly, in illuminating the history of wealth creation in the past through the conversion of materials into 'useful things' based on the consumption of energy, and providing insights into the future when wealth will be created by knowledge accumulation, de-materialization and institutional innovation. It is a must read for all of us who wish for a sustainable future for humanity."

Lan Xue, Dean of School of Public Policy and Management, Tsinghua University, and Co-chair, UN Sustainable Development Solution Network

Preface

This book has had a long gestation. It is, in effect, a follow-on of a book I wrote in 1994, entitled *Information, Entropy, and Progress* (Ayres 1994). That book was an attempt to explain evolution in terms of accumulation of "useful information," as distinguished from just information. I was reminded of this yesterday when I read a surprisingly favorable review of a new book entitled *Why Information Grows: The Evolution of Order, from Atoms to Economies* by Cesar Hidalgo (Hidalgo 2015). I could have used that title for my 1994 book or for this one.

There is only one problem, really. Information, in the proper sense of the word (as in information theory), is not wealth. In fact, it is mostly junk. At any rate, too much can be as harmful as too little. Information technology may have "progressed" by leaps and bounds, and it has made a lot of people wealthy in Silicon Valley. But there is little or no evidence that the rest of us have prospered thanks to smartphones or Facebook (or even Google, which I couldn't live without). A better word than "information" would be "knowledge." Economists do use the term "knowledge economy," where "knowledge" is intended to convey something like the "essence of information."

But knowledge is not well defined, and its role in driving growth is very unclear. I'm afraid Hidalgo—like many in the "commentariat"—has put the cart before the horse. While the rich countries have more information processing and denser information flows, that is not necessarily why they are rich. Having better universities would be a better explanation of relative wealth, but having a lot of oil in the ground probably helps even more. The real connection between economic growth (useful) information and knowledge is much subtler. It is what the latter part of this book is about.

So why the long delay between from 1994 and 2016? That is partly because a group of us with backgrounds in physics or other sciences have been arguing with mainstream economists (but not being heard) for many years. The topic of the argument is the proper role of energy in economic science. (The role of entropy in economics is not being discussed at all, so far as I am aware.) This is not the place to summarize arguments (which still continue) except to say that progress is agonizingly slow because there is a widespread conviction among supposedly well-educated people, including business leaders and decision-makers, that they don't need to know anything about basic science to make good decisions.

I went to the University of Chicago to study physics in 1954 at the time when its president, Robert Hutchins, and his sidekick, Mortimer Adler, were famously promoting the *Great Books of the Western World* (Adler et al. 1990). The original 54-volume set included only two on economics (Adam Smith Vol. 39; Marx and Engels Vol. 50), plus a scrap of J.S. Mill. Science was covered only slightly better (Ptolemy, Copernicus, and Kepler Vol. 16; Gilbert, Galileo, and Harvey Vol. 28; Newton and Huygens Vol. 34; Lavoisier, Fourier, and Faraday Vol. 45; Darwin Vol. 49). In the second edition (Adler et al. 1990), Volume 56 was added. It included Einstein, Eddington, Planck, Bohr, Heisenberg, and Schrödinger.

The fact that the choices of who to include, or not, were not made by physicists is clear from some of the obvious omissions in physical science: Boltzmann, Carnot, Clausius, Dirac, Fermi (who was at the University of Chicago at the time), Feynman, Gell-Mann, Gibbs, Leibnitz, Maxwell, Mayer, Mendeleev, Pauli, Prigogine, and so on (to the end of the alphabet). In economics, the absence of Arrow, Jevons, Keynes, Malthus, Marx, J.S. Mill, Ricardo, Samuelson, J-B Say, Schumpeter, Solow, Veblen, von Neumann, Walras, and Max Weber makes the same point.

Nothing in the first edition of the *Great Books* mentions the most important laws of nature, namely, the first and second laws of thermodynamics. The first law is conservation of energy and the second (entropy) law says that all spontaneous processes in nature go in one direction ("time's arrow"). Whether Volume 56 in the second edition mentions either of these laws, I do not know. But the fact that the non-scientists who compiled that list of "great books," and the "great ideas" in them, were unaware of those laws—and a lot else—is shocking.

After leaving Chicago, I spent 2 years (1956–1958) at King's College of the University of London, working on a Ph.D. in theoretical physics. It was impossible not to notice that the higher levels of the socioeconomic strata in Britain at the time were heavily recruited from students with honors degrees in *Literae Humaniores*, known as "The Greats" at Oxford University. That course was (and is) focused on reading the Greek and Roman classics (Homer, Virgil) in the original languages and writing weekly essays on a variety of topics. The ability to quote appropriate passages in Latin was one of the criteria for being "one of us" at the top levels of British society.

The prevailing attitude, as conveyed by the media, was that scientists were "boffins in the back room" where they were paid very modestly to discover or invent things for the rest of society, which the rest of society didn't necessarily want or need. The 1951 Ealing comedy "The Man in the White Suit," starring Alec Guinness, made that point very clearly. The fact that those clever "boffins" had also invented jet engines and radar, decrypted the German codes, and created the atomic bomb was very disconcerting. The nerdy people who made such a huge contribution to winning the war were ignored or (in one notorious case) actively persecuted.

This gap—a chasm—was central to the novels of C.P. Snow and his famous "Two Cultures" lecture at Harvard in 1959. But that didn't open the doors of the elite clubs on Pall Mall to boffins, nor did the great companies bring scientists into the executive suite or onto their boards of directors.

Back in the USA, working in my chosen field, I could not help but notice the rise of the Harvard Business School. (My sister-in-law, in the 1970s, divorced my brother in order to go to HBS. Her great ambition was to become the first female VP of Generous Electric, Inc.) But the point here is that HBS and its upcoming rivals were teaching smart young people that "management" is a science and that to be a good—or great—CEO of a company like GE it is not necessary to understand what they produce or how they produce it. All of that detailed stuff can be left to the "boffins in the back room." What CEOs do is grand strategy, which turns out to be about some combination of finance, law, stockholder relations, labor relations, and lobbying the government regulators. In other words, HBS thought that it is possible to run General Electric Co. without having a clue about how electric power is generated and distributed, or how it is used to do work, still less about the laws of thermodynamics.

Sadly, most of the people who run the world now have a grossly inadequate grasp of important ideas that are fundamental to how the world (and the economy) works. That degree of ignorance among the powerful is dangerous. Energy and entropy are among the fundamental ideas that cannot be safely ignored. But thermodynamics is inadequately understood because it is badly taught, or not taught at all (except in specialized science courses), in schools and universities. This book started as an ambitious—probably overambitious—attempt to explain energy and entropy to otherwise educated people who thought that energy is the secret ingredient of "Red Bull," or the reason for drinking coffee in the morning, or is just a topic for nerds with calculators. (This book has evolved somewhat *en route*.)

As for exergy and entropy, the words are scary and unfamiliar, but they should not be. I use the word "should" in the normative sense. *Exergy* is that part of energy that can do work. *Exergy* is what gets "consumed" and "used up." Engineers say that energy is "destroyed" when it does work, but that is a little overdramatic. *Anergy* is the useless part of energy that cannot do any work. *Entropy* is a measure of the state of the world that increases after every spontaneous change and whenever exergy is consumed.

Entropy is invisible and intangible. It is not a substance. There are no "entropy meters." It was originally defined by a relationship, much as positrons and neutrinos (and the former planet Pluto) were discovered: because they were missing pieces of a puzzle needed to satisfy a law of nature. For the record, the relationship is simple: the difference between total energy E and exergy B (in a chemical system) is the product TS of temperature T times entropy S. Of course T is measurable on a thermometer. Does that help? Probably not, if you didn't study science. I won't mention it again in this book.

Recently I realized that there is a deeper connection between the origin of the universe and the reality of today. This book is my best attempt to explain it. In brief, the second law of thermodynamics isn't only about irreversibility, the "arrow of time," or the "heat death" of the universe. It is far from it. The keyword in the title of this book is "complexity." I could have used the words "order" or "structure" or even "resilience."

Yet, the universe is 13.77 billion years old (according to the Big Bang theory), and apart from being very large, it is extremely diverse. There are many billions of galaxies containing millions of trillions of stars, many of which have planets, some of which probably have carbon-based life. Where there is life, proliferation and organization occur, resulting in increasing complexity. When the complexity reaches a certain level, intelligence emerges. Intelligence creates more complexity and, ultimately, knowledge.

Speaking of our own planet Earth, the variety of life forms—past and present—is astonishing. And within our own species, the variety of social organizations, religious beliefs, business plans, scientific theories, chemicals, products, artworks—and book titles—is also very large. My point is that the cooling and aging of the universe have been accompanied by an explosion of different, increasingly orderly, configurations of matter on all scales, from the microscopic to the cosmic.

In fact, the increasing complexity of the universe is causally related to the second law of thermodynamics and irreversibility. This book will explain some of the reasoning behind that statement. I hasten to point out that the underlying idea that biological evolution, in particular, is a consequence of the entropy law has been stated before, by others. I will cite the sources in due course.

This brings me to "wealth," the word in the title of this book. The first definition in a typical dictionary is "A great quantity or store of money, valuable possessions, property, or other riches." Is that what you thought the title of this book was about? Well, it is but only up to a point. It was the second definition that I had in mind: "A rich abundance or profusion of valuable resources, or valuable material possessions." In particular, I stress the notion of profusion or diversity. The reason a lot of money is called wealth is that it offers a lot of different choices. The more choices you have, the greater your wealth. If there is nothing for sale in the shops, as in Zimbabwe a few years ago or in Venezuela today, money is worthless. When the Berlin Wall came down in 1989, it was the range of choice—including bananas and oranges—in the shops of West Berlin that was so attractive to the people who had been trapped for so long behind the Wall.

The idea that increasing wealth is a consequence of information flow is being bandied about. There is undoubtedly some truth in that proposition. The Internet does seem to promote social organization. It can also destroy it. But I would emphasize the importance of knowledge, rather than information as such. We are all surrounded by a flux of useless information, much of which is counterproductive if not toxic. (Think about "cyber-wars" and all the complex and wasteful efforts to secure "privacy" and protect personal information of little value.) Information is not a source of wealth, except insofar as information contributes to knowledge. Knowledge is hard to define and hard to measure, but increasing knowledge surely explains why "produced" wealth keeps increasing while natural wealth is being dissipated.

This book concludes with several chapters on economic theory, as regards energy flow, economic growth, and wealth accumulation. For a rigorous discussion of those relationships, I recommend *The Second Law of Economics* by Reiner Kümmel of Würzburg University (Kuemmel 2011). The present book is much less mathematical (and less rigorous) than his but considerably broader in scope. There is no need for me (or anyone) to recapitulate the mathematical derivations in that book. They constitute a permanent contribution to economic growth theory. Instead I have tried to write for a larger but less mathematically sophisticated audience. I believe there is room for both books and that they should be viewed as complementary rather than competitive.

However, I think there is more to be said that less specialized readers—especially people interested in science—may find interesting. Darwinian natural selection plays an important role in economics, of course. But the role of complexity, as a precursor of selection, is rarely mentioned in the academic literature.

And here I should say for whom I am writing this book. One group consists of people who read books like Weinberg's *The First Three Minutes* (Weinberg 1977) or Lederman's *The God Particle* (Lederman 1993) or *What is Life*? (Schrödinger 1945) or *From Being to Becoming* (Prigogine 1980) or *Into the Cool* (Schneider and Sagan 2005) or the books by Carl Sagan or Jared Diamond or *Scientific American* and other comparable science publications. But I also want to speak to people who read popular economics books, like *The Constitution of Liberty* (Hayek 1960), *Capitalism and Freedom* (Friedman 1962), *More Heat than Light* (Mirowski 1989), *Debunking Economics* (Keen 2011a), or *The Global Minotaur* (Varoufakis 2011). In short, I will present some ideas relevant to both camps of C.P. Snow's *Two Cultures*, and I hope to convey some new ideas to both groups.

Fontainebleau, France Robert Ayres

Acknowledgments

Most books like this start (or end) by acknowledging the lifetime support of a spouse or partner. In some cases, this may be *pro forma*. In my case, it is definitively not so. My wife, Leslie, has contributed to all my books for more than 60 years, in every possible way except the actual writing. Without her I could not function. Enough said.

Once or twice in the past, I have made the mistake of carelessly overlooking someone who deserved acknowledgment. In the present case, I find myself in a dilemma. Some of the people who have influenced my ideas did so long ago. I could also list some authors whom I admire but have never physically met, but to keep this list from excessive length, I forebear to do so. To avoid any suggestion of rank-ordering, the list is alphabetical. It is long because I have been active for a long time and I have worked professionally in several fields of science. A fair number of those listed below are now deceased, but I am no less thankful for the times we spent together. A few are people I disagree with, but disagreement sharpens the argument. Here goes:

David Allen, Julian Allwood, Ralph D'Arge (dec.), Ken Arrow, Brian Arthur, Nick Ashford, Bob Aten, Rob Axtell, Jeroen van den Bergh, Alan Berman, Eric Britton, Colin Campbell, Michael Carroll, Tom Casten, Mike Chadwick, Xavier Chavanne, Cutler Cleveland, Joe (dec.) and Vary Coates, Bob Costanza, David Criswell, Paul Crutzen, Jim Cummings-Saxton (dec.), Otto Davis (dec.), Tiago Domingos, Cornelis van Dorsser, Faye Duchin, Nina Eisenmenger, Marina Fischer-Kowalski.

Paulo Frankl, Bob Frosch, Jeff Funk, Murray Gell-Mann, Gael Giraud, Fred Goldstein, Tom Graedel, Arnulf Grübler, Charles Hall, Bruce Hannon, Miriam Heller, Ludo van der Heyden, Buzz Holling, Leen Hordijk, Paul Horne, Jean-Charles Hourcade, J-M Jancovici, Michael Jefferson, Dale Jorgenson, Herman Kahn (dec.), Astrid Kander, Felix Kaufman, Yuichi Kaya, Steve Keen, Ashok Khosla, Allen Kneese (dec.), Andrey Krasovski, Michael Kumhof, Reiner Kuemmel.

Jean Laherrere, John (Skip) Laitner, Xue Lan (as he is known in China), Tom Lee (dec.), Tim Lenton, Dietmar Lindenberger, Hal Linstone, Amory Lovins, Ralph (Skip) Luken, Katalin Martinàs, Andrea Masini, Fran McMichael, Steve Miller, John Molburg, Elliot Montroll (dec.), Granger Morgan, Shunsuke Mori, Nebojsa Nakicenovic, Mancur Olsen (dec.), Philippe Pichat, Vladimir Pokrovski, Ilya Prigogine (dec.), Paul Raskin, Bob Repetto, Ronald Ridker.

Sam Rod (dec.), Don Rogich, Hans-Holger Rogner, Pradeep Rohatgi, Rui Rosa, Adam Rose, Ed Rubin, Tom Saaty, Warren Sanderson, Heinz Schandl, Bio Schmidt-Bleek, Uwe Schulte, Andre Serrenho, Gerry Silverberg, Herb Simon (dec.), Udo Simonis, Mitchell Small, Vaclav Smil, Kerry Smith, Rob Socolow, Gus Speth, Martin Stern, Jim Sweeney, Laura Talens, Joel Tarr, Ted Taylor, Iouri Tchijov, John Tilton, Michael Toman, Richard Tredgold (dec.).

Gara Villalba, Genevieve Verbrugge, Sylvestre Voisin, Vlasios Voudouris, Ingo Walter, Benjamin Warr, David Wasdell, Luk van Wassenhove, Chihiro Watanabe, Helga Weisz, Ernst von Weizsäcker, Eric Williams, Ernst Worrell, Philip Wyatt, Huseyin Yilmaz (dec.).

In the text, I have occasionally used the word “we” where “I” would normally suffice. You may think of this usage as a kind of “royal we,” but it often has a narrower sense of referring to several of my most active collaborators in recent years, especially Reiner Kümmel, but also Jeroen van den Bergh, Marina Fischer-Kowalski, Paul Horne, Astrid Kander, Steve Keen, Michael Kumhof, Dietmar Lindenberger, Kati Martinàs, Uwe Schulte, Andre Serrenho, Gerry Silverberg, Udo Simonis, Vlasios Voudouris, and Benjamin Warr.

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Chapter 1
Introduction

What, then, is the connection between energy, complexity and wealth? That will take some explaining, because the idea of complexity may be simply confusing (too complex?) while energy is neither money nor wealth, at least, not in any simple sense. Here I think it is appropriate to refer to a book I have found interesting, though I disagree profoundly with its key message. That book is *More Heat Than Light* by Philip Mirowski (Mirowski 1989). What I disagree is with his interpretation of the history of science. In his own words on p. 99:

> The discipline of physics owes its coherence and unity to the rise of the energy concept in the middle of the nineteenth century. However as soon as the discipline was consolidated, further elaboration and scrutiny of the energy concept began to undermine its original content and intent . . .

He goes on for another 20 lines of print to explain that energy does not exist. In the book itself, he mentions the vexing problem of "renormalization" (adding and subtracting infinities) in quantum field theory, the lack of energy conservation in Einstein's general theory of relativity, and the fundamental question of whether or not it makes sense to imagine that the universe was created out of nothing.

I agree that those questions, including the last one, are still vexing because we do not know what actually happened and what "causation" can possibly mean before time began. But some modern versions of quantum field theory have been formulated in a way that avoids renormalization while Einstein's theory of gravity has been challenged and (I think) superseded by another theory that does satisfy the energy conservation condition. (See Chap. 4). Frankly, I am sure, as Eddington was, that the laws of thermodynamics are fundamental laws of nature, and that any theory implying the contrary is wrong. There are "free lunches" in economics, but they do not contradict the first or second laws of thermodynamics.

Wealth, unlike energy, is a human concept. It did not exist until humans appeared on this planet. Wealth is a word that captures the notion of material possessions with value to other humans. Material possessions imply ownership, and ownership implies rights of use and rights to allow, or prohibit, rights of use by

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others. Owners may exchange these rights for money by selling the possession for money. But money is only valuable if there is a choice of goods or services available to purchase.

All wealth until very recently had a material base. A few thousand years ago cattle or slaves were wealth. Hundreds of years ago jewels, or bars of gold, or gold coins were wealth. Now a number on an account, or on a printed paper with a picture of a president, or a title to land or a house or a mining claim or a share of stock, or a financial derivative, or a bitcoin, can be wealth—again, assuming the availability of other goods or services to buy. The monetary value of a "good", such as a chicken or a ship, is usually determined in a marketplace. Or, it may be exchanged for another material object, such as a sack of grain, a tank full of oil, or a diamond ring.

Energy is the essence of every substance. Everything—including mass and every material thing—is a form of energy. The "theory of everything"—the *ne plus ultra* of physics—is therefore a theory of energy. Not only that, but energy flux is the driver of change. Nothing happens without a flow of energy. Not in the natural world and not in the human world. Thus, it is perfectly true that energy—not money—makes the world go round.

I'll try to keep it as simple as possible, but I have to begin at the beginning. The thesis of the book is summarized in Chap. 2 which follows. Part I of the main text begins with Chap. 3 about the history of human thought about energy and thermodynamics. Its purpose is to explain that the concepts of "energy" and its cousin "entropy", have changed meaning greatly over time. Even now they are understood differently (or even completely misunderstood) by most people. Chapter 4 focuses on the history of the cosmos, the sun, the origins of the elements and the "terra-forming" of Earth. Chapter 5 deals with the origins of organic chemicals, the origin of life, DNA, the oxygen catastrophe, the Cambrian explosion, the carboniferous era, and evolution since the asteroid that killed off the dinosaurs. Chapter 6 is all about long-term chemical changes in the Earth's atmosphere, hydrosphere and biosphere. Climate change is discussed there.

In Part II, Chap. 7 is about how our species *H. sapiens* came to dominate the Earth during the last several glacial episodes, starting half a million years ago with the taming of fire, the domestication of animals, language, social organization, slavery, money, and pre-industrial technology. Chapter 8 is about technology as it evolved after 1500 CE, from printing to coking, iron smelting, steam power, and the industrial revolution. Chapter 9 then focuses on new materials and new forms of energy, electric power, petroleum, the internal combustion engine, our current dependence on fossil fuels, and the demographic transition. Chapter 10 is about the coming shift from fossil fuels laid down during the Carboniferous Era to "Peak oil", renewables and energy efficiency technologies for the future.

Part III, starting with Chap. 11 discusses core ideas of economics. It explains why economic growth is an aspect of Darwinian evolution, by exploiting natural resource discoveries and innovations that made the resources useful and created new products and markets. Yet, mainstream economic theory today still neglects energy and complexity as the primary sources of economic surplus, and thus the drivers of growth. Current economic theory is inconsistent with the laws of thermodynamics. Chapter 12 discusses what economics has to say (and needs to say) about a world in which material resources are no longer unlimited, where the “cowboy economy” is in transition to the circular “spaceship economy”, and where knowledge is the only new resource. Yet the “circular economy” remains a figure of speech. Growth cannot continue indefinitely. Perpetual motion and perfect recycling are not possible in this universe. Appendix A provides the details of a theory of energy as a driver of economic growth.

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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