CHILDREN of the SUN

A History of Humanity's Unappeasable Appetite for Energy

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PREFACE

Children of the Sun is a history of how we access the energy to get work done, to move our muscles, to think, to hunt mammoths, to sow and harvest, to build pyramids, to power automobiles and space rockets, to boil water for tea. Very nearly all of the energy needed to do these things originates in the core of the Sun and travels as sunlight to Earth, where photosynthetic plants process it into leaves, stems, flowers, seeds, and roots. Animals like us eat these plants and/or animals that feed on this biomass and thus gain the calories to function.

Our next step toward biosphere domination (or wherever we're headed) was to discover how to tap sun energy concentrated in biomass—in wood, for instance—by burning it to produce light and heat where and when we wanted. We became the only species to control fire and to direct it for our purposes. Our ability to cook food—to predigest what we couldn't or preferred not to digest raw—gave us more efficient access to greater stores of nutrients. Our numbers increased. The next step was agriculture: with cultivated plants and livestock we assured ourselves of greater supplies of energy than we had ever had before. We increased again in numbers and geographical expanse.

And so we sat for our first few thousand generations, by half of which we were the most widely distributed of all large animals in the Eastern Hemisphere, and by no less than 10,000 years ago had achieved that status in all continents but Antarctica.

We were a successful species, but by our current standards nearly helpless. Our primary means to get work done was muscle, our own and animal. Yes, by AD 1000 we had windmills, watermills, and sailing ships, but in truth our societies ran on muscle, as illustrated by any number of old pictures of our ancestors slogging along on treadmills to provide the power to grind grain, lift water, and so on. We had gone about as far as we could go in numbers and altering the world in accordance with our wishes unless we utilized more efficient means of tapping sun power than agriculture and burning wood.

We lurched into the fossil fuel era some two to three hundred years ago with the invention of the steam engine. Like its successor, the internal combustion engine, the steam engine enables us to tap the concentrated energies of ancient biomass which subterranean heat and pressure have transformed into coal, oil, and natural gas. We created the means to transmit the energies we harvest by burning fossil fuels hundreds, even thousands of miles, by expressing it as electricity. Our technological civilization as it now exists would be impossible without the enormous consumption of these fossil fuels. Modern civilization is the product of an energy binge.

Binges often end in hangovers. Fossil fuel supplies are ultimately exhaustible and currently responsible for such worrisome effects as global warming. We must revive old ways of tapping sun power, such as windmills, and invent new ways to do so, such as solar cells, and/or we must utilize new sources of energy. Nuclear fission could produce all that we need, but is distrusted as dangerous. It may be Mother Nature's version of the Trojan Horse. The ideal solution may well be hydrogen fusion, the Sun's means of producing energy; but we don't know how to recreate that process as a practical procedure and may never learn how.

We have successfully met the energy challenge several times before with breakthroughs such as the invention of agriculture and the steam engine. But humankind's unappeasable appetite for energy makes the solutions ephemeral, and the challenge permanent.

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BEFORE I INVITE you to proceed to a more detailed consideration of these matters, I would like to thank the many who read all or parts of my manuscript and offered corrections and suggestions (which I usually but not always accepted, so their responsibilities are limited). These include Frances Karttunen, John McNeill, Steven Stoft, Kurt Keydel, Vladimir Strelnitski, Jerry Bentley, and my patient editors, Steve Forman and Sarah England.

PART ONE

THE LARGESS OF THE SUN

The Sun . . . contains 99.86 per cent of the mass of the solar system.

—*John Gribbin, cosmologist (1998)*[1]

I do good to all the world. I give them light and brightness that they may see and go about their business; I warm them when they are cold; and I grow their pastures and crops, and bring fruit to their trees, and multiply their flocks. I bring rain and cold weather in turn, and I take care to go round the world once a day to observe the wants that exist in the world and fill and supply them as the sustainer and benefactor of men.

—*Garcilaso de la Vega, El Inca (1612)*[2]

Great scientists, great artists, great athletes—Einstein, chalk in hand at the blackboard; Michelangelo, paint dripping down his arm, working on the ceiling of the Sistine Chapel; Lance Armstrong wheeling across the finish line of the Tour de France—strike us as wellsprings of energy. But no human being, indeed no life form whatever, produces more energy than it takes in, or produces any at all by itself. All humans and all organisms are dependent on external sources for fuels. All are parasitic.

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[1] John Gribbin, *Almost Everyone's Guide to Science: The Universe, Life, and Everything* (New Haven: Yale University Press, 1999), 169.

[2] Garcilaso de la Vega, El Inca, *Royal Commentaries of the Incas and General History of Peru*, trans. Harold V. Livermore (Austin: University of Texas Press, 1966), 42–43.

The two principal sources of energy upon which we earthlings depend are the upwellings of heat, magma, and gases from within the planet and the radiation from the Sun. The former empowers exotic organisms such as those that live by the hydrothermal vents of the deep ocean; they won't be mentioned again in this book because they have little direct influence on human history. The latter source, sunlight, is by every measure the greatest source of energy, the fuel of life, on the surface of our planet. Here we are all, in the words of Vladimir Vernadsky, the Russian geochemist, "children of the sun."[3]

The Sun is the center of a dust twirl of planets and lesser specks, and is also the center of human life and of the life forms on which humans are dependent. And no wonder: that star makes up very nearly 100 percent of the mass of the solar system. Our Earth is no more than a mote of debris left over from its formation. A million of our planet would fit inside the Sun.

At its core, where the environment is exponentially many times more hellish than Dante could have conceived, the pressure and temperature are so extreme that no solids, liquids, or gases can exist, only plasma, the uninhibited swarming of subatomic particles which is the fourth possible state of matter. There, nuclei (the relatively massive central points of atoms) of hydrogen undergo a transmutation that is the foundation of our lives. Despite being of like and mutually repellent electric charge (like similar poles of magnets repelling each other, north versus north, south versus south), they collide head-on because there is no way of not doing so. When four hydrogen nuclei collide and fuse, the result is one helium nucleus.

The mass of the one helium nucleus is 0.7 percent less than that of the four hydrogen nuclei, and the missing mass converts into pure energy. That is, per collision, a very tiny amount, but there are trillions of trillions of these collisions per second. Furthermore, the quantity of mass involved is not as decisively important as what happens to it. To measure that, we resort to Albert Einstein's famous formula for calculating the quantity of energy represented by a given mass, $E = mc^2$ (Energy equals the mass times the constant squared). Said mass may be small, but c, the constant, is the speed of light—*squared.* This is the awesome conversion which we replicate on a minuscule scale with our hydrogen bombs. It is no wonder that we are advised not to look directly at the Sun.

The energy created by hydrogen fusion in the Sun's core rises to its surface and blows out into space in all directions as light, the fuel of life. Approximately eight minutes later and 93 million miles away, the mote which is our planet receives a half billionth of this radiation. Half of that is reflected back into space or absorbed by atmosphere and clouds. The paltry remainder is the largess that made and makes life on our planet's surface possible, including the lives of Einstein, Michelangelo, and Lance Armstrong.

Life on Earth began an immensity of time ago and for millions upon millions of years thereafter was limited in its greatest extravagance to prokaryotes, one-celled organisms without nuclei. One of the most common of these was cyanobacteria, blue-green algae. They made their living by directly tapping sunlight. Our name for their chemical masterstroke is photosynthesis (from Greek words meaning "light" and "to put together"). Cyanobacteria contain a greenish substance, chlorophyll, which makes the alchemists' hyperbolized Philosopher's Stone seem feeble. Chlorophyll absorbs and harnesses the energy of light to split water and carbon dioxide molecules. This makes other molecules, simple carbohydrates, the fuel from which and by which yet other molecules essential to the functions of life are constructed.

At an inexpressibly important moment long, long ago certain enterprising prokaryotes or perhaps new-fangled eukaryotes (cells with nuclei) engulfed cyanobacteria and did not digest but incorporated and recruited them. These cyanobacteria lost all ability to exist independently and settled down forever to sinecures as distinct entities called chloroplasts inside their hosts. They are there still, almost

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[3] Quoted in Vaclav Smil, *The Earth's Biosphere: Evolution, Dynamics, and Change* (Cambridge, MA: MIT Press, 2002), 9.

all of their needs filled by their landlords, who in the aggregate are our plants. In return for lodging, the chloroplasts absorb sunlight (they will even migrate within cells to gain better access to the light) in order to produce and supply their hosts with simple sugar, the basic food of both plants and animals. Human food chains always ultimately lead down to plants with chloroplasts arranging themselves to catch the sun's rays.

In the process of photosynthesis the oxygen component of the dismembered water molecules is discarded and drifts away. This is the source of most of the oxygen in our atmosphere, which animals like us take up and, via slow combustion (the technical term is "respiration"), turn the food we have ingested into energy. We are thereby able to function, to build and rebuild ourselves, to stay alive from minute ro minute. The ash of this sedate burning is carbon dioxide, which we exhale, repaying the biosphere for the carbon dioxide which photosynthesis has used up. The energy that respiration produces drives our muscle to do "work." In physics, that noun specifically refers to the transfer of energy from one physical system to another, as when I apply pressure to these keys to type this sentence.

We gain access to that force via "prime movers" or indirectly from entities that tap prime movers. The prime mover concept dates back to Aristotle, and to St. Thomas Aquinas, who posited a mover who is never moved, but moves everything else, i.e., God. Physicists have pared the concept down to mean any machine (using that word broadly) that converts natural energy into work. I utilize muscle, humanity's first prime mover (it taps the oxidation of carbohydrates, a natural force), to press down my computer keys.[4] The windmill, a later prime mover, taps the movement of air to do the work of turning millstones and grinding grain into flour. A standard nuclear reactor taps the heat produced by atomic fission, a natural process, to transform liquid water into steam to drive turbines to provide us with electricity. (We use electricity to drive locomotives, elevators, streetcars, movie projectors, computers, and so on. You could think of them as secondary movers if there were such a category.)

When we first started, we fueled our personal prime movers with the food we acquired as simple harvesrers of wild plants and animals. After a long while we elevated ourselves to the status of complicated harvesters. We domesticated (negotiated alliances with) a few other species, as have, for instance, ants (as we shall see in chapter 3), so we could have sources of food, hide, fiber, bone, and help within easy reach. We harnessed fire (as have no other creatures), tapping sun energy by igniting biomass created by photosynthesis. The burning of recently living biomass—wood, for instance—has continued on into our time. In the last two centuries we have also been burning immense, almost immeasurable, quantities of fossilized biomass from ages long before our species appeared. Today, as ever, we couldn't be more creatures of the sun if we went about with solar panels on our backs.

In the last half century our demand for energy has accelerated to the verge of exceeding what is produced and can be produced by conventional ways of harvesting sun source energy. We are refining those ways, which typically tap the energy holding molecules together, through combustion, for instance. We are also trying to domesticate the energy holding atomic nuclei together, such as is extravagantly released in fission and fusion bombs. Our sun-struck physicists are even leapfrogging back over photosynthesis and committing hydrogen fusion in their laboratories.

The above, as we shall see in more detail, can all be counted as triumphs in the quest of the children of the sun for more energy. We will also see some failures in that quest. As a historian of large-scale change, I sift through truckloads of books and journals and try to come up with generalities to save my readers from being overwhelmed by what may seem to be temporal and spatial chaos. But I

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[4] Steven Vogel, *Prime Mover, A Natural History of Muscle* (New York: W. W. Norton & Company, 2001), is a good place to start on this subject.

worry about sounding like a high school teacher of mine who said there were four causes for the French Revolution, and when a student suggested a fifth, said no, there were only four. As an amulet against oversimplification, at the end of most of the following chapters I will add a coda about a person or event with the texture and grain of specificity (and occasionally with something that may even contradict my most recent pontifical pronouncement). In this way I hope to counter generalities that, like sleek limousines sweeping tourists from airports through gritty city neighborhoods to comfortable hotels, deprive readers of a sense of the ambiguities and the seemingly irreconcilable details of our past.

PART TWO

FOSSILIZED SUNSHINE

Man's function as a force of nature was to assimilate other forces as he assimilated food.

—*Henry Adams, historian (1906)*[1]

Collectively, heat engines are the motive force behind our civilization.

—*David Goodstein, physicist (2004)*[2]

For nearly all of our time on earth, we have been at least as feeble as other animals in the physical power to get work done. When Benjamin Franklin, whose discoveries in the field of electricity would prove so significant in energy distribution, was born in 1706, we humans were only marginally more powerful than we had been in the age of the Egyptian pyramid builders. Since then we had added water and windmills as prime movers (more about them in a few pages), but to accomplish most tasks—plow a field, harpoon a whale—humans still used muscle as their prime mover and food for fuel.

In 1706, we used horses, oxen, donkeys, water buffalo, and other domesticated animals to do some of the work, for example, hitching them up to millstones to walk in circles to grind grain. We often, very often, used people for the same purposes, by setting some to

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[1] Henry Adams, *The Education of Henry Adams* (New York: Penguin Books, 1995), 449.

[2] David Goodstein, *Out of Gas: The End of the Age of Oil* (New York: W. W. Norton & Company, 2004), 88.

plodding on treadmills to lift water in chains of buckets, and others to turning big hollow wheels from inside like hamsters in order to saw wood, drive bellows, knead dough, and so on. The eighteenth was the peak century of the slave trade because Europeans needed more muscle than their home continent could or would supply to exploit their American plantations, so they went to Africa to get it.

In that century an early pioneer in the development of a steam engine, John Smeaton, estimated that in prolonged efforts, humans produce (to express it in our terminology) about 90–100 watts of power apiece. A plantation owner or entrepreneur might try to compensate for such feebleness by utilizing more people, but there was no way to get a sustained 500 watts of power per individual even with a whip or improved diet.

Humanity had hit a ceiling in its utilization of sun energy. The combined efforts of a million slaves could not get a pound of West Indian or Brazilian sugar to Europe faster than a sailing ship. The labor of a million Roman candlemakers could not produce enough light to permit the staging of night games in their city's Colosseum. Humanity could produce Islam and Buddhism, algebra and calculus, Shakespeare and Palestrina, but it couldn't produce decent shoes for more than a minority of those who needed them, or enough type, paper, and ink for a single daily newspaper with a circulation of a million, or a means to get from Rome to Paris in less than a week. Humanity required an energy miracle commensurate with its domestication of fire if it was to become the bully of the biosphere.

By the time that Benjamin Franklin died in 1790, humanity had its miracle, a previously neglected kind of fuel and a new prime mover. The industrial revolution had been ignited, bringing with it an unprecedented acceleration of technological innovation, economic and political rearrangement and consolidation, and demographic increase and migration. The new means of exploiting sunlight radically altered the lives of the citizens of the English Midlands, then of the Ruhr, and, a few generations later, those of the inhabitants of Mongolia, the South Seas, the headwaters of the

Amazon, and of everyone else except a tiny and dwindling number of the most remote hunter-gatherers.

We will deal with the new prime movers one at a time in later chapters in the order that they arrived on the scene. They were heat engines, direct descendants of the pots that had been boiling over hearths for a very long time. They were machines that tapped sunlight by burning its manifestations in biomass. The difference in the fuels burning on most hearths and those burning in the new prime movers was in their energy density and in their age.

The energy density of recently cut wood or foliage or grass is slight per unit of weight or volume. A solution to that problem is to concentrate biomass: to somehow reduce an inconveniently bulky ton of wood to a neat pound of fuel with the same energy potential. Eighteenth-century people all over the world did something like that when they burned wood slowly in nearly airless conditions to make it into charcoal; but the reduction was insufficient and there weren't enough trees to supply enough wood for very long—and charcoal wasn't suitable for all or even most of the tasks humans wanted heat engines to accomplish.

Humans blindly turned to the greatest reductionist of all: time. Life has existed on our planet for eons, during which billions of generations of plants and animals have lived and died and left their corpses behind. Chance buried a fraction of these, and a fraction of this fraction has been subjected to conditions that transformed it into the fuels that empower our civilization: peat, coal, oil, and natural gas.

Peat—a light, spongy combustible—is what we might call the preliminary, the adolescent fossil fuel. It is vegetable matter, usually no more than a few thousand years old, that accumulated in stagnant bogs where conditions restricted the activity of bacteria and minimized the amount of oxygen, slowing decomposition. Its energy density is higher than that of fresh biomass, but still low; it burns smokily; and it smells. Its existence in enormous and easily accessible beds in many parts of the world and its low price are its recommendations.

Coal is what can happen to peat after a long time. It is the reduced and compacted remains of forests millions upon millions of years old, forests of club mosses, some 30 meters high, of giant horsetail rushes, of flora in a profusion barely equaled by our most luxuriant jungles today. Its energy density is at the very least triple that of peat.

Oil is what we have left of tiny organisms, phytoplankton, that lived in oceans long, long ago, died and accumulated in oxygen-deficient waters, and then were buried 7,500 to 15,000 feet deep long enough for pressure and heat to transform them into liquid. (Below 15,000 feet the conditions are so extreme that gas, not liquid, is the result.) This liquid then collected beneath impermeable caps of stone to await our pleasure. The energy density of oil is a great deal higher than that of coal and it is liquid and therefore easier to store and transport.

Fossil fuels are the tiny residue of immense quantities of plant matter. An American gallon of gasoline corresponds to about 90 tons of plant matter, the equivalent of 40 acres of wheat—seeds, roots, stalks, and all. Coal, oil, and natural gas are the end products of an immensity of exploitation of sunshine via photosynthesis over periods of time measured by the same calendars used for the tectonic shuffling of continental plates. We are living off a bequest of fossil fuel from epochs before there were humans and even before there were dinosaurs.

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COAL AND STEAM

And was Jerusalem builded here
Among these dark Satanic Mills?

—*William Blake, poet (1804)*[1]

The world is now entering upon the mechanical epoch. There is nothing in the future more sure than the great triumphs which that epoch is to achieve. It has already advanced to some glorious conquests. What miracles of invention now crowd upon us! Look abroad, and contemplate the infinite achievements of the steam power.

—*Robert H. Thurston, historian (1878)*[2]

Accident and evolution gifted humanity with culture, which made the species into a sprinter. Humanity had dashed ahead twice before, once in the Upper Paleolithic and again in the Neolithic. In the eighteenth century, humanity sprang out of the blocks the third time. The surge of mechanization that started in England was unprecedented in the speed of its advance and its general influence, but it wasn't all new in its basic physical materials. Wood still sufficed for many purposes; indeed, it still does in our developing nations, especially for cooking and warmth.

[1] *The Harper Anthology of Poetry*, ed. John F. Nims (New York: Harper & Row, 1981), 244.

[2] Robert H. Thurston, *The History of the Growth of the Steam Engine* (New York: D. Appleton & Co., 1878). Available at http://www.history.rochester.edu/steam/thurston/1878/. (Viewed June 3, 2003.)

Metals—copper, bronze, iron, steel—were expensive but available for tasks requiring special strength, hardness, and durability. The machines of this industrial revolution were new, but their components and basic concepts—wheels, levers, pulleys, screws, and so on—were of ancient lineage.

One of these parts was the wheel, which dates from about 5500 BP. A millennium or so later, Old World peoples had wonderfully useful wheel machines: wagons, chariots, potter's wheels, and others. The proof of their significance is the relative disadvantage of the societies that lacked the wheel, those, for instance, of the high civilizations of America. How often and for how long has a people without the wheel ever subjugated a people with the wheel?

In the first century AD, humans invented a complement to the wheel that became so common that it is hard to imagine life without it: the crank. It is a bar or rod attached to a shaft at a right angle, usually with a handle parallel to the shaft jutting out at the far end for the convenience of anyone who wants to turn or "crank" (the word is a verb as well as a noun) the shaft. With it, members of my grandparents' generation started the engines of Model-T Fords. Today, when I want to sharpen my pencil, I insert it into the pencil sharpener and turn . . . the crank.

The peoples who possessed and fell in love with the wheel and crank—the Chinese and Europeans, for instance—were using them to squeeze more energy out of sunlight long before the eighteenth century by exploiting the movement of water and wind.

The watermill, an ancient prime mover churning away on the Tigris and other Old World streams before Jesus or Mohammed, taps the potential energy stored in water deposited in ponds, lakes, snowpack, and glaciers at high elevations by sun-driven evaporation. The water makes that energy available as it flows back downhill toward the sea.[3] Watermills were at first, and for long after in

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[3] Tidal mills tap lunar, not solar, power; they are omitted for that reason and because they have been of major importance in very few locations.

Mechanism of a watermill, engraving from V. Zonca's *Nova teatro di machine*, 1607.

mid- and eastern Asia, structured with vertical axes—like revolving doors set up in streams. Compared to what followed, they were inefficient because the flowing water pushing the flaps or vanes in one direction was also, unless carefully diverted or otherwise restrained, pushing against the flaps revolving around the axis in the other direction. Some inventive soul—who, when, and where we don't know—shifted the wheel's axis to the horizontal and set up the wheel so as to dip into the moving water from above. The flow pushed the wheel in only one direction. This is the undershot wheel, illustrated on page 65.

It was an improvement, but worked well only on swiftly flowing streams. Then humans built flumes or chutes that brought water from higher elevations to the top of the wheel, where it poured into troughs that were the vanes of this new edition of the old wheel. This tapped the energy not only of water flow but of gravity, the weight and impact of the falling water. A well-built, well-lubricated "overshot wheel," as this kind is called, might produce four or five or even more horsepower. According to Fernand Braudel, the great French historian, an average watermill ground five times as much grain as two men working a hand mill. In the early twelfth century, France alone had twenty thousand watermills grinding wheat, crushing ore, and so on, the energy equivalent of a half million human workers.

In that century waterwheels were common along rivers and lesser streams right across Eurasia and North Africa from the Atlantic to the Pacific. Since then they have been built throughout the rest of the world, where many are still operating, especially in the Third World. If we include in our definition of watermills the giant turbines paired to our dams today that drive dynamos to produce electricity, then this prime mover is as important today as it ever was.

Mills constructed to exploit sun-driven wind—windmills, which first appeared in Persia in the first millennium CE—also started out like revolving doors. That kind were common right up to our time throughout Asia, where the demand for power exceeded what muscle and water could provide; but someone somewhere, probably in Western Europe in the twelfth century, invented a better windmill. He made a giant vertical fan of the revolving doors, faced it into the wind, and greatly improved the machine's efficiency, bequeathing us what we see in our minds when we think of windmills.

Windmills were and are very useful in windy regions like Southeast Iran, the coasts of China, and, famously, the Netherlands. In the latter in 1650 there were at least eight thousand windmills towering over the sodden countryside pumping water. Well into the second half of the twentieth century windmills were standard equipment in American farms, especially in the semi-arid plains. More and more of them are being raised today because windmills don't pollute.

But flowing water and wind were far from efficient expressions of sun energy. The first froze in winter and sometimes ran low in summer and, anyway, was not available everywhere. The second sometimes blew too hard and sometimes not at all. In the long run, the significance of the mills may be that the people who built and maintained them learned a great deal about levers, axles, cogs, pulleys, screws, and so on. Before the human species could make another quantum jump in exploitation of sun energy, it would have to gain access to much more energy than food or water or wind could supply; it would have to find a better fuel and then invent a more powerful prime mover.

Humanity lusted after concentrated sun energy, of which there were portents. The Byzantines invented Greek fire, a flammable liquid that stuck to everything and could be squirted short distances. Water didn't put it out and so it was very useful in naval battles. The Greeks kept the recipe for Greek fire secret, but it must have included the fossilized sun energy, petroleum, that seeped to the Earth's surface in many places in the Balkans and Middle East. The Chinese invented gunpowder, an extreme kind of fuel. At first it was used as an elixir, then in a sort of flamethrower, then in bombs to unleash a shrapnel of feces and broken crockery among the enemy. Not long after 2000 BP they were using it in guns. The ignition of a fuel—in this case, gunpowder—in a closed container produced enormous push, flinging missiles at velocities so swift that the human eye couldn't follow them. The cannon barrel and cannon ball were prototypes for the piston and cylinder.

Humans did not consider coal a fuel when they first met up with it, but valued it for its peculiar color and even used it in jewelry. In time they learned that it would burn, and a few were using it as a source of heat and light thousands of years ago. But accessible surface outcroppings of the fuel existed in only a few places, and a lot of that coal produced choking, eye-watering smoke. And wood was plentiful, at least to begin with, so there was no need to suffer coal for energy.

There were at least two false or, if you prefer, preliminary starts on revolutionizing industrial production, one in eastern and one in western Eurasia. The ironmongers and miners of China's Song dynasty started an industrial revolution of their own seven or eight hundred years before the Western Europeans got around to theirs. In 1078, China used huge quantities of charcoal to process ore into 125,000 tons of iron, twice as much as Europe (excluding Russia) produced four hundred years later. But then their revolution faltered as they ran into shortages of wood. These ironmongers began to switch to coal, of which China has large deposits in the north and northwest. That solved half their problem; but they did not tap the full sun energy of coal, which would have required inventing a new prime mover. Perhaps that was simply a matter of chance, which plays a more important role in history than many historians like to admit. Perhaps the explanation lies in the disasters that rolled over northern China: barbarian invasions, vicious civil wars, Yellow River floods. China's political and economic center of gravity shifted south and away from its richest coal deposits. Coal was not widely adopted as a substitute fuel for biomass in China until the twentieth century.

In the 1600s, when New York was born as New Amsterdam, and Cape Town and Malacca were also Dutch cities, Holland ran out of harvestable wood and couldn't shift to coal unless it imported it. The Dutch shifted to peat, a fossil fuel of which they had plenty. They warmed their homes, cooked their meals, and processed many of their manufactured products—brewed their beers, refined their sugar, baked their bricks—with peat fires. Rembrandt van Rijn painted his masterpieces as a citizen of the first society primarily powered by fossil fuels, arguably the first modern society. But, like the Chinese, the Dutch did not come up with a revolutionary prime mover. They started down the path that led to fossil fuel civilization, but halted halfway because peat, which fulfilled their immediate needs for fuel, didn't burn hot enough per unit of volume or weight to entice them on to invent a new prime mover.

The birthplace of the lasting, possibly perpetual industrial revolution turned out to be Great Britain. Many explanations have been suggested: a sturdy artisan class, Protestant discipline, an excellent transportation system of rivers and coastal waters, a market freer than most, a relatively dependable currency, relatively honest bankers, and so on, but these were characteristics of Dutch society as well. Whatever the cause or causes of Britain's industrial revolution, the presence of enormous quantities of coal under its soil was an essential ingredient for that revolution. The stimulus for the switch from biomass to coal as the primary source of sun energy was simply that England, Wales, and Scotland, like China and the Netherlands, were running short of forests. The price of firewood in Britain rose 700 percent between 1500 and 1630, much faster than general inflation. In 1608, a census of the number of "tymber trees" in seven of Britain's largest forests set the sum at 232,011. The number in 1783 was down to 51,500. The British imported wood from the Baltics and North America, but their chief solution to their fuel problem was to mine more and more coal.

At the end of the seventeenth century, London was already famous for its smoke. The diarist and gardener John Evelyn, as exasperated as a Los Angeles environmentalist on a bad smog day, complained that London resembled "Mount Aetna, the Court of Vulcan, Stromboli, or the Suburbs of Hell, rather than an Assembly of Rational Creatures, and the Imperial Seat of our incomparable Monarch."[4] Most of the city's coal came by water from Newcastle up the coast, hence the mysterious old saw about the inappropriateness of bringing coals to Newcastle.

Coal was plentiful in the English homeland, but surface outcroppings were used up fast, and by 1700 mine shafts were as deep as 200 feet. There were problems down there with gases and especially with flooding. Dig a 200-foot hole in a countryside with high rainfall, and even if you don't hit springs, the bottom of the hole will fill up with water. The miners tried lining the walls of mine shafts with sheep skins to hold back the water, but that didn't help at all. They dug tunnels to drain the water out of the mines, but this only worked when the shafts were in the side of a hill and gravity could be enlisted to carry the water down into the valleys. Muscle, animal and human, and sometimes watermills and windmills were put to work lifting the water out of the mines, but it was an endless battle that technology circa 1700 could not win. Britain's industrial revolution was drowning *in utero*.

Coal, the Carboniferous legacy of stored sunlight, would solve that problem. Coal would be burned to power the *heat engine*, which my desk encyclopedia defines as "a device that transforms disordered heat activity into ordered, useful, mechanical work."[5] The story of that kind of contrivance, of which today's nuclear reactors are examples, begins with the eighteenth century's steam engines.

Humans had known about the power of steam for as long as they had boiled water and watched the pot lid tremble and lift. In the first century AD the proto-scientist, Hero of Alexandria, made what we would describe as a sort of lawn sprinkler arrangement powered by steam and watched it spin. Yes, humanity knew that the expansion of steam could provide power, but it was a long walk from that realization to a practical steam engine.

There were enormous difficulties. There were no smiths who made parts in accordance with precise measurements. Metals resistant to high heat and strong enough and light enough to be used for boilers and cylinders, which would contain and restrain steam under pressure, weren't available in quantity. There had never been a useful machine combining piston and cylinder, unless you count the cannon ball and cannon as such. Inventing the first practical steam engine would have to be an event on the far frontier of possibilities.

The key concept could not be to use steam to *drive* pistons vigorously and rapidly because machines with such capabilities were barely imaginable. The way around that—to us an odd one—was to use steam to make a vacuum. Classical and medieval Europeans did not believe in vacuum: space existed because there was something in it, even if only air. But halfway through the seventeenth century a German, Otto von Guericke, pumped the air out of a sphere of two carefully fitted halves, and then sixteen horses couldn't pull them apart. In 1680, a Dutchman, Christian Huygens, suggested that exploding gunpowder under a piston in a cylinder would drive out the air and most of its own gases. What would be left would be nearly nothing, at least a partial vacuum. Then atmospheric pressure would push the piston down into the vacuum. Some bright soul might try to harness that motion to do work.

The man who created that engine was an Englishman, Thomas Newcomen, of whom we know very little beyond the dates of his birth and death, 1663 and 1729. We don't even know where he was buried. He was an ironmonger from Dartmouth, one of the robust artisans produced by Western Europe's growing economies. He had little if any formal education (in that he reminds us of Michael Fara-

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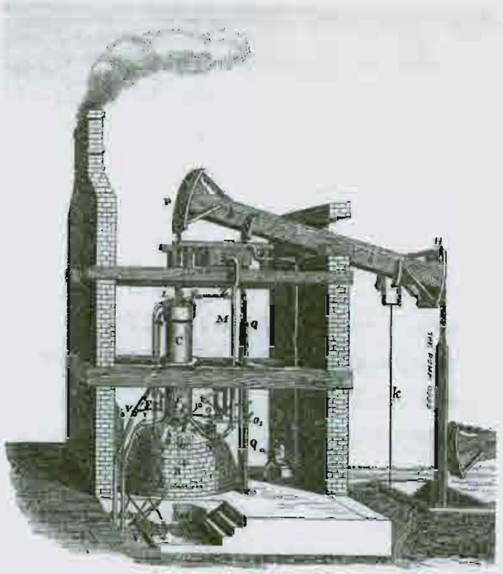
[4] Quoted in Barbara Freese, *Coal: A Human History* (Cambridge, MA: Perseus Publishing, 2003), 35.

[5] *The Cambridge Encyclopedia*, ed. David Crystal (Cambridge: Cambridge University Press, 1990), 554.

day, who figures importantly in the chapter on electricity). Perhaps he had read Huygens and the like, but probably not. He was a Baptist, a Nonconformist in religion like so many of the pioneers of Britain's industrial revolution. His admiring biographers identify him as the "first great mechanical engineer."[6]

Today, it is easier for us to imagine using hydrogen fusion to heat our homes than for Englishmen circa 1700 to imagine using fire to pump water out of mines. You set things on fire to destroy them or for warmth and light, not to push or pull, and Europeans didn't even have good fireplaces or stoves. Those that they had let most of the hot gases rise up the chimney to heat all outdoors. The Franklin (Benjamin Franklin) Stove, which detained the gases and tapped their heat before releasing them, didn't come along for more than a dozen years after Newcomen's death.

We are too accustomed to energy in plenty to comprehend the energy poverty of the world that Newcomen lived in. To illustrate: In 1682 in obedience to the order of Louis XIV, the "Sun King," fourteen waterwheels 12 meters in diameter were built near Versailles to harness the currents of the Seine to pump water to its fountains. They were together called "the eighth wonder of the world," but delivered at the very best 124 and usually not more than 75 horsepower. We scorn automobile engines of such feebleness today; three centuries ago an engine that small and of such power would have been worshipped.



Newcomen Engine, as modified by Richard Trevithick at Bullan Garden, Dolcoath, from *Life of Trevithick*, 1775.

Newcomen, with the help of a plumber named John Cawley or Calley, built a steam machine close by a coal shaft 51 yards deep at Dudley Castle, Staffordshire, in 1712 (see illustration on page 73). He didn't use gunpowder explosions to produce vacuums and move pistons, but steam. The machine's boiler held 673 gallons of water. Its cylinder, vertical, was 21 inches in diameter and 7 feet 10 inches tall. The fit of the piston and cylinder was loose and had to be sealed with a wet leather disk. Steam from the coal-heated boiler admitted into the cylinder lifted the piston up. Then cold water sprayed into the interior of the cylinder. The voluminous steam condensed to a small amount of liquid, producing a vacuum in the cylinder. *Then* came the power stroke, for which all the above was preparatory, as atmospheric pressure drove the piston down into the evacuated cylinder. The piston was attached to a rocker beam, the motion of which could drive a chain of buckets, a bellows, and so on.

Newcomen's first machine made twelve strokes a minute, raising 10 gallons of water with each stroke. Its strength is estimated at 5.5 horsepower, not impressive to us, but the "fire engine," as it was sometimes called, was a sensation in power-starved Britain and Europe. Soon there were scores of Newcomen engines, most nodding at the pitheads of Britain's mines, which now could be dug twice as deep as before. In 1700, Britain produced 2.7 million metric tons of coal; in 1815, 23 million tons. That sum was twenty times in energy equivalent what the existing woodlands of Britain could

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[6] L. T. C. Rolt and J. S. Allen, *The Steam Engine of Thomas Newcomen* (New York: Science History Publications, 1977), 13.

produce in a year. If that quantity of coal were burned in steam engines (a lot of it, of course, went for heat and cooking), the amount of power created would have equaled that of 50 million men.

At least fifteen hundred Newcomen machines were built in the eighteenth century. The rapidity of their spread in an age still, by our standards, more medieval than modern provides a measure of the need they answered. The first Newcomen engine on the continent was constructed at Königsberg in 1722. When Newcomen died in 1729, his engines were operating in Saxony, France, Belgium, and perhaps Spain. The first Newcomen engine in the New World was built in 1753 at the juncture of Belville and Schuyler Avenues in North Arlington, New Jersey. In 1775, John Smeaton built a Newcomen engine to drain Kronstadt's great drydock, which two large windmills were not keeping dry enough. This had a cylinder 5 foot 6 inches in diameter.

Thomas Newcomen's invention was the first machine to provide significantly large amounts of power not derived from muscle, water, or wind. It was a new prime mover. It utilized fire—a natural force—to heat water, to make steam, to do work. It was the first practical machine to use a piston in a cylinder. It worked night and day. If I were to attempt anything so simple-minded as to pick a birthday for the industrial revolution, it would be the first day that Newcomen's engine began operating in 1712.

In the eighteenth century, the Newcomen machine saved Britain's coal industry if not from watery demise then certainly from soggy stagnation, enabling Britain to continue with industrialization. Without increasing supplies of fossilized and concentrated sun energy, Britain's industrial revolution would have fizzled like China's. Without Newcomen's invention there would have been many fewer people in the eighteenth century thinking in terms of heat engines. Without Newcomen's invention James Watt, who for some reason is commonly credited as *the* inventor of the steam engine, actually would have had to invent the first one.

The Newcomen engine was grossly inefficient, as beginnings usually are. It was an impressive prime mover compared to muscle, water-, and windmills, but was wildly wasteful of fuel. It heated water into steam, introduced that into a cylinder, and then sprayed water into the cylinder. An egregious proportion of the fuel's energy was wasted reheating the cold cylinder at every stroke. Most of the Newcomen engines stood at the pitheads of coal mines where coal was cheaper than elsewhere, but even there it was not quite free. Big Newcomen engines consumed coal to the value of £3,000 a year, a hefty sum.

Moreover, as we, with our advantage of hindsight, can proclaim, the Newcomen engine was too big and awkward to be adapted for many tasks. It might possibly do for large ships, but not for land transportation. One at least was built to travel about on a wagon, but it was in the same category as Dr. Johnson's dog that could walk on its hind legs—interesting, but not really practical.

In addition, there was a problem with the kind of motion it supplied. Most of the machines of the budding industrial revolution required rapid, steady, and rotary motion. The Newcomen rocker arm moved slowly, not always evenly, and up and down, not round and round. When smoothly flowing rotary action was required, mill owners used Newcomen engines to raise water to pour down on waterwheels, and then the wheels did the work.

The Newcomen engine was the only practical steam engine for sixty or seventy years. Then a generation of mechanical engineers matured who were familiar with its defects, acquainted with the sciences, and had access to better materials, tools, and more skillful craftsmen than Newcomen had ever had. For instance, after 1774, British engineers who wanted pistons of precise measurements could get them from a new machine for boring cannon barrels.

The first hero of the new generation was James Watt, a Scot, a Presbyterian, a Nonconformist like Newcomen, well educated, and friendly with scientists and venture capitalists. The most important of the latter was Matthew Boulton, who wrote to Watt that he had two motives for investing in his project: their friendship and his "love of a money-getting, ingenious project. . . ." Watt was repairing a model of a Newcomen engine in 1764 when it occurred to him that the engine wasted fuel reheating the cylinder at every stroke. Instead of spraying water into the hot cylinder, why not let the pressure of the steam and the descending piston push the steam into an adjoining and unheated chamber to condense?

A dozen years later he installed two such engines, one to pump water and another to blow air into blast furnaces. They functioned satisfactorily, and by 1790 Watt had joined Boulton in the wealthy elite. By 1800, the Watt engine was producing three times as much power per bushel of coal as even the latest models of the Newcomen engine, and was pumping water out of mines, turning out flour, paper, iron, and so on and on. In the years around the turn of the nineteenth century, after Watt's patent ran out, improvements and applications of his engine came in a rush. The original version consumed too much coal and was too big and heavy to be a practical power source on vehicles or ships. It was also restricted in power and speed by its Newcomen-like dependence on atmospheric pressure to drive the piston into the cylinder as the steam was being expelled. Moreover, the arrangements Watt provided to transform the piston's linear motion to circular motion were more ingenious than effective. Within a few years high-pressure steam engines with pistons driven both back and forth by steam and linked to wheels by cranks and connecting rods were revolutionizing British activities at home and, a few years later, elsewhere.

The magnitude of the influence of the steam engine was clearly apparent in transportation. Primitive locomotives on rails began puffing along early in the nineteenth century. In 1830, one called the *Rocket* pulled a train from Liverpool to Manchester. A decade later, Britain had 1,400 miles of railroad track, continental Europe 1,500 miles, and the United States, sprawled across a continent, 4,600. In 1869, the United States, by then a nation with two populated coasts and a mostly vacant middle, tied the coasts together with the first transcontinental railroad. Elsewhere men with political influence and access to cartloads of capital were thinking about a Cape-to-Cairo railroad, a Trans-Siberian railroad, and other such awesome ventures.

The revolution that steam enacted on the oceans was at least as spectacular. In 1838, the paddle wheelers *Sirius* and *Great Western* raced from British ports to New York City for the honor of being the first vessel to make the westward crossing by steam only. The winner was the *Sirius*, but only because it set sail (an anachronistic verb we still use) ten days before the *Great Western*. The *Sirius* ran out of coal off New Jersey and burned cabin furniture, all the spare yards, and one mast under the boiler of its 320-horsepower steam engine to get to New York four hours before its rival. The *Sirius* made the crossing in eighteen days and ten hours at an average speed of 6.7 knots an hour. The *Great Western* averaged 8 knots an hour and completed the passage in fifteen days. It had four boilers, two engines of the latest design, and arrived in New York with 200 tons of coal in its bunkers. Both ships crossed the Atlantic in about half the time usually taken by ships dependent on wind.

ROBERT H. THURSTON, one of the first historians of the steam engine, opined in 1878 that Watt's hometown, Greenock, originally a fishing village, now "launches upon the water of the Clyde a fleet of steamships whose engines are probably, in the aggregate, far more powerful than were all the engines in the world on the date of Watt's birth, January 19, 1736."[7] But shipping was merely one spectacular manifestation of the impact of Watt's innovation; its influence was greatest in the textile industry, the first to be mechanized. As early as 1800, the steam-driven spinning mule (a machine for spinning cotton thread and winding it on spindles) could produce as much per unit of time as two hundred to three hundred human spinners.

[7] http://www.history.rochester.edu/steam/thurston/1878/ chapter 3, n.p.

The production of manufactured articles rose exponentially, as did trade, internal and worldwide. Between 1771 and 1775, England imported 5 million pounds of raw cotton; in 1841, 58 million pounds. In 1834, it exported 556 million yards of woven cotton goods. In that year, over 8 million "mules" were at work in England's cotton mills, which employed 220,000 workers. Most of the power in the cotton mills was supplied not by muscle but by the newer prime movers: 11,000 horsepower by waterwheels and 33,000 horsepower by steam engines. The factories of England and, soon after, New England turned out thousands of miles of cotton thread and cloth annually, making more inexpensive and decent clothing available than ever before. The ramifications of this textile explosion were not all positive, however. Plantations in the southern United States shifted to a monoculture of cotton cultivation, a labor-intensive endeavor. And the power there was still supplied by the primitive prime mover of muscle, in the form of slavery, an institution whose slumping status was revived by the profits to be made from the new textile mills.

The industrial (i.e., steam) revolution of the nineteenth century radically altered the global economy and thereby the global balance of power. For instance, the speed and output of England's mills blighted and nearly extinguished the ancient textile industry of India, disrupting the lives of thousands there. During the eighteenth century, India, China, and Europe had accounted for about 70 percent of the world's gross domestic product, each providing roughly (very roughly) one third. By 1900, China's share of the world's manufacturing output was down to 7 percent, India's to 2 percent; Europe's was 60 percent and the United States's 20 percent.

Steam immensely enhanced the speed and dependability of transportation, and spurred migration within countries—from rural to urban, from settled to frontier—often via railroad. Myriads of migrants left Europe for its overseas colonies and the United States: 400,000 people a year from 1850 to 1900, and then 1 million a year from 1900 to 1914. It was as if the shift to steam had pumped Europe full and it was exploding and flinging fragments of itself over the oceans. In the same decades millions left India and China for the Americas, South and East Africa, Mauritius, the Pacific Islands, and elsewhere to work in plantations, to build docks, roads, and railroads. Many sent their wages back home to their families and eventually rejoined them there; others brought their families to join them overseas, and yet others acquired spouses to found new families in the new lands. Whatever the origins of the migrants, the vast majority crossed the oceans by steamship. The total number of all the ocean-crossing migrants between 1830 and 1914 was an amazing 100 million.

Nothing like this colossal increase in productivity, shifts in global power and reach, alterations in locus of global hegemony, and movement of goods and people had ever happened before. Taking the measure of the steam engine's gravitas, of its historical *mass*, using the word as physicists do, is like trying to judge the significance of the tectonic drift of the continents. Let us consult expert witnesses.

Friedrich Engels was an honest witness of the human costs of the early industrial revolution. He was appalled by the horrors that followed when English factory owners obliged laborers to work to the tempo, mechanical and economic, of the industrial revolution: the illnesses and accidents, the malformations of bones and joints and minds dictated by repetitive labor, the hunger, the insecurity, the general wear and tear that shortened lives. A good proto-sociologist (though occasionally succumbing to the temptation of the exclamation mark and often to that of making prophecies), he collected statistics on England's factory workers circa 1840:

> Of 1,600 operatives employed in several factories in Harpur and Lanark, but 10 were over 45 years of age; of 22,094 operatives in diverse factories in Stockport and Manchester, but 143 were over 45 years old. Of these 143, 16 were retained as a special favour, and one was doing the work of a child. . . . Of

> fifty worked-out spinners in Bolton only two were over 50 and the rest did not average 40 and all were without means of support by reason of old age! . . .
>
> In all directions, whithersoever we may turn, we find want and disease permanent or temporary, and demoralization arising from the condition of the workers; in all directions slow but sure undermining, and final destruction of the human being physically as well as mentally.

Engels predicted that soon the day would come when the proletariat would rise and then "will the war cry resound through the land: 'War to the palaces, peace to the cottages!'—but then it will be too late for the rich to beware."[8]

Charles Dickens was also appalled by the poverty, hunger, disease, and anguish of the peasants who migrated from countryside to city to work in the new factories and, as well, by the ever-thickening coal smoke of the industrializing cities. In his novel *Hard Times*, he provides a description of Coketown, his fictional but accurately representative city of the early industrial revolution:

> It was a town of machinery and tall chimneys, out of which interminable serpents of smoke trailed themselves for ever and ever, and never got uncoiled. It had a black canal in it, and a river that ran purple with ill-smelling dye, and vast piles of buildings full of windows where there was a rattling and a trembling all day long, and where the piston of the steam-engine worked monotonously up and down like the head of an elephant in a state of melancholy madness.[9]

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[8] Friedrich Engels, *The Condition of the Working Class in England* (New York: Viking/Penguin, 1987), 179, 221, 292.

[9] Charles Dickens, *Hard Times* (London: Folio Society, 1994), Book I, chapter V, p. 18.

Dickens also noted, grudgingly and as an afterthought, that the new mills produced "comforts of life which found their way all over the world."[10] He saw both sides of the coin of industrialism, withheld predictions, and contented himself with outrage.

The American statesman and advocate for American industry Daniel Webster was in 1818 much more single-minded than Dickens. He focused on the positive characteristics of the steam engine: its power, adaptability, and promise. To the members of the Boston Mechanics' Institution, he extolled the virtues of the steam engine:

> It rows, it pumps, it excavates, it carries, it draws, it lifts, it hammers, it weaves, it prints. It seems to say to men, at least to the class of artisans: "Leave off your manual labor; give over your bodily toil; bestow your skill and reason to the directing of my power, and I will bear the toil, with no muscle to grow weary, no nerve to relax, no breast to feel faintness." What further improvements may still be made in the use of this astonishing power, it is impossible to know, and it were vain to conjecture.[11]

Power had been about muscle for all of human history, and the most effective way to marshal it had been by assembling serfs and slaves. Now, by golly, the best way was to get yourself a steam engine.

THE NINETEENTH CENTURY is sometimes called the age of coal and steam and ours the age of oil and the internal combustion engine, but the former age continued on into the next century and is still with us. Coal, for instance, is at present the most important fossil fuel for making steam to spin our dynamos and produce our electricity, which the peoples of the richer societies consider as

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[10] Ibid.

[11] *The Works of Daniel Webster*. Vol. 1 (Boston: Charles C. Little & James Brown, 1851), 186.

much their birthright as (ironically) air to breathe. Furthermore, we now have techniques to transform coal into liquid combustibles and other essentials, and there are many nations—China, for instance, and, increasingly, the United States—with a good deal more concentrated energy as coal than as oil under their soils. The hard black fuel has continued and will continue as a crucially important factor in world history. The effects of the first stage of the fossil fuel revolution that appalled and entranced the witnesses quoted above fester and foster today in developing nations, from the grim *maquiladoras* of Mexico's Tijuana to the silky nightclubs of China's Shanghai.

CODA:

NELLIE BLY BEATS PHILEAS FOGG BY EIGHT DAYS

Phileas Fogg, hero of Jules Verne's trendy novel, *Around the World in Eighty Days* (1873), completed his circumnavigation in eleven weeks and three days. Taking the Suez Canal instead of the Cape of Good Hope route saved him weeks, but his greatest advantage was that he traveled by coal and steam, not sail, i.e., by a much more concentrated product of sun energy than wind. (Incidentally, he ran out of coal and had to burn his vessel's superstructure under the boiler of its steam engine to complete the final leg of his voyage—an obvious echo of what happened to the *Sirius* off New Jersey in 1838.)

A decade and a half after the publication of Verne's book, Nellie Bly, a reporter at the *New York World*, suggested to her editor that the newspaper should sponsor her in an attempt to beat Phileas Fogg's record. He tried to dissuade her, saying that it was not a job for a woman, who would have too much luggage and wouldn't have a gentleman to protect her. She answered that if the editor sent a male reporter around the world, "I'll start on the same day for some other newspaper and beat him."

She won that argument and left to go round the world with one bag and no protector on the morning of November 14, 1889. Six days later she debarked in England. On arriving in France she visited with Jules Verne, and then continued on to Brindisi, Italy, where she caught a ship for Egypt and on to Colombo, Ceylon. She was booked for immediate departure from Colombo for China, but there was a delay of five days. Then she had a piece of luck, a record-setting passage to Hong Kong in spite of headwinds and monsoon storms.

In Hong Kong she saw the American flag at the United States Consulate, the first she had seen since leaving home. "That is the most beautiful flag in the world," she said, "and I am ready to whip anyone who says it isn't." No one spoke. From China she traveled on to "the Land of the Mikado," where she spent 120 hours. Her passage across the Pacific was stormy, but she arrived hale and hearty in San Francisco on January 23, 1890, where she was welcomed enthusiastically. She had completed 21,000 miles in sixty-eight days.

Snows blocked the passes through the Sierra Nevada, so Nellie took the southern route through the Mojave Desert and crossed the continent in four and a half days, reaching Jersey City, her embarkation port, at three-fifteen in the afternoon of January 25.[12] The circulation of the *New York World* was soaring, and she was a media celebrity, one of the very first. There was a popular song entitled "Globe-Trotting Nellie Bly," and soon a Nellie Bly board game that followed square-by-square every day of her circumnavigation. She had circled the world in seventy-two days, six hours, eleven minutes, and fourteen seconds, beating Phileas Fogg's fictional record by more than a week.

One more note about Nellie Bly. She not only proved that you

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[12] I have assumed that all the locomotives and ships involved in this journey burned coal, not wood. I do so because wood was in short supply in many regions and these trains and ships were whenever possible chosen for their speed. Some American locomotives were still burning wood circa 1890, but surely not those that carried Bly across North America in four and a half days.

could go round the world in less than eighty days, but also that speed at a rate of a new society a week often promotes nothing so much as fatigue. She summed up what she had learned in her great adventure thus:

> There is really not much for Americans to see in the foreign lands. We've got the best of everything here; we lack in nothing; then when you go over there you must be robbed, you get nothing fit to eat and you see nothing that America cannot improve on wonderfully.[13]

The revolution instigated by Newcomen and Watt only served to confirm what Bly had already known to be true when she climbed the first gangplank.

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[13] Brooke Kroeger, *Nellie Bly: Daredevil, Reporter, Feminist* (New York: Random House, 1994), 168–69.

5

OIL AND THE ICE (Internal Combustion Engine)

> For God's sake, be economical with your lamps and candles! Not a gallon you burn, but at least one drop of man's blood was spilled for it.
>
> —*Herman Melville (1851)*[1]

> Oil is probably more important at this moment than anything else. You may have men, munitions, and money, but if you do not have oil, which is today the greatest motive power that you use, all your other advantages would be of comparatively little value.
>
> —*Walter Long, House of Commons (October 1917)*[2]

A concern of humanity for millennia and its obsession for the past two centuries has been to find ways to tap energy so as to maximize its availability wherever and whenever it is wanted. The pairing of coal and steam to drive engines was an enormous advance in that search, but the search didn't—couldn't—stop there. Humanity always wants more power in smaller units of volume and weight, of greater portability. Humans want to carry sun-power like six-shooters in a cowboy movie. For that they would need new fuels and new prime movers.

By 1900, locomotive engines were operating at five times the

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[1] Herman Melville, *Moby-Dick; or The Whale* (Harmondsworth, UK: Penguin Books, 1972), 306.

[2] Daniel Yergin, *The Prize: The Epic Quest for Oil, Money, and Power* (New York: Simon & Schuster, 1992), 177.

pressure and efficiency of those that propelled the *Rocket* in 1830. Engineers and mariners had discovered that propellers drove ships through water more efficiently than paddle wheels, and soon there were bigger and faster steamships. But all that was little more than variation on existing technology. A prerequisite for a real breakthrough was a fuel of greater energy density than coal and easier portability. Coal came in chunks and pieces, with a lot of space in between. You could grind it into a powder, but powders even as fine as dust include a lot of air, too, and are miserably unpleasant to deal with. Coal was awkward to move: you couldn't *pour* it, so to speak. At Port Said, Nellie Bly sniffed that her ship was re-coaled by "hurrying, naked people rushing with sacks of coal up a steep gangplank . . . every one of them was yelling something that pleased his own fancy and humor."[3] There must be some more efficient way to distribute domesticated sun energy.

The answer was petroleum, usually called oil in American English. Often a more recent legacy of past sunlight than coal, oil is a product of similar processes. The energy density of oil is roughly 50 percent higher than most coals. It also has the advantage of being a liquid and is therefore more compact, easier to store, and easier to transport than coal. You can run it from point A to point B through pipelines. You can even run it from airplane to airplane through hoses suspended in midair.

Nevertheless, its usefulness had been overlooked for thousands of years. It was used for a miscellany of purposes—weaponry, waterproofing, lubrication, salves, once in a while as a fuel—but there was not a strong demand for the sticky, smelly substance that oozed out of the ground here and there. That demand wouldn't come until we spent a century or so learning that we couldn't depend on whales for the means to lengthen our days and shorten our nights.

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[3] Nellie Bly, *Around the World in Seventy-two Days* (New York: Pictorial Weeklies and Brentanos, 1890).

Homo sapiens isn't and never was a nocturnal species. Humans and their hominid ancestors had spent their nights sleeping or at least hiding. Campfires and fireplaces supplied some light, but not much. Torches supplied some more, but were undependable and smoky. Upper Paleolithic artists utilized primitive lamps—probably not much more than wicks floating in dishes of fat—and painted masterpieces in what otherwise would have been pitch-black caves, but that was despite, not because of, the quality of the artificial lighting. Twenty thousand years later, the enormous majority of humans still went to bed not long after sunset because there was not much else you could do in the dark.

The eighteenth century in European history is known as the Age of Enlightenment, which refers to the philosophical innovations of the time and not to an increase in nighttime illumination, but the title works well for both. Both the *philosophes* and streetlights were products of a nascent faith that the quality of human life could be intentionally improved. That would, of course, require a lot more sunlight energy. European cities were growing, along with appreciable numbers of people with enough money to frequent the new coffeehouses to eat, drink, chat, and celebrate after sundown. There were also a lot of urban poor and literally dislocated people from the countryside whose acquaintance the celebrants wouldn't want to make in dark streets.

London will serve nicely as stand-in for all the big cities of Europe and America. It had been long noted as especially dark, probably because of its latitude and the consequent long winter nights. Then in the seventeenth century a few streetlights appeared. By 1700, the City (when capitalized that title refers specifically to the municipal district inside or near the ancient stone walls) shone with streetlights from 6:00 p.m. to midnight for 117 of the darker nights annually. The year 1700 will do as the first marker of our shift from a genetically inherited diurnal cycle to the present self-directed cycle, a shift whose effects—bodily, psychologically, socially—we don't yet fully understand.

Lamplighter refilling an oil lamp in London; anonymous engraving from Knight's *Old England*, 1800.

By 1736, the City enjoyed 4,000 hours of streetlighting annually, and London ascended to the status of one of Europe's brighter metropoli. The lamplighter, with ladder, fuels, wicks, and all, became a common sight. The Age of Enlightenment was underway, but even so, all of London's streets were dark at night some of the time and most of them all of the time. One evening in 1763 James Boswell, to cite one illustrative example, took full advantage of the favors of a "jolly young damsell" on Westminster Bridge with no concern whatsoever about being seen and interrupted.

Gloom was cheap and light cost money, so illumination inside the houses and shops was also, by our standards, inadequate. Common candles were made of tallow and smoked and smelled and guttered and went out. Lamps didn't give much light and also smoked and smelled and often went out. Their design was poor and you had to keep trimming the wick. Their fuels, vegetable oils and animal fats, weren't consistently flammable and didn't soak upward through the wick as nimbly as a proper illuminant should. Benjamin Franklin reasoned that getting more air to the flame via a hollow wick might improve performance. He tried using a bullrush as a wick, but it was too narrow, and he was soon too busy being a rebel and diplomat to pursue the idea.

Ami Argand, a chemist, friend, and associate of Watt and Boulton, and an innovator who might have been one of the first humans to ride a balloon aloft but for his weak heart, independently came up with the same idea. His lamp wick was held between two concentric metal tubes: the outer tube supported the wick; the inner was hollow, and air rose through it, improving combustion. He also added a glass chimney to protect the flame and increase the draft. In 1783 a contemporary wrote, "The effect of this lamp is exceptionally beautiful. Its extraordinary bright, lively, and almost dazzling light surpasses that of all ordinary lamps. . . ."[4] Argand's lamp produced less smoke and up to ten times more light than previous lamps. When he died in 1803, there were tens of thousands of his lamps illuminating streets, shops, and homes on both sides of the Atlantic. (He should, like Watt, have been rewarded with riches, but the French Revolution, with its chaos and inflation, made sure that he wasn't.)

Argand's lamp inspired a "prodigious importation of whale oil"[5] in Britain, France, and elsewhere. Oil obtained from whale blubber burned more evenly than the other illuminants and with less smoke; sperm whale oil was the very best of all. Such oil meant brighter nights for some and wildly dangerous adventures for others, particularly Americans, who set off on a worldwide pursuit of the sperm whale.

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[4] Wolfgang Schivelbusch, *Disenchanted Night: The Industrialization of Light in the Nineteenth Century*, trans. Angela Davies (Berkeley: University of California Press, 1988), 11.

[5] John J. Wolfe, *Brandy, Balloons, and Lamps: Ami Argand, 1750–1803* (Carbondale, IL: Southern Illinois Press, 1999), 124.

Sperm oil, according to John Adams, arguing with the British prime minister about admitting American exports soon after the United States gained independence,

> gives the clearest and most beautiful flame of any substance that is known in nature, and we are all surprised that you prefer darkness, and consequent robberies, burglaries, and murders in your streets, to receiving . . . our spermaceti oil. The lamps around Grosvenor Square, I know, and in Downing Street, too, I suppose, are dim by midnight and extinguished by two o'clock; whereas our oil would burn bright till 9 o'clock in the morning, and chase away, before the watchmen, all the villains, and save you the trouble and danger of introducing a new police into the city.[6]

In the last years before the American Revolution, London had been spending £300,000 annually for whale oil for streetlamps. Most of it came from the North American colonies, two thirds from Nantucket, an island off the coast of Massachusetts where the residents had made themselves into the best whalers in the world. The Basques, Dutch, English, Germans, and other Europeans had been whaling in the northern Atlantic for several centuries, but the object of their search in those waters was and would continue to be chiefly right whales and other species whose blubber provided an illuminant inferior to that obtained from the sperm whale. "Les Nantuckois," as Thomas Jefferson, American minister to France, called them, led the way in pursuing sperm whales in warmer waters.

For several generations of whalers, American and European, the perennial problem was not one of demand but of supply. The demand for sperm oil for streetlights, lighthouses, and for lamps in millions of homes slacked off only during wars. The whalers' problem was that they were too effective as hunters for their own good. Although limited in power to wind and human muscle, they were able so to thin out whale populations in vast areas of the oceans (such as the Madeira grounds, the Twelve-Forty grounds, the Delagoa Bay grounds, and the Japan grounds) as to render hunting there economically unrewarding. Then they would sail on, discover another whale-rich expanse of ocean, and set to work decimating the giants there. By the 1770s they were off the coasts of Africa and Brazil and as far south as the Falklands. Edmund Burke declared that there was "No sea but that is vexed by their fisheries," and the whalers weren't even around Cape Horn yet.

They accomplished that in the 1790s, rushed into the Pacific, and in a little more than a half century decimated several whale, especially sperm whale, populations in that ocean, the vastest feature on the surface of our planet. In 1848, a whaler from Sag Harbor, New York, 11,000 miles around the Horn from home, passed through the Bering Strait to hunt bowhead whales under the unblinking sun of the Arctic summer. At first, when whales were plentiful, voyages of two years filled a whaling ship's holds with barrels of oil and profits easily exceeded expenses. Now there were voyages of four years and even five years that didn't pay. Humanity's yearnings for the convenience of light at night, though implemented through what we would call a primitive technology (find a fat whale, row up to it, and stick it with a spear), were endangering whole species of *Cetacea.*

There were two choices. One, conservation, unthinkable in the middle of the nineteenth century except by prophets like the primal environmentalist George P. Marsh; or, two, find a substitute for sperm whale oil. That substitute would require new raids on Carboniferous accumulations.

Back in the 1790s, William Murdock, an associate of Watt and Boulton, had discovered how to make coal gas by heating coal in the absence of air, and how to store the gas and distribute it by pipeline. By the middle decades of the nineteenth century, coal gas was

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[6] Quoted in Alexander Starbuck, *History of the American Whale Fishery* (Secaucus, NJ: Castle Books, 1989), 85.

displacing whale oil lamps for city lighting, public and private. But it was far from an ideal illuminant. Storing it and piping it to the customer was burdensome and expensive, and it was poisonous and explosive.

Kerosene, which Abraham Gesner, a Canadian chemist, discovered how to distill from petroleum in 1853, proved in many circumstances to be a better choice. It was almost as good an illuminant as sperm oil, and much cheaper. But would there be enough to satisfy a soaring demand for kerosene? In 1859, E. L. Drake, previously a ne'er-do-well, was searching for it at the suitably named Oil Creek in Titusville, Pennsylvania. He rejected the idea of actually digging for it, and chose to seek it out with a drill driven by a small steam engine. He hit it on August 29 at 71 feet, initiating America's and the world's first petroleum rush, much like California's gold rush of ten years before. Before that boom ended in 1879, Oil Creek spouted 56 million gallons of petroleum, kerosene lamps were spreading everywhere, and the American whale fishery was a business of minor importance.[7]

Then the history of human exploitation of sun energy took another violent turn, as it would again and again in the industrial age. The revolution in lighting did not cease with the gaslight and kerosene lamp any more than it had with Argand's lamp. A few decades after the Oil Creek rush, something brighter and safer, Edison's electric light (about which much more will be said in the next chapter), began to displace the preceding means of illumination. That advance would have blighted the demand for oil but for another technological revolution, this one in transportation, which sustained and multiplied humanity's addiction for this kind of fossilized sun energy.

By the middle of the nineteenth century the steam engine was providing the means to transport large numbers of people and heavy, bulky freight between major and even minor cities, but only when the demand for such service was strong and prolonged enough to justify the long and expensive effort of building railroads and large steamships. But what about shorter distances and the needs of small groups and individuals? Horses were useful, but tired easily, were sometimes uncooperative, and often couldn't be repaired. The steam-driven automobile, which first appeared early in the nineteenth century, might do as a substitute for the horse; but its engines and boilers were awkward and heavy and it was not to prove broadly adaptive.

In steam engines the burning of the sun-source fuel transformed water into steam, which then drove the pistons. That struck some engineers and inventors as indirect and inefficient. Why not tap the burning fuel directly? Why not in some way or other burn it *inside* the piston? Wouldn't an *internal* combustion engine (ICE) be better than a steam engine? The first experiments along this line were those that had spurred Newcomen and the other early inventors working with the steam engine. In the seventeenth century some visionaries, inspired by firearms, tried to build gunpowder-piston engines. They failed because there was no way to control the rate of explosion or to recharge the cylinder with gunpowder after the explosion, but the idea of an ICE persisted.

Men of many nationalities took up the idea, but it was the Germans who contributed the most to the invention of the basic ICE. In 1863, Nikolaus August Otto, a traveling salesman turned engineer, built one reminiscent of Newcomen's steam engine, as had others in prior decades. The fuel, an illuminating gas (probably coal gas), exploded inside a vertical cylinder, drove the piston up, and then the piston's weight and atmospheric pressure pressed it back down. That engine was a good start and won him some fame, but it wasn't the powerful, smoothly running machine he had in mind.

Theory is fast but application is slow; Otto worked for more than a dozen years trying to make a machine that could safely con-

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[7] Whaling, revived by new technology—harpoon cannons, steam-powered factory ships, and catcher boats—continued and even expanded, but not in America and not in answer to the demand for light.

tain a series of explosions and harness their power. His common sense dictated that the number of piston advances and retreats per power stroke should be minimized. (In the Newcomen engine every other stroke—i.e., the atmosphere stroke—was a power stroke, and in the newer, double-acting engines, with steam pushing the piston to and fro, all strokes were power strokes.) Another sensible admonition forbade sharp compression of the fuel mixture because that might set off unscheduled and dangerous explosions. But common sense doesn't always know what it is talking about.

In 1876, he patented his revolutionary four-cycle engine. The Otto engine, as it is called, functions as follows. Energy supplied by a battery or hand crank or some other outside source initiates the first step of four, drawing the piston back, which sucks fuel and air into the cylinder. Then the piston advances, compressing the fuel-air mixture: this is crucial to assuring full and even combustion. A flame or spark ignites the mixture and a nuanced explosion drives the piston back, the one power stroke of four. In the final stroke the piston advances, expelling the exhaust gases. Now the engine is running on its own and should in theory continue to do so until the fuel is exhausted.

Steam engines needed a long warm-up period and had to be kept hot to be available for use. Otto's engine was not only more efficient per unit of fuel than comparable steam engines, but could be turned on and off as needed. Steam engines, with few exceptions, were big and heavy. His kind of engine was lighter and more adaptable and convenient for shopwork and transportation. Applications of Otto's invention came in a rush. By 1900, there were perhaps 100,000 such engines bearing his name and innumerable others of similar design churning away in machine shops, breweries, pumping stations, and on the road.

There would be other kinds of internal combustion engines, notably the diesel (an invention of another German, Rudolf Diesel), which functions efficiently on a diet of unrefined oil. In time the turbine engine appeared, an ICE that is especially efficient and, with adaptations, especially well suited as the jet engine of faster aircraft. Only the modern rocket engine is more efficient, but it has limited applications. Otto's was the first practical ICE and it is still with us under millions of automobile hoods.

Karl Benz and an assistant seated in the Benz Motorwagon, the first automobile to be sold to the public, 1886.

Karl Benz, Gottlieb Daimler, and Wilhelm Maybach, associates of Otto, were protagonists in the next chapter of the story of the ICE. They invented a carburetor that mixed gasoline and air efficiently. (Gasoline, a dangerously flammable distillated crude oil, had previously been considered a worthless byproduct of kerosene production and was usually discarded.) In 1885, they produced not the original automobile but the first that actually worked, a threewheeler. Five years later, the first Mercedes-Benz automobile rolled out onto the road (and thus immortalized Mercedes Jellinek, the daughter of Emil Jellinek, a wealthy automobile fancier).

The ICE even empowered humans to fly. In 1903 the Wright brothers, Orville and Wilbur, flew, one at a time, in a heavier-than-air vehicle. The most onerous of their problems had been the building of an engine powerful enough to raise their plane up off the ground and speed it along in the air and yet light enough to be carried aloft. Clément Ader, France's nominee as the inventor of the first plane actually to fly, had tried a steam engine. His *Avion III* was a bat-winged craft with a pair of 20-horsepower steam engines that may have gotten off the ground in 1897. But steam engines with boilers filled with water were simply too heavy per horsepower, so the Wright brothers designed an engine, an ICE, of their own. Their 1903 engine produced 12 horsepower and weighed, with fuel and all accessories, only 200 pounds. Their flights, Orville wrote, were "the first in the history of the world in which a machine carrying a man had raised itself by its own power into the air in full flight, had sailed forward without reduction of speed, and had finally landed at a point as high as that from which it started."[8]

The airplane was the most spectacular manifestation of the advantages of ICE, but for most of humanity the earthbound motor vehicle was clearly more important. At first, automobiles were thought of as successors to the carriage, playthings for the wealthy. The Americans, led by Henry Ford, changed that through mass production and mass advertising. In 1903, this son of Irish immigrants and former engineer with the Edison Illuminating Company (see the next chapter) launched the Ford Motor Company with his Model-A. Five years and twenty models later, he presented the world with the first Model-T, the famous "Tin Lizzie," eventually available in nine models ranging from a two-passenger touring car to a light truck, all on the same chassis. The Model-T was strong, durable, and easily operated and repaired by amateurs. After Ford got his assembly lines moving, it was an inexpensive means of individual and family transportation. (His assembly lines were driven by electric motors—more about that in the next chapter, too.) At first his workers took 750 minutes to assemble the major components of a Model-T. In time they got that down to 93 minutes.

In 1925, a Model-T cost $260 and middle-class people—even workers in the Ford plants—could afford one for themselves. Ford Motor Company produced 16 million Model-Ts before discontinuing that model in 1928. Ford's company, of course, continued to produce motor vehicles, now in competition with Packard, Pierce-Arrow, Austin, Morris, Fiat, and others. The auto industry flooded the richer and, increasingly, the poorer nations with automobiles, and the nations bound themselves together with meshes of surfaced roads. (Asphalt, by the way, is, like gasoline and natural gas, a kind of petroleum.) Hundreds of millions of people began to think that driving a vehicle powered by an ICE was a normal, even indispensable, human behavior.

The vehicles burned fossil sun power, gasoline usually, the demand for which soared. The petroleum seekers who had started at Oil Creek field in Pennsylvania rushed on to California, Texas, Oklahoma, and elsewhere in the United States. By 1900, they were pumping oil in Romania, in Baku on the Caspian Sea, and Sumatra, in the Dutch East Indies. By World War I, they had moved on to Mexico, Iran, Trinidad, and Venezuela. In the middle decades of the twentieth century, they were discovering new fields in every continent but Antarctica, most notably in the Middle East, and were even beginning to drill into the sea bottom.

The ICE powering the automobile, truck, and tractor has for a century been the most influential contrivance on the planet. It has allowed us to move from farm to city and helped us at the same time to increase agricultural production immensely. It has allowed us to live in cities without tens of thousands of horses and their tor-

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[8] Charles H. Gibbs-Smith, *The Aeroplane: An Historical Survey* (London: Her Majesty's Stationery Office, 1960), 41.

rents of urine and tons of feces. At the end of the twentieth century there were fewer horses but a half a billion cars in the world, not including trucks, buses, tractors, tanks, and so on. Our factories were turning out nearly 50 million new ICE vehicles a year, and we humans required 70 million barrels of oil daily.

During the twentieth century the addiction to oil became a major factor in international affairs and figured in war after war fought by the technologically advanced nations. World War II (1939–45) is a case in point. The leaders of Germany and Japan were convinced that their nations must free themselves of dependency on others for oil. The Soviet Union had oceans of its own oil and France, Britain, and their allies could draw on other oceans of oil under the soils of the United States and elsewhere overseas. Germany and Japan, with no such sources, lusted after the fossil fuel riches of Romania, the USSR, and the Dutch East Indies; they dispatched armies and navies to seize them.

The armed forces of World War II were largely propelled by oil burning in the cylinders of ICEs. The conflict began in Europe with the *Blitzkrieg* (lightning war), a sudden and rapid advance spearheaded by German tanks and planes. It ended with a Soviet assault on Berlin in April 1945, which included 8,000 tanks and 11,000 planes. The ICE enabled the belligerents to wage war not only on enemy armed forces but on their civilian populations as well. The war in the Pacific began, as far as the United States was concerned, with a Japanese air raid on the American military bases in Oahu, Hawaii. It ended with American raids on Japanese cities; on March 10 and 20, 1945, American planes bombed four of these, leveling 83 square kilometers of buildings and killing about 100,000 people. A month later, American B-29s delivered two nuclear bombs, killing at the very least another 100,000. The ICE had enlarged the battlefield to take in every square foot of the Earth's surface.

CODA:
THE ICE, PEACE AND WAR, AND THE TAXIS OF PARIS

During 1914 the ICE enabled France to survive invasion. In August of that year, German armies swept through Belgium into France and swung round and south toward the capital of France. On September 6, they were thirty miles from Paris. What ensued was the First Battle of the Marne, September 6–12, 1914, which saved the city.

One of the key factors in that Allied victory was the four thousand (some sources say six thousand) reinforcements which the French were able to get from Paris to the front on the critical days of September 7 and 8. These soldiers could have marched the thirty miles, but that would have left them exhausted and would have taken at the very least a full day, by the end of which the battle and possibly the war might have been lost. Horses? Impossible. There was no way instantly to procure thousands of horses, much less fodder for them and wagons for them to pull. Steam locomotives could have towed the reinforcements to the front in minutes, but all the railroads within a hundred miles of Paris were jammed with divisions retreating, divisions advancing, with supply trains going no one knew where anymore, with trains loaded with wounded and thousands of refugees. Near Troyes, some trains were taking twenty-four hours to travel six miles.

General Joseph Gallieni, military governor of Paris, ordered the requisition of the hundreds of taxis in Paris. Gendarmes stopped taxis and proclaimed, "Requisition. Go back to your garage."

"But I have a fare," the cabbie would often answer.

"Never mind. Your fare must get out."

"How will I be paid? By meter or flat rate?"

"By the meter."[9]

The taxis gathered at the Esplanade des Invalides and other staging points. There they took on their cargoes of French soldiers, the *poilus*, and careened off to the front, sometimes two and three abreast. The fortunes of war wavered back and forth, and then for the first time in weeks tilted in favor of the Allies. By the twelfth of the month, the Germans were in retreat. They would never come as close to Paris again in that war.

For their services in the First Battle of the Marne, the Parisian cabbies were paid 27 percent of the amounts registered on their fare meters and were elevated into the fellowship of France's legendary heroes.

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[9] Georges Blond, *The Marne: The Battle That Saved Paris and the Course of the First World War*, trans. H. Easton Hart (London: Prion Books, 2002), 180.

6

ELECTRICITY

> . . . The dynamo itself was but an ingenious channel for conveying somewhere the heat latent in a few tons of poor coal hidden in a dirty engine-house carefully kept out of sight; but to Adams the dynamo became a symbol of infinity. As he grew accustomed to the great gallery of machines, he began to feel the forty-foot dynamos as a moral force, much as the early Christians felt the Cross.
>
> —*Henry Adams (1905)*[1]

In the middle decades of the nineteenth century humanity continued to lust after more power, but power per se was not the immediate problem. One heat engine might be more powerful than the muscular strength of a thousand or more servants, *but*—a very important but—there is more to getting work done than power. An engine powerful enough to bend steel girders on this side of town is useless if what you want is to fold newspapers on the other side of town. Muscle servants, especially the human ones, can be easily moved from this side of town to where their strength is needed. They can be switched from job to job, employing their muscles for hod-carrying *here* in the morning and for shelling walnuts over *there* in the afternoon. Human muscles can be utilized for tasks as crude as hacking trails through the jungle and as delicate as painting scenes on porcelain teacups.

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[1] *Henry Adams: Novels, Mont Saint Michel, The Education* (New York: Literary Classics of the United States, 1984), 1067.

Heat engines tend to be immobile, especially the giant ones that produce enough power to drive whole factories. The steam locomotive and the gasoline-driven automobile certainly move, but characteristically only along prepared roads. A heat engine might lift 100 tons, but was, in itself, not useful if what you wanted to do was drive one sewing machine in a millinery shop up two flights of stairs and down the end of the hall or light a lamp on a farm a hundred miles out in the backcountry. Distribution, focus, differentiation, and gradation of prime mover power were the challenges for a society that wanted more material goods, more convenient transportation, more light—more of *more*—in the middle decades of the nineteenth century. The answer was electricity.

Evidence of electricity had, of course, always been present in our lives, from lightning bolts blasting steeples to little boys scuffing along a rug in cold weather to deliver shocks to little girls' noses. The ancient Greeks discovered that rubbing amber somehow changed it so that it attracted feathers (the word "electricity" is derived from the Greek name for amber). But this added nothing to the possibilities of humanity ever being able to do anything useful with the phenomenon. Very little would happen in that category until ways were found to evoke electricity in forces great enough and of sufficient duration to be a subject for thoughtful examination.

That started to happen when William Gilbert, Queen Elizabeth I's physician, learned that there were a number of substances in addition to amber that gained magnetic qualities when rubbed. A hundred years later another Englishman, Francis Hawksbee, created a real electrostatic machine by attaching a crank to a hollow glass globe, rotating the globe at high speeds, and rubbing it with a leather pad. This machine produced sparks for entertainment and enough electricity for real experiments.

Now some way to store electricity for deliberate and thoughtful consideration was needed. The initial answer to that need was the Leyden jar, named after the city in Holland where Pieter van Musschenbroek is supposed to have invented it in 1746. The first model was simply a jar of water with a wire sitting in it vertically, half in, half out of the water. In later models the jar was wrapped in metal coating, inside and out. The wire was charged with electricity from a big version of Hawksbee's machine. The charge, caught in the bottle, persisted for some time, even for several days, to be summoned when wanted.

Electrostatic machines and Leyden jars provided electricity in jolts of energy suitable for tricks and some experiments, but not really suitable for the kind of investigations that would lead to major advances in scientific understanding. What scientists needed was electricity in a steady flow. An Italian, Alessandro Volta, provided that toward the end of the eighteenth century amidst the confusion and fury of the French Revolution. The Leyden jar stored electricity. Volta's invention made electricity.

He did so with chemistry. He stacked copper, zinc, and cardboard disks moistened with saltwater, building what we call the voltaic pile. The copper loses electrons to the wet cardboard and the zinc gains electrons. Unattached electrons flow out of the pile through insulated wires. This, the first battery, produces electricity until the fluid dries out or the zinc dissolves. It was a marvel and Napoleon took time off from battles to give Volta a gold medal, the cross of the Legion of Honor, and 6,000 francs.

Within a few years there were piles weighing tons—the Royal Institution in London had one with 4,000 copper and zinc disks—and other and better batteries soon appeared to provide science and technology the means to investigate and perhaps to domesticate a thoroughly mysterious force of nature.

In 1820 a Danish professor, Hans Christian Ørsted, noticed in the midst of one of his lectures on electricity that the wire he held in his hand, connected to a small Voltaic battery, was somehow affecting the needle of a compass on the desk. He subsequently discovered that no matter where north was, the needle would position itself at right angles to the wire. If he reversed the flow of electricity through the wire, the needle swung 180 degrees and took up the opposite position. Electromagnetism can be tapped to make things move; it can do work. Electric motors are descendants of his tiny experiment.

The next electromagnetic hero was an Englishman, Michael Faraday, whose career provides the best kind of evidence in favor of meritocracy. He was one of a blacksmith's ten children and a man of very little formal education, who happened to attend a public lecture by the famous Sir Humphry Davy. He came away fascinated, wrote to the scientist, became his assistant, and in time succeeded him as head of the Royal Institution laboratory. Faraday repeated and elaborated on Ørsted's experiment, and soon had not only needles rotating but disks revolving. That was satisfying; but, he wondered, if electricity and magnetism could be manipulated to produce movement, would it work the other way around? In 1822 he wrote in his notebook: "Convert magnetism into electricity."

Nine years later, Faraday discovered that when he thrust a bar magnet in and out of a coil of wire attached to a galvanometer, the instrument indicated that a current of electricity had been created. Magnetism *and motion* made electricity. Faraday proceeded to build the first dynamo or generator, a metal disk rotated by a hand and crank between the poles of a horseshoe magnet, producing a weak flow of electricity. (Joseph Henry made much the same discovery in America at approximately the same time, but Faraday published first.)

Ørsted and Faraday had discovered an intimate relationship between electricity, magnetism, and motion. Given control of the first two, humans could produce motion. Given control of the second two, humans might be able to produce electricity. The first descendants of Faraday's dynamo were quite similar in design—a loop of wire spinning between the poles of permanent magnets, or vice versa. The volume of electricity that was produced was insufficient to drive large motors, but it was enough to inspire inventions that opened the era of worldwide electrification. The United States, just beginning industrialization and overflowing with clever and ambitious young men, would play a central role in the saga of turning European science into fame and dollars.

The first breakthrough invention was the telegraph; it didn't require a lot of electricity to carry a message. Samuel F. B. Morse was an artist who worked in both America and Europe. When he started painting, the best long-range signal system in existence consisted of big semaphores on towers, which was useless in bad weather, tricky at night, and capable of transmitting only the simplest messages. Painting didn't satisfy him, and in time he turned away from his canvases to join the ranks of those who theorized that electric current, which could flow through wires for remarkably long distances day and night, might be suitable for communication. Morse, assisted ably by Alfred Vail, made some useful improvements in the equipment of telegraphy. But his greatest contribution was probably an "alphabet" of dots and dashes by which the staccato opening and closing of a circuit could be utilized to represent letters and numbers. That is what we call Morse Code.

He tinkered with his telegraph for years and spent more time than that pleading for money from governments and private investors on both sides of the Atlantic. (One of his voyages across that ocean was on the swift steamer, the *Great Western*, mentioned in chapter 6—there was a lot going on in the 1830s.) Success came to Morse in the 1840s, about a dozen or so years after Faraday had first published his discoveries on electromagnetism. The climactic moment came on May 24, 1844, when publicity-wise Morse sent the famous and pious message, "What hath God wrought?" down a wire that stretched from the Mount Clare depot in Baltimore to the Supreme Court Building in Washington, D.C. A dozen years later there was a telegraph line connecting Washington and New York.

The Morse telegraph system answered a powerful need and spread with amazing speed. In 1861 the first transcontinental telegraph signal pulsed along a line on poles stretching from San Francisco to New York. In 1857 and 1858 the first attempts at laying a telegraph cable between continents, specifically from Newfoundland to Ireland, ended in failure, frustrating but not stopping the pioneers of electricity and of venture capitalism. After a pause for the American Civil War, they renewed the attempt, failed again in 1865, and then in 1866 completed the first transoceanic cable for transmitting messages by electrical pulse. The signal was feeble, but the miracle had been achieved. Now people could correspond instantly across an ocean. The world had for many purposes—economic, diplomatic, intellectual, literary, journalistic—abruptly shrunk by the measure of the width of the Atlantic.

Two decades more and another American, Alexander Graham Bell, made his contribution. (His indispensable aide was Thomas A. Watson, the man who answered the very first telephone call, the impromptu "Watson, come here. I want you," delivered by Bell when he spilled acid on himself.) Bell parlayed his understanding of the processes of human speech production (he had spent years working to provide the deaf with the means to communicate) with what he taught himself and picked up from people like Joseph Henry about electricity to produce the first practical telephone. He patented his invention in the United States in 1876. You could now actually *talk* to someone across town, and soon, with someone in the next city, and soon, other countries. The world's girth diminished again.

Access to electricity revolutionized communication, but would do so across the whole range of human activity—city lighting, industry, transportation, entertainment—only if massive voltages became available. Faraday's dynamo had produced just a wisp of current. Its early successors, which, like the original, used natural magnets, produced more electricity, but not enough more to power a new civilization. Natural magnets were simply not powerful enough.

Joseph Henry and other innovators wrapped current-carrying, insulated wires around big horseshoes of soft-core iron and turned them into electromagnets, which for all practical purposes could be made as powerful as needed. One of Henry's could lift a ton. In 1866, a German, Werner von Siemens, tried electromagnets in the generator he was attempting to invent, and the electric current flowed like the Rhine. Other Europeans, for instance the Belgian Zénobe Théophile Gramme, made other alterations to dynamo design, improving function.

The prime mover of electricity had been muscle at first (Faraday's muscle spinning the loop between the arms of a magnet), but in the later decades of the nineteenth century generators were being driven by internal combustion engines, at first reciprocating and then, in the final years of the century, turbine engines. The ancient prime mover, the watermill, was adapted for the same purpose, and then the windmill.

With the refinement of electromagnets and dynamos there was enough dependable electricity to drive big electric motors empowering advances in transportation. The first public electric railroad was probably the one that began operation in Lichterfelde, Germany, in 1881. The first London Underground railway (subway in American English) was dug in 1887–90—steam engines were unsuitable underground, but electric motors made no smoke and gave light, too.

The most spectacular advance in electrification was in urban illumination. Back in 1850, there was not a city on earth in which every street was lighted every night and few in which most streets were lighted. The houses of the wealthy were illuminated by candles and lamps burning whale oil, solidified and liquid. Kerosene lamps wouldn't appear in great numbers until the petroleum age opened in a decade or so. Even after that, the best answer for years to the demand for urban lighting was coal gas illumination, which many cities adopted for outdoor illumination and which individuals introduced into their shops and homes.

For most of the nineteenth century coal gas was, on balance, the superior source of light. It burned brightly and could be transported by pipe. Soon many of the larger cities in the Western world had big storage tanks of coal gas called gasometers (which confusingly also referred to meters for measuring amounts of gas) and underground pipes leading to customers' homes, offices, and workshops. Coal gas was much cheaper than whale oil and was widely adopted for streetlighting. London was the first of the big cities to do so. In 1822, it already had four gas companies and forty-seven gasometers.

Gaslight was a great improvement on what had come before, but soon innovators were wondering whether electricity, which experimenters and charlatans far back in the eighteenth century had used to make bright sparks and eerie glows, mightn't prove better. The heat of the flame of coal gas was unpleasant in sultry weather, and in winter, when you shut the windows, it burned up the oxygen in the room and left you with a headache. More than a few textile mills illuminated by gaslight caught fire and burned down. Wind could blow out a gas flame but the gas would continue to flow, setting the scene for disaster. You wouldn't want to leave children alone with the gas's open flame, and the gasometers might explode, wiping out whole neighborhoods.

Such objections were heard more and more often as electric lights became available. The earliest to be used extensively was the arc light. Run a strong current through two sticks of carbon in contact, then draw the two apart and the electricity will arc the gap, burning the carbon and producing a dazzling light. The arc light was (and is) an excellent means to illuminate large areas—city squares and stadiums, for instance—and was utilized to do so for some of the more famous streets of the world and for a few entire neighborhoods. There were plans to light whole cities: imagine the Eiffel Tower decked out with arc lights. But the shadows the big arcs on towers threw on one side of a city street were as black as the other side was bright, and the light was much too dazzling for home use. Imagine a reading lamp with a glaring arc light fizzing and sizzling by your cringing ear.

Dozens of people tried their hand at creating incandescent lamps, piling up a good deal of data from which later inventors benefited. The winner of the race, as the reader knows, no doubt, was Thomas Edison. He was very bright, an extremely hard worker with a fine staff of experimenters, and he hired very good lawyers to defend his inventions and attack his rivals' claims in the courts. His problem was to find some substance—a wick or filament—that would heat up when electricity flowed through it and glow brightly for a good long time. He and his staff tried hundreds of candidates and finally created a lamp consisting of an airless glass bulb containing a filament of carbonized thread. They ran electricity through the filament and it shone for forty-five hours before going out. Edison patented it in 1880. (He and others kept on looking for better filaments; Edison settled on carbonized bamboo for some years, but tungsten became standard in the next century. An inert gas was substituted later for the vacuum.)

Edison's light bulbs did not dazzle and glare like arc lights, provided more light than coal gas, and did not impose a constant threat to ignite wall hangings, clothing, or human hair. They did not consume oxygen or smell in the slightest. (In 1913, Marcel Proust wrote of the "stifling sensation that, nowadays, people who have been used for half a lifetime to electric light derive from a smoking lamp or a candle that needs to be snuffed.") Light bulb energy came by wires, which, unlike gas pipes, could be arranged and rearranged as wanted. You didn't literally have to set fire to an electric bulb as you did a gaslight. Electricity, unlike gas, did not explode. It might electrocute you, of course, but that affected individuals, not whole buildings and neighborhoods.

The most advantageous characteristic of electricity was that it was eminently transportable. You could build your generator by a coal mine, for instance, and burn the fuel right there to produce electricity; or build it next to Niagara Falls and exploit falling water to produce electricity and then dispatch the product through wires (renamed cables when they got big enough) to distant customers. Fossil fuels, including coal gas, had to be ordered beforehand and carried by rail and wagon or run through pipes, which was awkward and consumed time and money. Flip a switch and electricity was right there on the spot—the perfect servant—to drive your locomotive, printing press, elevator, or sewing machine.

Buildings of the Chicago World's Fair illuminated at night; photograph by C. D. Arnold, 1893.

In 1882, Edison opened the first electric power station supplying private customers at 255–257 Pearl Street in New York City. At first it served only eighty-five customers and lighted four hundred light bulbs, but coal gas was on its way to demotion from being a source of both light and heat to being a source for the latter only. At some moment in the later years of the nineteenth century, Western civilization plumped for electrification. It was an epochal decision soon taken up, at least in intention, by the rest of humanity. It has no precise date: there was no formal Declaration of Electrification. It was not made by a commission or a legislature, but by whole populations informally and gradually over a period of years that began, shall we say, with Morse's telegraph. The best we can do for a date is to find in the record a substantial block of evidence unambiguously demonstrating that it had been made.

The four hundredth anniversary of Christopher Columbus's discovery of America, venerated by citizens of the United States, arrived a half century after Morse's triumph. A commemoration proportionate to the Columbian triumph would have to be truly impressive; a world's fair might suit. Several cities battled for the honor, and Chicago won. That city's hope was to literally outshine Paris, whose World's Fair of 1889 had wowed the customers with Gustave Eiffel's new tower.

The Chicago World's Fair, better known as the Columbian Exposition or the White City, was officially opened at a locale a few miles from downtown on May 1, 1893. (A year late, you may notice, but major demonstrations of a civilization's prowess aren't thrown together in a day.) President Grover Cleveland spoke to a crowd of scores of thousands from a platform seating three thousand:

> As by a touch the machinery that gives life to this vast Exposition is now set in motion, so in the same instant let our hopes and aspirations awaken forces which in all time to come shall influence the welfare, the dignity, and the freedom of mankind."[2]

He pressed down on a key closing a circuit and, as a choir sang Handel's Hallelujah Chorus, an engine burning oil (coal would be too smoky) started running, secondary machines began to function, the fountains to spout, and the biggest world's fair to date officially opened its gates to the public.

The Columbian Exposition was the full-bore affirmation of the supremely self-confident Western civilization expressed specifically by Chicago, which would soon be appropriately called "the city of the big shoulders." The draining and leveling of the site, 686 acres of wetlands, and the raising of its buildings, had been a largely elec-

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[2] Jill Jonnes, *Empires of Light: Edison, Tesla, Westinghouse, and the Race to Electrify the World* (New York: Random House, 2003), 263.

trified effort. Dredges, stone crushers, sharpeners, the bigger saws, the pumps, the cranes, the spray painters were powered by electricity. The night crew, of course, operated under electric lights. The White City's biggest buildings, all designed by American architects in the classic style with pillars and domes, were grouped around a gigantic lagoon, 250 by 2,500 feet. The biggest single structure, the Manufactures and Liberal Arts Building, was the largest roofed building ever built. It was big enough to have enclosed at one and the same time the cubic footage of the U.S. Capitol, the Great Pyramid, Winchester Cathedral, Madison Square Garden, and St. Paul's Cathedral.

The exposition's prime movers were fifteen steam engines with the aggregate capacity of 13,000 horsepower driving, when required, sixteen generators to produce 8,955 kilowatts of power, enough to light 172,000 incandescent bulbs. The generators supplied the power for all sorts of electric tools, for fountains spouting 100 feet high, for a moving sidewalk as long as the lagoon, a pickpocket detector, an electric chair, and much, much more.

There was the largest searchlight in the world, an arc light that weighed 6,000 pounds. There was an incandescent bulb 8 feet tall on top of an 80-foot column. There was an 11-ton cheese and a 1,500-pound chocolate Venus. The latter weren't directly dependent on electricity, but the spectators wanting to see them arrived on trolleys and boats with electrical motors. There was a gigantic vertical merry-go-round, the creation of George W. G. Ferris, whose name has come down to us as the generic term for such devices. This particular monster of delight weighed 1,200 tons, was 250 feet in diameter, and had thirty-six cars carrying forty passengers each. When full, it carried 1,440 passengers. It was favorably compared to the Eiffel Tower. No wonder the author Hamlin Garland wrote his father, "Sell the cook stove if necessary and come. You *must* see the fair."[3]

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[3] Quoted in David F. Burg, *Chicago's White City of 1893* (Lexington: University of Kentucky Press, 1976), 180.

"Nearly everything," David F. Burg, informs us, "that glowed, that sounded, that moved at the fair was powered by electricity."[4] The exposition was open for only half a year, from May to October of 1893, but in that time over 27 million people, Americans and foreign visitors, viewed its marvels. They were awed: electricity seemingly enabled humanity to project and direct the power of its prime movers to any target and for any purpose.

HENRY ADAMS, one of the most perceptive students of human history, concerned himself not so much with dates and details as with the driving forces. He sifted through contemporary civilization for something that might represent, symbolize, the force of his time, and found it in the 40-foot electrical dynamo exhibited at the Paris Exhibition of 1900. He found himself disposed to pray to it, prayer being "the natural expression of man before a silent and infinite force."[5] Many since have been similarly moved. In 1920, Vladimir Ilich Lenin proclaimed like an Old Testament prophet to the All-Russia Congress of Soviets, "Communism is Soviet power plus electrification of the whole country," and the USSR, as soon as it even started to recover from its civil war, began to build electric power plants and some of the biggest hydroelectric dams yet. The United States manifested equal faith in technology by building similarly huge hydroelectric dams—such as the Hoover Dam on the Colorado River, the Grand Coulee on the Columbia, and several in the Tennessee Valley—whose electric energy would prove to be crucially important in the development of the nuclear bombs that ended World War II. Since the war the developing world has followed suite with, for instance, a dam on the Paraná between Paraguay and Argentina, and the epochal Three Gorges Dam now being built on the Yangtze River in China. Per capita consumption of electricity in this world of ours has risen from 1,445 kilowatts in

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[4] Ibid., 204

[5] *Henry Adams*, 361.

Nighttime Map of Our Planet. A composite of hundreds of pictures taken by orbiting satellites by the National Aeronautics and Space Administration.

1980 to 2,175 in 2000, and will continue to soar in the developing nations.

What is the magnitude of this change? I refer you to the nighttime depiction of our planet above, a composite of hundreds of pictures by orbiting satellites (obviously, it cannot be dark all over the earth at once). Note that the only large areas without visible electric lights are the oceans, polar regions, deserts, and the sparsely settled interiors of the continents—and North Korea. The enormous majority of human beings live within a few feet or, at most, a short walk, of electric outlets.

CODA: AMUSEMENT AND EXECUTION BY ELECTRICITY

In the eighteenth century, experimenters learned that human flesh and bone could transmit electricity, which could be amusing. Jean-Antoine Nollet (often known simply as abbé Nol let) contributed significantly to advances in electrical science, but is com-

monly remembered best for his tricks. For the edification of Louis XV, king of France, he arranged 180 gendarmes in a circle holding hands and had one of them touch the brass ball in the lid of a charged Leyden jar. The shock ran through all 180 instantly and they jumped and gasped in perfect unison. The king loved it. The abbé tried the trick again with two hundred Carthusian monks and yet again with six hundred assorted people at the Collège de Navarre. It was a real crowd-pleaser.

Electric current could be dangerous as well as amusing. In 1750, when Benjamin Franklin was preparing to electrocute a turkey (to eat, probably), he touched what he shouldn't have touched and knocked himself out. The shock, he recorded, was "a universal blow throughout my whole body from head to foot, which seemed within as well as without," but he recovered in a day.[6] The means to create an electrical charge and to store it in the middle years of Franklin's century were such that the electrocution of an adult human being was unlikely. The voltage wasn't high enough. Lightning, however, could provide enough: Franklin, famously flying a kite in a thunderstorm in 1752, elicited a spark when he could have called down a thunderbolt. The next year Georg Richman, a Swedish experimenter, tried a similar experiment in St. Petersburg and was killed.

In the 1880s, dynamos still couldn't match the voltage of thunderbolts, but were quite capable of producing enough to kill a human, which, in fact, had already happened accidentally. It was inevitable that someday it would happen purposely. On March 29, 1889, William Kemmler (alias John Hort) of Buffalo, New York, killed Tillie, his consort, with an ax. He was easily apprehended and convicted—he even seemed anxious for punishment—and the judge condemned him to die by electricity. Perhaps the novelty of such an execution persuaded the judge or perhaps electrocution seemed more merciful than the rope. Kemmler would be the first in the world to be so executed as a formal act of justice.

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[6] Quoted in Jonnes, *Empires of Light*, 27.

The sentence triggered a debate in the courts and press about whether such an execution would or would not count as "cruel and unusual punishment," forbidden in the U.S. Constitution. There was also some question as to whether electricity could be depended upon to do the job.[7] Edison confidently testified that electrocution would work, recommending that the subject's hands should be placed in a jar of water diluted with caustic potash and connected to the electrodes. Kemmler himself decided that it would be less painful to die by electricity than by hanging.

The execution took place on August 6, 1890, in Auburn, New York. When the switch on the line connecting a prison dynamo and the electric chair was thrown, Kemmler snapped up straight and strained against his bonds. According to the *New York Times* reporter, he became "as rigid as though cast in bronze, save for the index finger of the right hand, which closed up so tightly that the nail penetrated the flesh on the first joint and the blood trickled out on the arm of the chair."

The current was turned off; doctors examined Kemmler and pronounced him dead. One of the witnesses, Dr. Alfred W. Southwick, an advocate of electrocution as a merciful means of execution, declared: "There is the culmination of ten years' work and study. We live in a higher civilization from this day."[8]

But Kemmler's chest still rose and fell: he seemed to be breathing. The switch was thrown again. Kemmler went rigid again. For an instant there was a blue flame at his neck. His clothes caught fire. There was a very strong smell of burned meat. Now there was no question as to his death.

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[7] This debate was one episode in the struggle between the advocates of direct current (DC) versus those of alternate current (AC), which we don't have to go into here.

[8] Jonnes, *Empires of Light*, 211–12.

PART THREE

ENERGY AT THE TURN OF THE THIRD MILLENNIUM

> The most fundamental attribute of modern society is simply this: ours is a high-energy civilization based largely on combustion of fossil fuels.
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> —*Vaclav Smil, geographer (2003)*[1]

Political and military titans such as Caesar Augustus and Genghis Khan had no more than continental effect at most, and usually a great deal less than that. But the changes initiated by the pioneers of modern technology—Newcomen, Watt, and their steam engines, Otto and the internal combustion engine, Edison and electric lights—have been so massive that they would surely attract the attention of any intelligent organisms in passing spaceships. Newcomen and the rest of them utilized new prime movers and new ways to use them to do work and make profits. In doing so, they altered human society and the biosphere drastically and certainly more abruptly than anything since the advent of agriculture and perhaps even the domestication of fire. Estimates of the gross world product (GWP) are incurably imprecise, but they are useful in conveying the magnitude of change. In 1900 the GWP, measured in 1990 U.S. dollars, amounted to something like $1 trillion; in 1950, $5 trillion; and by the end of the century, $29 trillion.

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[1] Vaclav Smil, *Energy at the Crossroads: Global Perspectives and Uncertainties* (Cambridge, MA: MIT Press, 2003), 1.

That awesome increase was made possible by mass transportation, giant freighters, elevators, refrigerators, cranes, and other large technologies, and by dynamos producing gigawatts (billions of watts) of electrical power. Almost all of these innovative devices were driven by the burning of fossil fuels or by motors whose electrical energy was derived from combustion of fossil fuels. Most of our electrical energy, despite the photographs of gigantic dams with thousands of tons of water pouring through penstocks as big as subway tunnels and turbines spinning like tornados, is produced by dynamos driven by burning fossil fuels.

John P. Holden, of Harvard's Kennedy School of Government estimates that humanity's primary energy use has increased twenty times over since 1850 and nearly five times over since 1950. The United States, bellwether of the profligate societies, consumed 2,000 kilowatt-hours of electrical energy per individual in 1950, and 32,700 per individual in 2000. Electric plants typically burn tons and tons of coal every day. In 1900, coal production was about 1 billion metric tons; in 1950, 3.5 billion tons; and toward the end of the century, 5.2 billion. Although coal production has continued to rise, oil now supplies more of the world's energy than coal. In 1900, the world production of oil amounted to about 100 million barrels a year. At the end of the twentieth century, the annual total was far over 20 billion barrels.

There is enough coal still in the ground to last us for generations. Our immediate fossil fuel problem pertains to oil, which is the highest in energy density of the fossil fuels and, being a liquid, the easiest to transport and store. The question is not *if* but *when* we will have an oil shortage. It may be generations from now or, as some shrewd analysts predict, in this generation. Kenneth S. Deffeyes, professor emeritus of oil geology at Princeton University, has meticulously considered all the pertinent information, subjected it to sophisticated mathematical analysis, and predicts that world oil production will peak in the first decade of the twenty-first century. After oil production maximizes, whether it be in this decade or decades hence, the trend in oil prices will then be upward, with, one might predict, grim results economically, and politically and militarily as well.

Most, perhaps all, of the billion-barrel, "elephant" oil fields have been discovered and are producing already. Smaller fields will certainly be found, abandoned wells will be squeezed again by means of steam injection and such, liquefying and pushing oil to the surface. Exploratory drilling in waters kilometers deep in the Gulf of Mexico and off West Africa is already underway. But it seems that the gravy days of the oil industry are long gone. We have pumped out and burned in a century the easily accessible accumulations of liquid fossilized sunlight. Fortunately, at least in the short run, there are other sources of oil. Enormous deposits of solid petroleum exist in Canada and Venezuela in tar sands and oil shale to which we may have to resort someday. At present, however, the processes to produce from such sources fuels that are conveniently transportable and burnable are difficult and dauntingly expensive.

Natural gas, which refineries used to burn (or "flare") to be rid of it because it was as worthless as gasoline before the automobile, is now used as fuel for all kinds of purposes. The globe's crust contains huge amounts of it. There is also an icelike form of water (gas hydrates) with cavities containing combustible gas in vast quantities beneath the ocean floor. It is likely that natural gas will take the place of oil as our most important fossil fuel.

The problem is not that we will run out of oil or natural gas in any absolute sense; there will always be some somewhere, most likely in the Middle East, which makes for diplomatic and military complications. But for now let us focus on a relatively simple economic problem: the amount of energy expended to procure petroleum energy is creeping up on the amount of energy gained. For instance, horizontal drilling, one of the clever techniques for getting more out of waning wells, is currently producing in Oman a liquid that is 90 percent water and only 10 percent oil. Getting rid of the water is expensive in energy and therefore in money. It is a matter of "energy returned on energy invested" (EROI)."[2] In the oil fields of the United States the EROI in the 1930s was at least 100 to 1. Today, it is down to about 17 to 1.

The EROI concept was devised by economists, who measure much of what is important but not all. Ecologists examine the *full*—not just the financial—cost of fossil fuels. What happens to our environment when we burn even natural gas, which is relatively clean? We get energy, yes, but also effluvia to dirty our laundry (we could live with that); pollutants to kill our forests; fumes and particulates, including carcinogens, to choke our lungs; and carbon dioxide and other gases to transform the atmosphere into a lid that hampers normal Sun-to-Earth respiration.

Heat engines and electric power plants burning fossil fuels emit millions of tons of sulfur dioxides, nitrogen oxides, and other pollutants into the air. There the sunlight transforms them into other, often more dangerous effluents, which descend to the Earth as acid rain, corroding statues and buildings, leaching soil fertility, poisoning plants, poisoning lakes and rivers, and killing the fish. Acid rain is common downwind of cities and power plants everywhere.

Air pollution from fossil fuels taxes the lungs, causing asthma, bronchitis, emphysema, and other respiratory disorders, including cancer. In Los Angeles the "smog,"—a complicated end product of automobile exhaust fumes drifting aloft in the Southern California sunlight—started people coughing in the 1940s. Citizens of England's capital city had been accustomed to coughing for centuries; then, in December 1952, an especially thick and long-lasting "London fog"—coal smoke—killed over four thousand people. Atmospheric pollution in the cities of the developing world often exceeds that of the cities of the developed world.

The balance of entering and exiting sun energy in our atmosphere is delicate. If too much bounces back into space, the glaciers

advance; but if too little exits, global warming ensues, humanity swelters, climates change erratically, and malaria and other tropical diseases spread. This, the notorious "greenhouse effect," has often occurred in the past when volcanoes spewed their gases in abundance into the atmosphere. It is happening now as we burn immense quantities of fossil fuels, releasing into the air in a single year the carbon accumulations of many, many years.

We have to adjust to the long-range realities of our energy situation. One, we can substitute for fossil fuels environmentally friendly sources of energy, which, if utilized wisely, won't pollute and cannot be exhausted. Two, we can find a new, more powerful, and yet clean prime mover.

Let us consider environmentally friendly sources of energy, which include manifestations of sunlight that we have already touched on, starting with biomass. When you burn biomass, you release pollutants, most importantly CO_2, but then, at least in theory, plants grow to replace those burned and absorb the pollutant.

Wood has been our favorite biomass fuel for many thousands of years. Indeed, wood was the most important fuel in the United States until the last years of the nineteenth century. Millions of hectares of the forests of the temperate zone were mowed down to satisfy the needs of modernizing societies for open farm- and ranchland, construction materials, and fuel. The professional logger is as suitable a symbol of the early industrial revolution as the mill worker, and vast clear-cut hinterlands are as characteristic of that period as Dickensian slums.

With the shift from wood to coal and oil, the trees have returned in much of the temperate zone where there is room for them. Southern New England, for instance, has more trees today than in Henry Thoreau's time. If we properly balance harvesting and new growth, temperate zone dwellers might permanently enjoy a supply of this biomass. At present 40 to 50 percent of humans, most of them living in the tropics, still rely on wood for fuel. There the forests, opened up by trucks and chain saws burning gasoline, are being consumed locally for fuel and for massive exports to the rich

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[2] Charles Hall et al., "Hydrocarbons and the Evolution of Human Culture," *Nature*, 426 (Nov. 20, 2003), 320.

nations like Japan and the United States. But in the tropics, where the sun can bake the dirt stone-hard and the rains tear it away and carry it off, the trees have not rushed back to reoccupy former forestland.

Wood is available for many purposes, but not in sufficient quantity as the fuel for a newly massive infusion of energy. Even heavily forested Austria, Sweden, and Finland supply no more than 15 percent of their energy needs with wood. Plantations of fast-growing trees like sycamore, poplar, and silver maple are a help, but the energy demand of the industrialized societies of the temperate zone is far too great to be answered with wood of any origin. The situation in the tropics where the forests are shrinking rapidly is worse.

Organic wastes of other kinds—stubble from harvested fields, pulp from paper mills, refuse from sugar cane mills, trash and garbage collected in our cities—are available in quantity. In many cases burning them to produce electricity is cheaper than disposing of them otherwise. Fast-growing plants like switchgrass cultivated for fuel would be of some help, as would tree plantations, but the unpleasant truth is that leaves, stems, and organic debris don't contain enough energy to run our cities for more than a few days per year.

The exploitation of plants such as sugar cane and maize as the raw material for chemical transformation into such fuels as ethanol and methanol is promising. We are already cultivating these and could easily raise more, but we have to be tough-minded about easy breakthroughs. According to some experts, the United States would have to plant maize in most of its entire expanse to produce enough ethanol to replace the gasoline it consumes annually. There is less hope that Europe and Japan, with more people per square mile than the United States, could raise enough in energy crops to fill their needs. And if one asks the question how much energy one gets out of such crops as compared to how much energy one expends to cultivate and process them, the answer is not encouraging. At the present time Americans expend 70 percent more energy in producing a gallon of ethanol than they get out of that gallon. This might be accomplished more efficiently, but probably not 70 percent more efficiently. Ethanol has a truly dreadful EROI.

We are still all children of the sun, and tapping that source directly could solve all of our energy problems. Techniques and devices to do this already exist. Architects know how to maximize passive benefit from the sun by orienting buildings and positioning windows. Engineers know how to trap the sun's heat in various materials, most successfully in water and salt solutions. They know how to focus sunlight with reflectors to heat water to steam to drive turbines. They know how to change sunlight into electricity with photovoltaic cells. These cells are expensive per watt, but have been used with great success in orbiting satellites and in spacecraft and remote locations on earth.

But draping our countrysides with solar cells would fully answer power requirements in only a few sun-baked nations, such as Saudi Arabia. They wouldn't help much in Scandinavia, Canada, and Russia during their dark winters or, for that matter, anywhere at all at night. We can and have come up with practical methods of storing solar energy for delayed use, but that is a complicated and expensive pursuit.

Hydroelectric power has been an essential source of energy for a long time and will continue as such, but most of the rivers suitable for big dams in the developed nations have already been dammed or are filled to the banks with freighters, ferries, and barges. There are suitable rivers for such structures in the developing nations—for instance, a dam at the Three Gorges of the Upper Yangtze will soon be producing an abundance of megawatts of power—but such locations are rare (and rife with social and ecological effects, but that is another story). The future of hydroelectric power probably lies in thousands of unpretentious dams on minor rivers, which will require attention to the difficulties—technological and political—in the collection and distribution of energies gained in small quantities.

Geothermal energy—heat drawn out of the ground—is subtracted from the planet's sum of energy forever, but that total is practically infinite, at least for the next billion years. Geothermal energy is available everywhere if you drill deeply enough, but thus far is tapped for energy in only a few places where magma lifts close to the surface, as in Iceland, Hawaii, and New Zealand. Windmills have undergone a renaissance: the towers of wind turbines poke up higher into the wind and their propellers have been redesigned to take maximum benefit of aerodynamic lift like airplane wings. But they produce energy plentifully only where the winds blow strong and constant.

At the end of the twentieth century, the industrialized nations obtained only 8 percent of their primary energy from wood, hydro-, and geothermal sources. That total doesn't include all sources—waves and tides, for instance—but even with all these added, the final sum at present falls far short of requirements.

"Hydrogen, hydrogen," the environmentalists chant to ward off panic and despair. The more thoughtful corporate executives and even a president of the United States have lately joined in. We are told that hydrogen, the solar fusion of which has made higher life forms possible, will enable all humans to attain and maintain a high standard of living. That happy state will last forever because hydrogen is by far the most plentiful element in the universe. It exists in inexhaustible quantities in the waters of our oceans.

Hydrogen burns (oxidizes) easily, producing heat but no pollutants because hydrogen combines with oxygen to make pure H_2O. Mayor Richard Daley of Chicago once even drank a glassful of the exhaust from one of the hydrogen-powered buses he was publicizing and suffered no harmful effects. Hydrogen, like electricity, is a wonderfully convenient means to transmit energy and, unlike electricity, does not disappear when inactive. Store it as a gas in a tank to inflate picnic balloons or as a liquid in the hold of a giant freighter to empower a nation, and you can transport it where you will and use it as you will.

There are complications, of course. Only if the ingredients are

pure will the afterproduct be the same. Since purity is costly, in practice less than pure ingredients are used in hydrogen burning, leaving some pollutants—nitrogen oxide, for instance, one of the ingredients of acid rain. However, one mustn't be so insistent on the best that one rejects the better. Burning hydrogen endangers the health of humanity and of the biosphere a great deal less than burning biomass or fossil fuels.

One doesn't have to burn hydrogen to tap its energy potential, however. One can use it in pollution-free fuel cells. In these the hydrogen atoms are stripped of their electrons, which are harvested to make electric lights shine, to run computers, sewing machines, automobiles—to do work. This energy production goes on noiselessly because a fuel cell has no moving parts. The hydrogen nuclei, divested of their electrons and longing for negative companionship, meld with oxygen atoms to, again, make water. Fuel cells are too expensive now, but that may change.

There is a big worm in the manna, however. Hydrogen is a gregarious element that freely joins with other elements to form molecules and is very rarely available in pure form on earth. Considerable energy has to be spent to break it loose. Currently, the cheapest and most accessible source of hydrogen by far is the fossil fuels, which are, after all, *hydro*carbons. But using this source to cure our pollution problem is more than a little like curing a nicotine addiction by switching from cigars to cigarettes. There are other sources of hydrogen: H_2O, for instance. We can use a moderate electrical charge to split liquid water into its constituent gases, hydrogen and oxygen. The technique is accomplished innumerable times every semester for the edification of high school students in physics and chemistry classes around the world.

Electrolysis, as it is called, is a cheap and simple way to obtain a little hydrogen. Obtaining a lot—enough to power a city, a nation, an industrializing world—is a colossal challenge. The United States alone consumes 12 million barrels of petroleum a day for surface transportation: the energy equivalent in hydrogen for that amount of petroleum would be at least 230,000 tons of hydrogen. Such quantities are mind-boggling; but the problem, again, is not one of quantity. The oceans are full of hydrogen. The problem is obtaining enough electricity to break hydrogen in such enormous quantities out of the watery embrace of oxygen.

Let us again consider the case of the United States, the diva of an energy-extravagant civilization. In order to provide the electricity needed to pry loose enough hydrogen to meet its full requirements, the United States would need 400 gigawatts (400 billion watts) of electricity in addition to what it already generates. Another two hundred Hoover dams would do the job; but even if Americans were willing to accept the costs in dollars and environmental damage of that many huge new dams, there aren't rivers in size and number big enough for such structures in North America. Perhaps Americans could placard the continent with solar panels and erect forests of windmills from sea to sea. We might launch huge solar cells into orbit or deck the Moon's surface with them to transmit sun power by the thousands of megawatts down to receivers on Earth. (Perfect aim would be crucially important, of course.) Perhaps, but that solution might still fall short and is certainly not politically likely. The political problem is that very few citizens are willing to have solar panels, windmills, or other energy devices constructed in their neighborhoods. The semi-official title of the resistance is NIMBY (not in my backyard).

Perhaps we will solve our energy dilemma by doing everything mentioned in the last few pages, cobbling together a variety of environmentally friendly sources of energy. That would be complicated. The alternative is to utilize a new and very powerful prime mover that doesn't pollute. It already exists: the nuclear reactor waits at our elbow like a superb butler.

9

THE ANTHROPOCENE

No matter what else happens, this is the century in which we must learn to live without fossil fuels.

—*David Goodstein, physicist (2004)*[1]

It is very difficult to predict, especially the future.

—*Niels Bohr, physicist, Nobel laureate*[2]

Nobel laureate Paul Crutzen recommends that we drop the title, the Holocene, that geologists have given to the last ten thousand years, face up to hair-raising reality, and call it the Anthropocene—that is to say, the human epoch. He reasons that humans have gained so much power from fossil fuels that we have become a major factor, in some ways *the* major factor, in how the biosphere functions. We are as at least as powerful as ancient Nordic gods, from whom we haven't heard since the *Götterdämmerung.*

Our gain in power when we graduated from nearly exclusive dependence on recently derived sun energy—from muscles as the

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[1] Goodstein, *Out of Gas: The End of the Oil Age*, 37.

[2] Richard L. Garwin and Georges Charpack, *Megawatts and Megatons: A Turning Point in the Nuclear Age* (New York: Alfred A. Knopf, 2001), 223. This aphorism was something Bohr repeated often.

prime mover—to buried sun energy—to coal, oil, and natural gas engines as prime movers, is almost too colossal to measure. John R. McNeill, an environmental historian, estimates that in the twentieth century humans used up a third more energy than they had in the hundred centuries between the dawn of agriculture and 1900. Jeffrey S. Dukes, an ecologist, estimates that between 1751 and 1998, we burned up 13,300 years worth of sunshine as manifested in plant and animal life here on our planet.[3] (The actual number of years must have been far, far greater than 13,300 because Dukes, in order to simplify his calculation, assumed a world 100 percent covered with plants and conditions totally conducive to their transformation to oil.)

The statements of McNeill and Dukes may strike the reader as too extreme to be believed. Let me provide specific illustrations of the difference between the amount of energy we could command before and after the fossil fuel or heat-engine revolution.

In 1586, nine hundred men and seventy-five horses directed by Dominico Fontana brought their strength to bear through thirty-seven windlasses to lift a 312-ton Egyptian obelisk from its base to move it from Curco di Nero to Piazza di San Pietro in Rome. Muscles are unlikely to achieve more than that because their strength per individual creature is slight and it is very difficult to focus the power of more than a few creatures on single specific tasks. Fontana's feat was as admirable an example of crowd control as of simple physics.

Rockets are our most efficient prime movers. On July 16, 1969, the Saturn V rocket, the biggest internal combustion engine yet, set off for the Moon with a roar so loud that one witness, Norman Mailer, thought that at last "man now had something with which to speak to God."[4] At launch the rocket weighed 6.4 million pounds. The first-stage engines burned nearly 5 million pounds of that sum in refined kerosene and liquid oxygen in 150 seconds to produce 160 million horsepower, or 7.5 million pounds of thrust. When the engines of the first stage stopped, the rocket was at an altitude of 41 miles traveling at 5,400 miles per hour. Getting from there to the Moon was relatively easy.

WE OF THE first years of the twenty-first century have access to more energy than we have the experience to wield intelligently. We of the richer societies make decisions we are not qualified to make almost every time we enter a voting booth or an automobile showroom or a grocery store, decisions that will in the long run have drastic effects on the lives of our descendants and on our planet. We of the poorer societies are too hungry in the short run for a decent standard of living to make wise decisions about the long run. As one citizen of Brazil put it, "We're not going to stay poor because the rest of the world wants to breathe."[5]

A good first step toward making informed decisions on the long run might be to decide what *normal* means to us *vis-à-vis* our energy situation because that is the baseline from which we launch our inquiries. "Normal" is often taken to mean how things are now. For the citizens of the rich societies today, normal involves vast expenditures of energy to empower a multitude of devices from aircraft carriers to desktop computers. This definition has penetrated deeply into the attitudes of people everywhere. For instance, Iraqis, citizens of a war-wracked nation in 2005, complain bitterly because the supply of the miracle juice, electricity, is not continuous in their cities.

But their view—our view—of what is normal is wrong. Street-

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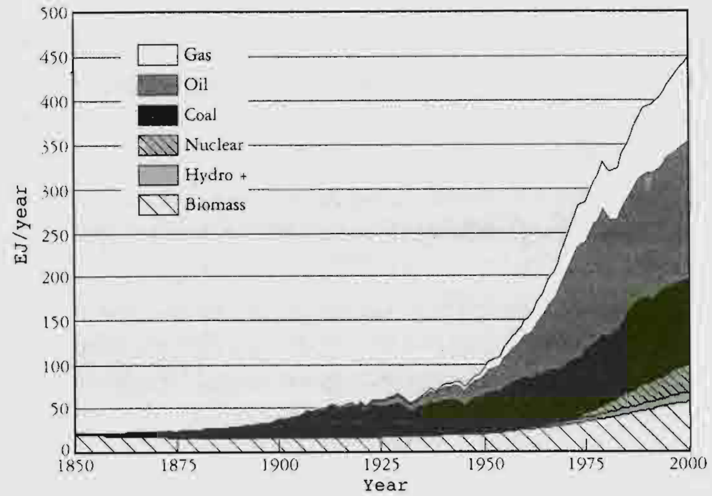
[3] J. R. McNeill, *Something New Under the Sun: An Environmental History of the Twentieth-Century World* (New York: W. W. Norton & Company, 2000), 15; Jeffrey S. Dukes, "Burning Buried Sunshine: Human Consumption of Ancient Solar Energy," *Climatic Change*, 61 (November 2003), 37–38.

[4] Norman Mailer, *Of a Fire on the Moon* (Boston: Little, Brown, 1970), 100.

[5] Michael Williams, *Deforesting the Earth: From Prehistory to Global Crisis* (Chicago: University of Chicago Press, 2002), 499.



Graph of World Energy, 1850–2000

Human energy consumption as measured in exajoules. A joule is the power required to produce one watt for one second; an exajoule is a million million million joules.

lights, toasters, automobiles and other such devices which are found or at least coveted everywhere are artifacts of a fossil fuel and prime mover revolution that in its full florescence is no more than a century and a half old (see the graph above). Since that is longer than living memory, most of us in the richer societies can only recall times of immediate access to abundant energy. That abundance tempts us, successfully, to believe, for instance, that having energy flow down lines from far away and illuminate our rooms when we flip the switch is normal rather than miraculous.

The most obvious challenge to our capacity to extend such a miracle to all of humanity is demographic. In spite of its hideous wars, pandemics, disruptions of family structure, and industrial contaminations, the Anthropocene has witnessed a population increase in every major region of the world. During the last forty years, the number of people doubled on earth. We are the first humans to witness such an explosion in such a short time.

It is likely, barring catastrophes such as comet strikes, an accelerated AIDS pandemic, or thermonuclear exchanges, that the population increase will continue for at least a generation or two more. Fertility rates have begun to decline and the rate of increase is slowing, but even so it is probable that between 2000 and 2050 we will add more people than were alive in 1950. Most of the new arrivals will be born in the poorer nations, where the fertility rates are dropping more slowly than in the developed world. Most of the new arrivals will live in cities, none of which are self-sustaining. In 2000, only four of the nineteen cities with populations of 10 million or more were in the rich nations.

By 2050, the citizenry of the rich societies will include large numbers of the middle-aged and elderly, who in many cases will be, speaking broadly, consuming more than they will be currently producing. In the poorer societies there will be enormous numbers of people in what are potentially the most productive years of life, but who, in order to produce, will need, food, clothing, education, and jobs in unprecedented quantities.

The demand for more power in the twenty-first century will be enormously greater than in the twentieth. At present rates, the demand will double by 2035. We will be hard put to procure enough fossil fuel at prices low enough to meet that demand, and in any event the health of the biosphere cannot tolerate the amounts of pollution and the rising temperatures that would come with multiplications of fossil fuel combustion as currently practiced.

WE ARE, I'M glad to say, not totally unprepared for the energy crisis that is coming. We know how to raise fossil fuel engines' efficiency, to minimize their emissions, and so to stretch out the time we have to learn our new role as, we hope, benign gods of the biosphere. We have already accumulated a lot of experience in building and maintaining windmills, photovoltaic cells, hydrogen fuel cells, and so on. New and truly safe nuclear power plants may well be possible. Surely we can bury radioactive wastes so deep that they will not endanger us or our descendants. And perhaps our physicists will turn another of their glorious tricks and successfully domesticate hydrogen fusion to initiate a golden age.

We have reason to believe that we are capable of environmental sanity; but first we have to accept that the way we live now is new, abnormal, and unsustainable. Very few of us would choose to reject the benefits of coal, oil, and natural gas and return to the good old days of no shoes, hunger pangs, and chills. But the truth remains that winning streaks are rarely permanent.

Fossil fuels in some ways remind me of amphetamines ("speed" in the vernacular). Amphetamine pills, like the fossil fuels, are enormously stimulating. The taker doesn't tire, seems to think and in general to function better and faster, and is happier. But people who take the pills can become dependent on them, which is unfortunate because their supply cannot be guaranteed. Furthermore, people who take them may suffer distorted comprehensions of reality. Lastly, amphetamines, taken in large dosages for too long, are poisonous.

We children of the sun may be standing on the peak of our energy achievements poised for the next quantum leap upward—like Paleolithic hunter-gatherers scratching wolf puppies behind the ears or like Newcomen and Watt noticing that steam has push as well as heat. Or we may be teetering there, destined to participate in nature's standard operational procedure of pairing a population explosion with a population crash.

CODA: ESTRANGEMENT FROM THE SUN

The electricity blackout of August 2003 along the eastern region was the biggest in the history of North America. Various officials, harassed for quick explanations, blamed it on lightning, a nuclear power accident, and the "blaster" computer worm. Somebody who said he was an Islamic terrorist claimed credit for his band of brothers. The truth was that on the fourteenth day of the month in Ohio, the Hanna-Juniper electric transmission line sagged into tree branches long overdue for pruning and a short circuit occurred, challenging an electrical grid system already wavering under the burden of normal demand.

This initiated an epidemic of disconnections between power plants, most of them driven by fossil fuel combustion or falling water (both vehicles of sun energy), and the consumers of the electricity. A hundred plants, linked together for purposes of reciprocal assistance, failed. Like a line of staggering drunks, elbows locked together for mutual support, they tumbled down en masse.

Fifty million children of the sun living in 9,300 square miles of the northeastern United States and adjoining Canadian provinces, the homelands of some of the wealthiest and most technologically sophisticated people in the world, abruptly found themselves without electricity.

Elevators stopped, trapping passengers. Computer screens went blank. Automatic bank machines reverted to being uncommunicative blocks of metal, plastic, and glass. Wire telephone service continued, but couldn't keep up with the demand. Cellular phones, being battery-powered, continued to work, but the cellular phone centers, where the antennas that forward the calls are located, failed. Airline traffic stumbled as means of communication from ground to aircraft faltered and the equipment for checking electronic tickets turned off.

In several cities, Cleveland, for instance, failure of electric pumps endangered the purity of the drinking water and citizens were advised to boil their water—a dubious suggestion if you had an electric stove. Some urban sewage plants stopped functioning: New York City's dumped 490 million gallons of raw waste into its waterways. The weather was hot and air conditioners were inoperative. Mayor Michael Bloomberg advised New Yorkers "to go home, open up your windows, drink lots of liquids." He told them they would be doing a lot of walking.

True enough: Traffic lights blinked out and traffic jams paralyzed above-ground urban transportation. Railroad schedules crumbled into chaos. Subway trains rolled to a halt; it took two and a half hours in New York to guide stranded riders out of the tunnels and back to street level. Getting transportation out of Manhattan back home to the outer boroughs and suburbs was nearly impossible and some daytime Manhattanites slept in the park or on city streets that night. Thousands of people began to walk out of Manhattan over the bridges, the only practical means of mass exit left.

There was, amazingly, very little looting or mugging in the darkness. Some urbanites got to see the Milky Way for the first time in their lives, a pleasant compensation for inconvenience. There were a few unintentional fires started by people inexperienced in the use of candles.

THE BLACKOUT PARALYZED society for no more than hours in most places and for never more than a day or so elsewhere. For many people, the brief loss of energy being delivered from the Sun as electricity turned out to be more of an adventure than a disaster. For others, the blackout of 2003 was a premonitory vision, acutely foreshortened to enhance comprehension, of our possible course in the next few centuries.