sources are coded blue, while niche ideas like hydroelectricity that cannot conceivably fulfill a quarter of global demand are colored red. Intermediate players that can satisfy a substantial fraction of demand are coded yellow.

- **Difficulty**. This field tries to capture the degree to which a resource brings with it large technical challenges. How many PhDs does it take to run the plant? How intensive is it to maintain an operational state? This one might translate into economic terms: difficulty serves as a crude proxy for expensive.
- **Intermittency**. Colored blue if the source is rock-steady or available whenever it is needed. If the availability is beyond our control, then it gets a yellow at least. The possibility of substantial underproduction for a few days earns red.

Storage can offset this concern, at increased cost. Seasonal storage is particularly impractical, which hampers solar resources.

- **Demonstrated**. To be blue, a resource has to be commercially available today and providing significant energy to society. Proof of concept on paper, or prototypes that exhibit some of the technology, do not count as demonstrated.
- **Electricity**. Can the technology produce electricity? For most sources, the answer is yes. Sometimes it would make little sense to try.[7] For other sources, it is impractical.
- **Heat**. Can the resource produce direct heat? Colored yellow if only via electric means.
- **Transport**. Does the technology relieve the looming decline in oil production? Anything that makes electricity can power an electric car, earning a yellow score. Liquid fuels are blue. Bear in mind that large-scale migration to electric cars is not guaranteed to happen, as the cars may remain too expensive or impractical to be widely adopted, among other challenges related to grid infrastructure for mass-scale charging.

7: For instance, biofuels *could* be used to make electricity, but renewable liquid fuels are too rare to squander in this way.

See additional discussion on page 292 and in Sec. D.3 (p. 397).

- **Acceptance**. Is public opinion[8] favorable to this method? Is resistance likely, whether justified or not? This dimension encompasses environmental concerns, threats to health and safety, and unsightliness in natural settings.

8: . . . judging by U.S. attitudes

- **Backyard**. Is this something that can be used domestically, in someone's backyard, rooftop, or small property, managed by the individual? Distributed power adds to system resilience.
- **Efficiency**. Over 50% earns blue. Below about 10% gets red. It is not the most important of criteria, as the abundance score implicitly incorporates efficiency expectations, but we will always view low efficiency negatively.

Environmental impact has no column in this matrix, although the "acceptance" measure captures some of this. Climate change is an obvious negative for fossil fuels, but not so much as to have resulted in curtailed global demand thus far (see Fig. 8.2; p. 118). None of the alternatives presented here contribute directly to carbon dioxide emissions, earning an added advantage for all entries.

Each energy source can be assigned a crude numerical score, adding one

point for each blue box, no points for yellow boxes, and deducting a point for each red box. Certainly this is an imperfect scoring scheme,[9] giving each criterion equal weight, but it provides *some* means of comparing and ranking sources.

9: See Section 17.3 for an alternate approach.

	abundance	difficulty	intermittency	demonstrated	electricity	heat	transport	acceptance	backyard?	efficiency	Score
Natural Gas	for now						buses, trucks via electric			for heat elec/transport	8
Petroleum	for now				mis-spent					for heat elec/transport	7.5
Coal	for now						via electric (and trains?)			for heat elec/transport	7.5

Figure 17.1: Fossil fuel matrix of attributes. Blue is good (+1 point); yellow is neutral (0 points).

The conventional fossil fuels each score 7–8 out of 10 possible points by this scheme, displayed on the right side of Figure 17.1. Some attribute ratings are divided into heating versus electricity production for a few of the scoring categories.

The overall impression conveyed by this graphic is that fossil fuels perform rather well in almost all criteria. Because fossil fuels collectively supply about 80% of global energy usage, they are each classified as having intermediate abundance. But even this is not a permanent condition—providing significant motivation for exploring alternatives in the first place. Getting energy out of fossil fuels is trivially easy. Being free of intermittency problems, fully demonstrated, and versatile enough to provide heat, electricity, and transportation fuel, fossil fuels have been embraced by society and are frequently used directly in homes. Efficiency for anything but direct heat is middling, typically registering 15–25% for automotive engines and 30–40% for power plants.

The commonly discussed alternative energy approaches display a wider range of ratings. Immediately, some overall trends are clear in Figure 17.2. Very few options are both abundant *and* easy. Solar photovoltaic (PV) and solar thermal are the only exceptions. A similar exclusion principle often holds for abundant and demonstrated/available—again satisfied only by solar PV and solar thermal. This uncommon combination plays a large role in the popularity and promise of solar power.

Intermittency mainly plagues solar and wind resources, although many natural sources (hydroelectric, tidal, wave, biofuels) present mild inconvenience due to intermittency.

Electricity is easy to produce, resulting in many options. Since the easiest and cheapest will likely be picked first, the less convenient forms of electricity production are less likely to be exploited.[10]

Transportation needs are hard to satisfy. Together with the fact that oil production will peak before natural gas or coal, transportation may appear as the foremost problem to address. Electric cars are an obvious—albeit expensive—solution. Besides being unclear how we might all afford[11] electric cars, the technology has a number of drawbacks relative

10: Because the list is ranked by overall score, those near the bottom are disfavored as sources of electricity, likely correlating with economic disadvantage.

11: Battery cost remains high: about $10,000 per 100 miles (160 km) of range.

	abundance	difficulty	intermittency	demonstrated	electricity	heat	transport	acceptance	backyard?	efficiency	Score
Solar PV						via electric	via electric				5
Solar Thermal			some storage				via electric				5
Solar Heating			some storage								4
Hydroelectric			seasonal flow			via electric	via electric	not universal	micro-hydro		4
Biofuel/Algae		gunk/disease		some R&D	mis-spent				small scale?		4
Geothermal/Electricity	hotspots						via electric				4
Wind						via electric	via electric	noise, birds, eyesore			3
Artificial Photosynth.		catalysts		active devel.	mis-spent				?		3
Tidal			daily/monthly variations			via electric	via electric				3
Conventional Fission		high-tech					via electric	waste/fear			2
Uranium Breeder		high-tech		military			via electric	proliferation			2
Thorium Breeder		high-tech					via electric	waste/fear			2
Geothermal/Depletion		deep drill		rarely?				deep wells	impractical		2
Geothermal/Heating		deep drill		rarely?				deep wells	impractical		1
Biofuel/Crops	food / cellulosic	annual harvest	seasonal	ethanol, etc. / R&D effort	mis-spent			food/land competition	small beans		1
OceanThermal		access/ maintenance				via electric	via electric				1
Ocean Current		access/ maintenance				via electric	via electric				1
Ocean Waves			storms/lulls	many one-off designs		via electric	via electric	eyesore			1
D-T Fusion	lithium	future-tech					via electric	trit/neutron contamination			1
D-D Fusion		farther future					via electric				1

Figure 17.2: Alternative energy matrix of attributes. Blue is good (+1 point); yellow is neutral (0 points), and red is bad (−1 point). Only green-labeled entries contribute more than a few gigawatts to our energy today, out of the 18,000 GW total. This comparison is meant to help differentiate attractive directions for future energy implementation.

to fossil fuels and does not lend itself to air travel or heavy shipping by land or sea (see Sec. D.3; p. 397). A car filling its gasoline tank is transferring energy at an astounding rate of 15 MW, equivalent to 3,000 homes running air conditioning. Limited range and slow charge times[12] do not permit electric transport to simply replace transportation as we currently know it.

12: A 220 V 40-Amp circuit, which is on the high end of practicality for a residence, will charge a single car at a rate of about 20 miles of range per hour.

Few of the options face serious barriers to acceptance, especially when energy scarcity is at stake. Some energy sources are available for individual implementation, allowing distributed power generation as opposed to centralized resources. For example, a passive solar home having PV panels, wind power, and some method to produce liquid fuels on-site would satisfy most domestic energy needs in a self-sufficient manner.

Cost is not directly represented in the matrix, although the difficulty rating may serve as an imperfect proxy. In general, the alternative methods have difficulty competing against cheap fossil fuels. It is not yet clear whether the requisite prosperity needed to afford a more expensive energy future at today's scale will be forthcoming, as prosperity historically has been closely tied to the availability of natural resources,

and these are precisely what our populated planet strains the most.

17.2 Tally for Individual Alternative Sources

A single chapter cannot adequately detail the myriad complex considerations that went into the matrix in Figure 17.2. The previous chapters address a number of the considerations, but many of the quantitative and qualitative aspects for each were developed at the Do the Math website. The key qualities of each resource in relation to the matrix criteria are discussed in this section, focusing especially on less obvious characteristics.

Solar PV (Sec. 13.3; p. 201): Covering just 0.4% of Earth's land area with PV panels that are 15% efficient satisfies global annual energy demand, qualifying solar PV as abundant. PV panels are being produced globally in excess of 100 gigawatts (GW) peak capacity per year,[13] demonstrating a low degree of difficulty. Most people do not object to solar PV on rooftops or over parking areas, or even in open spaces.[14] Solar panels are well suited to individual operation and maintenance. Intermittency is the Achilles' heel of solar PV, requiring storage solutions if adopted on a large scale. To illustrate the difficulty of storage, a lead-acid battery large enough to provide the United States with adequate backup power would require more lead than is estimated to be accessible in the world and would cost approximately $60 trillion at today's price of lead [112]. Lithium or nickel-based batteries fare no better on cost or abundance. Pumped storage is limited by a small number of suitable locales.

13: . . . translating to about 10–15 GW of average power production added per year

14: . . . especially sun-saturated deserts

[112]: Pickard (2012), "A Nation-Sized Battery?"

Solar Thermal (Sec. 13.8.2; p. 219): Achieving comparable efficiency to PV but using more land area, the process of generating electricity from concentrated solar thermal energy has no problem qualifying as abundant—although somewhat more regionally constrained. It is relatively low-tech: shiny curved mirrors, tracking on (often) one axis, heat up oil or a similar fluid to drive a standard heat engine. Intermittency can be mitigated by storing thermal energy, perhaps even for a few days. A number of plants are already in operation, producing cost-competitive electricity. Public acceptance is no worse than for PV, but the technology generally must be implemented in large, centralized facilities.

Solar Heating (Sec. 13.8.1; p. 218): On a smaller scale, heat collected directly from the sun can provide domestic hot water and home heating. In the latter case, this can be as simple as a south-facing window. Capturing and using solar heat effectively is not particularly difficult, coming down to plumbing, insulation, and ventilation control. Technically, solar heating potential might be abundant, but since it is usually restricted to building footprints (roof, windows), it gets a yellow rating. Solar heating does not lend itself to electricity generation or transport, but it has no difficulty being accepted and almost by definition is a backyard-ready technology.

Hydroelectric (Chapter 11): Despite impressive efficiency, hydroelectric potential is already well developed in the world and is destined to remain a sub-dominant player on the scale of today's energy use. It has seasonal intermittency,[15] does not directly provide heat or transport, and can only rarely be implemented on a personal scale. Acceptance is fairly high, although silting and associated dangers—together with habitat destruction and the forced displacement of people—do cause some opposition to expansion and have resulted in removal of some hydroelectric facilities.

15: A typical hydroelectric plant delivers only 40% of its design capacity.

Biofuels from Algae (Sec. 14.3.2; p. 234): Because algae capture solar energy—even at less than 5% efficiency—the potential energy scale is enormous.[16] Challenges include keeping the plumbing clean, possible infection,[17] contamination by other species, and so on. At present, no algal sample that secretes the desired fuels has been identified or engineered. No one knows whether genetic engineering will succeed at creating a suitable organism. Otherwise, the ability to provide transportation fuel is the big draw. Heat may also be efficiently produced, but electricity production would represent a misallocation of precious liquid fuel.

16: However, low EROEI may make the enterprise non-viable.

17: . . . for example, a genetic arms race with evolving biological phages

Geothermal Electricity (Sec. 16.1; p. 275): This option makes sense primarily at rare geological hotspots. It will not scale to be a significant part of our entire energy mix. Aside from this, it is relatively easy, steady, and well demonstrated in many locations. It can provide electricity, and obviously direct heat—although often far from locations demanding heat.

Wind (Chapter 12): Wind is neither super-abundant nor scarce, being one of those options that can meet a considerable fraction of present needs under large-scale development [70]. Implementation is relatively straightforward, reasonably efficient, and demonstrated the world over in large wind farms. The biggest downside is intermittency. It is not unusual to have little or no regional input for several days in a row. Objections to wind tend to be more serious than for many other alternatives. Wind turbines are noisy and tend to be located in prominent places (ridgetops, coastlines) where their high degree of visibility alters scenery. Wind remains viable for small-scale personal use.

[70]: Castro et al. (2011), "Global Wind Power Potential: Physical and Technological Limits"

Artificial Photosynthesis: Combining the abundance of direct solar input with the self-storing flexibility of liquid fuel, artificial photosynthesis is a compelling future possibility [113]. Being able to store the resulting liquid fuel for many months means that intermittency is eliminated to the extent that annual production meets demand. A panel in sunlight dripping liquid fuel could satisfy both heating and transportation needs. Electricity can also be produced, but given an abundance of ways to make electricity, the liquid fuels would be misallocated if used in this way. Unfortunately, an adequate form of artificial photosynthesis has yet to be demonstrated in the laboratory, although the U.S. Department of Energy initiated a large program in 2010 toward this goal.

[113]: Andreiadis et al. (2011), "Artificial Photosynthesis: From Molecular Catalysts for Light-driven Water Splitting to Photoelectrochemical Cells"

Tidal Power (Sec. 16.2; p. 280): Restricted to select coastal locations, tidal power will never be a large contributor to global energy. The resource is intermittent on daily and monthly scales but in a wholly predictable manner. Extracting tidal energy is not terribly hard—the efficient technology is similar to that found in hydroelectric installations—and has been demonstrated in a number of locations around the world.

Conventional Fission (Sec. 15.4.4; p. 255): Using conventional uranium reactors and conventional mining practices, nuclear fission does not have the legs for a marathon. On the other hand, it is certainly well demonstrated and has no intermittency problems—except that it cannot accommodate intermittency on the demand side (variable load). Compared to other options, nuclear power qualifies as a high-tech approach—meaning that design, construction, operation, and emergency mitigation require more advanced training and sophistication than the average energy producer.

Acceptance is mixed. Germany and Japan plan to phase out their nuclear programs by 2022 and the 2030s, respectively, despite being serious about CO_2 reduction. Public unease also contributed to a halt in licensing new reactors in the United States from 1978–2012. Some opposition stems from unwarranted—yet no less real—fear, sustained in part by the technical complexity of the subject. But some opposition relates to political difficulty surrounding proliferation and the onerous radioactive waste problem that no country has yet solved to satisfaction.

Uranium Breeder (Sec. 15.4.4.2; p. 258): Extending nuclear fission to use plutonium synthesized from ^{238}U, which is 140 times more abundant than ^{235}U, gives uranium fission the legs to run for at least centuries if not a few millennia, ameliorating abundance issues. Breeding has been practiced in military reactors, and indeed some significant fraction of the power in conventional uranium reactors comes from incidental synthesis of plutonium (^{239}Pu) from ^{238}U. But no commercial power plant has been built to deliberately tap the bulk of uranium for power production. Public acceptance of breeder reactors will face even higher hurdles because plutonium is more easily separated into bomb material than is ^{235}U, and the increase in radioactive waste from an expansion of nuclear power causes trouble.

Thorium Breeder (Box 15.5; p. 260): Thorium is more abundant than uranium and only has one natural isotope,[18] qualifying it as an abundant resource. Like all nuclear options, thorium reactors fall into the high-tech camp and include new challenges[19] that conventional reactors have not faced. A few small-scale demonstrations have been carried out, but nothing in the commercial realm; bringing thorium reactors online at scale is probably a few decades away, if it happens at all. Public reaction will likely be similar to that for conventional nuclear: not a deal breaker, but some resistance on similar grounds. It is not clear whether the novelty of thorium will be greeted with suspicion or enthusiasm. Although thorium also represents a breeding technology (making fissile

18: . . . thus enrichment is not a bottleneck

19: . . . such as a liquid sodium medium for the reactor core

^{233}U from ^{232}Th), the proliferation aspect is severely diminished for thorium due to a highly radioactive ^{232}U by-product[20] and virtually no easily separable plutonium.

20: . . . making it deadly to rogue actors

Geothermal Heating allowing Depletion (Sec. 16.1.2; p. 277): A vast store of thermal energy sits in Earth's crust, permeating the rock and moving slowly outward. Ignoring sustainable aims, boreholes could be drilled a few kilometers down to extract thermal energy out of the rock faster than the geophysical replacement rate, effectively mining heat as a one-time resource. In the absence of water flow to distribute heat, dry rock will deplete its heat within 5–10 meters of the borehole in a matter of a few years, requiring another hole 10 m away from the previous, in repeated fashion. The recurrent large-scale drilling operation across the land qualifies this technique as moderately difficult.

The temperatures are marginal for running heat engines to make electricity with any respectable efficiency,[21] but at least the thermal resource will not suffer intermittency problems during the time that a given hole is still useful. Kilometer-scale drilling hurdles have prevented this technique from being demonstrated at geologically normal (inactive) sites. Public acceptance may be less than lukewarm given the scale of drilling involved, dealing with tailings and possibly groundwater contamination issues on a sizable scale. While a backyard might accommodate a borehole, it would be far more practical to use the heat for clusters of buildings rather than for just one—given the effort and lifetime associated with each hole.

21: . . . especially given that many easier options are available for producing electricity

Geothermal Heating, Steady State (Sec. 16.1.1; p. 276): Sustainable extraction of geothermal heat—replenished by radioactive decay within the Earth—offers far less total potential, coming to about 13 TW of flow if summed across all land. And to get to temperatures hot enough to be useful for heating purposes, boreholes at least 1 km deep would be required. It is tremendously challenging to cover any significant fraction of land area with thermal collectors 1 km deep. As a result, a yellow score for the abundance factor may be generous. To gather enough steady-flow heat to provide for a normal U.S. home's heating demand, the collection network would have to span a square 200 m on a side at depth, which is likely unachievable.

Note that technologies known as "geothermal" heat pumps are not accessing an energy resource; they are simply using a large thermal mass against which to regulate temperature.

Biofuels from Crops (Sec. 14.3; p. 230): While corn ethanol may not even be net energy-positive, sugar cane and vegetable oils as sources of biofuel fare better. But these sources compete with food production and arable land availability. So biofuels from crops can only graduate from "niche" to moderate scale in the context of plant waste or cellulosic conversion. The abundance and demonstration fields are thus split: food crop energy is demonstrated but severely constrained in scale. Cellulosic matter becomes a potentially larger-scale source but is undemonstrated.[22] Growing and harvesting annual crops on a relevant scale constitutes a massive, perpetual task and thus scores yellow in difficulty—also driving down EROEI.

22: . . . to the point that perhaps this should even be red

If exploiting fossil fuels is akin to spending a considerable inheritance, growing and harvesting our energy supply on an annual basis is like getting a manual labor job: a most difficult transition. The main benefit of biofuels from crops is the liquid fuel aspect. Public acceptance hinges on competition with food or even land in general. Because plants are only about 1–2% efficient at harvesting solar energy, this option requires the commandeering of massive tracts of land.

Ocean Thermal: The ocean thermal resource uses the 20–30°C temperature difference between the deep ocean[23] and its surface to drive a ridiculously low-efficiency heat engine. The heat content is not useful for warming any home (it's not hot). But all the same, it is a vast resource due to the sheer area of the solar collector (i.e., the ocean). Large plants out at sea will be difficult to access and maintain, and transmitting power to land is not easy. The resource suffers seasonal intermittency at mid-latitudes, but tropical installations would obviate this effect. No relevant/commercial scale demonstration exists. Like many of the other sources, this one produces electricity[24] only. In terms of acceptance, few likely care what we put to sea: out of sight, out of mind. Ocean thermal is not a backyard solution!

23: . . . a few hundred meters down

24: . . . far from demand locations

Ocean Currents (Sec. 16.3; p. 281): Large-scale oceanic currents are slower than wind by about a factor of ten, giving a kilogram of current 1,000 times less power than a kilogram of wind. Water density makes up the difference to make ocean current comparable to wind in terms of power per rotor area. Not all the ocean has currents as high as 1 m/s, so the total abundance is put in the same category as wind, although this is likely far too generous and probably should be red. Placing machinery underwater (corrosive) and far from demand classifies this option as difficult. On the plus side, the current should be stable, eliminating intermittency worries, unlike wind. None of our electricity mix comes from ocean currents at present, so it cannot be said to have been meaningfully demonstrated. For the remaining categories: it is electricity only; we might expect little resistance to underwater installations; and no backyard opportunity.

Ocean Waves (Sec. 16.4; p. 282): While they seem strong and ever-present, waves are a linear-collection phenomenon, and not an areal phenomenon. As a consequence, not that much power arrives at shores all around the world (a few TW at best). It is not particularly difficult to turn wave motion into useful electricity at high efficiency, and the proximity to land makes access, maintenance, and transmission far less worrisome than for the previous two ocean-based cases. Intermittency—largely seasonal—is moderate as storms and lulls come and go. Prototype concepts abound, and a few are being tested at commercial scale. So this is further along than the previous two oceanic sources, but not so much as to earn a blue box. Push-back would be moderate from people whose ocean views are spoiled, or who benefit from natural wave energy hitting the coast. Few people have access to waves in their backyard.

D–T Fusion (Sec. 15.5; p. 264): The easier of the two fusion options, involving deuterium and tritium, represents a longstanding goal under active development since 1950. The well-funded international effort, ITER, plans to accomplish a 480 second pulse of 500 MW power[25] by 2035. This defines the pinnacle of hard. Fusion brings with it numerous advantages: enormous power density; only moderate radioactive waste products; and abundant deuterium.[26] Fusion would have no intermittency issues, can directly produce heat and derivative electricity, but like the others does not directly address transportation. The non-existent tritium can be knocked out of lithium with neutrons, and even though we are not awash in lithium, we have enough to last many thousands of years in the absence of demand for batteries. We might expect some public opposition to D–T fusion due to the necessary neutron flux and associated radioactivity. Fusion is the highest-tech energy we can envision at present, requiring a team of well-educated scientists/technicians to run—meaning don't plan on building one in your backyard, unless you can afford to have some staff PhDs on hand.

25: Compare to a real power plant: years-long "pulse" at 3,000 MW thermal power.

26: . . . though no natural tritium

D–D Fusion (Sec. 15.5; p. 264): Replacing tritium with deuterium means abundance of materials is no concern whatsoever for many billions of years. As a trade, it's substantially harder than D–T fusion.[27] D–D fusion requires higher temperatures, making confinement that much more difficult. It is for this reason that we make a single exception to the scoring scheme and give D–D fusion a −2 score for difficulty.

27: . . . or we would not even consider D–T

17.3 Student Rankings

In Winter 2020, students at UC San Diego did Problem 11 from this chapter, which asks them to come up with their own weighting for the ten attributes in the comparison matrix, rather than the simple but poorly-justified practice of giving each category the same weight. This section reports the result from that exercise.

On average, the weights did not deviate dramatically from uniform, the adjustments being within a factor of 1.5 for all cases: ranging from 0.66 to 1.47, when each student's weighting was re-normalized after the fact to add to ten points. The attributes getting a clear boost were abundance, efficiency, and transportation capability. Those getting lower weight were the backyard criterion, acceptance, and ability to produce heat.[28] What this says is that students, on the whole, value solutions that can get the job done efficiently and preserve transportation, not caring as much about individual resilience or acceptance.[29]

28: One wonders if students in colder climates would disregard heating capability.

29: In other words, centralized power less bound by public opinion is okay.

Table 17.1 summarizes the outcome of this experiment, in which we see broad agreement with the nominal uniform-weighting scheme, mostly serving to downgrade the scores of some entries, and only promoting one (thorium breeding). Note that the exercise preserved the blue/yellow/red color scheme of the figures and only changed relative

Table 17.1: Result of student weighting of the comparison matrix attributes. Notable gaps between scores appear between fossil fuels and solar, between solar and the middle group, and between the middle group and the final group (right). When differences between student scores and the nominal scores in Figures 17.1 and 17.2 exceed rounding error, the result is shown as a Δ, helping highlight the main differences between student scoring and the nominal uniform-weight result.

Resource	Score	Δ	Resource	Score	Δ	Resource	Score	Δ
Gas	7.3	−0.7	Hydroelectric	3.6		Conv. Fission	1.6	
Oil	6.8	−0.7	Algae/Biofuel	3.6		Geotherm. Depl.	1.4	
Coal	6.7	−0.8	Geotherm. Elec.	3.3	−0.7	D–T Fusion	1.4	
			Solar Heat	3.2	−0.8	Wave	1.3	
			Tidal Capture	3.0		Ocean Thermal	1.3	
Solar Thermal	5.4		Wind	2.9		Ocean Currents	1.0	
Solar PV	5.1		Uranium Breeder	2.8		D–D Fusion	1.0	
			Artif. Photosyn.	2.8		Geotherm. Heat	0.7	
			Thorium Breeder	2.5	+0.5	Biofuel/Crops	0.4	−0.6

importance of the attributes—thus much of the behavior is "baked in" based on the author's judgment of color assignment. Still, shifting emphasis on the attributes will shuffle the order somewhat, and that itself is interesting. Any ambitious reader is welcome to mess with the color scheme as well to see what happens.

17.4 Upshot: The Fossil Fuel Gap

The subjective nature of this exercise certainly allows numerous possibilities for modifying the box rankings in one direction or the other. The matrices embody some biases, but no attempt by anyone would be free from bias. The result, in this case, is dramatic. Even allowing some manipulation, the **substantial gap** between the fossil fuels and their renewable alternatives would require excessive "cooking" to close.

A key take-away from this chapter is that we can devise methods to compare disparate sources of energy in a systematic way. The outcome does not provide an authoritative answer, but what it *can* do is:

- help guide our thinking;
- expose gaps that we might not otherwise appreciate;
- bring attention to the complexity of energy choices: it's more than how many terawatts are available.

One lesson is that a transition away from fossil fuels *does not appear at this time to involve superior substitutes*, as has been characteristic of our energy history. The alternatives might be *good enough*, even if not *as good as* what we are accustomed to using. Fossil fuels represent a generous one-time gift from the earth. From our current vantage point, it is not clear that energy—vital to our economic activity—will be as cheap, convenient, and abundant as it has been during our meteoric ascent to the present. If not for finite supply and the CO_2 problem, fossil fuels would continue to satisfy our energy needs—shifting focus to various other global-scale

problems resulting from human pressures[30] on the planet. Because of the downsides of fossil fuels and the inferiority of the substitutes on a number of fronts, it is unclear how we might patch together an energy portfolio out of the alternatives that allows a continuation of our current lifestyle. Even if the physics allows it, many other practical and economic barriers may limit options or successful implementations.

Adding to the hardship is the fact that many of the alternative energy technologies—solar, wind, nuclear power, hydroelectric, and so on—require substantial up-front energy investment to build and deploy. If society waits until energy scarcity forces large-scale deployment of such alternatives, it risks falling into an "energy trap" in which aggressive use of energy needed to develop a new energy infrastructure leaves less available to society in general—a political non-starter. If there is to be a transition to a sustainable energy regime, it is best to begin it now.[31]

30: . . . which could conceivably get only *worse* if humans "solved" energy, effectively unconstrained

See Sec. 18.3 (p. 310) for more discussion of the energy trap.

31: We can't count on better options showing up, and may need to get busy migrating to available choices. Fossil fuels not only drive climate change, but create an addiction that is best tapered slowly rather than risk chaos and war if we remain completely reliant on a dwindling crucial resource.

17.5 Problems

1. What is your overall assessment of our energy future given the presentation of alternatives to fossil fuels presented in this chapter? What key take-aways do you form?

2. What, to you, is the biggest surprise in the rank order of alternatives in Figure 17.2?

3. One consideration not present in the alternative energy matrix is EROEI. Identify at least one example that would likely receive a boost (move up in the rankings) if EROEI is considered, and at least one example that would likely move down as a result of considering it. Refer back to Chapter 14, both tables and text.

4. (Suggest double-credit problem) Count up the number of blue, yellow, and red squares for all ten attributes (columns) in Figure 17.2. Score each attribute the same way as energy resources were scored: +1 for blue; nothing for yellow; −1 for red.
    a) What category has the highest score? What does this tell you about alternative energy in terms of what is easy?
    b) What category has the lowest score? What does this tell you about what attribute is hardest to satisfy in energy production?
    c) Which two categories have the largest number of blue squares and which two have the lowest number? What do you learn in terms of what is easy and not so easy?
    d) Which category has the largest number of red squares and which *two* have the lowest number? What do you learn in terms of what is hardest and what is least difficult to satisfy?

5. Why is it so hard to satisfy transportation needs? What is it about fossil fuels that has made transportation so much easier than electrified transport would be?

6. Verify—showing work—the claim on page 292 that a car refueling at a gasoline station is transferring energy at a rate in the neighborhood of 15 MW if the transfer rate is about 6 gallons (23 L) per minute[32] and gasoline contains about 34 MJ per liter.

32: Time it yourself some time.

7. What is at about the backyard[33] attribute that earns so many red scores? What does this tell you about access to energy and the complexity of its capture/use?

33: . . . just shorthand for energy on a personal scale at home

8. What two resources are crippled by intermittency? How might that challenge be mitigated so that it is less problematic? What are some difficulties in this solution?

9. If biofuels turn out to be hampered by low EROEI values, the only transportation-friendly option left is artificial photosynthesis, which was not covered in this book because it's not a "real thing" at this time—as captured by the two red squares for difficulty and demonstrated. Two questions:
   a) What other resources are in a similar "not real yet" state, based on the same red squares?
   b) What is most encouraging about the prospect of obtaining liquid fuels from sunlight? What problems does it solve for solar power and for transportation?

10. Figure 17.2 left out firewood as an energy resource, even though it has been with us for a long time and will no doubt continue to provide home heating. What would the ten colors be for this resource of intermediate abundance in the context of home heating? What would its score be, and which sources is it then tied with? Justify each of your color choices.

⚠ Different students may get different results, but this will provide some appreciation for considerations that enter the creation of such a scoring scheme.

11. (Suggest triple-credit problem) For the sake of simplicity and transparency, the scoring system used a simple uniform weighting for each of the 10 attributes, but it is unlikely all ten are equally important. Make up your own weighting scheme.[34] For each energy resource, blue cells *add* the corresponding category's weight, and red *subtracts*, and yellow does nothing. Re-score the matrix using your own weights—including the fossil fuels. Now re-order the matrix from highest to lowest score and comment on any major upheaval from the nominal ordering. What are the big surprises? Did the fossil fuel gap persist?

34: A category might be worth 2 points, 0.3 points, 5 points, or whatever you wish; need not add to 10

First, make sure you can reproduce the scoring in the present table based on all weights being 1.0.

Part IV

Going Forward

We have layered an artificial world atop the natural one.
Which do you think will stand the test of time?
The sooner we dovetail back to the natural,
the greater our chances for success become.

Easter Island stands as a testament to humans' ability to do really dumb things, like cutting every tree on the island. Who cut down the last one? Photo by Sophie Hurel.

18 Human Factors

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Energy has occupied center-stage in this book because it is the physical currency of activity. Fossil fuel availability permitted the Industrial Revolution and all that came with it. Human civilization has never before faced the prospect of such a crucial global resource either disappearing or being abandoned due to other ills (e.g., climate change).

Despite the mixed suitabilities of alternative energy sources presented in Chapter 17, *some* physically viable avenues *are* open to us. In other words, physics itself does not preclude development of an energy landscape consisting primarily of solar, wind, and hydroelectric power, plus a few small contributions from a variety of other sources. Life may be different; less air travel or transportation in general, as one possibility. The enormous solar potential combined with decent storage technologies could *conceivably* maintain our 18 TW appetite without fossil fuels. Or we could scale back and not expect to live in such a profligate manner, viewing our current ways and expectations in the broader human experience as anomalous, temporary, and not important to preserve.

In any case, the barriers are not completely due to physical constraints—though we must heed limits where they exist. A practical concern is the expense of a non-fossil energy infrastructure: both in energy and financial terms. It is possible that the prosperity required to afford such a dream is physically unavailable.[1] Another limitation involves people and how they work collectively, which is the focus of this chapter.

1: If it were easy to conjure wealth, energy, and material goods, why would any person or country be poor?

18.1 Personality

Discussion of personality may seem out of place in a physics-based textbook. But how we react to a looming crisis—both individually

or collectively—becomes a central question. Physics and nature are indifferent to the choices we make, and whether or not these choices serve our long-term interests. Success or failure therefore depends more on our attitudes and reactions to physical reality than it does on physics itself. While this section addresses how personality preferences might influence human reaction to crisis, it is by no means the only determining factor. Education, socio-economic status, financial interests, and many other attributes can play a role. Yet underneath it all, we are humans, and possess various traits that influence our reactions.

A common fallacy is that a collection of people, possessing access to the same set of facts,[2] will respond similarly. Having only occupied one person's head, each of us cannot easily comprehend the reactions another might have to a situation. A variety of metrics have been devised to characterize different personalities and preferences, which play a role in shaping reactions. The Big–5 and Myers–Briggs are among the most well known. The former provides a scale for each of five traits:

1. Openness: creative and curious vs. careful and regimented
2. Conscientiousness: degree of organization and efficiency
3. Extraversion: socially energetic vs. preference for quiet or alone
4. Agreeableness: engaging and sympathetic vs. aloof or cranky
5. Neuroticism: easily rattled vs. confident and stable

The Myers–Briggs scheme[3] has four categories that are usually represented as binary (either/or) labels, but in truth also exist on a continuum as do the Big–5 traits. Each category in Myers–Briggs acquires a one-letter label, in the end generating 16 possibilities.[4] The categories are:

1. I/E: Introvert vs. Extravert: are parties draining or energizing?
2. N/S: iNtuiting vs. Sensing: preference for abstract vs. concrete direct-sensory information
3. T/F: Thinking vs. Feeling: preference for intellectual/logical or emotional reasoning
4. J/P: Judging[5] vs. Perceiving: decisiveness vs. keeping options open

If you have never taken a Myers-Briggs type test, the following three citations include links to online tests [114–116]. These sites, and many others, offer descriptions of the types. For instance, here is a link[6] to a description of the INTJ type from [114]. Other types are linked from that page.

Many scientists find themselves in the INTX camps.[7] Technically speaking, the last category (J/P) reflects whether a person relies more heavily on the N/S axis (if P) or the T/F axis (if J). In the case of INTP, abstraction/theory is valued over logic, and the reverse for INTJ. Figure 18.1 provides an indication of the frequency of each type.[8]

A survey of visitors to the author's Do the Math website, which presents a quantitative look at energy and resource use much in the same spirit as

2: . . . itself a perplexing challenge in an ecosystem of polarized information flow

3: Myers–Briggs often triggers a reaction among knowledgeable individuals that it is an invalid, or debunked personality measure. If you are one of those, please reserve judgment until seeing how it is framed, and accompanying data.

4: . . . ignoring the inconclusive "X" label that can take the place of any letter when someone is not strongly to one side or the other in a category

5: . . . not meaning judgmental

6: . . . can also access from citation link

7: Experimentalists are more likely to be J and theorists are more likely to be P.

8: Keep in mind that real people can blend attributes and do not always fall cleanly into a given "box," so the 16 tidy categories is somewhat artificial.

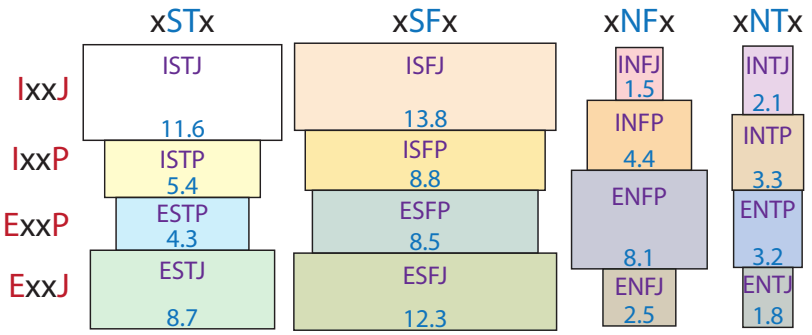

Figure 18.1: Frequency of Myers–Briggs types from one collection of data, as percentages [117]. Areas are proportioned accordingly. Don't take the numbers literally: they are not as precisely determined as decimals indicate, but visually at least this representation gives a decent sense for distribution. Note how significant it is when a two-thirds majority of interest-selected individuals piles into the small INTJ and INTP boxes at upper right, as described in the text.

this text, found that a staggering 44% of about 1,000 survey respondents shared the *same* INTJ type as the author, despite INTJs constituting only about 2% of the population. The over-representation of INTJ is thus about a factor of 20, and beyond question a statistically significant result (see Figure 18.2). The adjacent INTP cohort accounted for an additional 21% of visitors, despite being about 3% of the population. Thus about two-thirds of the site visitors represented 5% of the population for more than a factor-of-ten anomaly. While the Myers–Briggs scheme is not free of criticism (see Box 18.1), the result from *Do the Math* is pretty convincing that the Myers–Briggs scheme is measuring *something* relevant. Had the site asked for astrological sign, we can be pretty sure that representation would have been essentially uniform: no statistical anomalies. Myers–Briggs is evidently telling us *something*.

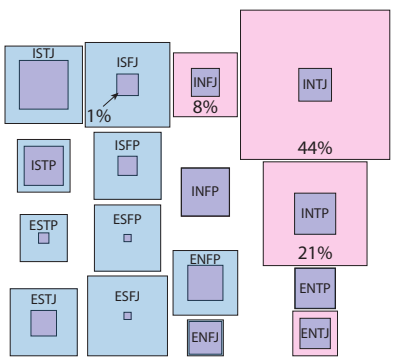

Figure 18.2: Stunning Myers–Briggs personality disparity between Do the Math readership and the general population. Areas of blue boxes represent frequency of types in the general population, as a variant of Figure 18.1. Pink areas reflect the readership of Do the Math, and overlaps appear purple. Visible pink means over-representation on the site, and visible blue indicates under-representation. 73% of the readership occupies the top right corner of the personality types, even though these three boxes only capture 7% of the population. A result this extreme, involving over 1,000 respondents, is absurdly far from random. Percentages are shown in the three most overwhelmingly over-represented boxes, plus a 1% box for reference.

What if objection to the Myers–Briggs framework correlated strongly with Myers–Briggs type?

Box 18.1: Criticism of Myers–Briggs

Much of the criticism of the Myers–Briggs personality type indicator owes to the binary nature of each result, unlike the Big–5 percentage for each category. The argument is that people are more complex than this, and do not fall into 16 distinct and tidy categories. But any Myers–Briggs test will indicate where you fall on the spectrum from the hard extremes—based on the number of answers in the survey toward each direction. Some people fall in the middle of a category and get an X designation. 16 rigid types is illusory and unnecessary.

It is easy enough to accept this valid criticism yet still value the fact that people *do* spread out in their preferences. Also, some of the dimensions map onto the more widely-embraced Big 5 scheme.

The most important aspect of personality that bears on our energy/resource challenges, and a key reason for covering the topic at all in this book, is that the Myers–Briggs "S" types constitute 73% of the population, yet are most resistant to the argument that unprecedented disruptive changes are on the horizon. S-types place more value on direct sensory input than on abstraction. Things directly experienced—seen with their own eyes, heard by their own ears, personally touched, smelled or tasted—carry much greater weight than "theory." Presented with

warnings about climate change, a hard-over S-type [118] might hold up a snowball (as Senator Inhofe famously did in front of Congress in 2015) to demonstrate—in their mind—how preposterous this global warming talk is. When warned about potential hardships following fossil fuel availability, an S-type may look out the metaphorical window and sense that everything seems to be fine.

[118]: Weiler et al. (2012), "Personality type differences bet. Ph.D. climate researchers and the general public: implications for effective communication"

Box 18.2: Scientists Have a Type

Scientists tend to be NT types, combining a preference for abstraction and models with a favoring of logical thought. Note that not all scientists are alike; it is good to have diversity, so it is possible to find any personality type within the science community. But the NT types will be perhaps more attracted to scientific pursuits as a good match to their personality preferences. The NT combination is the most rare, comprising 10% of the population (see Figure 18.3). Meanwhile, SF—the diametric opposite of NT—is over four times as prevalent.

When it comes to forming rational plans for future unseen challenges, NT types are well suited to the task. Ironically, if N–type predictions of future threats were faithfully heeded and mitigated, the threats would be averted and their failure to materialize would make the N–types look like terrible predictors to the S–type crowd! Failure by success.[9]

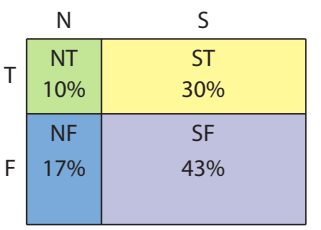

Figure 18.3: Distribution of N/S and T/F traits among the population.

9: This irony can also plague successful governance: people take for granted clean air, water, and food ensured by invisible, effective government. This quiet success creates complacent room for anti-government sentiments, potentially culminating in its failure.

18.1.1 Consequences and Coping

The S-type asymmetry[10] in human populations may confer an overall adaptive advantage. In stable times, recent history and apparent conditions provide reliable guidance to the likely future. It is understandable, therefore, that humankind would have difficulty adapting early to an upcoming reversal of fortunes, or even acknowledging its possibility. The prevailing narrative of growth and progress are so firmly rooted in society that the mere suggestion of a more primitive future[11] is discordant enough to be rejected by cultural antibodies—alien enough to resist comprehension, as if spoken in a foreign language.

10: . . . nearly 3 to 1

11: . . . fewer resources and possessions, no space colonies, closer to nature

The growth narrative's firm grip is easy to understand: Earth has always been large enough to accommodate human cravings, for countless generations. Yet 8 billion people competing for finite resources[12] at an unprecedented rate, climate change, deforestation, fisheries collapse, species loss, and a host of other crises signal that the prevailing narrative may simply be *wrong*[13] (Figure 18.4).

12: See Fig. 8.1 (p. 116) for a visual reminder.

13: Recall that Chapters 1 and 2 made a compelling case.

Timely, effective mitigation is possible only by seriously entertaining a radically new paradigm *before* widespread disruption becomes unmistakably evident. Is it possible to implant a wholly different narrative

Figure 18.4: The growth narrative is. . . *wrong*. Sung to the tune of a clock chime striking three; inspired by Dr. Cox in S1:E9 of *Scrubs*.

about the long-term relationship of humans to this planet, or is it cooked in to human nature[14] that we fail this challenge?

14: See Sec. D.6 (p. 408) for additional discussion.

One aspect of this dilemma is a pattern of unwillingness to accept personal responsibility for our predicament. Our own habits and expectations place demands on planetary resources that lead to global-scale challenges larger than we have ever faced. People have a tendency to blame others for their plights. In this complex world, it is never difficult to identify some other contributor to our problems: capitalists, socialists, liberals, conservatives, environmentalists, illegal immigrants, other religions, other powerful countries. What fraction of the blame might we assign to ourselves, and is it honest/accurate? In the end, we as humans must accept responsibility for the conditions we—and our expectations—create.

The human penchant for blaming and even demonizing "others" might lead to resource wars in the face of hardships imposed by limited resource availability. Such a path is lamentable on many levels, not least of which is that precious resources and energy would be channeled toward destructive acts rather than using them to build a better future. Are humans capable of mounting a transformative effort of global cooperation on a scale even greater than that of, say, World War II if we are not fighting an enemy other than ourselves and our own resource demands? Can we identify a precedent in which human societies have done so in the past at a large/relevant scale?

The first step in avoiding these pitfalls is awareness of the roles that human personality and psychology play in these problems, as this section has attempted to point out. One thing that became evident to the author on the basis of the Do the Math survey was that like seems to attract like: the communication style of the blog was a magnet for those of the same or adjacent types. But the message had startlingly little grip on the S crowd—especially the population-dominant xSFx types (second column in Figure 18.2). Perhaps a concerted effort to recruit all personality types to communicate important messages will better reach a broader audience, in terms that are more resonant with recipients.

One other coping mechanism is simple: time. The world a child is born into is by definition "normal" to the child. Future generations who do not grow up spoiled by abundant fossil fuel energy will not fight for a bygone lifestyle, and will simply adapt to the world as they find it—where the S–types shine. One way or another, nature will settle on a solution, and humans will be part of that solution, whatever its form. Ideally, we can guide ourselves into a mutually agreeable coexistence.

18.2 Policy vs. Individual Action

From where does power[15] stem? Monarchs of old claimed divine provenance as a source of power. Authoritarians might use a combination of personality and strong military backing. Some countries put on a show of democracy, while exercising power to thwart rivals and control the legal apparatus—resulting in sham elections.

15: Wait, Watt? For once, we are not talking about Joules per second.

In a functioning democracy, power is meant to come *from the people*. Votes send ineffective or crooked politicians packing, replacing them with folks promising to be faithful servants to the people and to the country's constitution. If democracy works as planned, then how far can a politician be from the sentiment of the people[16] and still get elected (or re-elected)? Since presumably politicians cannot afford to stray far from the views of their constituents, are democratic politicians leaders or followers?

16: If 73% of the people are S-type personalities, then our policies will lean toward satisfying that contingent.

What would happen in a functioning democracy if the government told people what to eat, how many kids to have, or what temperature to set in homes? If people are not *already* willing to make the changes on their own,[17] how can a democratic government impose "responsible" choices when those choices involve unwanted sacrifice in some form? If democratically-elected politicians are constrained to only offer "better," more personally attractive choices, a democratic world may no longer have the flexibility necessary to address our fundamental challenges.

17: . . . and in fact, already *changing* habits on their own accord

It feels icky to point out flaws in democracy, as this form of government has admirably lifted countless individuals up and promoted enlightened progress. It really is the best in many respects—except for this fundamental flaw in a world of constraints and possible reductions.

So if democratic governments turn out to be ineffective at promoting substantive change involving reduction, what can be done if indeed that's the necessary course of action? Citizens are free to take charge of their own choices, for the greater good. Yet, individual action as a response to our predicament often provokes criticism and debate. The argument is that only policy has the teeth to bring about effective change. If person A uses less of a resource, it just leaves person B free to use more of it.

But consider that *voting* is also an individual action. One person's vote seldom makes any measurable difference: it is a tiny drop in the bucket. Yet, if everyone[18] concluded that the individual action of voting was wasted and meaningless, the result would be disastrous: gross underrepresentation and distortion of the will of the people.

18: . . . or even a large majority

We understand in the context of voting that individual action leads to collective representation, and tend to practice this right even though policy does not demand that we do so. We see it as part of a civic responsibility—as the right way to participate in our society. Our system can tolerate a certain fraction of individuals who won't donate time to their civic responsibility, but things fall apart if we have too many such people.[19] Next time someone challenges your individual efforts to improve the world in some way, labeling them as meaningless, ask them to be consistent with their espoused principles and please refrain from

19: The technical term for these people is: jerks.

voting in the future, lest they be labeled hypocrites. Often such objections are rooted in defense: they *want* stuff, and your giving something up is a threat to their perceived moral "right" to have it. The sense of sanctimony and righteousness of the individual making sacrifices—even if not intentional—can be very offputting.

One other aspect of individual action is that it could influence others to follow, thus amplifying the individual's effect. This approach is perhaps most effective if others see benefits for themselves, and are not made to feel bad for not already being "woke" to the right side of the practice.

18.3 The Energy Trap

If we unwisely mount a response only *after* we find ourselves in fossil fuel decline—as crisis responders, not proactive mitigators—we could find ourselves in an energy trap: a crash program to build a new energy infrastructure requires up-front energy, for decades. If energy is already in short supply, additional precious energy must be diverted to the project, making peoples' lives seem even harder/worse.[20] A democracy will have a hard time navigating this decades-long sacrifice.

Let's flesh this concept out a bit more. In the financial world, money can be borrowed on the promise of paying it back.[21] In this way, something is created from nothing, essentially. Modern monetary systems are based on *fiat currency*, rather than being tied to physical gold or silver. This means money can be "willed" into existence by the financial system. Energy does not work that way. To build a hydroelectric dam, solar panels, wind turbines, or a nuclear plant, all the energy must be available up front. Nature offers no financing!

Recall from Sec. 14.3.1 (p. 231) that the EROEI, or energy returned on energy invested, describes the ratio of output energy over the lifetime of the resource to the input energy needed to secure it in the first place. For many cases, like a hydroelectric dam, nuclear plant, wind turbine, or solar panel, most of the energy *input* happens before any energy is delivered. In other cases, like biofuels, the investment may be more drawn out and seem more like an efficiency. In the context of the energy trap, we will focus on the input as an up-front investment.

Example 18.3.1 If a solar panel has an EROEI of 6:1, that "1" unit has to be paid *up front*, even though ultimately the panel will more than pay for itself, energetically. How many years of the panel's energy needs to be available up front if the panel lasts 30 years in the sun?[22]

The 6 in the EROEI figure relates to the total output of the resource. So we equate 30 years of operation to the number 6, meaning that 1 "unit" is 5 years of output (Figure 18.5). Since the input is 1 unit (in

20: Amid consternation over energy shortfalls and likely high prices, pulling more energy away from people will not be popular.

21: . . . with interest

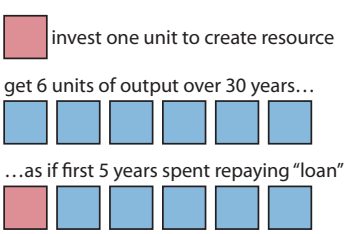

Figure 18.5: Energy "payback" time for 30 year resource with EROEI of 6:1.

22: Any EROEI estimate must assume some resource lifetime in order to compute the amount of energy delivered.

6:1 construction; see Sec. 14.3.1; p. 231), we conclude that it takes 5 years of the panel's output energy to fabricate the panel. So its first five years are spent paying off the "loan," in a sense.

As another example, development of a resource that will last 40 years and whose EROEI is 10:1 will require 4 years of its energy output ahead of time[23] to bring it to fruition.

23: . . . from a resource that is *already* producing energy

Example 18.3.2 In order to replace the current 15 TW[24] now derived from fossil fuels with a renewable resource whose lifetime is 40 years and EROEI is 10:1,[25] what options might you suggest for diverting the 15 TW into construction and how long would it take under those options?

24: ~80% of the 18 TW total

25: . . . or a combination of resources having similar EROEI and lifetime

It takes four years of the ultimate resource output to create the resource in this scenario. In one extreme, *all* 15 TW from fossil fuels could be diverted into the effort over a four year period[26] to develop 15 TW of the new resource. Or half of the 15 TW fossil resource could be dedicated to the effort over 8 years, or a quarter over 16 years, or 10% over 40 years.[27] Choosing this last path for a 40-year resource means "starting over" at this juncture, essentially forever re-investing 10% of available energy into perpetuating a resource with EROEI of 10:1.

26: . . . leaving nothing for societal needs

27: Even a 10% diversion will "hurt" and be unwelcomed.

Imagine now that we find ourselves having reduced access to oil,[28] driving prices up and making peoples' lives harder. Now the government announces a 16 year plan to divert 25% of energy into making a new infrastructure in an effort to reduce dependence on fossil fuels. That is a huge additional sacrifice on an already short-supply commodity. Voters are likely to respond by tossing out the responsible[29] politicians, installing others who promise to kill the program and restore relief on a short timescale. Election cycles are short compared to the amount of time needed to dedicate to this sort of major initiative, making meaningful infrastructure development a difficult prospect in a democracy. And this is before addressing the likely contentious fights about *what* the new infrastructure should be, out of the table of imperfect[30] options.

28: . . . as the most plausible example; the first to peak

29: . . . in the true sense of the word

30: See Chapter 17, for instance.

Now it is perhaps more apparent why this is called an energy trap: short-term political and economic interests forestall a proactive major investment in new energy, and by the time energy shortages make the crisis apparent, the necessary energy is even harder to attain. Short-term focus is what makes it a trap.[31]

31: Is this a human limitation?

One wonders how democracies will fare in the face of declining resources. The combination of capitalism and democracy have been ideal during the growth phase of our world: efficiently optimizing allocation of resources according to popular demand. But how do either work in a decline scenario, when the future is not "bigger" than today, and may involve sacrifice? We simply do not yet know. This is a giant unauthorized experiment that is not operating from a script. Chapter 19 will return to this notion.

18.4 Fermi Paradox Explained?

Having discussed some of the top-level challenges facing our technological society, it is too tempting to speculate on how universal our trajectory might be. We do so in the context of the Fermi Paradox [119], which asks: **if** the universe produces a reasonably high probability of intelligent life developing, why have we seen no credible evidence[32] of advanced civilizations? Yes, this is a bit of a tangent,[33] but it could be interpreted as a relevant data point in the likelihood that we maintain an advanced civilization for a long duration.

32: . . . in the form of communications or alien visits

33: Normally, this kind of tangent might go in a box, but it is big enough to be awkward in that format, thus a whole section.

The setup to the question is a "big if." The usual approach to estimating the number of intelligent species in our galaxy[34] is via the *Drake Equation* [120]. The equation is simple, just multiplying the number of stars by a chain of probabilities: that the star has planets at all; that one of the star's planets is "habitable;" that the environment is benign and that life has had enough time to develop; and finally that the life develops into an intelligent form, capable of communicating. Also factored in is the likelihood that any such species would endeavor to reach out, and how long their civilization lasts in that state so that we might overlap[35] in time. For the Milky Way galaxy, 100 billion stars—almost all of which we now know are likely to have planets—gives a huge start so that even if the chance of intelligent life arising is one in a million, we're left with quite a margin.

34: . . . or the whole universe, if thinking more broadly

35: The notion of "overlap" is complicated here by the 100,000 light-year scale of the galaxy, so that by the time a signal arrives at Earth, the civilization may be long gone already.

But maybe our trajectory is pretty typical. By the time an intelligent species arises, the many millions or billions of years of life leading up to that event may ubiquitously lead to deposits of fossil fuels.[36] The first species smart enough to utilize the planet's fossil fuels does so with reckless abandon. Because evolution does not skip steps, we should not expect to find a species *wise* enough to *refrain* from rapid fossil fuel use emerging before a species who is *just* smart enough to use them, but not smart enough *not* to. So the "intelligent" species short-circuits the battery[37] in a blaze of glory that may even involve baby-step excursions into space before either climate change or other resource/planetary limitations removes the fossil fuel source that made it all possible. Lacking wisdom and foresight, solid plans are not in place to handle the withdrawal, which does not go well and leaves the species in a crippled lower-tech state. Rebuilding from the ashes is then much less likely to explode without that one-time elixir that made it all possible the first time.[38] A simple, and possibly quite satisfying life may await, but it may not involve traveling or communicating across space for others to learn of our existence.

36: . . . buried remnants of life

37: Fossil fuels can be thought of as a solar-charged battery that we are discharging almost a million times faster than the time it took to charge it: see Box 10.2 (p. 169).

38: Also, easily accessed surface metal deposits have long disappeared, bringing into question whether a Bronze Age would be possible to replicate.

This notion is, of course, highly speculative and of little practical value. Except it may allow us to think "bigger" than ourselves and ponder whether it is surprising that we might fail to achieve a Star Trek future. It is at least *somewhat* relevant to note that the universe we peer into does *not* have an evident intergalactic intelligent presence. Perhaps the

combination of evolution and fossil fuels makes our path—including a possible decline to follow—a very natural and expected outcome, leaving the universe a quiet place.

For extended thought on this subject, see Sec. D.6 (p. 408).

18.5 Upshot on Humanity

We face unprecedented pressures on resources and on our environment, as human population *and* standard of living both surge on a finite planet. Nature will not allow this trend to continue indefinitely. While much of this book has pointed out limitations of one form of energy or the other, we should be clear that physics does not preclude a satisfying route to the future that operates within planetary limits. It would appear that the real barrier is human limitations in accepting physical constraints. Failure (as a whole) to:

1. process abstract information;
2. anticipate situations that have never yet arisen;
3. make individual sacrifices[39] for the greater good, even if not mandated;
4. recognize that awaiting a clear-and-present crisis may leave us unable to mount a timely response;
5. acknowledge that our loneliness in the universe might constitute evidence that intelligent species don't routinely "make it."

39: For how many generations in a row are humans capable of leaving tempting global resources "on the shelf," while being perfectly capable of exploiting them?

Of course, *individuals* in a society may not share all of these shortcomings. But if these failings are *collectively* prevalent, the more cognizant individuals have too little sway.

Can we collectively overcome these limitations? Can we use the gift of intelligence[40] to bypass built-in limitations? Only by being well aware of the barriers do we have any meaningful chance of managing them. This chapter aimed to at least raise awareness so that readers can begin to think about the role that human nature plays in the challenges ahead.

40: Are we smart enough to recognize and mitigate our shortcomings?

18.6 Problems

1. If each of the four axes in the Myers–Briggs type happened to be equally[41] likely—that is, 50% chance of being I and 50% chance of E, etc., and uncorrelated, then how probable would you expect each of the 16 types to be, in percent?

41: ⚠ they are not, in reality

Hint: the total should add to 100%.

2. Approximate probabilities for the four different axes in the Myers–Briggs type appear as follows:[42]

42: You can recreate this table by adding numbers in Figure 18.1.

Axis	% Share	% Share
I/E	I: 51	E: 49
S/N	S: 73	N: 27
F/T	F: 60	T: 40
J/P	J: 54	P: 46

If we imagine that the four axes do not correlate with each other,[43] we could approximate the fraction of the population that is ESFP as $0.49 \cdot 0.73 \cdot 0.60 \cdot 0.46 = 0.103$, or approximately 10%.[44] What would you expect the most abundant personality type to be, and what percentage of the population would be this type? What is the rarest, and what percentage would you expect in this type? How do the results compare to the probabilities in Figure 18.1?

43: ⚠ in practice, they do

44: Actual frequency is 8.5%, which is close but not exact.

Hint: Largest factors yield the largest product.

3. Reproduce the numbers in Figure 18.3 from the percentages in Figure 18.1. The visual width of each of the four columns in Figure 18.1 also speaks to this.

4. In reference to box sizes in Figure 18.2, answer the following questions:

   a) Which three types are vastly over-represented[45] in the survey?
   b) Which three types turn out to be almost perfectly represented?
   c) Which column is most poorly represented (what common letters in four associated types)?
   d) Which two types are most vastly under-represented, and by roughly what factor,[46] based on area of the squares?
   e) What relationship do you notice between the types in comparing the two most over-represented types and the two most under-represented types?
   f) How would you explain to a fellow student who disparages the Myers–Briggs scheme as little better than astrology what this figure/result means in terms of far-from-random outcomes and predictiveness?

45: . . . i.e., far more respondents than is consistent with the general population frequency of Figure 18.1

46: Form a rough guess on ratio of areas.

5. Imagining for a moment that the distribution of human personality types is adaptive[47] in an evolutionary sense, we might try to understand the asymmetry between "S–types" and "N–types." When trying to plot a course for the future, what advantages does each type bring, and what disadvantages? Another way to frame the question is: how can the contributions of each help things go right, and how might each one contribute to wrong decisions?

47: . . . emerging to best serve collective survival interests

6. How might you propose getting people of all personality types on board with a collective campaign to fight a credible future threat that may involve sacrifice and the recognition that our own habits are part of the problem?

7. Let's say you have decided to reduce your footprint[48] in some way. You run into someone who challenges your choice, pointing

48: E.g., allow a larger indoor temperature range as it gets colder/warmer outside; eating less meat; conserving water via shower habits

out that your effort is so small in the grand scheme of things that it cannot make a credible difference, and others will just use more—offsetting your sacrifice. Do you believe that is correct? If not, what argument would you offer in support of your decision?

8. Let's say that the U.S. were willing to divert a one-time investment of 10 qBtu out of its 100 qBtu annual energy budget toward building a new energy infrastructure having a 10:1 EROEI and a 40 year lifetime. How many qBtu will the new resource produce in its lifetime, and now much per year? How many years before the amount of energy put in is returned by the output?

   Hint: you never need to convert qBtu: it's just some energy unit.

9. If some country or the entire world committed to a one-decade program to replace fossil fuels with solar photovoltaics at an EROEI of 6:1 (Table 14.1; p. 232) based on a 36 year panel lifetime expectation, what fraction of that region's[49] energy would have to be poured into this effort?

   49: . . . country or world, depending on the chosen confines of the problem

10. Imagine that we hit energy decline as a result of less energy available each year in traditional fossil forms, experiencing 5% less energy each year[50] A new renewable energy infrastructure effort will require up-front energy, reducing the available energy even further.[51] Imagine yourself as a politician wanting to get elected *after* such a program has been started, and you think you can get elected by pledging to kill the program. What is your pitch to the voters to get elected?

    50: . . . a steep decline

    51: . . . maybe by another 10% for a 40-year plan at EROEI of 10:1 and a 40-year lifetime resource

11. The Milky Way has about 100 billion stars (10^{11}). If 50% of stars have planetary systems, 10% of those have a rocky planet in the habitable zone, 10% of those are in benign[52] environments, 0.1% manage to produce life of some form, and 0.1% of those result in intelligent life, how many instances of intelligent life might we expect to emerge in our galaxy?

    52: . . . stable star without flares and cosmic rays

    Note that we have no solid understanding of the probability that life emerges or that having done so intelligent life will form, so these numbers could be optimistic or pessimistic.

12. What would it take, in your view, to overcome the collective human failings summarized in Section 18.5? How do we crack this predicament?

19 A Plan Might Be Welcome

Having discussed some of the human factors related to accepting and mitigating challenges, we now turn to the question of what humanity's goal might be if we could collectively start rowing in the same direction.

First, we will have to assess the form that our actions have taken in the absence of a coherent plan. Next, we address challenges inherent in devising and adopting a roadmap for our future. Finally, a possible target is presented that bears consideration as we grapple with possible modes of human society going forward.

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19.1 No Master Plan

The "adults" of this world have not established a global plan for peace and prosperity. This has perhaps worked okay so far: a plan hasn't been necessary. But as the world changes from an "empty" state in which humans were a small part of the planet with little influence to a new "full" regime[1] where human impacts are many and global in scale, perhaps the "no plan" approach is the wrong framework going forward.[2]

Most decisions are made based on whether money can be made or saved in the short or intermediate term. The market then becomes the primary arbiter of what transpires, constrained only by a light touch of legal regulations and public sentiment. Earth and its ecosystems have little voice[3] in our artificially-constructed societal framework—at least in the short term.

Perhaps we are structuring our world *exactly* backwards. An attempt to put a monetary value on the earth and its intricate biological web—a web that by construction[4] is exactly the foundation humans rely upon for survival—produces absurdly large numbers in the sextillions of dollars

1: 96% of mammal mass on Earth is now humans and their livestock [121].

2: In rare cases, small islands like Tikopia operated under plans to live within finite bounds. Now, Earth is effectively a small island and needs to shift to a "small-island" plan.

3: Consider whether a tree or a polar bear can sue a lumber or oil company.

4: . . . that humans evolved into

Uh. Shouldn't I have more pieces? Photo credit: Tom Murphy

(Box 19.1). In this context, the $100 trillion global annual economy is such a minuscule fraction of the value of the earth. Yet reflect on the question: which valuation drives almost all of our decisions?

Box 19.1: Earth's Dollar Value

How much would it cost to purchase a barren planet and then to layer atop it a complete, functioning ecosystem?[5] Starting with the basics, the cost of rough rock, sand, or dirt in the U.S. bottoms out at about $5 per cubic yard.[6] It is the very definition of "dirt cheap." We'll upgrade the volume to a cubic meter[7] for ease. The earth is roughly 10^{21} cubic meters in volume, so even if given a smoking deal on the materials at $1 per cubic meter, the price tag is in the sextillion dollar regime ($\$10^{21}$). The high central density of the earth makes the price tag even higher under the more sensible cost per ton,[8] considering the 6 sextillion ton mass of the earth. This is an admittedly naïve way to price a planet, but it puts a scale on things.

A similarly simple calculation applies to minerals. Ignoring the material in the molten mantle, using crustal abundances and only the stuff in the 30 km crust under dry land,[9] the continental crust contains $0.6 quintillion ($\$0.6 \times 10^{18}$) of silver, $3 quintillion in gold, $5 quintillion in copper, and $20 quintillion in nickel.[10] Aluminum leaps up to $2 sextillion, but probably reflects the energy-intensive extraction process.

By these estimates, the earth is already worth something in excess of $\$10^{21}$, and that's before adding biology, whose billions of years of tuning under evolution is not something we even have the skill to replicate, let alone affix a price tag. Perhaps an evolved biology is more valuable than the raw materials. Given all the barren planets in the universe, an argument can be made that a biologically diverse planet would fetch a premium price. Comparing this to the global $\$10^{14}$ budget, the economy registers at less than a millionth the worth of the planet, yet all our decisions are made based on what is good for the tiny flea, ignoring the essential and much larger canine host.

5: . . . actually many connected ecosystems

6: . . . not including delivery

7: . . . would cost 30% more, but we'll ignore this small adjustment

8: . . . rather than by volume

9: . . . just 0.4% of Earth's volume

10: For instance, gold is about $60,000 per kilogram, and according to crustal abundances in Table 15.9 (p. 258), gold is 4 parts per billion of the crust by mass. The crust in question has a volume of 4.4×10^{18} m^3 and a mass around 1.3×10^{22} kg. The expected mass of gold is then about 5×10^{13} kg, and would cost $\$3 \times 10^{18}$. Notice that the total values are amazingly close for these metals: rarer is more expensive in inverse proportion and thus in rough balance.

As human actions on this planet close the door on one species after another, it is important to realize that we are losing an investment of millions upon millions of years of evolutionary fine-tuning that led to this splendid place we call home. The human race has set about to negligently, unwittingly destroy its home, showing essentially no regard for its worth.

Box 19.2: Clueless Cat Analogy

In analogy, domestic cats cannot possibly comprehend why they should *not* be allowed to claw the sofa. To their minds, the sofa is

there, has always been there, feels "right" and good on their claws, and surely can serve no other purpose than to satisfy their urges. How could they possibly understand what it would cost to replace, or why we even care about the appearance to begin with? It would be an even better analogy if the cats' very survival depended[11] on maintaining an unspoiled sofa, in ways the cats could never grasp.

11: . . . for instance, if their food source depended on a pristine sofa for some reason

Maybe humans as a species are as clueless[12] as the cats in Box 19.2 about their present actions. In some sense, this possibility provides a compelling reason to stop. If we can't understand the consequences of our actions, maybe that signals a tremendous risk and we should cease until we have a better grasp: do no more harm until we know what we are about. Unfortunately, there's no money in that idea.

12: Why would evolution have resulted in a being smart enough to fully grasp this exceedingly complex reality? Maybe humans are smart enough to ruin things, but not smart enough to refrain from the ruining. Sec. D.6 (p. 408) explores this further.

19.1.1 The Growth Imperative

Lacking a master plan, the current situation can be described as operating on "autopilot," guided—rather cleverly and impressively—by market forces. In a world far from environmental limits, this model effectively maximizes growth, development, innovation, and prosperity.[13]

13: . . . although resources are not typically well-distributed, leading to inequality

Much as it is in the case of fossil fuels, it is hard to fault growth for all the good it has brought to this world. Yet, as with fossil fuels, nature will not allow us to carry the model indefinitely into the future, as was emphasized earlier in this book. Growth must be viewed as a *temporary phase*,[14] emphasizing the need to identify a path beyond the growth phase. Before discussing how this might manifest, the list below illustrates the dominance of growth in our current society.

14: Recall that Chapter 2 made the argument that economic growth *can't* continue indefinitely.

1. If a politician or activist calls your phone during an election cycle, ask if their platform supports growth.[15] Of course it does. It is hard to find mainstream politicians opposed to growth, and this is fundamentally a reflection of attitudes among the populace.
2. Communities make plans predicated on growth. Most seek ways to promote growth: more people, more jobs, more housing, more stores, more everything.
3. Financial markets certainly want growth. Recessions are the scariest prospect for banks and investors. What would interest rates or investment even *mean* without growth? What role would banks play?
4. Social safety net systems[16] are predicated on growth both in the workforce (as population grows) and the economy (so that interest accumulates). In this way, post-retirement pay can be greater than the cumulative contributions that an individual pays during their career. A retiree today is benefiting not only by accumulated interest on their past contributions to the fund, but on a greater workforce today paying into the fund. If growth falters in either or both (workforce/interest), the institution is at risk. It is essentially a

15: . . . in terms of the economy, jobs, community, housing, you name it

16: . . . pensions, retirement investment, social security, government health care

slow-moving pyramid scheme that cannot be sustained long-term, given limits to growth. It was a neat idea for the growth period, but its time will come to an end.

5. Various figures from this text (Fig. 1.2; p. 7, Fig. 3.2; p. 31, Fig. 7.7; p. 109, Fig. 8.2; p. 118, Fig. 9.1; p. 139) show a relentless growth in people and resources—often looking like exponential growth. Growth has been a central feature of our regime for many generations.

In other words, human society is deeply entrenched in a growth-based model for the world. This does not augur well when the finite planet dictates the impossibility of indefinite growth.

19.2 No Prospect for a Plan

Not only do we lack a plan for how to live within planetary limits, we may not even have the *capacity* to arrive at a consensus long-term plan. Even within a country, it can be hard to converge on a plan for alternative energy, a different economic model, a conservation plan for natural resources, and possibly even different political structures. These can represent extremely big changes. Political polarization leaves little room for united political action. The powerful and wealthy have little interest in substantial structural changes that may imperil their current status. And given peoples' reluctance to embrace austerity and take personal responsibility for their actions, it is hard to understand why a politician in a democracy would feel much political pressure[17] to make long-term decisions that may result in short-term hardship—real or perceived.

17: . . . discussed in Sec. 18.2 (p. 309)

Globally, the prospects may be even worse: competition between countries stymies collective decision-making. The leaders of a country are charged with optimizing the prosperity of their own country—not that of the whole world, and even less Earth's ecosystems. If a number of countries *did* act in the global interest, perhaps by voluntarily reducing their fossil fuel purchases in an effort to reduce global fossil fuel use, it stands to reason that other countries may take advantage of the resulting price drops[18] to acquire more fossil fuels than they would have otherwise—defeating the original purpose. Then the participating countries will feel that they self-penalized for no good reason. Unless all relevant nations are on board and execute a plan, it will be hard to succeed at global initiatives. The great human experiment has never before faced this daunting a set of global, inter-related problems (see Box 19.3 for an underwhelming counterpoint). The lack of a global authority to whom countries must answer may make global challenges almost impossible to mitigate. Right now, it is a free-for-all, sort-of like ~200 kids lacking any adult supervision.

18: . . . from lowered demand

Box 19.3: What About Ozone?

Scientists discovered an alarming decrease in stratospheric ozone (O_3) in the latter part of the twentieth century—particularly acute aver the Antarctic, earning the title "ozone hole." A global agreement in 1989 called the Montreal Protocol banned the use of chlorofluorocarbons.[19] Substitutes largely—but not entirely—mitigated the ozone problem. Ozone depletion has improved by 20% since 2005 [122]. While the problem is not yet gone, or solved, it is encouraging that global policy can at least reverse and possibly fix a problem.

On the scale of things, this was an easy problem to solve. Climate change and fossil fuel dependence are *much* harder, making the ozone comparison a false equivalency. Getting energy out of fossil fuels *demands* the release of CO_2. We can't "just" switch[20] to some other liquid fuel that doesn't have this problem, as this book makes clear.

Problems are not all the same size. Switching to alternate refrigerants was painful, but not so much that countries and industries could not absorb the cost. Asking to abandon primary energy sources is a *much* bigger ask. Witness the fact that the *rate* of CO_2 emissions grows every year, despite global awareness of the problem.

19: . . . often found in refrigerant fluids and aerosol cans

[122]: Nunez (2019), "Climate 101: Ozone Depletion"

20: An analogy is if your doctor told you to avoid monosodium-glutimate (MSG) in your food, you'd be able to find substitutes and still do fine. If your doctor asked you to avoid carbohydrates, protein, and fat—sort-of like the three fossil fuels that are the staple of our diet—we'd be down to what, exactly? Progress in eliminating MSG says little about prospects for addressing the much larger problem.

Many residents of the U.S. also remember great concern over acid rain in the 1970s and 1980s, along with other environmental damages that seem to have been fixed. Part of this is real, and part is illusory. The real part is that coal-fired power plants did adopt technology to scrub sulfur and other trace pollutants out of the emissions stream. This is relatively easy compared to dealing with CO_2, which is not a tiny fraction of emissions, but practically *all* of it.[21] The illusory part of reduced acid rain impact on the U.S. environment has to do with *moving* much of the manufacturing capacity overseas. What happened to environmental quality in Asia as a result? Local solutions are not global ones.

21: It's one thing to rinse off (scrub) cans before putting them in the trash. It's another thing entirely to eliminate the production of trash (CO_2) altogether.

Whether trying to bring about change on a national or global level, the associated political decisions are especially fraught if any form of sacrifice is involved. Examples may be reduced travel, less "comfortable" thermostat settings, taxes or other cost structures making energy and resources more expensive, or more responsible diets. Imposing any such hardships may be politically untenable. Yet, if constrained to operate under a condition of no sacrifice in solving our problems, the only viable paths forward may be closed off, thus setting the stage for failure. In an attempt to have everything, we risk winding up with nothing.

Box 19.4: Paris Agreement and Kyoto Protocol

The United Nations is the closest thing to a global government, but in practice only has as much authority as member nations wish it to

have. Occasionally, the U.N. sponsors international pacts to set limits on CO_2 emissions in a quest to limit the harm of climate change. The Kyoto Protocol of 1997 and Paris Agreement of 2015 are the most notable of these.

Despite the best of intentions, the agreements have not yet shown effectiveness, in that CO_2 rises faster than ever (Fig. 9.1; p. 139). Countries fail to meet their target reductions, and suffer no penalties: what authority would enforce the targets, and how? Until people are willing to voluntarily use less and/or pay more for energy, these scientifically solid and well-meaning international agreements will lose out to political pressures for cheap comfort at a national level.

Author's note: while this box downplays the impact of international agreements, I still would rather have them than not, in that they *do* have *some* impact on emissions and serve as a very public symbolic statement of concern. I'm just not sure they are nearly enough, lacking enforcement and focusing only on climate change: one evident symptom of a much deeper disease about planetary limits and ecosystems. These agreements do not address fundamentals of growth and resource exploitation, and so are band-aids at best. Sometimes band-aids are the appropriate choice for minor wounds, but don't expect them to cure potentially fatal diseases.

19.2.1 Who Makes the Plan?

So how might a viable plan emerge? Who might produce one? Corporations cannot be expected to lay out a responsible plan for our future. Their interest is in company health and profits.[22] In fact, corporations have a fiduciary obligation to their shareholders to maximize profit. Demonstrable failure to do so is technically illegal, and could result in damaging lawsuits.

22: . . . usually confined to short-term: quarterly, annual

Governments are in a better position, presumably interested in the long-term health and viability of the country. Many governments, however, are constrained by election cycles that in the U.S. are every 2, 4, or 6 years. Decades-long planning is not natural in such high-turnover[23] systems. Authoritarian governments may be in a better position to effect long-term planning, and even have the ability to impose sacrifice for longer-term goals. Yet, here again the goals are not aimed at achieving global peace and prosperity, but rather securing that particular country's fortunes and survival.

23: . . . or even the *threat* of high-turnover

Similar limitations apply to the military sector. Military bodies *do* have the luxury to form long-term strategic plans, and can recognize real threats[24] to the global order. The only problem is that their charge is to win the day: in the event of a global resource competition, they vie to end up in control, generally through use of force or strategic superiority.

24: The author has been visited by U.S. military strategists concerned about the repercussions of diminishing petroleum supply.

The job of formulating a plan may be best suited to the academic world, as academics have the freedom to pursue research in any direction of their choosing, can spend entire careers focused on the effort, and can afford to think over longer timescales than their own lifetimes. An academic agenda *can* be global in scope, rather than fighting for the interests of a single corporation or country. As long as an academic is able to demonstrate impact—typically via substantive and original contributions to published literature—they may uphold their end of the tenure pact.[25] Ideally, academics of all stripes would gather to formulate a viable future plan for how human civilization might carry forward in a way that respects realities from the realms of physical sciences, engineering,

25: Contrary to a common misconception, it is rare for tenured professors to rest on their laurels. Tenured professors by-and-large are intensely driven to push the boundaries of knowledge (which is what earns tenure), and are unlikely to change character upon being granted tenure. In fact, tenure should be looked at not as a reward for past accomplishments, but an investment in a future that (based on past accomplishment) promises to continue bearing fruit.

economics, political science, sociology, psychology and cognitive science, history, anthropology, industrial studies, communications, and really all other academic fields. Every field of study has a stake in the fate of human civilization and has meaningful understandings and insights to contribute.

Of course, any such plan that might emerge will be attacked from all sides, derided as alarmist academic fantasy. It is exceedingly difficult to imagine that the entrenched world will just decide to get started rebuilding the world according to "the plan." But the hope is that if conditions eventually deteriorate to the point that continuation of business as usual is clearly not viable, enough people may remember the plan and dust it off to see what insights it might contain.[26] In such a scenario, hopefully it is not too late to salvage a satisfying future.

26: In this sense, we might view such a master plan as a "break glass in case of emergency" safeguard.

A vital group has been left out of the discussion thus far: people. The vast majority of people are not on corporate boards, in positions of government or military power, or in academic roles. Any effective adaptation to a different future plan will need people to be on board, which means educating them on the choices ahead and the consequences of our actions. Broad support will likely be crucial in redesigning our world to gracefully adapt to the realities of planetary limits.

19.3 Economic Regimes

A very nice metaphor presented in the 2003 documentary *The Corporation* is that early attempts at mechanized flight were doomed to fail because the contraptions were not built on aerodynamic principles of sustainable flight. All the same, the would-be pilots launched off cliff edges and momentarily felt the thrill of flying: the wind was in their hair. Meanwhile, the ground was rushing up. Likewise, our economy and society are not built on principles of sustainable steady-state operation. Even though it feels like quite the amazing rush,[27] it is not hard to see evidence that the ground rushing up. Our only chance is to develop a steady-state economic model—one that is based on principles of long-term sustainability in *partnership* with Earth's ecosystems.

27: The wind is in our collective hair; this is fun!

Paying heed to true sustainability is challenging. Firstly, it is difficult to define what it means. Much depends on the lifestyle imagined. The earth can support fewer people if resource consumption per capita is high, for instance.

A story illustrates the challenge. An economist named Herman Daly worked at the World Bank in a division focused on the interaction between the economy and the environment. When his division was asked to issue a report on this interaction, an early draft had a standard depiction of the economy showing firms and households (Figure 19.1). Firms supplied goods and services to households, while households

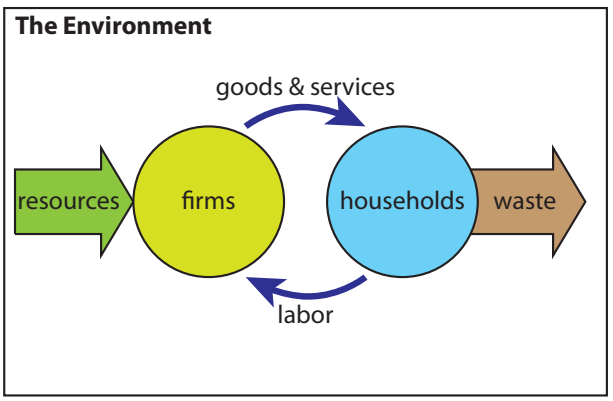

Figure 19.1: Standard concept of the economy, but importantly surrounded by a finite box labeled "The Environment." Most instances of this figure avoid the insinuation that the economy is contained in a finite domain, in part because it raises the uncomfortable question of how close we are to filling up the box.

provided labor for the firms. Resources fed the firms and waste was emitted from the households (and firms). Dr. Daly said: "great, now draw a box around this and label it: The Environment. The obvious point is that all economic activity takes place *inside* the environment. The next draft came back sporting a box drawn around the figure, but no label. Dr. Daly's response: "It *looks* nice, but unless the box is labeled The Environment, it's only a decorative frame." The next draft eliminated the figure altogether.

Once a box is drawn around the economy, many uncomfortable questions arise: how big should the box be (Figure 19.2)? Are we running out of room? What happens when the box fills up? Economists and governments are not prepared to answer such questions.

A nascent field called Ecological Economics [123], of which Herman Daly is a pioneer, has emerged from deep concerns about interactions between human activity and natural systems. Unlike the more established branch called Environmental Economics, which preserves the basic foundations of neo-classical economics and attempts to put prices[28] on environmental factors, ecological economics abandons the growth paradigm and tries to establish rules for maintaining an indefinite relationship with our planet's resources and natural services.

Herman Daly described the different philosophies by analogy to loading a boat. Macro-economics concerns itself with the overall distribution of products within the boat. It is unwise to load all the cargo into the front or back, or all on one side: much better to uniformly load the boat so that it stays level. In analogy, an economy wants to strike a balance across the wide variety of goods and services offered, so that it is not riddled by giant surpluses in one area and deficits in another. Micro-economics deals with the details of how to efficiently manufacture and sell the contents of each box: materials; supply chains; labor; marketing; distribution. But traditional economics has no concept for *how much* cargo the boat should hold—much like we have not established the size of the "box" within which the economy operates (as in Figure 19.2).

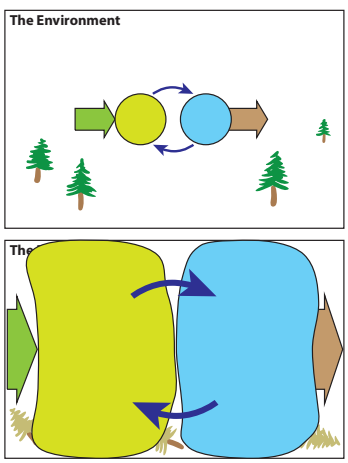

Figure 19.2: Does our economy have ample room, or is it straining the limits of the environment?

28: Economics lingo would call this "internalizing externalities." Typically, the price additions are too minor to be disruptive or fully capture the cost to nature, which is very hard to assess objectively.

In effect, our "boat" has no "waterline" painted on its side to indicate when it is fully loaded. The word "macro" in macro-economics makes it sound like the "big picture" view, but it's really just intermediate. By analogy, we might say that micro-economics is about understanding all the complex workings within a house or building. Macro-economics concerns itself with the distribution of various building types and functions within a city. Missing is a branch evaluating how many cities can fit on Earth and be supplied by the environment. Ecological Economics attempts to address this shortcoming, which is not important in an "empty" earth but becomes crucial as the human scale begins to dominate the planet.

19.3.1 Steady State Economy

Chapter 2 demonstrated that economic growth cannot go on forever. Continuing to operate as if growth can—and should—persist risks irrevocable damage to that from which all value ultimately depends and derives: a healthy natural environment. The sooner we can jump ship to a new economic model that can survive the long haul, the better.

A few key principles will help flesh out aspects of how a steady state economy might work. A critical goal is to reduce the flow (or demand) of resources into the economy, and reduce the waste (pollution, CO_2, for instance) back into the environment. This would be akin to diminishing the sizes of the two thick arrows in Figure 19.1. One approach would be to levy substantial taxes on every tree that is cut, mineral that is mined, drop of oil that is extracted, or wild animal that is unnaturally removed from the environment. Likewise, a heavy tax would accompany disposal of waste and emissions of pollutants. Meanwhile, labor would no longer be taxed. Labor can *add* value to resources already in hand. The idea is to tax the damaging things, not the beneficial things.

Think about what happens under these conditions. Buying a newly manufactured item becomes expensive. Throwing away an old device becomes expensive. Repair (labor) becomes cheaper. Say goodbye to the disposable economy, or "planned obsolescence." Durable goods and lifetime warranties become popular. Items are designed to facilitate upgrade or repair. For instance, once you own a large display at high resolution, good contrast, and good color representation, it should satisfy for a lifetime.[29] Human visual acuity is static, and modern displays are effectively perfect, relative to our biological hardware. If a small electronic component fails, the environmental cost of manufacturing a whole new unit and disposing of the old one is enormous—especially compared to the environmental cost of replacing the small failed component. At present, repair cost often exceeds the cost of replacement and disposal.[30] Under the new arrangement, we begin to place greater value in craftsmanship, community resources, and high-quality goods.[31]

29: Functional upgrades could potentially be modularized to small inserts.

30: . . . disposal is essentially free now

31: . . . less plastic junk!

Consider now the effect on our consumer treadmill.[32] Let's say you find the perfect toothbrush. When it is worn out, you try to get the same one again. But the company has changed its style, so the one you like is no longer available. Why does this happen? The company has a standing army of designers and marketers that must continually "improve" the product to stay competitive in the market. If we all bought less stuff, or more durable items that lasted far longer, the demand for manufacturing would wane. Markets and politicians shudder to contemplate this, as the result would be recession and loss of jobs.

32: It's like a treadmill in that we never stop consuming and disposing, even if it's somewhat pointless. See the Story of Stuff video.

But a widespread cessation of constant disposal and replacement of low-quality goods would mean that not as much income would be *required* to satisfy basic needs and to enjoy a quality life. Maybe all those jobs are not really *necessary*. Maybe a lot of what presently occupies society is a bunch of wasted effort in service of growth[33] and not serving ourselves or the planet well in the process. What if it only takes 10 hours of work per week to live comfortably, having reduced the flow and expense of low-quality stuff once planned obsolescence is—rather poetically—rendered obsolete? Perhaps we could spend more of our time enjoying life, community, family, friends, the natural world, while still retaining scientific literacy and basic technology standards.

33: Is growth our master?

It seems that humanity got stuck in a frenetic lifestyle because money and an unrealistic vision of our future trajectory told us to do so.[34] Maybe we need to rethink what we want life to be about, and not simply accept that productivity and profit are the drivers that matter. Are we the boss of money, or is money the boss of us?

34: Ask yourself: to what end?

Careful thought [124, 125] has been put into how to modify the present financial system toward a steady state. The process has been compared to converting an airplane, which must keep moving forward in order to stay up—as the current economy must grow to survive—into a helicopter that can remain stationary. And this transformation would ideally happen mid-flight. It's a difficult prospect. Moreover, none of the necessary steps would ever spontaneously happen without the population first embracing the ultimate goal of a steady-state economy. Therefore, a collective push to abandon our current economic model must initiate the process, and it is unclear how this ground swell might materialize.

[124]: Daly (2008), "A Steady-State Economy"
[125]: Chang (2010), *Moving Toward a Steady State Economy*

It is possible that a steady-state economic framework—for all its merits and careful thought—is ultimately naïve and infeasible. Individuals may be naturally driven to work very hard to build an empire and improve their own lot. It is not obvious that human nature is suited to a steady state existence: competition and acquisition of power may be built in.[35] Imposing rules to prevent outsized accumulation of wealth or power may seem oppressive and would be hard to sustain, unless societal values uniformly shunned excessive wealth, power, and consumption. But for how many generations could such a state of affairs be maintained? It seems like an unstable scenario.

35: . . . as a product of evolutionary pressures

19.4 Upshot on the Plan

Humanity has historically not needed a master plan. Plenty of space, resources, and natural services allowed unwitting expansion. Yes, wars occasionally broke out over contested resources, but generally in localized regions. This state of affairs will continue to be true until it isn't any more. That is to say, just because something has never happened before does not mean it cannot. Earth has never hosted 8 billion high-demand humans, yet here we are. Human imagination is not the ultimate limit in this physical world. At this juncture, it would be prudent to heed the warning signs and attempt to make a plan for survival/prosperity.

Currently, it is hard to imagine any global consensus arising around a plan. Even if able to maintain the current level of global resource demand,[36] those who use resources at a much higher rate than average[37] may have to scale back as the world equilibrates, and this will not easily be agreed upon. Academic circles may be the only place from which a credible plan might emerge,[38] but any such plan would likely be ridiculed and discarded as impractical.

36: It is not at all clear that we could.

37: Ahem, America.

38: Who else would pay for it?

The silver lining is that some folks *have* thought about alternative ways to structure the economy allowing abandonment of growth and living within ecological limits. Some of the elements of this plan are very appealing. Only if embraced on a large scale would it be feasible to migrate in this direction, and it is unclear what circumstances might bring about such an attitude change, if it is possible at all.

19.5 Problems

1. To visualize the scale of the $100 trillion global economy relative to the value of the earth—conservatively one million times larger—let's think in terms of animal volume. Volume scales like the cube of linear dimension. How much would you have to shrink a dog in linear scale for its volume to be one-millionth its original size? If the typical scale of a dog is 0.5 m, how large is the shrunken version, and what animal is about this size?

2. Subjectively, how much more do you think a planet teeming with biodiversity is worth compared to a comparable planet harboring no life at all? Express as a factor: 1.2 times as much, 2 times as much, 10 times as much, 100, 1 million etc.

   The value likely goes up if your own biology is adapted to that same life-filled planet: it becomes special to you as almost a part of you.

3. In analogy to the clueless cats in Box 19.2 and the paragraph following, describe how we might plausibly destroy something valuable on our planet without understanding it fully enough to repair the damage.

4. What institutions can you think of that are prevalent now but will be rendered obsolete—or at least radically diminished—if the economy stopped growing permanently?

5. Why do you think we have not yet formulated a master plan for how humans can live on the earth indefinitely without exceeding limits?

6. Do you see a route to global acceptance of a plan? What would it take to get there? Would we first need a global government having authority over all nations?

7. What is your major in college, and what insights or contributions do you imagine may be offered by this field of study in formulating a workable plan for the future of human life on this planet?

8. Presently, the American tendency is to buy a missing tool for a job that may not be needed again for a very long time, if at all. It is likely that some nearby neighbor already has the same tool collecting dust. What do you imagine would be advantages and disadvantages of pooling resources in a lending arrangement?

9. Why do you think the field of traditional economics does not recognize limits to growth, and does not have a macro-macro branch looking at the whole planet and its finite nature?

10. A central question in mapping a comfortable future has to do with how large our economy is with respect to physical boundaries.[39] One solution would be to set aside some fraction of the planet (land and ocean) off limits to human extraction of any plants, animals, or other resources. What fraction seems tolerable to you? If it turns out that half needs to be protected to guarantee long-term survival, do you think that's possible/practical? How many generations do you think could maintain the discipline to preserve that rich world in a pristine state?

11. What do you find appealing about a steady-state economic model? What do you find worrisome?

12. Section 19.3.1 contains four instances in which the economy is compared to analogous systems. What are these four, and which do you find most impressionable/memorable?

13. Do you think that human nature—the desire to improve one's lot and expand empire—is compatible with a steady state economic model? Can you see a way that it might work?

14. Are you left thinking that we are likely to establish and implement a viable global plan for how humans might live prosperously on the planet indefinitely, or do you think it is more likely we will fail to do so and "wing it" into whatever fate awaits?

39: It is even possible we have exceeded those steady-state bounds and are spending down an irreplaceable inheritance right now.

20 Adaptation Strategies

We made it to the final chapter. How are we doing? Anxious? Excited? Alarmed? Inspired? This book has compressed a perspective that took the author many years to absorb. Exposure in one short sprint would likely be overwhelming, and might even generate an impulse to reject the message as both unfamiliar and grim—thus hopefully wrong?

Up to this point, the theme of the book might be characterized as one of closing lots of exits. Growth can't continue indefinitely—requiring a whole different economic model. Space is not a realistic escape hatch. Fossil fuels are what made this life possible, but will not last and are causing disruptive climate change. The alternative options all have their own practical limitations, and offer no drop-in replacements for fossil fuels. At least sunshine offers a ray of light as a super-abundant energy flow. But when it comes to making collectively smart decisions about a future path, more obstacles surface on the human side. Success requires long-term planning and not the more common crisis response.

This chapter changes gears a bit to touch on individual actions and values that could amount to big things in aggregate. At the very least, it may provide individual-scale escape hatches allowing some peace of mind about personal contributions to the problem.

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20.1 Awareness

How many people do you know who are concerned about a legitimate threat of collapse of our civilization? It is an extreme outcome, and one without modern precedent. It seems like a fringe, alarmist position that is uncomfortable to even talk about in respectable company. Yet the evidence on the ground points to many real concerns:

Growing your own food is a great way to lower your impact and be closer to nature. Photo credit: Irina Fischer.

1. The earth has never had to accommodate 8 billion people at this level of resource demand;
2. Humankind has never run out of a resource as vital as fossil fuels;
3. Humans have never until now altered the atmosphere to the point of changing the planet's thermal equilibrium;
4. We have never before witnessed species extinction at this rate, or seen such dramatic changes to wild spaces and to the ocean.

Just because something big has not happened yet does not constitute strong evidence that it cannot or will not. But more important than that argument—which is always true—is the number of credible causes for concern that are evident today.

Also important to recognize is that a challenge cannot be effectively mitigated unless it is first identified and acknowledged. The very lack of collective awareness about a credible risk of collapse is *itself* unsettling. If open discussion of the possibility of collapse were not so uncomfortable and off-putting, we would stand a better chance of preventing its unfolding. It would be a huge relief to be wrong about the concern. But not taking it seriously represents a colossal risk.

Box 20.1: The Y2K Scare

The Y2K[1] scare in 1999 offers a good template for how to mitigate a potential disaster. Computer systems became the dominant means for managing financial and government records, transactions, and accounts in the 1960s through 1980s. A two-digit code was used for the year in many records, not anticipating the roll-over to 2000 decades away. The early programmers either doubted that their code would still be functioning in 2000[2] or assumed it would be cleaned up in time. In the year or two leading up to Y2K, the issue got tons of coverage and predictions of mayhem, as peoples' digital lives—a new phenomenon—were tossed into any number of unknown upheavals. But the very fact that the issue dominated public consciousness was exactly what ensured a smooth transition. Every bank and agency got on the job and Y2K came and went without a ripple. It would be great to see a repeat in the case of potential collapse. The lack of a specific time prediction is one barrier, unlike Y2K. Without a firm deadline or a clear-and-present danger, the temptation to delay serious attention is strong.

1: Y2K is short for year-2000.

2: Surprise—it was!

A key contributor to awareness is in how information sources and activities shape opinions and views. A world overflowing with information can be difficult to navigate, and has a tendency to coagulate into isolated domains that cater to predispositions. The result can be disagreement on basic facts, making coordinated progress difficult. Luckily, attentive individuals can perform an assessment of the trustworthiness of various information outlets. The process is to watch an entire live event, like a

debate or a hearing, and see how the event is covered by various news sources. Does the coverage[3] reflect the event as you experienced it? Did it focus on the key developments or on distractions that might be emotionally "triggering?"

3: Boring coverage turns out to be a decent indicator of accuracy!

Entertainment is another source/activity that can influence mindsets in subtle ways. For example, the grossly simplified and virtual world of video games promotes a false sense of what is possible—rather than helping model responses to real-world challenges, constrained by many layers of practical considerations. Reaching level 42 without suffering too many damage points is a fairly empty accomplishment[4] that just means having followed some game designer's artificial and arbitrary rule set pretty well, combined with some skill in pressing buttons. More impressive is building or creating something, repairing something, or having some beneficial impact in the external world that would not otherwise have happened.

4: Sure, some games aim to improve cognitive skills, which *could* transfer to real-world application. Is this the most effective path to making a difference?

Likewise for movies and shows, which can provide healthy joy and social bonding. But because the industry is not constrained to follow rules of nature, it is easy to form dangerous misconceptions about what humans are capable of doing.[5] As a result, not only does the likelihood of disappointment increase, but the necessary sort of deliberate and unglamorous work that must be initiated well before crisis becomes apparent is less likely to materialize if the populace is trained to hold out for unrealistic and spectacularly successful outcomes.[6]

5: . . . a space-faring future; an untrained hero saving the world; the message that anything can be built—just awaiting a genius idea from an unlikely source

6: . . . jet packs, flying cars, fusion power, Mars colonization, teleportation, food replication, and warp drive—always just in time

20.2 Communication

In a democracy, collective public awareness drives the issues politicians serve. Only by having voters demand action will progress follow. Conversations with friends and family then become necessary to raise awareness among others. Effective communication that accomplishes this goal without turning people off is tricky. When the message contains bad news or suggests sacrifice, the effort can easily backfire.

It is important not to polarize the conversation by "bossing" people or projecting a sense of authority. An effective strategy is to fairly represent uncertainty, while still conveying credible concern. Caveats like "it seems that," or "it appears to me that," or "I may be wrong, but" go a long way to taking the edge off of the message and inviting the listener into a constructive conversation. It is possible to couch the language in uncertainty while still hitting the main points. Words like "possible," "likely," "plausible," and "risk" can be useful to soften the tone but still express concern.

Division in the U.S. is frighteningly high right now, so that distrust is a real barrier to sharing a common factual basis. The communication needs to be "we," not "you." For instance, "we really should be concerned

about X" rather than "I think you should X." It is best to try to convey a sense that we are all in this together. Expressions like "I worry that," or "Do you also feel that. . . " bring a human touch and invite a sense of inclusion and collaboration.

One potentially interesting approach is to appeal to the fundamentally conservative nature of most people. This is conservative with a small "c," rather than the Conservative (right-leaning) political party. In this sense, conservative means:

1. low risk: let's not gamble the future on speculative notions;
2. conservation[7] of resources and quality of the earth environment;
3. laying the groundwork for future generations (e.g., grandchildren) to have a livable world.

7: It's right there in the name!

By these traditional definitions of conservative, many in the Conservative wing are more fairly labeled as free market radicals—willing to risk future stability and damage our environment in exchange for short term financial gain. This approach is not inherently conservative.[8] Political identities in the world may, in fact, be ripe for a massive realignment wherein many traditionally conservative values pair more naturally with the political "left" (liberal wing) than with the "right." In recent decades, the left has been more concerned about environmental issues and ecological damage. It would make sense that the most conservative—or low risk—proposals for future paths would emerge from the political left.■

8: Ask yourself: what conservation efforts have Conservatives championed lately?

An apt analogy is that our society is, metaphorically, barreling toward a cliff. Faced with credible warnings, the low-risk (conservative) approach would be to alter course: get serious about a non-fossil infrastructure and transition away from growth. At the very least, let off the gas pedal: reduce resource use while we learn more. Keeping the foot down on the pedal and seeking to accelerate as fast as possible is probably the least wise[9] decision, yet best characterizes the current approach.

9: This decision would be okay if we *knew* that the cliff is not there, but we can't know that, and plenty of evidence suggests reason for concern.

Unfortunately, a common tendency of people on the receiving end of the kind of message this book advances is to get frustrated when the story is *not* tied up neatly into a happy ending. Perhaps our story-telling culture has irreversibly conditioned people to expect resolution at the end of every movie or show. Nature and the world are under no such obligations to satisfy our psychological need for closure, so it is unfair to blame the messenger for accurately conveying the perils and uncertainty of our times. Perhaps people seek a hopeful conclusion so that they can walk away unencumbered—satisfied that everything is under control and that somebody will figure something out. But this tendency is perhaps counter-productive, in that only by internalizing and burdening oneself with the daunting nature of our challenge will it be possible to mount a collective and effective response. If human nature is such that unpalatable stories don't gain traction, it is another way to say that we are not built to overcome a global dilemma of this scale. So push back

on any criticism demanding that you need to supply a happy picture at the end of the story. Challenge the listener to deal with the tension, as this book has attempted to do. Tough love.

20.2.1 Predicament, not Problems

It may also be advisable to avoid characterizing the set of interconnected global challenges as "problems," because the word *problem* implies a *solution*. It implicitly isolates the issue at hand into a stand-alone simple issue, promoting "what if we just. . . " proposed solutions. The real story is far more intricate, and more like a game of whack-a-mole.[10] A simple "fix" to one corner of the problem makes something worse elsewhere. A better word is predicament, intoning a more serious and possibly intractable situation. Perhaps a predicament can be viewed as an *interconnected set of thorny challenges* rather than a collection of isolated problems.

10: . . . a game where heads pop up out of holes to be hammered down, only to see other heads pop up elsewhere

Predicaments don't have solutions, but responses. Piecemeal fixes are unlikely to "solve" the current predicament in a way that permits moving on and relegating the problems to the past.[11] But we *can* imagine re-crafting our world, *responding* to the challenges by adapting our mode of living to be compatible with planetary limits. Problems can be faced head-on and be defeated, whereas predicaments call for stepping around and finding a different path.

11: . . . as was the case for curing polio, for instance

20.3 Personal Adaptation and Guidelines

Previous chapters have discussed the challenges democratic governments have in imposing any form of reduction that feels like sacrifice to the population. Since political power in democracies starts with individuals, we focus here on what individuals can do to reduce their demand on energy resources. If enough individuals are *not* willing to make such adjustments, it is doubtful that the U.S. government, for instance, would exert authority over this sensitive domain of personal freedom.

This section addresses ways to take personal control of energy expenditures.[12] The presupposition is that the reader is *interested* in ways to reduce their impact, or footprint, on the planet and its resources. Collective progress on this front would reduce the current 18 TW demand on energy, making it that much easier for fossil fuel replacements to satisfy a more modest demand. A voluntary course of reduction on a broad enough scale would reduce vulnerability to forced reduction that would ultimately accompany declining fossil resource availability or climate-motivated reduction targets. It is also good preparation for potential scarcity.

12: Energy usage correlates strongly with resource usage, in general.

We will first look at attitudes and framing, then some overarching guidelines, followed by specific quantitative assessment of energy expenditures. Readers can identify for themselves areas for potential change in their own habits and expectations.

20.3.1 Overall Framing

In the absence of a major shift in public attitudes toward energy and resource usage, motivated individuals can control their own footprints via personal decisions. This can be a fraught landscape, as some people may try to out-woke each other and others will resist any notion of giving up freedoms or comforts—only exacerbated by a sense of righteous alienation from the "do-gooders."

Some basic guidelines on effective adaptation:

1. Choose actions based on some analysis of impact: don't bother with superficial stuff, even if it's trendy.
2. Don't simply follow a list of actions or impart a list on others: choose a more personalized adventure[13] based on quantitative assessment.
3. Avoid showing off. It is almost better to treat personal actions as secrets. Others may simply notice those choices and ask about them, rather than you bringing them up.[14]
4. Resist the impulse to ask: "what should I *buy* to signal that I'm environmentally responsible?" Consumerism and conspicuous consumption are a large part of the problem. Buying new stuff is perhaps counterproductive and may not be the best path.
5. Be flexible. Allow deviations. Rigid adherence makes life more difficult and might inconvenience others, which can be an unwelcome imposition. Such behavior makes your choices less palatable to others, and therefore less likely to be adopted or replicated.
6. Somewhat related to the last point, chill out a bit. Every corner of your life does not have to be perfect. We live in a deeply imperfect world, so that exercising a 30% footprint compared to average is pretty darned good, and not *that* much different than a "more perfect" 25%. Doing a few big things means more than doing a lot of little things that may drive you (and others) crazy.
7. In the end, it has to matter to *you* what you're doing and why. It's not for the benefit of others.[15]

The first two items on the list are not easy: most people are not themselves equipped to quantitatively evaluate the impact of their choices. But some simple guidelines can help.

13: . . . resulting in a mindful pursuit and not an impersonal set of imposed chores

14: A joke illustrates the usual pitfall: "How will you know if a new acquaintance is vegan? Oh, don't worry, they'll tell you within 10 minutes."

15: . . . except, of course, in the broadest collective sense: it's for people you will never meet who are not even alive yet, and for other life on Earth you will never see.

20.3.2 Energy Assessment Principles

This section contains a number of key insights that can guide actions. Each starts with a simple statement in bold font, followed by elaboration and then an example or two[16] for most.

Heat is costly. Anything whose job it is to create thermal energy (heat) is a power-hog: clothes dryer; home heating; hot water heater; space heater. A small device called the Kill-A-Watt is handy for assessing power draw by plug-in appliances.

Example 20.3.1 How much energy does it take to dry a load of clothes using a 5,000 W clothes dryer?

Assuming it takes about an hour to run, this is 5 kWh, or 18 MJ.

Example 20.3.2 How much energy does it take to heat all the water in a 40 gal (150 L) tank from 10°C to 50°C?

Recalling Def. 5.5.1 (p. 73) or the definition of the kilocalorie, heating 150 L (150 kg) by $\Delta T = 40$°C will take 6,000 kcal, which converts to 25 MJ or 7 kWh of energy.

How often is it on? Duty cycle matters a lot: how often it's on. A microwave oven uses a lot of power, but not so much energy, because it is hardly ever running. The Kill-A-Watt mentioned above accumulates kWh and allows determination of the average power of a device.

Example 20.3.3 How much energy is a 1,500 W microwave oven at home likely to use in a day, compared to a 25 W television tuner box running 100% of the time?

The microwave might be on for 12 minutes per day, or 0.2 hours. That makes 0.3 kWh[17] for the microwave and 0.6 kWh for the tuner box. Time matters.

Large ΔT is costly. The power it takes to maintain a temperature difference is *proportional to the temperature difference*.[18] For related reasons, a refrigerator in a hot garage has to work especially hard[19] to maintain a large ΔT.

Example 20.3.4 How much more daily energy does it take to keep a home at 25°C inside when it is 5°C outside versus keeping it at 15°C inside?

In the first case, ΔT is 20°C, while it's just 10°C in the second case. So it will take twice as much energy to keep the interior at 25°C compared to 15°C.

Use common units. Cross-comparison of energy usage is made more difficult by different units. Table 20.1 provides conversions to kWh as a

16: A number of the examples require some thought and estimation, which is not typical of assigned problems but may be advantageous here to promote the kind of thinking that is useful when applying to personalized situations.

17: . . . 1.5 kW times 0.2 hours

18: See heat loss rate and Sec. 6.3 (p. 86).

19: . . . and at lower efficiency according to Eq. 6.10 (p. 95)

standard. In terms of power, many appliances are rated in Btu/hr, which is 0.293 W. So a hot water heater at 30,000 Btu/hr is equivalent to about 10 kW and will consume 5 kWh if running for half-an-hour, for instance. Putting everything in the same units (kWh as a suggestion here) allows useful comparisons of choices.

Table 20.1: Conversions to kWh.

Energy Quantity	kWh
1,000 Btu	0.293
2,000 kcal diet	2.3
1 L gasoline	9.7
1 kg gasoline	13
1 gal. propane	26.8
1 Therm (gas)	29.3
1 gal. gasoline	36.6

Example 20.3.5 In a month, the utility bill for a house shows 600 kWh, 20 Therms, and the two cars of the household used a total of 60 gallons of gasoline. How do these stack up, when assessed in the same units?

Using Table 20.1, the gas amounts to 586 kWh—almost identical to electricity—and the gasoline totals about 2,200 kWh, far outweighing the other two.

Electricity source matters. Your local source for electricity[20] can impact choices. It should be possible to determine your local mix via online sources [126]. The fact that conventional power plants tend to convert chemical energy into delivered electricity at 30–40% efficiency needs to be considered in comparing direct use of a fossil fuel against electrical solutions based on fossil fuel. A heat pump design for a water heater can compensate for this loss, and then some.[21]

20: . . . coal vs. natural gas vs. hydroelectric, for example

[126]: Nuclear Energy institute (2019), *State Electricity Generation Fuel Shares*

21: . . . if the COP is higher than 2.5, for instance, which it usually will be

Example 20.3.6 A hot water heater using natural gas is likely about 85% efficient at transferring the heat of combustion into the water (enclosed, insulated), while an electric hot water heater manages to get 100% of the delivered energy into the water via a heating coil immersed in the water. If the source of electricity is also natural gas form a power plant achieving 40% efficiency at converting thermal energy into electricity and then transmitting it to the house at 95% efficiency, which method uses more total fossil fuel energy, and by what factor?

We compare 85% efficient for the direct usage to 40% times 95% times 100%.[22] The ratio of 85% to 38% is 2.2, so it will take 2.2 times more gas at the power plant than in the home to produce the same result in heated water.

22: This last one is for the immersed coil, and does nothing to the answer.

Weight is a guide. A rough rule of thumb is that the energy cost of consumer goods is not too far from the energy contained in the *equivalent weight*[23] *in gasoline*, meaning 13 kWh/kg (Table 20.1). Should you use paper or plastic bags? The one that weighs more probably required greater energy and resource use. Should you drive back home if you forgot your reusable bag? Compare the amount (weight) of gasoline you'll use to the weight of the disposable bags the store uses.[24] High-tech gadgets, like smart phones, almost certainly break this rule and cost far more energy to produce than their gas-equivalent weight—as can be approximated in the next point.

23: . . . really we mean mass

24: . . . almost certainly *not* worth it to drive back; can you manage without any bags at all and not risk dropping anything?

Example 20.3.7 Should you buy a new, more efficient refrigerator that will use 1.8 kWh per day (75 W average) instead of your current one that uses 2.4 kWh/day (100 W average)?

At a mass around 150 kg, the refrigerator's manufacture might require ~2,000 kWh,[25] taking about 9 years to pay back at the 0.6 kWh/day saving. This is long enough that considerations such as material resources and disposal might tip the scale against replacement.

25: . . . 150 kg times 13 kWh/kg

Cost is a guide. A secondary approach to figuring energy content is to suspect that the item's cost is appreciably greater than the cost of the energy that went in. Perhaps a reasonable number is that 15% of the total cost goes toward energy.[26] Conveniently, a typical retail price of electricity of \$0.15/kWh then translates to 1 kWh for each \$1 of consumer spending. When results from the two approaches (by mass or by price) differ, the higher energy cost number may be the safer bet.

26: This is not a capricious estimate, as it is approximately representative of energy costs in our society as a whole—stacked a little higher here to better reflect manufacturing activities, which are bound to be more energy-intensive than the economy as a whole. Also note that energy intensity, as seen in Fig. 2.2 (p. 19), is characteristically around 5 MJ/\$, which is 1.4 kWh/\$ and not far from our rule of thumb here.

Example 20.3.8 What do the two methods say about a 1,500 kg car that costs \$25,000 and a smart phone that costs \$1,000 and has 200 g of mass?

The car estimates are 1,500 kg times 13 kWh/kg for about 20,000 kWh or \$25,000 times 1 kWh/\$ for 25,000 kWh. In this case, they're pretty close and it hardly matters which one we favor.

For the phone, the mass estimate is just 2.6 kWh, but by price it would be 1,000 kWh. In this case, for reasons argued above, the larger one is more likely on target.[27]

27: We would not go so far as to say that either method is "right." They should be viewed as very approximate guidelines that at least can help differentiate big deals from insignificant things.

Focus on the big. Keep your eye on the big impacts. We are not actually under threat of running out of landfill space, for instance. So while recycling is a preferred approach,[28] very visible in society, and should be practiced when possible, the impact is not dramatic: it still takes a lot of energy to process recycled goods. Metal recycling (especially aluminum) is most effective from energy and resource standpoints, and paper from a resource standpoint (trees), but plastic is less clear on both energy and resource bases. Reducing its use may be best.

28: Better yet is to try getting by without purchasing items that require later disposal.

Example 20.3.9 How effective is it to buy a water bottle for my daily needs?

Compare the weight and cost of the water bottle to the weight and cost of all the plastic cups it displaces[29] as a reasonable guide to the relative impact.

The best of all worlds is not buying something for the purpose, but finding something you *already have* that will get the job done.

29: Consider the duration of ownership or of usage and how many disposable cups are avoided.

Reduction rules. Reduction is by far the action with the biggest impact. Buy less stuff. Live more simply. Travel less often and less far.[30] Adapt

30: A side benefit to these actions is saving money, maybe working less hard and retiring earlier.

yourself better to the climate.[31] Eat more responsibly. The next section digs into related actions in more quantitative detail.

31: It is okay to put on more clothes and sit under blankets in a cooler winter house.

20.3.3 Quantitative Footprint

A useful exercise is to compare your own energy footprint to national averages. How much more or less are you using? For some categories, information is hard to assess. For instance, how much oil is used to transport the goods you buy and the food you eat? How much energy is used in the industrial and commercial sectors on your behalf?[32] In part, your level of consumerism is a good clue, but it still may be hard to compare to others. The following items offer some guidance. The first two entries can be derived from Fig. 7.2 (p. 105), after unit conversions and dividing by the U.S. population.

32: Wouldn't it be great if consumer goods had labels revealing embedded energy and resulting CO_2?

Electricity: A typical American uses 12 kWh of electricity per day in their residence. To get your own share, look at an electricity bill for your residence and divide by the number of people living in the place and by the number of days[33] in the billing period.

33: . . . usually a month: about 30 days

Example 20.3.10 In 2019, the author's utility bills[34] indicate total use was 3,152 kWh for a household of two. What is the daily average per person and how does it compare to the national average?

3,152 kWh divided by 365 days and 2 people is 4.3 kWh per person per day, about one-third of the national average.

34: See the banner image on page 68 for a one-month sample.

Natural Gas: A typical American uses about 13 kWh of natural gas per day in their residence, amounting to 0.44 Therms per day.[35] To get your own share, look at a gas bill for your residence, if applicable, and divide by the number of people living in the place and by the number of days in the billing period.

35: . . . typical billing unit; one Therm is 29.3 kWh; see Table 20.1

Example 20.3.11 In 2019, the author's utility bills[36] indicate total use was 61 Therms for a household of two. What is the daily average per person and how does it compare to the national average?

61 Therms divided by 365 days and 2 people is 0.084 Therms (2.4 kWh) per person per day, about 20% of the national average.

36: See the banner image on page 68 for a one-month sample.

Gasoline: A typical American buys about 400 gallons of gasoline[37] per year for personal transportation, amounting to a daily equivalent of 41 kWh[38] of energy use. Keep track of your fuel purchases[39] and compare how much you use. In the case of multiple occupancy in the car, your share can be computed by dividing how many gallons were used in the trip by the number of people. Knowing an approximate fuel economy[40] for the car and distance traveled is enough to estimate fuel usage.

37: Personal transportation accounts for about 65% of gasoline in the transportation sector.

38: . . . 36.6 kWh per gallon, or 9.7 kWh/L

39: This practice is good for tracking fuel economy as well.

40: . . . e.g., miles per gallon or L/100 km

Example 20.3.12 The author's household has two vehicles,[41] one of which drove 400 miles and used 22 gallons of gasoline in 2019, and the other covered 8,660 miles using 69 gallons. What is the daily average use per person in the household, and how does this compare to the national average?

A total of 91 gallons for two people is about 45 gallons per person, equivalent to 4.5 kWh/day, and 11% of the national average.

41: . . . a non-commuting truck and a commuting plug-in hybrid that mostly uses electric drive, charged at home (the electrical demand for which is represented in Example 20.3.10)

Air travel: Expressing an average in this case is inappropriate, as many Americans do not fly at all, while all use some combination of electricity, gas, and gasoline in some capacity. The average works out to 2,300 miles (3,700 km) per year when averaging all people, but among those for whom air travel is a utilized, the number is generally a good bit higher. To put it in context and enable useful comparisons, we will compare it to ground transportation.

Typical passenger jets get approximately 90 miles per gallon (m.p.g.) *per seat*[42] (2.6 L/100 km) for a fully-occupied plane—worse if seats are empty: down to 45 m.p.g. per passenger if half full, for instance. So traveling 1,000 km in a full airplane uses the same amount of fossil fuel energy per person as driving the same 1,000 km in an efficient doubly-occupied car that gets 45 m.p.g. (5.2 L/100 km). For an 80% full airplane,[43] the effective per-passenger mileage is about 70 m.p.g., coming to an energy cost of about **0.5 kWh per mile (0.32 kWh/km) per passenger**. Because air travel tends to involve *long* trips, the energy used (thus CO_2 emissions) for air travel can easily exceed that for personal car usage, as is seen in the next example.

42: The airplane as a whole gets less than *one* mile per gallon, but each passenger's share of gallons used makes it better on a *per-passenger* basis. It takes almost the same amount of energy to fly a plane from point A to point B independent of passenger load. Most of the energy is used to fight air resistance, which is related to the size and speed of the airplane, essentially independent of the number of passengers inside.

43: . . . guessing this to be typical

Example 20.3.13 The author, in 2019, flew about 4,200 miles for personal travel and 9,600 miles work-related. How many kWh per day does this translate to in the two categories, and how does it compare to expenditures in electricity, gas, and personal gasoline?

For personal air travel, 4,200 miles times 0.5 kWh per mile is 2,100 kWh or 5.8 kWh/day, which is slightly larger than the 4.3, 2.4, and 4.5 kWh/day from electricity, natural gas, and personal gasoline computed in previous examples, but still really in the same ballpark. Business travel[44] accounts for 13 kWh/day, *by itself* exceeding the sum of household expenditures.

44: Ugh. Wish I didn't have to.

Example 20.3.14 If three people are traveling from San Diego to San Francisco at a distance of 700 km, how good does the car's gas mileage need to be to beat an 80% full airplane that would get 90 miles per gallon per passenger if full?

Being 80% full knocks the effective fuel economy down to 72 m.p.g. per passenger. For the three people in question, a car achieving 24 m.p.g. (9.8 L/100 km) will match the airplane's energy expenditure, so

Note that we didn't need the distance. This may seem like a "trick," but consider that life is even trickier: real-world problems have no (or maybe *all available*) information provided, and it's up to us to sort out what's relevant.

anything getting better performance will deliver the three people at a lower energy cost.

Diet Impacts: Modern agricultural practices result in a 10:1 energy expenditure on the production, distribution, and waste of food—so that each kilocalorie of food eaten requires 10 kcal of energy input [97]. A typical 2,100 kcal/day diet translates into 2.4 kWh/day, and applying the 10:1 ratio means that about 24 kWh of energy input is required to cover a typical American's diet—which is substantial on the scale of residential/personal energy use. Because food is also grown for livestock and poultry, then those animals convert the food to meat at some low efficiency, raising animals for meat is a net energy drain: directly eating the grown food ourselves[45] would use less energy and fewer resources.

[97]: Pfeiffer (2006), *Eating Fossil Fuels*

45: . . . preferably in not exactly the same form!

20.3.4 Dietary Energy

This last point on food energy deserves some elaboration, setting the stage for a quantitative evaluation of diet choices. For any food type, it is possible to characterize the amount of energy spent producing the food as a ratio to the metabolic energy contained in the food.[46] Key results of some such studies ([127] and [128]) are provided in Table 20.2. Treat these as *rough* guides rather than absolutely definitive numbers, since specific agricultural, feeding, or fishing practices play a huge role in the energy requirements: large variations can be expected, in practice. All the same, fruits and vegetables consistently require small energy expenditures relative to meat and dairy products.

46: In this sense, it is the inverse of EROEI: energy *invested* to extract the food divided by energy *delivered*.

[127]: Eshel et al. (2006), "Diet, Energy, and Global Warming"

[128]: Pimentel et al. (2007), *Food, Energy, and Society*

Category	Type	Ratio	Distrib.	Category	Type	Ratio
Red Meat	Lamb	83	1.8%	Plant-based	Tomatoes	1.67
	Pork	27	62.6%		Apples	0.91
	Beef	16	35.6%		Potatoes	0.83
Poultry	Chicken	5.5			Peanuts	0.71
Fish	Shrimp	110			Dry Beans	0.65
	Salmon	18			Rice	0.48
	Tuna	17			Wheat	0.45
	Herring	0.9			Corn	0.40
Dairy/Egg	Eggs	8.9	11%		Soy	0.24
	Milk	4.9	89%		Oats	0.20

Table 20.2: The ratio of energy invested in producing various common foods to the metabolic energy delivered by the food (sort-of an inverse EROEI), broken into five categories. High ratios indicate large energy costs. When known, the distribution *within* the category is given for standard American diets. Beef is grain-fed, salmon is farmed, and milk is a stand-in for dairy products more generally. Data synthesized from [127, 128].

Let's be clear about what Table 20.2 says. The production of 100 kcal of rice requires an input of 48 kcal, making it a net energy gain. Meanwhile, 100 kcal from beef takes 1,600 kcal of energy to produce, as an energy loser. Lamb and shrimp are very costly, while herring is a steal. It may seem surprising that eggs require more energy input than chicken,[47] but consider that it takes longer for a chicken to produce its weight in eggs than for a chicken to get large enough to be processed for meat.

47: Owning egg-laying chickens and feeding them scraps is a delightful win, however.

Armed with this information, it is possible to assess a dietary energy factor[48] for various dietary choices.

48: "Dietary energy factor" is a term used in this textbook; not likely to be found elsewhere.

Definition 20.3.1 *The **dietary energy factor** is a weighted sum of individual energy ratios for food categories:*

$$\text{d.e.f.} = f_v \cdot R_v + f_{rm} \cdot R_{rm} + f_f \cdot R_f + f_p \cdot R_p + f_d \cdot R_d, \qquad (20.1)$$

where f_x factors are the fraction of one's diet in form "x," in energy terms (calories; kcal), and R_x values are the aggregated relative energy ratios for food category "x," as found in Table 20.3. Subscripts indicate vegetables, red meat, fish, poultry, and dairy/eggs, respectively. Note that care must be exercised to insure that all five f_x factors add to one.

Category	Energy Ratio	Relative Ratio, R_x	American Diet, f_x	Lacto/Ovo Diet, f_x	Vegan Diet, f_x	Poultry Diet, f_x
Plants	0.65	1	0.72	0.80	1.0	0.72
Red Meat	24	37	0.09			
Fish	36	55	0.01			
Poultry	5.5	8.5	0.05			0.15
Dairy/Egg	5.3	8	0.13	0.20		0.13
d.e.f.			6.1	2.4	1.0	3.0

Table 20.3: Dietary energy factor computations for various diets. Energy factors are aggregations over categories from Table 20.2, assuming equal distributions when unknown (e.g., each fish type is 25% and each plant type is 10% of that category's intake). The net effect, at bottom, is a weighted sum of the individual energy ratios, and spans large factors in terms of energy impact.

In Table 20.3, the first column of numbers is a weighted average of factors from Table 20.2, using the distribution weights listed where available, and assuming equal spread otherwise. The next column scales the energy ratios so that the vegetable category has $R_v = 1$,[49] making the dietary energy factor a measure of energy requirements *relative to* a strictly plant-based diet. For instance, red meat requires 37 times as much energy as vegetable matter, for the same metabolic energy content.

What follows in the table are four diet types, reflecting the average American diet and three variants, each having its own set of f_x factors.[50]

Example 20.3.15 Let's replicate the American diet result in Table 20.3 using Eq. 20.1.

Using $f_v = 0.72$, $f_{rm} = 0.09$, $f_f = 0.01$, $f_p = 0.05$, and $f_d = 0.13$, then $R_v = 1$, $R_{rm} = 37$, $R_f = 55$, $R_p = 8.5$, and $R_d = 8$, the dietary energy factor computes to $0.72 + 3.33 + 0.55 + 0.425 + 1.04 = 6.07$, confirming the final row. By breaking things out this way, the red meat category stands out as contributing more[51] than any other category.

Compared to a strictly plant-based (vegan) diet, the typical American diet requires about six times the energy. Since the average American diet accounts for 24 kWh per day, a vegan diet is therefore down to 4 kWh/day. A vegetarian diet partaking of dairy and eggs (lacto-ovo diet) is 2.4 times[52] the vegan diet, or a little less than 40% of the American diet (about 9 kWh/day). Just replacing all meat consumption with chicken (final column) cuts energy demand in half. These are just a few of the countless examples that may be explored using Eq. 20.1 or variants thereof to evaluate the energy impact of dietary choices.

Get on it! Evaluate your own diet and how you might modify it.

49: The second column of numbers is the first column divided by 0.65.

50: Note: contrived to add to 1 in each case.

51: Red meat is 3.33, which is 55% of the total energy cost while providing only 9% of the dietary benefit.

52: The actual number depends on the fraction of calories coming from dairy/eggs (f_d), and can be dialed at will: it's not stuck at exactly 2.4.

Example 20.3.16 What is the dietary energy factor for a diet in which one-third of caloric intake is from red meat, 10% is from dairy/eggs, and the rest is plant matter?

Setting $f_{rm} = 0.33$ and $f_d = 0.10$, we require that $f_v = 0.57$ in order that all three sum to 1.0. Now using $R_{rm} = 37$, $R_d = 8$, and $R_v = 1$, the dietary energy factor computes to $12.2 + 0.8 + 0.57 = 13.6$ for red meat, dairy, and vegetable matter, respectively. This diet requires more than twice the production energy as a standard American diet.

It is possible to abandon Eq. 20.1 and roll your own formulation following similar principles. Rather than adopt the distributions from Table 20.2, the technique can be customized to any diet for which energy factors can be found.

Example 20.3.17 A diet that is 35% rice, 35% wheat, 15% corn, 10% milk, and 5% chicken has an energy cost of $0.35 \cdot 0.48 + 0.35 \cdot 0.45 + 0.15 \cdot 0.40 + 0.10 \cdot 4.9 + 0.05 \cdot 5.5 = 0.17 + 0.16 + 0.06 + 0.49 + 0.28 = 1.15$. This has not been normalized to $R_v = 1$ yet,[53] so we divide by the aggregate 0.65 value for the plant energy ratio found in Table 20.3 to get a dietary energy factor 1.8 times that of a strictly plant-based diet. Note from the sum that milk and chicken are the largest two contributors, despite being a small fraction of the diet.

53: In other words, if performing the same sort of calculation for 10% contributions from each of the ten plant-based foods in Table 20.2, the raw result would be 0.65.

The 10:1 input:output energy ratio mentioned at the beginning of this diet segment may at first glance not square with the whole-diet energy factors computed here (e.g., a factor of 6 for the typical American diet). Missing is **food waste**. The U.S. produces 1.8 kcal of food value for every 1 kcal consumed [127]. This amount of waste may be hard to fathom, but consider waste at restaurants, cafeterias, and grocery stores when perishable items are not consumed before health standards suggest or require disposal. Still, this is an area ripe for improvement.

[127]: Eshel et al. (2006), "Diet, Energy, and Global Warming"

20.3.5 Flexitarianism

Echoing Point #5 in the list in Section 20.3.1, it is worth pointing out that energy and resource concerns are a largely *quantitative* game. One need not become a strict vegan to affect energy demands substantively. For instance, eating meat one meal a week,[54] and tending to stick to poultry when doing so would drop the energy factor of Eq. 20.1 to a value so near to 1.0 that the difference is of little consequence.

54: . . . out of about 40 meals

Example 20.3.18 For instance, if one meal per week, or about one in 40 of your meals looks like the last column in Table 20.3—72% plant-based and the rest poultry and dairy—what is the dietary energy factor for this diet?

Since only one in 40 meals is of this type, multiply the poultry and

dairy contributions by $\frac{1}{40}$ and adjust f_v to bring the total to 1.0. Doing so yields $f_v = 0.993$, $f_p = 0.00375$, and $f_d = 0.00325$. Multiplying by the respective R_x values and summing produces 1.05.

Thus, the one meal of poultry/dairy per week achieves 99% of the journey from normal-American (6.1) to full vegan (1.0), from an energy perspective.

The result of Example 20.3.18 is so nearly 1.0 that it is essentially indistinguishable from a purely plant-based diet, quantitatively. This is especially true in the context that the rule-of-thumb factors are themselves not to be taken literally as high-precision numbers. All pork will not have an energy ratio of 27.0. All tuna will not be 17.0. All wheat will not be 0.45. The methods of producing the food—of all types—become important at this stage. Note that gardening (and canning) one's own food is a way to nourish ourselves at a super-low resource burden—undercutting the nominal vegan energy factor even further.

The quantitative focus suggests an approach best called flexitarianism. If energy and resources are the primary concern, rather than ethical issues around eating meat,[55] then the occasional meat treat is no big deal. Under this scheme, it is still possible to enjoy traditional foods on special occasions like holidays.[56] If a friend serves meat at a dinner party, just do the quick calculation and realize that you can easily offset later[57] and make this special-occasion meal disappear into the quantitative noise. The perception you generate is therefore more likely to be as a grateful friend, rather than as a person whose needs are difficult to satisfy.

55: . . . valid in its own domain

56: . . . arguably making them *more* special

57: . . . or note that you have already offset it by prior actions

More people are likely to be attracted to join in responsible behaviors if they are not too rigid or strict. Imagine ordering a bean, rice, and cheese burrito only to take a bite and discover a morsel of meat inside. Score! Meat Treat! It doesn't have to be a bad thing, if resource cost is what matters most. This flexibility can also apply to waste food. Before watching meat get thrown into the trash, intercept with your mouth. From a resource point of view, *wasting* meat—or any food, really—is also something we should strive to avoid: better that the energy investment produce metabolic benefit than be utterly wasted.

20.3.6 Discretionary Summary

We don't have direct and immediate control over all the energy expenditures made on our behalf in the same way that we have control over our own light switches and thermostats. Yet, we must accept our communal share of energy and resources used by governmental, military, industrial, agricultural and commercial sectors providing us with structure, protection, goods, and services. The 10,000 W average American power frequently used as a benchmark throughout this book—and mapping to 240 kWh per day—is not all in our direct control. Individuals can make

political, consumer, and dietary choices that exercise limited control over these distant activities, but effects are small and gradual.

Sector	American (kWh)	Author (kWh)
Electricity	12	4.3
Natural gas	13	2.4
Gasoline	41	4.5
Air travel	3.2	5.8
Diet	24	9
Total	93	26

Table 20.4: American average and author's 2019 expenditures energy on a daily average basis expressed in kilowatt-hours.

Of the things that *are* under our discretion, as discussed in the sections above, Table 20.4 summarizes the average American values and those of the author in 2019.[58] Recall that the average American air travel corresponds to just 2,300 miles (3,700 km) per year. If adding consumerism to the personally-controlled energy toll, perhaps an average American spends $10–20,000 per year[59] on "stuff," which would amount to another 25–50 kWh per day if using the rule-of-thumb 1 kWh/$ from Section 20.3.2.

58: . . . only counting personal travel, and a mostly vegetarian (though not vegan) diet.

59: The author might guess $5,000 for himself as an upper limit, or another 13 kWh per day in this mode.

Combining the discretionary factors in Table 20.4 and a consumerism estimate, Americans have direct control over about half of their total energy footprint.[60] As the author demonstrates, it is possible to make drastic cuts to this portion—in this case a factor of three lower than average. Mostly, this comes about by a combination of awareness, caring, and tolerance for a simpler life without every possible comfort.

60: Recall: 240 kWh per day total.

Box 20.2: Out of Our Control

Many energy expenditures are part of a consensus social contract that individuals cannot easily control. Examples would be lighting and interior temperature control policies for large common spaces like office buildings, campuses, libraries, and airports, for instance. Likewise for street lighting in neighborhoods and along highways. Only by large scale shifts in values would the community potentially prioritize energy and resource costs over financial cost or public health and safety.

20.4 Values Shifts

In the end, a bold reformulation of the human approach to living on this planet will only succeed if societal values change from where they are now. Imagine if the following activities were frowned upon—found distasteful and against social norms:

1. keeping a house warm enough in winter to wear shorts inside;

2. keeping a house so cool in summer that people's feet get cold;
3. having 5 cars in an oversized garage;
4. accumulating enough air miles to be in a special "elite" club;
5. taking frequent, long, hot showers;
6. using a clothes dryer during a non-rainy period;
7. having a constant stream of delivery vehicles arrive at the door;
8. a full waste bin each week marking high consumption;
9. having a high-energy-demand diet (frequent meat consumption);
10. upgrading a serviceable appliance, disposing of the old;
11. wasteful lighting.

At present, many of these activities connote success and are part of a culture of "conspicuous consumption." If such things ran counter to the sensibilities of the community, the behaviors would no longer carry social value and would be abandoned. The social norms in some Scandinavian countries praise egalitarianism and find public displays of being "better" or of having more money/stuff to be in poor taste. Abandonment of consumerist norms could possibly work, but only if it stems from a genuine understanding of the negative consequences. If curtailment of resource-heavy activities is imposed by some authority or is otherwise reluctantly adopted, it will not be as likely to transform societal values.

While it may seem objectionable, it is worth recognizing that public shame carries surprising power.[61] A recent experiment in Bolivia put traffic monitors on the streets wearing zebra costumes[62] to combat irresponsible driving habits endangering pedestrians. The zebras would "call out" violators by making a show and pointing to the offenders. That simple action has been effective. Other cultures have required perpetrators of unsavory acts to stand in a public place for a day wearing a sign announcing their transgression, recognizing the power of public shame. It is difficult to imagine similar remedies today, and for many good reasons.[63]

Yet our society has perhaps gotten too far away from personal ownership of actions. Anonymity in our modern world promotes rude behavior: on roads, on the internet, and in heavily-populated urban areas, where often no one within sight is familiar. If environmentally costly activities were to acquire taboo status, it is pretty certain we would see far less of it, for fear of shame.

61: The author became aware of this power in the context of student project demonstrations open to the whole department to watch. The prospect of public failure provided supplemental motivation for students to work super-hard—harder than the author typically observed in other courses.

62: The costumes served to simultaneously maintain anonymity and allude to black-and-white crosswalk patterns.

63: . . . e.g., not a very nurturing approach to promote change

20.5 Flexibility as an Answer to Uncertainty

No one has a crystal ball. No one can credibly say what the future holds. Anyone claiming that we're heading for certain complete collapse should not be trusted. But neither should someone who says everything will be glorious. It is not hard to find either sort of message in this world, yet we cannot discern with confidence which is ultimately correct.

While this text may seem more aligned toward a grim outlook, it is somewhat intentional as a means to raise awareness toward what seems like a minority view—without crossing the line and claiming any certainty on the possible perils ahead.

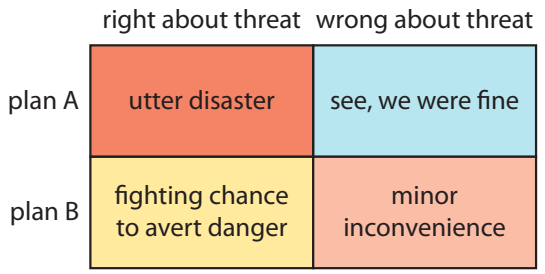

Figure 20.1: Asymmetric risk in the face of a potential devastating threat. Plan A is the natural response if the threat is not believed to be real, and Plan B is appropriate for mitigating the threat. The downside of the threat being real but sticking to Plan A is catastrophic, whereas pursuing Plan B unnecessarily is not ideal, but not nearly as bad. We don't get to choose reality (column), but we do get to chose the plan (row). Are we feeling lucky, or conservative?

Another rationale for this book's tone relates to asymmetric risk (Figure 20.1). If we take potentially catastrophic threats seriously and at least formulate plans to mitigate them, then little harm is done if the threat does not materialize: just "wasted" time and effort being careful.[64] But ignoring the threat could mean "game over." Even if the probability of the threat is low, like 10%, it is worthy of attention if the consequences of ignoring it could be devastating. People routinely buy insurance for similar reasons: to mitigate low-probability but potentially debilitating events.

64: . . . and oh darn—we might end up with a renewable energy infrastructure earlier than we really *had* to have it! After all, it's pretty clear that we need to get there *eventually*.

That said, how does a person navigate their own life choices under a cloud of existential uncertainty? One answer is to pick avenues that can be useful in either eventuality. Choosing a route that only makes sense if things hum along as they have done for the past many decades could be risky. So put some thought into directions that are likely to be valued whether or not the human endeavor suffers large setbacks. Be flexible. Mostly, this involves imagining a more difficult future and asking what paths still work in that scenario, while still having a place in today's world.

What skills or functions will likely always be valuable? One approach is to think about what elements of human existence are likely to always be present. We will always need food, shelter, health care, transportation, fabrication capability, resource utilization, wisdom, and entertainment. The exact form ranges from primitive to high-tech. But not every profession supported today has an obvious place on this list. In the face of this, it seems worthwhile to learn the *fundamentals* of any vocation you elect to pursue, so that if deprived of all the technological assistance available today, you can fall back on the basics and still achieve some worthwhile results.

A first step may be to become less reliant on technology for simple tasks. Use brains more and devices less. The practice will lead to greater mental capacity—in any outcome. Do math in your head. Learn and retain[65] important facts and concepts, so that Google is not required to form full thoughts.

65: . . . internalize; own

Try modes of living that are less cushy than normal, even if temporarily. A week-long backpacking trip is a great way to feel like a part of nature, and come to understand that some level of discomfort or hardship is tolerable—or even confidence-building.[66] The first few days may be a difficult adjustment, but it is surprising how well and how quickly adaptation can happen—given time, decent weather, and a constructive attitude. After doing this a few times, minor inconveniences or discomforts that arise might be met with far greater grace. The person who remains stable in the face of adversity will be more resilient than many of their peers, and can help others hold things together in crisis.

66: Ideally, start small on a one- or two-night trip, and accompany someone experienced at backpacking to learn how to avoid rookie mistakes that could turn you off of the activity forever.

Keep in mind that humans evolved outdoors, dealt with seasons, and often went many days without food. When did we become so fragile that we need to live within a narrow temperature range to be comfortable, and lose our heads if we don't get three square meals a day? What would our ancestors think of us? By learning to toughen up, the future—whatever way it goes—will have less power over us. We can strive to be less vulnerable and at the mercy of events beyond our control. We will have some agency to cope and help others cope with any variety of outcomes. Just by having some confidence in our ability to deal with a bit of adversity or discomfort will allow us to keep cooler heads and be able to recognize important opportunities if and when they come along, rather then being paralyzed by distress.

Hopefully, such preparedness will never be truly needed. And how bad would it be if we "built some character" along the way for no reason.

20.6 Upshot on Strategies

No one can know what fate awaits us, or control the timing of whatever unfolds. But individuals *can* take matters into their own hands and adopt practices that are more likely to be compatible with a future defined by reduced resource availability. We can learn to communicate future concerns constructively, without being required to paint an artificial picture of hope.[67] Our actions and choices, even if not showcased, can serve as inspiration for others—or at least can be personally rewarding as an impactful adventure. Quantitative assessment of energy and resource demands empowers individuals to make personal choices carrying large impacts. Reductions of factors of 2 and 3 and 4 are not out of reach. Maybe the world does not *need* 18 TW to be happy. Maybe we don't *have* to work so hard to maintain a peaceful and rewarding lifestyle once growth is not the driver. Maybe we can re-learn how to adapt to the seasons and be fulfilled by a more intimate connection with nature. The value of psychological preparedness should not underestimated. By staring unblinking into the abyss, we are ready to cope with disruption, should it come. And if it never does in our lifetimes, what loss do we

67: The hope lies in how we *react* to the challenges, not necessarily in eliminating, conquering, or denying them.

really suffer if we have chosen our adventure and lived our personal values?

In this sense, the best adaptation comes in the form of a mental shift. Letting go of humanity's self-image as a growth juggernaut, and finding an "off-ramp" to a more rewarding lifestyle in close partnership with nature is the main goal. The guidelines provided in this chapter for quantifying and reducing resource demands then simply become the initial outward expressions of this fresh vision. Ignore the potentially counterproductive allure of fusion, teleportation, and warp drive. Embrace instead a humbler, slower, more feasible future that stresses natural harmony over conquest and celebrates life in all forms—while preserving and advancing the knowledge and understanding of the universe we have worked so hard to achieve. Picture a future citizen of this happier world looking back at the present age as embarrassingly misguided and inexplicably delusional. Earth is a partner, not a possession to be exploited. Figuratively throwing Earth under the bus precludes our own chances for long-term success. A common phrasing[68] of this sentiment is that humans are *a part* of nature, not apart from nature. Let's not lose the path in a flight of fossil-fueled fantasy.

Continuing the freeway metaphor, the current path has us hurtling forward to certain involuntary termination of growth (a dead end, or cliff, or brick wall), very probably resulting in overshoot and/or crash.

68: . . . attributed to Marc Bekoff, 2002

20.7 Problems (Predicaments?)

1. What barriers do you sense that suppress open communication about collapse possibilities?
2. Why is the lack of open acknowledgment that collapse is a distinct possibility itself more likely to facilitate exactly that outcome?
3. Try constructing a statement that communicates the grave risk we create for ourselves as we flirt with potential collapse without being too off-putting or unjustifiably certain.
4. Try crafting a diplomatic and persuasive response to someone who says that the problem with your story—concerning possible bad outcomes—is that it's a real downer and lacks a message of hope.
5. Come up with an example in life of a predicament that can't be directly solved, but perhaps side-stepped to get around it without eliminating or "solving" the problem's origin.
6. A person loses their snazzy stainless steel water bottle that they carry everywhere—again. So they go to the store to replace it. What elements of the list in Section 20.3.1 are in danger of being violated?
7. Which of the following devices is likely to consume a lot of power, when it is on/running? Explain your selection.

a) laptop computer
b) phone charging
c) toaster oven
d) television/display
e) lighting for a room

8. A microwave oven and a space heater might each draw 1,500 W of electrical power. What determines which one uses more *energy*, and describe a realistic scenario in which one uses a lot more energy than the other.

9. If the temperature outside is steady at 10°C, how much more energy must you expend over some period of time[69] in order to keep the inside at a shorts-and-short-sleeves temperature of 22°C vs. a dress-more-warmly 13°C inside?

69: . . . effectively power, then

10. A utility bill for April indicates that your household used 480 kWh of electricity and 20 Therms of natural gas. In addition, your household has two cars, each using an average of one gallon of gasoline per day. Convert everything to kWh per day for direct comparison, and also express in W or kW of average power to put in context against the 10 kW American overall average.[70]

70: ⓘ Most is outside the home.

11. Following the setup for Problem 10, if the household consists of two people, what is the per-person footprint in terms of kWh per day for electricity, natural gas, and gasoline, and how does this compare to U.S. national averages per person?

12. In looking at the utility bill referenced in Problem 10, and converting Therms to kWh, it may seem that natural gas is a larger energy expenditure. But if your local electricity is primarily sourced from natural gas, converting the combustion energy into electricity at 40% efficiency (via a heat engine), what is the *effective* amount of kWh used in the form of natural gas for the electricity, and now how does this compare to the gas used directly in the household?

13. Use the two rule-of-thumb approaches (by mass and by cost) to estimate the energy investment in a farm tractor, whose mass is 2,400 kg and cost is $25,000. If the results are even within a factor-of-two of each other, we can conclude that the estimate is probably pretty decent as a rough guide.

14. Use the two rule-of-thumb approaches (by mass and by cost) to estimate the energy investment in a laptop computer, whose mass is 1.4 kg and cost is $1,300. If the estimates are strikingly different, which do you suspect is more representative of the truth?

15. You and three friends want to take a trip together and are debating whether to fly or drive in a gasoline-powered car. In the context of fossil fuel energy use (and thus CO_2 emission), how good does the car's fuel efficiency need to be (in miles per gallon) in order for

the driving option to use less fuel (per person) than would a fully-occupied airplane, if the airplane gets 90 m.p.g. per passenger? Is it easy to find cars whose performance is at least this good?

16. What does the dietary energy factor become for a person who gets one-quarter of their energy from meat, but only in the form of chicken—the rest from plant matter? How much of the way[71] from the standard American dietary energy factor (6.1 times vegan) to a purely plant-based diet is this?

17. What does the dietary energy factor become for a person who is mostly vegan, but eats like a standard American one day a week—on that day getting 28% of their energy as outlined in the American column of Table 20.3? How much of the way[72] from the standard American dietary energy factor (6.1) to a purely plant-based diet is this?

18. What fraction of caloric intake in a Lacto-ovo diet (dairy/eggs but no meat or fish) would allow a dietary energy factor of 2.0, which is 80% of the way from the American 6.1 to the vegan 1.0?

19. How might you imagine our society managing to change values to shun heavy resource usage: what might transpire to make this happen? Do you think this would be a desirable outcome?

20. List three professions around today that will be very unlikely to exist if we revert to a lower energy/resource, less high-tech state.

21. Describe the circumstances and outcomes of the four boxes in Figure 20.1 in the context of a tornado reported heading for your town—which may or may not hit your house if it even hits your town at all. Plan A would be to do nothing in preparation. Plan B would be to board up the windows on your house and take cover in a tornado shelter. Describe the relative costs and feelings about your decisions in the aftermath for all four scenarios.

22. Comparing the human body to a car with a gas tank, and recognizing that a human can *live*[73] for about two weeks without food, provided adequate water and shelter. How many skipped meals does this represent, on the standard of three meals per day? If the body had a fuel gauge indicating how close to "empty" (death) we are, what percentage of "full" does our gauge typically read when we "pull into the station" for another fill-up (meal) in the standard case when we get three meals per day?

71: For example, going from 6.1 to 3.8 is a move of 2.3 of the 5.1 total distance to get to 1.0, or 45% of the way "home."

72: See margin note for Prob. 16.

73: . . . not comfortably, and this is *not* recommended!

Note that, unlike a car, the body does not function just as well at 25% "full" as it does when it is 100% full. Thus the analogy is very flawed. Yet, in primitive times, it was surely routine to dip well below hunger levels not often tolerated today.

Epilogue

This book may be distressing for some: a body-slam to hope. The message can be more than some are ready to take in, or of an unacceptable flavor. I myself first approached this subject—when assigned to teach a general-education course on energy and the environment—with great enthusiasm, intending to sort out to my own satisfaction how I thought our gleaming future would migrate to renewable energy.

As I "ran the numbers" on various sources, I came to appreciate the tremendous quantitative advantage that solar power has over the alternatives. Being a hands–on person, I started cobbling together various off-grid photovoltaic systems, learning the practical ins and outs of stand-alone solar power[1] coupled with storage as a crucial means to mitigate intermittency of the solar resource. My wife and I also bought a plug-in hybrid vehicle in 2013 to learn the pros and cons[2] of electric cars, while preserving the ability to do occasional longer trips on gasoline. My commute to work is via an electric-assist bicycle charged by my off-grid solar system for a fossil-free transportation option.[3] I have found adventure and delight in challenging myself to live a lower–energy lifestyle, and know from personal experience that dialing down demand does not have to be a crushing defeat for the human race. Our ambitions[4] might suffer, but our spirits need not.

This book takes an approach that deliberately asks the wrong question, chapter after chapter: how can we keep going in a manner resembling the present form in the face of declining fossil fuel resources and/or a commitment to wean ourselves from fossil fuels as a mitigation strategy for climate change? This approach manifested itself as: can we get 18 TW of power[5] from this or that alternative resource? In most cases, the answer was no. Solar is the glaring exception. Also, nuclear breeders—bringing a tangle of tough problems—and the perpetually intractable nuclear fusion could offer long term provision of electricity. But none of the abundant resources easily replace liquid fuels for transportation, and effective utilization of the abundant yet intermittent solar resource depends critically on storage capabilities.

Thus, pretending that the goal is to keep 18 TW and carry on—business as usual—after a tidy substitution of energy turns out to be misguided. The real question becomes one of adapting to a new landscape: one in which our ambitions are checked by planetary limits. Indeed, if energy became essentially unlimited by some technology, I shudder to think what it would mean for the rest of the planet.[6] An age-old saying goes: *With great power comes great responsibility.* Humans have achieved great power, but have not yet demonstrated a respectable degree of responsibility in prioritizing the protection of plants, animals, and ecosystems.

1: . . . as a miniature model of what society at large may one day hope to do in a solar–dominated energy landscape

2: We have watched battery capacity drift down to about 65% presently.

3: Charging the car from the off-grid system would require a substantial upgrade in system size and battery capacity, costing approximately $10,000.

4: So far, human ambitions have been for the most part unconstrained by physical limitations. Just as a child must eventually shed fantastical dreams and beliefs, so too might the human race need to reign in unrealistic hopes for our future.

5: . . . or some sizable fraction thereof

6: A children's story called *Don't Let the Pigeon Drive the Bus* echoes the sense that great power in the hands of incompetence can be bad news. We would not put a toddler in command of an arsenal.

Should attention to planetary limits turn out to be a crucial element in the assessment of our situation, then we owe it to ourselves to get it straight. Imagine that you are running across a rooftop and have to make a quick decision about whether to jump a large gap between buildings.[7] Would you appreciate a lightning-quick analysis of physics concluding that a successful jump is impossible? Certainly, such insight would be valuable, permitting the formation of an alternate plan, and saving yourself from the unfortunate fate of misplaced faith in your jumping abilities or in some fanciful notion of gravity's weak grip over the chasm.[8]

Humanity is staring at a leap unlike anything history has prepared us to face, having accelerated ourselves to previously unimaginable speeds by the grace of fossil fuels, but now confronting their inevitable removal from the menu. The past offers little guidance on how to navigate such a situation, so we need to do our level best to soberly assess the challenges and recognize what *is* and what is *not* within the realm of practical expectations. I would love to be wrong about the numerous concerns raised in the book, but the asymmetric risk of trying the leap and failing could lead to a devastation that frightens me. Please, let us not risk it all on unfounded hopes or magical thinking.[9]

The situation reminds me of the housing bubble in the U.S. in the early 2000s. My wife and I bought a house when we moved to San Diego in 2003, and soon became worried about a potential crash[10] leaving us "underwater"—owing more than the reduced worth of the house. I pored over articles on the matter, and found two camps. One camp provided rafts of alarming quantitative analysis of the peril: sub-prime lending, soaring price-to-income ratios, unprecedented unaffordability by average families, vulnerability to any weakness in other sectors. The other camp said that the housing market was manifesting a new normal, that San Diego's universal appeal would prevent a price drop, that scary lending practices were easily skirted by re-financing before interest payments ballooned. I chose to go with the quantitative analysis over the hand-wavy platitude-based set of beliefs, and am glad that I did.

Now consider the quality and nature of common counter-arguments to the core message in this book. Humans are smart, innovative, and will figure out something. People 200 years ago could not have possibly predicted our capabilities today, so we are likewise ill-equipped to predict how amazing the future will be. I get the appeal. I really do. But does that mean we get to dismiss the difficulties exposed by careful analysis? Can we ignore the fact that we are pushing planetary boundaries for the first time ever? I would argue that this time really *is* different.[11] The facts are inescapable:

- The world has never before been strained with 8 billion people.[12]
- Fossil fuels bear tremendous responsibility for our recent climb.

7: . . . as might happen in a movie

8: *The Matrix*, while an excellent movie, encourages physics-breaking thinking. Not to be a kill-joy, but it probably *is* air you're breathing, and that probably *is* a spoon.

9: More often, *lack* of critical thought is to blame: unconscious assumptions about how the future will unfold based on recent, anomalous history.

10: Aha! Am I just a recurrent predictor of crashes? Not at all. Numerous times, I had faith in rising markets and prospects for achieving success in difficult endeavors. Meanwhile, I blew off concerns of Y2K (Box 20.1; p. 329) and even downplayed the COVID-19 pandemic in early 2020—in both cases on the premise that high levels of awareness and fear would trigger massive attention and mitigating actions by responsible governments and stakeholders. In the COVID case, my faith in competence was sadly misplaced: I was too optimistic.

11: The wolf *did* come in the apocryphal tale. The adults should accept some responsibility for their failures, rather than throwing the "boy who cried" under the bus.

12: . . . and growing

- Fossil fuels are a one-time resource—an inheritance—that will not continue propelling the future, and nature does not guarantee a superior substitute.
- Wild spaces on the planet are rapidly diminishing as development spreads and resources are culled. Permanent extinction of species accompanies pollution and habitat loss.
- Climate change and habitat destruction threaten a mass extinction and environmental disruption whose full consequences are unpredictable.
- Modern human constructs[13] have not stood the test of time, and are unlikely to do so given that they have not been founded on principles of sustainable harmony within planetary limits.

13: . . . economic, political, societal, agricultural, provision of energy and material resources, manufacturing, buildings, and virtually everything else

Any convincing counter-argument about why we need *not* take this seemingly perilous position seriously would itself need to be serious—relying less on general faith in human abilities and more on nuts-and-bolts details: *How* are we going to supply energy needs without fossil fuels? It isn't good enough to say "solar and wind," without specifying how we deal with the glaring mismatch between demand and intermittent energy availability. What would we use to provide sufficient storage? Do we have the materials and means to make enough battery capacity? What is our strategy for battery upkeep and replacement? How will we afford the new scheme and its prohibitive up-front costs? What about agriculture: how do we permanently fix soil degradation; aquifer depletion? How do we halt deforestation, habitat loss, and resulting permanent extinctions? What is the specific global governance plan to protect planetary resources and deal with the consequences of climate change? How do we structure economies to be complacent and functional without a foundation in growth?

Those who tend to dismiss collapse perils are unlikely to detail a cogent plan of the sort solicited here, because to do so would require some acknowledgment that the exercise is necessary and valuable. No one yet has produced a comprehensive and widely accepted plan for just how all this is supposed to work out!

As it is, **we have no credible global plan**[14] to deal with these foundational global problems. We owe it to ourselves to do a better job than *imagine* that the future may work out just fine.[15] We need to face the challenges, put pencil to paper, and craft a plan that could work—even if it involves some compromise or sacrifice. Let us not forget that we do not have the authority to conjure any reality we might dream: we have no choice but to *adapt* to the physical world as we find it.

14: . . . largely due to lack of consensus that we even *need* a non-growth plan

15: The burden of proof is on those who argue for continued modernity: ample evidence indicates that humans can live in primitive relation to nature for tens of thousands of years, but *no* evidence demonstrates that it can survive in anything like the mode of the last century or two for very long. Even the universe fails to deliver evidence (see Sec. 18.4; p. 312).

Returning to the analogy of receiving quantitative analysis on a contemplated leap across a chasm—having indicated serious shortcomings in the notion of maintaining current luxuries—please think twice about trying to carry our resource-heavy ways into the future in heroic fashion. Ignominious failure, not glory, may lie there. But this does not mean the human endeavor has been all for naught, and that we should just sit down and cry about dashed dreams.[16] Let's be smart about this: heed the warning signs; alter course; re-imagine the future; design a new adventure.

16: If the dreams were never realistic, then good riddance!

Contrary to what the tone of the book might suggest, I am a fundamentally optimistic person, which has fueled a lifetime of pursuing tough

challenges and succeeding at (some of) them.[17] Indeed, my irrational hope is that a textbook like this may help get people thinking proactively about changing the course of humanity. In that spirit of wild-eyed optimism, I leave you with the following upbeat-adjacent thoughts about the world into which we may endeavor to gracefully adapt:

- Crisis is opportunity: we have a chance to transform the human relationship with this planet.
- Imagine the relief in shedding an old narrative of growth and faulty ambitions that only seems to be creating increasingly intractable problems—instead side-stepping to make a fresh start under a whole new conception of humanity's future. It's liberating!
- People alive today get to witness and shape what may turn out to be the most pivotal moment in human history, as we confront the realities of planetary limits.
- Committed pursuit of steady-state principles could set up rewarding lives for countless generations.
- Nature is truly amazing, and making it a *larger* part of our world[18] could be very rewarding.
- We, as individuals, are privileged to witness and celebrate the much grander phenomenon of life in this universe: let's be humble participants and value this role over some misguided, ill-considered, hubristic, and perhaps juvenile attempt at dominance.
- We have learned so much about how the universe works, and have the opportunity for greater insights still if we can find a glide-path to a long-term sustainable existence. We have built much of value that bears preservation. Posterity[19] relies on a successful embrace of a new vision.
- We may yet learn to value nature above ourselves, to the enduring benefit of us all.

That would be a fine way to end the book, so pause for a moment to take in that last point. Richard Feynman once mused about what one, compact sentence transmitted to the future would best help a derailed, post-apocalyptic society get back on track.[20] He decided: "Everything is made of atoms." Personally, I think that misses the mark—putting too much emphasis on the values of (some small subset of) our present civilization. Think about what *you* would want to communicate. For me, the final point above might suggest something along the lines of: Treat nature at least as well as we treat ourselves.

17: This is harder for pessimists to pull off: one has to believe in what is *possible* to get started on years-long ambitious undertakings.

18: . . . as opposed to hacking it down to ever-smaller parcels

19: Billionaires who strive for immortal recognition by launching the human race into space are likely to fail and be forgotten, while those who set us on a truly sustainable path have—by design—a better shot at long-term respect.

20: . . . as if the present track would even be deemed desirable: if such a catastrophic derailment comes to pass, maybe our wisdom is not worth so much.

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Changes and Corrections

An electronic textbook has the luxury of being able to correct inevitable typos and mistakes prior to the release of an updated edition. This page reports such corrections. Page ii has information on when this PDF file was produced relative to its initial release on eScholarship.

Changes in the text are marked by a red square ■ which is hyperlinked (in electronic versions) to an entry below. The page number in the entry is also hyperlinked for easy return.

1. Page viii: Demonstration of correction scheme. The page reference returns to the invocation.
2. Page 18: Corrected erroneous energy value for Taiwan in Figure 2.1 (error in Wikipedia table).
3. Page 19: Corrected erroneous energy value for Taiwan in Figure 2.2 (error in Wikipedia table).
4. Page 61: Added Mt. Everest to Figure 4.5.
5. Page 331: Replaced political musings specific to the U.S. with a more general statement.

This page is intentionally blank to make room for corrections without altering pagination of this edition of the book.

Part V

Appendices

Math and Equations A

Depending on background, math and equations may be an intimidating "foreign language" to some students. This brief appendix aims to offer a refresher on techniques, and hopefully inspire a more peaceful relationship for students.

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A.1 Relax on the Decimals

First, we can form a more natural, forgiving relationship with numbers. Like your friends, they need not be held to exacting standards: they are simply trying to tell you something useful. Remembering that π is roughly 3 is *far* more important than committing any further decimals to memory. If a friend traced out a circle in the sand and asked how much area it had,[1] the poorly-defined and irregular boundary defies precise measurement, so why carry extra digits. Maybe just recognize that the radius is roughly one meter, so the area is about 3 square meters. Done.[2] The message here is to give yourself a break and just not over-represent the precision (number of decimals) in your answer.

1: Now that's a quality friend!

2: Also notice that the circle fits within a square 2 meters on a side, so the area should be less than 4 m^2: it hangs together.

Part of the reason students have a rigid relationship with numbers is because homework and test problems tend to come pre-loaded with numbers assumed to be exactly known. But the real world is seldom so generous, leaving us to forage for approximate numbers and estimations.

Some classes formalize the concept of significant digits, which is all well and good. But such systems can *add* to the stress of students learning the material (one more thing that can be wrong!).

By being approximate in our use of numbers, we are liberated to do math in our heads more readily. Practice can make this into a life-long skill that becomes second nature. It is helpful to know some shortcuts.

Example A.1.1 To explore the flavor of approximate math, let's consider the statement:

$$\pi \sim \sqrt{10} \sim \frac{10}{3} \sim 3.$$

Your calculator will disagree, but that's why we use the $\sim$ symbol (similar) instead of = (equal). Another common option is $\approx$ (approximately). Your calculator is not as clever as you, and can't appreciate when things are close. It's pedantic. Literal. You can be better.

How do we use this loose association? We saw one example of using $\pi \sim 3$ before, so will not repeat here.

What about $\sqrt{10} \sim 3$?[3] This implies that $3 \times 3 \sim 10$, which is true enough (because 9 and 10 are very close; only 10% different). This means if you pay me \$30 per day for a month, I know immediately that's about \$1,000. Is the month 30 days, or 31? Who cares? Knowing I'll have an extra ~\$1,000 is a good enough basis to make reasonable plans, so it's very *useful*, if not precise.

How about $\frac{10}{3} \sim 3$?[4] This one is actually pretty similar to saying that $\sqrt{10} \sim 3$, since both imply $3 \times 3 \sim 10$. To use another example, let's say you land a \$100,000/yr job, but can only work for 4 months (a third of a year).[5] If $\frac{10}{3} \sim 3$, then you'd expect to get about \$30,000. Why mess around being more precise? Taxes will be larger than the imprecision anyway. Again, it's good enough to have a sense, and make plans.

Much like we have multiplication tables stamped into our heads, it is often very useful to have a few *reciprocals* floating around to help us do quick mental math. Some examples are given in Table A.1 that multiply to 10. Students are encouraged to add more examples to the table, filling in the gaps with their favorite numbers.

The values in Table A.1 are selected to multiply to 10, which is an arbitrary but convenient choice. This lets us "wrap around" the table and continue past three down to 2.5, 2, etc. and learn that the entry for 1.5 would be 6.67. To make effective use of the table, *forget where the decimal point is located*! Think of the reciprocal of 8 as being "1.25–like," meaning it might be 0.125, 12.5, or some other cousin. The essential feature is 125. Likewise, the reciprocal of 2.5 is going to start with a 4.

Example A.1.2 How is Table A.1 useful to us? We can turn division problems, which tend to be mentally challenging, into more intuitive multiplication problems. Several examples may highlight their usefulness.

What is one eighth of 1,000? Rather than carry out division, just multiply 1,000 by the reciprocal—a "125–like" number. In this case, the answer is 125. We can use common sense and intuition to reject 1,250 as $\frac{1}{8}$ of 1,000, as we know the answer should be significantly *smaller* than 1,000. But 12.5 goes too far. Also, we can recognize that $\frac{1}{8}$ is not too far from one-tenth,[6] one-tenth of 1,000 would be 100, close to 125.

How many hours is one minute? Now we are looking for one-sixtieth ($\frac{1}{60}$) of an hour, so we pull out the "167–like" reciprocal and weigh the choices 0.167, 0.0167, 0.00167, etc. Well, $\frac{1}{60}$ can't be *too* far from $\frac{1}{100}$, which would be 0.01. We expect the result to be *a little bigger* than $\frac{1}{100}$, leaving us to have one minute as 0.0167 of an hour.

Now we do a few quick statements that may not match our table *exactly* for all cases, but you should be able to "read between the lines" using blurry numbers to reconcile the statements. One out of seven

3: Really $\sqrt{10} \approx 3.162$.

4: Really it's about 3.333.

5: Money examples often seem easier to mentally grasp because we deal with money all the time. To the extent that money examples are easier, it says that the math itself isn't hard: the unfamiliar *context* is often what trips students up.

Table A.1: Reciprocals, multiplying to 10.

Number	Reciprocal
8	1.25
6.67	1.5
6	1.67
5	2
4	2.5
3	~3

6: This is where "blurry" numbers are useful: $8 \sim 10$ if you squint.

Study Table A.1 for each of these statements to see how it might fit in.

Americans is roughly 15%. A month is about 8% (0.08) of a year. Six goes into 100 a little more than 16 times. Four quarters make up a dollar. π fits into 10 about π times. Each student in a 30-student class represents about 3% of the class population.

Some students view math and numbers as dangerous, unwelcoming territory—maybe like deep water in which they might drown. But think about dolphins, who not only are not afraid to immerse themselves in deep water (numbers), but frolic and play on its surface. Numbers can be that way too: flinging them this way and that to see that a calculation makes sense in lots of different ways. Humans are not natural-born swimmers, but we can learn to be comfortable in water. Likewise, we can learn to be quantitatively comfortable and even have fun messing around. So get your floaties on and jump in!

A.2 Forget the Rules

Math, in some ways, is just an expression of truth—a logic about relationships between numbers and their manipulations. It is easy to be overwhelmed by all the rules taught to us in math classes through the years, and students[7] can lose sight of the simple and verifiable logic underneath it all. Most math mistakes come from faulty or deteriorating memorization. The good news is that we can usually do simple tests to make sure we're getting it right. The lesson is *not to memorize math*! Math makes logical sense, and we can create the right rules by understanding a few core concepts. This section *attempts* to teach this skill.

7: . . . teachers, too!

Consider for a moment the concept of language (and see Box A.1 for fun examples). Language is riddled with rules of grammar and spelling, yet we learn to speak without needing to know what adjectives or prepositions are. We learn the rules later, after speaking is second-nature. And unlike math, the rules of language can defy logic and have many exceptions. In this sense, math is much easier and more natural. It is the language of the universe. We would likely share no words in common with an alien species[8], but we can be sure that we would agree on the integers, how they add and multiply, all the way up through calculus and other advanced mathematical concepts. We can use its innate nature to expose the rules for ourselves.

8: Except, perhaps we would learn that we inexplicably share the word "sock."

Box A.1: Rules of Language

Let's step aside for a moment to explore how rules of language are obvious to us without explicit thought.[9] Consider the following constructions: trlaqtoef; flort; aoipw; squeet; yparumd. None of these are English words, but only two of them are even worthy of consideration as viable words. The others violate "unspoken" rules

9: . . . acknowledging that this exercise may be less intuitively obvious to non-native English speakers

about how letters might be arranged in relation to each other. We recognize the nonsense without being able to cite specific rules. Math can work the same way: we can rely on intuition to rule out nonsense.

How about this collection of four words: that, how, happen, did. Now arrange them into a single sentence, ignoring punctuation. Notwithstanding how Yoda might arrange things, only one of the 24 possible arrangements[10] makes a single valid sentence. Have you intuited what it is? How did that happen? Without conscious thought, you understand the underlying rules of grammar well enough to see the answer without having to sift through all the combinations. Math *can* work like that, too.

10: The number of combinations is 4! (four-factorial), or $4 \cdot 3 \cdot 2 \cdot 1$. It is a worthy exercise to write out all 24 combinations, not only to verify the result but to give practice in how to systematically shuffle the words in an orderly manner—inventing your own functional rules as you go. You might even stumble on *why* $4 \cdot 3 \cdot 2 \cdot 1$ is the right way to count the combinations based on your method of systematizing.

A.3 Areas and Volumes

This book, and the problems within, often assume facility in computing areas or volumes of some basic shapes. Students who have focused on *memorizing* formulas may see a jumble of π, r to various powers, and some hard-to-remember numerical coefficients. For circles and spheres, how do we bring order to the mess?

A helpful trick is to turn the circle into a square, or the sphere into a cube, where our footing is more secure. Hopefully it is clear that the perimeter (length around) of a square whose side length is a will be $4a$. The area will be $a \cdot a = a^2$. Units can help us, too: if $a = 3$ m, then the perimeter should also be a length with units of meters and the area should be in square meters. It would never do to have something like a^2 describe a perimeter (wrong units) or to have the area *not* contain something like a^2. The cube version has volume a^3.

About those circles and spheres: The task is to fit a circle or sphere inside of a square or cube, so that $a = 2r$. In other words, the *diameter* ($2r$, where r is radius) fits neatly across the side length of the square. The perimeter of the circle should be smaller than the $4a$ perimeter of the square,[11], but a good deal larger than $2a$, which would represent a round trip directly across the square, through its center.[12] So the circle perimeter is between $2a$ and $4a$, probably not far from $3a$. Since $a = 2r$, the perimeter should be somewhat close to $6r$. Suspecting that $\pi \sim 3$ shows up somewhere, the leap is not far to the perimeter being $2\pi r$.

11: . . . literally cutting corners

12: This path would look like a line across the square, traversed twice as a there-and-back trip.

Likewise for the area: a circle within the square has an area smaller than that of the surrounding square (a^2), but surely larger than half the square area—maybe around three-quarters. In terms of radius, the whole square has area $a^2 = 4r^2$, and three-quarters of this is $3r^2 \sim \pi r^2$. Correct again!

Volume is a little harder to visualize, but again the sphere will have a volume smaller than that of the cube: $a^3 = 8r^3$. Maybe the sphere's

volume is about half that of the cube, so $4r^3$. But where would a π go? It's always a multiplier in these situations, so we can harmlessly throw in a $pi/3 \sim 1$ factor to get a volume $\frac{4}{3}\pi r^3$.

The point is that forgetting the exact formulas is not fatal: just back up to a more familiar setting and build out from there. For cylinders, just combine elements of circular and rectangular geometries to realize that the volume is the area of the circle times the height[13] of the cylinder. External surface area is twice the areas of the end-caps (each πr^2) plus the perimeter of the circle times the height—as if rolling out the skin into a rectangle and calculating its area.

13: . . . or length, if on its side

A.4 Fractions

Stressed about fractions? Do you have an intuitive sense for what half a pie ($\frac{1}{2}$) would look like? A fifth of a pie ($\frac{1}{5}$) ? Which is larger: one-third ($\frac{1}{3}$) of a pie or one-quarter ($\frac{1}{4}$) ? Do you have an immediate sense of how many quarters are in a dollar? Back to the pie: if a friend hands you two pie plates, each containing a third ($\frac{1}{3}$) of a pie, do you now have less than half of a pie in total, more than half, or exactly half? If you had little trouble picturing and answering these questions, then you're all set!

But isn't there a lot more to fractions: rules of adding, subtracting, multiplying, and dividing? What about common denominators and all that business? The point of this section is that you can build on your natural intuition[14] to verify and construct the right rules for how the mechanics of fractions should work. You're not in the dark!

14: . . . as expressed in the first paragraph

First, representation. What does $\frac{1}{5}$ mean? Literally, we can say that we divide *something* (a pie, for instance) into 5 pieces (denominator) and extract 1 (numerator). Implicitly, we are *multiplying* the *something* (pie) by the fraction $\frac{1}{5}$. Now what about something like $\frac{3}{5}$? We can interpret this multiple ways,[15] which we will express several ways:

15: . . . all correct, and depends on context of the problem at hand

$$\frac{3}{5}pie = \frac{1}{5}(3\ pies) = \frac{6}{10}pie = \frac{3}{10}(2\ pies) \tag{A.1}$$

Figure A.1 shows the first two options in Eq. A.1 graphically. We can either slice one pie into five slices and take three of them, or slice three pies into five equal pieces and take one. Either way, we end up with the same amount. The possibilities are endless, and it is worth concocting your own variants. The last steps in Eq. A.1 hint at one type of freedom: we could split one pie into 10 pieces and select 6. Or we could split two pies into ten pieces and take 3 of those to end up with the same amount of pie.

Let's formulate rules about multiplication of fractions based on stuff we know (intuition). What is the rule for the general multiplication of two fractions, expressed symbolically so we can substitute *any* number

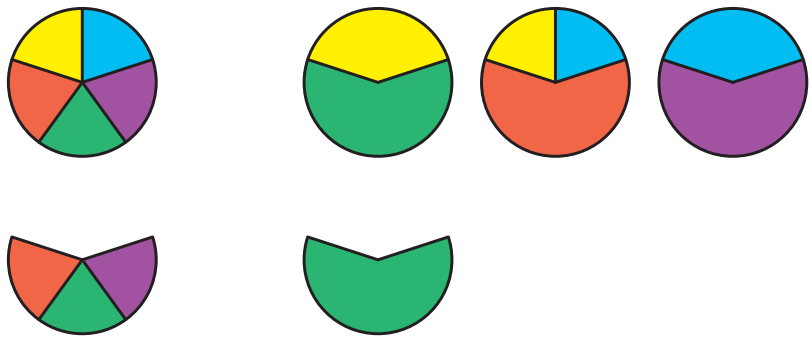

Figure A.1: Paralleling Eq. A.1, we can slice one pie into five equal pieces (left) and keep three of them (lower left); or we can split three pies into equal-area pieces (same color; sometimes split up across different pies) and take one of the resulting pieces. In both cases, the bottom row is the same amount of pie: $\frac{3}{5}$ of one pie equals $\frac{1}{5}$ of three pies.

for any symbol (placeholder) and get the right answer? In other words, what should the question marks be in the following:

$$\frac{a}{b}\cdot\frac{x}{y}=\frac{?}{?} \tag{A.2}$$

To answer, pick a scenario you *already know* and back-out the answer. You know that one half of one-half is one quarter. You also know that one half of $\frac{4}{5}$ must be $\frac{2}{5}$, or that three thirds must be a whole "one." In math terms:

$$\frac{1}{2}\cdot\frac{1}{2}=\frac{1}{4};\quad \frac{1}{2}\cdot\frac{4}{5}=\frac{2}{5};\quad \frac{3}{1}\cdot\frac{1}{3}=1. \tag{A.3}$$

From these examples—and others that can be fabricated as wished or needed—it is possible to arrive at the conclusion that

$$\frac{a}{b}\cdot\frac{x}{y}=\frac{a\cdot x}{b\cdot y}. \tag{A.4}$$

In other words, just multiply the numerators together and multiply the denominators together, simplifying by common factors as needed.

Example A.4.1 What is $\frac{2}{5}$ of the fraction $\frac{15}{24}$? By the straight rules, we get 30 in the numerator and 120 in the denominator.[16] Many common factors appear in the numerator and denominator (even the original $\frac{15}{24}$ could have been reduced to $\frac{5}{8}$) to give the final answer of $\frac{1}{4}$.

16: We can apply our lesson on reciprocals (see Example A.1.2) and realize that multiplying 24 by 5 is a lot like dividing it by 2, up to a decimal place. This gives us something 12–like and thus 120.

One more framing of fractions and their relationship to multiplication and division: dividing by 8 is the same as multiplying by $\frac{1}{8}$. Multiplying by $\frac{2}{3}$ is the same as dividing by $\frac{3}{2}$. Multiplication and division are thus essentially the same, only having to flip the number or fraction upside-down into its reciprocal.

How can our intuition assist us in figuring out addition and subtraction of fractions? Use what you know:

$$\frac{1}{2}+\frac{1}{2}=1;\quad \frac{1}{2}+\frac{1}{4}=\frac{3}{4};\quad \frac{3}{4}<\frac{1}{2}+\frac{1}{3}<1. \tag{A.5}$$

Hopefully, the first two statements in Eq. A.5 are apparent enough. The

last one bounds the answer by what you already know. Since $\frac{1}{3}$ is larger than $\frac{1}{4}$.[17] So adding $\frac{1}{2} + \frac{1}{3}$ must be larger than $\frac{1}{2} + \frac{1}{4} = \frac{3}{4}$. By similar logic, since one-third is smaller than one-half,[18] their sum must be smaller than 1.

Adding fractions like $\frac{1}{2}$ and $\frac{1}{3}$ is where common denominators come in. We can add numerators *only if the fractions share the same denominator*. We **never add denominators**. We can't replicate the middle example in Eq. A.5 by adding numerators *and* denominators, or we would get the nonsense answer $\frac{2}{6} = \frac{1}{3}$, rather than $\frac{3}{4}$.

So how would we ever recreate the whole common denominator scheme based on intuition? Let's return to the case of $\frac{1}{2} + \frac{1}{3}$. We have already bounded it to be between 0.75 and 1.0 (in Eq. A.5), which is already useful as a check to whatever rule we might try. Looking at the problem graphically, as in Figure A.2, we see that overlaying $\frac{1}{2}$ and $\frac{1}{3}$ naturally creates a missing gap of $\frac{1}{6}$. How do 2 and 3 in the denominators conspire to form 6? Via multiplication, of course. Re-expressing $\frac{1}{2}$ as $\frac{3}{6}$ and $\frac{1}{3}$ as $\frac{2}{6}$,[19] allows us to add the numerators directly, having made the denominators the same: $\frac{3}{6} + \frac{2}{6} = \frac{5}{6}$.

To some students, this may seem like an unnecessary and elementary review,[20] but the main point is that when in doubt, use what you already know to test your technique and verify that you are doing things right. If the rules you are trying to apply seem to work for a few different known cases, then you're probably golden. Approaching math this way makes you the boss of the formulas, rather than the other way around.

17: Splitting a pie into three parts will surely leave larger pieces than splitting it into more (4) parts, so ($\frac{1}{3} > \frac{1}{4}$).

18: If such statements are less than intuitive, think about pie or money, where the natural context lends itself to better intuition.

The point of this section (and appendix) is that you can use *what you already know* to check whether you are applying the right rules, and even re-create the rules that work—verifying that you get the answers you expect for cases you know and trust. Discover for yourself! Doing so gives you full ownership of the math. It's no longer something someone taught you to do: you've taught it to yourself, and that is far more powerful.

19: . . . by multiplying top and bottom by the missing factor—or the "other" denominator value

Figure A.2: Graphically, it is easy to see that $\frac{1}{2} + \frac{1}{3} = \frac{5}{6}$. You can always concoct similar/familiar scenarios to verify (and re-invent) the rules.

20: . . . which is why it is relegated to an appendix

A.5 Integer Powers

Raising a number to a power, like 4^3, is just a mathematical shorthand for $4 \cdot 4 \cdot 4$. Think of all the room we save in the case of 4^{23}!

So what are the rules for dealing with exponents when we raise the whole thing to another power, or when we multiply two exponentiated pieces together, or if we divide by (or invert) the thing? In other words, what are:

$$(x^a)^b = ? \quad x^p \cdot x^q = ? \quad \frac{1}{x^n} = ? \tag{A.6}$$

Notice that the the symbols used in this equation are just stand-ins for numbers, and have no intrinsic significance—whether we use n or p or a for an exponent is irrelevant. For that matter, x is not special either and we could have used a hexagon to stand in for the base in these relations, as a symbolic placeholder.

The theme of this appendix is: discover the rule through your own experimentation. Tackling in stages, what is $(7^4)^3$? We can write out 7^4 as $7 \cdot 7 \cdot 7 \cdot 7$ easily enough. If we cube this number, it's the same as

writing this set three times, all multiplied together, or $(7 \cdot 7 \cdot 7 \cdot 7) \times (7 \cdot 7 \cdot 7 \cdot 7) \times (7 \cdot 7 \cdot 7 \cdot 7)$, which is just 12 sevens multiplied, or 7^{12}. So we have discovered/formulated the rule:

$$(x^a)^b = x^{a \cdot b}. \tag{A.7}$$

We *multiply* the exponents when raising the inner exponent to an outer one.

How about $3^2 \cdot 3^5$? What is the rule there? The process[21] is similar to before, expanding out to $(3 \cdot 3) \times (3 \cdot 3 \cdot 3 \cdot 3 \cdot 3)$, which just looks like seven threes multiplied together, or 3^7. Therefore, our rule is:

$$x^p \cdot x^q = x^{(p+q)}. \tag{A.8}$$

We *add* exponents when multiplying two pieces, each having their own exponent. Note that this does *not* work when the bases are unequal, as you could verify yourself for $3^2 \cdot 5^4$.

Finally, what about inversion, or dividing by x^n? As a preview, a negative power is equivalent to putting the item in the denominator, so that $x^{-1} = \frac{1}{x}$. To see this, consider Eq. A.8 in the case where p and q are opposite sign but the same magnitude. For instance, following the "add the exponents rule" we get that $3^4 \cdot 3^{-4} = 3^{4-4} = 3^0 = 1$, because anything raised to the zero power is 1.[22] The only thing we can multiply into $3 \cdot 3 \cdot 3 \cdot 3$ in order to get 1 is $\frac{1}{3 \cdot 3 \cdot 3 \cdot 3}$. This means that 3^{-4} is the same as $1/3^4$, or more generally:

$$\frac{1}{x^n} = x^{-n}. \tag{A.9}$$

Negative exponents therefore flip the construction to the denominator, or denote a division rather than multiplication.

21: Note that some care must be exercised in selecting the example. For instance, picking both exponents as 2 would leave some ambiguity: is the result of $4\,2 + 2$, 2×2, or 2^2?

22: Think of the exponent as how many instances of a number are multiplied together in a chain, implicitly all multiplied by 1. If we have zero instances of the number, then the implicit 1 is all we have left in the multiplication. In other words, 1 is the starting point for all multiplications, just like zero is the starting point for all additions.

A.6 Fractional Powers

In the previous section, we only dealt with integer powers, so that we could write out 3^4 as $3 \cdot 3 \cdot 3 \cdot 3$. How would we possibly write $3^{1.7}$? Yet it is mathematically well defined. A calculator has no trouble.

We can get a hint from Eq. A.8. Consider, for example, $5^{\frac{1}{2}} \cdot 5^{\frac{1}{2}}$. We know that we can just add the exponents, which in this case add to a tidy 1, meaning that the answer is just 5. Therefore we interpret $5^{\frac{1}{2}}$ as the square root of 5, since multiplying it by itself yields 5. So we can re-express our familiar friend as a fractional power:

$$x^{\frac{1}{2}} = \sqrt{x}. \tag{A.10}$$

In principle, then, we could approach $3^{1.7}$ by taking the tenth-root of 3 and raising it to 17^{th} power: $3^{1.7} = (3^{\frac{1}{10}})^{17} = 3^{\frac{17}{10}}$.

More generally, in Chapter 1, we saw that we can represent any base, b, raised to some arbitrary number, n, as:

$$b^n = e^{n \cdot \ln b} = 10^{n \cdot \log_{10} b}, \tag{A.11}$$

where we use the exponential function and its inverse function (natural log, ln), or alternatively the base-10 equivalents. If, for some reason, we lacked a y^x calculator button, these approaches allow more fundamental ways to get at the same thing.

A.7 Scientific Notation

The single-biggest mistake students make when it comes to scientific notation is easily remedied by understanding it not as a set of rules, but for what it's actually doing.

Most of the time, students get it right: they see 1.6×10^2 and move the decimal to the right two times to get 160. A little harder is negative exponents, like 2.4×10^{-2}. Moving the decimal point twice to the left results in the correct 0.024 answer.

The hangup can come about if the process is misconstrued as simply "counting zeros." Ironically, a student might correctly convert 6×10^3 by adding three zeros to the 6 to get 6,000, but then mistake 10^3 for 10,000—thinking: start with 10 and add three zeros.

The sure-fire way is to connect to the concept of integer powers, so that 10^3 is simply $10 \cdot 10 \cdot 10$, which is unmistakably 1,000. Likewise, 10^{-4} is four repeated (multiplied) instances of 10^{-1}, each one representing $\frac{1}{10}$, or 0.1. String four together, and we have $\frac{1}{10{,}000}$, or 0.0001. So fall back on the basics.

Example A.7.1 We can also apply the rule of multiplying exponentiated quantities covered in Eq. A.8. So 3.2×10^3 times 2×10^2 can be written out as $3.2 \cdot 2 \cdot 10^3 \cdot 10^2$ (order does not matter), which we can recognize as 6.4×10^5.

What about division: 2.4×10^{13} divided by 8×10^7? Several ways to approach this might be instructive. Let's ignore the pre-factors (2.4 and 8) for now and focus on the powers of ten. The standard practice is to subtract the exponent in the denominator from that in the numerator: $13 - 7 = 6$ in this case, so that we are left with $\frac{2.4}{8} \times 10^6$. We could also represent the 10^7 in the denominator as 10^{-7} in the numerator, as per Eq. A.9. Now we just add the exponents to get the same result. Or we *could* invert the 8×10^7 to become 0.125×10^{-7} and multiply this by 2.4×10^{13}.

But I want to present the way I would do it to make it easy enough

to perform in my head. Recognizing that 24 is divisible by 8, I am strongly tempted to re-express the first number as 24×10^{12}. See what I did there? I multiplied the prefactor by 10, and decreased the exponent by one accordingly to end up at the same place. Now I have $\frac{24}{8}\times10^{12-7}$, which reduces to 3×10^5. All methods get the same answer,[23] which turns into another lesson that math provides many paths to the same answer, which can be used to check and reinforce.

23: The frolicking dolphin tries several and revels in the reinforcement that comes from consistency.

A.8 Equation Hunting

Students often form a counter-productive dependency on formulas. Experts focus on learning the *concept* expressed by an equation, since an equation is very much like a sentence that speaks some truth.[24] Once the fundamental principle is mastered, the equation or formula is automatic, and can be *generated* from a place of understanding—which is more permanent than memorization.

24: . . . perhaps within some context or set of assumptions

The practice is more common and natural than it might seem at first. Let's say a person has a take-home pay of $50,000 per year. Rent is $2,000 per month, groceries and other bills come to $1,000 per month. How much is left per month for discretionary spending? Where is the formula for *that* problem? Of course, you wouldn't bother hunting for a formula in this case and would instead build your own math. You essentially create your own formula on the fly. Whether you first divide the annual figure by 12 and then subtract the monthly expenses, or multiply monthly expenses by 12 before subtracting from the annual amount and *then* dividing by 12, the result is the same: a little more than $1,000 per month.

It is also clear in this context that it makes little sense to perform math down to the penny, since the grocery and other expenses are not going to be exactly the same each month. The lesson is that most people are expert enough in managing money that they don't scramble to find printed formulas whenever they want to figure something out, and they are also forgiving on precision because they know from context not to take it all too literally.

This book *tries* to foster a more expert-like approach to the material. For instance, Def. 5.3.1 (p. 71) introduces the concept of power without explicitly saying $P = \Delta E/\Delta t$. It just says that power is how much energy is expended in how much time. If a student internalizes *that* idea, then why print a formula? By doing so, a student may bypass real understanding[25] and rely on the formula as a crutch, never planting the core idea firmly in the brain. Shortcuts can end up disadvantaging students, as attractive as they may look in the moment. The student who masters the concepts will be in a far better position to deploy them in a wider variety of circumstances—including unfamiliar test questions.

25: . . . which in this case is not a heavy lift

A.9 Equation Manipulation

Physics instructors often joke that they teach students the "three Ohm's Laws." The joke is that only one is needed: $V = I \cdot R$. The other forms: $I = \frac{V}{R}$ and $R = \frac{V}{I}$ can be derived from the first. Rigid memorization leads some students to remember all three forms, rather than simply move things around in a way that maintains the relationship.

The rules are easy enough to generate on your own. Think of an equation as a perfectly balanced see-saw—maybe an elephant sitting on both sides. The equation is only valid if it remains balanced. You may add a chicken, but do it to both sides. You may multiply or divide the number of elephants, as long as it is done the same way to both sides. Dividing both sides of (the first) Ohm's Law above by R leads to the second form, for instance.

Example A.9.1 Let's say you are given something you consider to be an ugly equation, or you simply want to solve for one variable. Using symbols for everything,[26] we might have

$$\frac{a}{b} + c = \frac{x+y}{z}$$

Let's say we hate the appearance of fractions. Multiply both sides by b:

$$a + b \cdot c = b\frac{x+y}{z}$$

Now multiply both sides by z to eliminate the remaining fraction:

$$a \cdot z + b \cdot c \cdot z = b \cdot (x+y)$$

What if you wanted a solution for y? Guess we're going to have to return b to denominator status, as we need to divide both sides by b.

$$x + y = \frac{a}{b} \cdot z + c \cdot z$$

And finally we subtract x from both sides to get

$$y = \frac{a}{b} \cdot z + c \cdot z - x$$

Whatever you want to do, just do it to both sides.

26: It is easy to substitute numbers anywhere you wish at any time

It's not always so straightforward. Sometimes we have to "undo" or "invert" a mathematical function. Consider for instance a familiar problem: find the side length, a, of a right triangle whose other side is b and hypotenuse c. We know from the Pythagorean Theorem that $a^2 + b^2 = c^2$, so that $a^2 = c^2 - b^2$. But we want a, not a^2. How do we "undo" the square? Take a page from Eq. A.7. We want a to the power of 1, so we want to raise a^2 to whatever power will neutralize the 2 via multiplication.

Looks like $\frac{1}{2}$ (square root) will do the trick. But we need to treat both sides:

$$a = \left(a^2\right)^{\frac{1}{2}} = \sqrt{a^2} = \sqrt{c^2 - b^2} \tag{A.12}$$

In this case, the power $\frac{1}{n}$ can be said to perform the inverse function of the power n. In more familiar contexts: subtraction is the inverse of addition; division is the inverse of multiplication. Less familiarly, but in similar veins: the sine is "undone" by arcsine;[27] the exponential e^x is undone by the natural log ($\ln x$); 10^x is undone by $\log_{10} x$, etc.

27: . . . and the other way around, for all these examples

If you have not done it before (or recently), mess around on a calculator, starting with a custom number you make up that is pleasing to you and recognizable.[28] Square it and then take the square root. Calculate the sine and then inverse sine (ASIN). Take the exponential and then natural log—or other way around. Get to know these things on your own terms!

28: Something like 1.23456 would work, but make it your own!

A.10 Units Manipulation

In the real world, numbers often are packaged with associated units. The radius of the earth is 6,378 km. If we change the unit, we change the number, too. Earth's radius becomes 6,378,000 m or 3,963 miles. Most generally, we aim to quantify something in nature, and the numeric value is utterly dependent on the units we choose to represent the physical reality.

Because the numbers are often *meaningless* without the accompanying units, we should[29] carry around the units in all manipulations. Any time we do something to the number, we need to do the same thing to the unit.

29: Full disclosure: I don't always do so, in haste. But I know they belong there and will throw them back in if I get tangled or end up suspecting a nonsense result.

Example A.10.1 If we travel 4 meters in 2 seconds, we have

$$\frac{4\,\mathrm{m}}{2\,\mathrm{s}} = \frac{4}{2} \cdot \frac{\mathrm{m}}{\mathrm{s}} = 2\,\mathrm{m/s}.$$

Dividing the numbers alone to get 2 is not the whole story. We also divided the units to create a new one that was not in the initial set (m and s).

If we fill a room whose floor area is 10 square meters with water one meter deep, the volume is

$$10\,\mathrm{m}^2 \cdot 1\,\mathrm{m} = 10 \cdot 1\,\mathrm{m}^2 \cdot \mathrm{m} = 10\,\mathrm{m}^3.$$

So we multiply the meters together just like we do the numbers, following the same rules but acting as if they are variables and keeping it symbolic.

More complicated arrangements follow the same rules. For example, the force of drag[30] on an object moving at speed v through a medium of density ρ is $F_{\text{drag}} = \frac{1}{2} c_{\text{D}} A \rho v^2$, where A is the frontal (cross-sectional) area of the object and c_{D} is the dimensionless drag coefficient.[31] The dimensions of area are m^2; density is kg/m^3 (mass per volume), and velocity is m/s (distance over time). The whole arrangement therefore has dimensions:

$$\text{m}^2 \cdot \frac{\text{kg}}{\text{m}^3} \cdot \left(\frac{\text{m}}{\text{s}}\right)^2 = \frac{\text{m}^2 \cdot \text{kg} \cdot \text{m}^2}{\text{m}^3 \cdot \text{s}^2} = \frac{\text{kg} \cdot \text{m}^4}{\text{m}^3 \cdot \text{s}^2} = \frac{\text{kg} \cdot \text{m}}{\text{s}^2}.$$

The end result matches the definition of Newtons, and can be verified by the (possibly familiar) $F = ma$ form of Newton's Second Law,[32] whereby we have mass in kg times acceleration in m/s^2 making $\text{kg} \cdot \text{m/s}^2$.

When performing a chain of multiplications or divisions, we can carry the units around and multiply, divide, or (hopefully) cancel them as we go.

Example A.10.2 Let's say we want to know how much energy, in Joules, the U.S. uses in a year based on knowledge that the average citizen accounts for 10,000 W (a Watt is a Joule per second) and the U.S. has 330 million people. First, let's work with the 10,000 W per person metric:

$$\frac{10^4\,\text{J/s}}{\text{person}} = \frac{10^4\,\text{J}}{\text{person} \cdot \text{s}},$$

where we have just moved the seconds into the denominator to multiply "person" (order doesn't matter). Most of the problem is in going from seconds to years. It would like like this:

$$\frac{10^4\,\text{J}}{\text{person} \cdot \text{s}} \cdot \frac{60\,\text{s}}{1\,\text{min}} \cdot \frac{60\,\text{min}}{1\,\text{hour}} \cdot \frac{24\,\text{hour}}{1\,\text{day}} \cdot \frac{365\,\text{day}}{1\,\text{year}}$$

Notice that each of the factors we multiply, even though they carry a non-unity numeric value, are *essentially* identities that describe equal intervals on top and bottom, in differing units.[33] So we are effectively multiplying by 1 repeatedly in a **unit conversion** process.

Also note that the chain we construct allows a boatload of cancellations, as almost all units present appear in both the numerator and denominator once. The only ones that do not are J in the numerator and year and person in the denominator. When we carry out the multiplication above and cancel units, we find that we are left with:

$$3.15 \times 10^{11}\,\frac{\text{J}}{\text{year} \cdot \text{person}}.$$

Oops, the units are helping us here by reminding us that we need to multiply by the population (3.3×10^8 persons) to get the answer

30: This choice is intentionally unfamiliar and complicated–looking to demonstrate that units can help bring a sense of order and correctness even in alien contexts.

31: The drag coefficient, c_{D}, is usually in the range 0.3–1.

32: Force equals mass times acceleration

33: E.g., 24 hours and 1 day describe the same time interval.

we sought.[34] In this case, we end up with 1.04×10^{20} J/year, which is what we were after.

We just carried out unit conversions (in time) in Example A.10.2, when we multiplied by constructs like 60 s/1 min. The key to unit conversions is to arrange a fraction expressing *the same physical thing* in both the numerator and denominator, just using different units. So we're looking for equivalent measures. *Most* of the time, one of them will be 1, numerically, as in the following example.

Example A.10.3 We might want to convert the 1.04×10^{20} J/year from Example A.10.2 into quadrillion Btu per year. We know that 1 Btu is 1,055 J, and that a quadrillion is 10^{15}. So we arrange the following:

$$1.04 \times 10^{20} \frac{\text{J}}{\text{year}} \cdot \frac{1\,\text{Btu}}{1,055\,\text{J}} \cdot \frac{1\,\text{quadrillion}}{10^{15}} \approx 100\,\text{quadrillion Btu/year}.$$

Finally, units can help guide correct usage of factors in a problem. In Example A.10.3, what if we did not know whether to divide or multiply by 1,055? The fact that we wanted to eliminate Joules told us we needed the Joules in the denominator, and so the relation 1 Btu = 1,055 J told us the 1,055 travels with Joules and must be in the denominator.

But what if we are faced with a problem whose application is not as apparent?[35] Let's explore how this might go in a less familiar setting.

Example A.10.4 For some inexplicable reason, you put a brick in the refrigerator, which is 20°C colder than the brick is, initially, and want to find out how long it will take for the brick to cool off. The brick has a mass of 2.5 kg, will dump its heat into the refrigerator at a rate of 10 W (10 J/s), and has a specific heat capacity of 1,000 J/kg/°C.[36] So you feel overwhelmed by lack of familiarity, right? Good, because the units are here to help.

You want an answer in time units, and see one instance in the 10 J/s rate at which heat leaves the brick. To get seconds "up top," you want to make sure the 10 W value is in the denominator. This puts Joules in the denominator, and we don't want it to survive to the final answer. We notice Joules in the specific heat capacity thing in the numerator, so that thing must go in the numerator. Let's take stock of where that leaves us.

$$\frac{1}{10\,\text{J/s}} \cdot \frac{1,000\,\text{J}}{\text{kg} \cdot^\circ \text{C}} = 100\,\frac{\text{s}}{\text{kg} \cdot^\circ \text{C}}$$

It looks like if we multiply by the mass in kg and multiply by the temperature difference, we're home free. Doing so results in 5,000 seconds. Whenever possible, try to extract the most context/intuition out of an answer as you can. Does 5,000 seconds mean a lot to you? Divide by 60 (or multiply by $\frac{1\,\text{min}}{60\,\text{s}}$) to get 83 minutes. Better. Or another factor of 60 and we're at 1.4 hours. That seems like the most natural

34: So units, handled carefully, can provide important clues as to how to get the problem right.

35: . . . or we don't know the formula, which is no bad thing, as we then have the chance to construct it from what we know, like a real expert!

36: This construction means that kg and °C are *both* in the denominator together.

way to express the answer.

It is also useful to pause and reflect on our operations and whether they made sense. For instance, since we multiplied by mass to get the cooling time, it implies that a larger brick would take longer, which is sensible. If heat left at a rate faster than 10 W, it would cool down faster, again making sense.

At this point, we could create our own formula based on requiring the units to work! See: formulas are not sacred tablets to be memorized—they are just statements that make logical sense and can be created *by* you to accomplish a task.

We will do one more example in an unfamiliar context, this time involving some ambiguity that your wits can help resolve.

Example A.10.5 An outer wall on a sealed brick building measures 5 m long and 2.5 m high, having a thickness of 0.1 m. You are asked how fast heat (thermal energy) is being lost through the wall.[37] It is 20°C warmer inside the wall than it is outside, and you are told that brick has a thermal conductivity of 0.6 W/m/°C.[38] Thermal what? But don't panic.

We want an answer in J/s, or W. We see Watts in the numerator of the thermal conductivity, so we want that in the numerator of our answer. We would need to multiply by meters and by °C to cross the finish line. Seems simple enough. But meters shows up three times in the dimensions of the wall. Which should we choose? Or is it a combination?

Engage the intuition. Put yourself in the building next to the wall, mentally. It's warm inside, cold outside. Will I need more heaters (power) or fewer if the wall is taller? If the wall is wider? If the wall is thicker? What does your intuition say?

You might reason that a thicker wall will require less power to keep warm, but that a larger area (increasing width or height or both) would make the job of maintaining temperature more challenging. This suggests that the power will *increase* if width or height increase, and *decrease* if thickness increases. So we should multiply by width and height (or equivalently, by area) and divide by thickness. Area over thickness indeed has units of meters, which we already concluded we needed as a multiplier to get our desired outcome. Putting things together, we have

$$0.6\frac{\text{W}}{\text{m}\cdot^\circ\text{C}}\cdot\frac{5\,\text{m}\cdot 2.5\,\text{m}}{0.1\,\text{m}}\cdot 20^\circ\text{C} = 1,500\,\text{W},$$

which is about the output of one space heater.

37: The units would be energy per time, or J/s, which is a power (W).

38: This construction means that m and °C are *both* in the denominator together.

A.11 Just the Start

It is well beyond the scope of this book to engage in an exhaustive review of math concepts. Hopefully what has been covered provides a

useful foundation. The key lesson is that the knowledge and intuition students already hold in their heads can be leveraged effectively to recreate forgotten rules of math. Just remember: it all makes sense and hangs together. Creating customized simple problems[39] allows a way to make sure the math rules being applied replicate the right answer. If not, a few tests can often get things back on the right track. By doing so, students can claim greater personal ownership of the math, and have a better internal mastery of its workings.

39: . . . whose answers are already known or can be figured out

Chemistry Primer/Refresher B

This book does not rely heavily on past knowledge of chemistry, but it is helpful to know a few basic elements that play a role in fossil fuels, biological energy, and climate change. This section could act as a refresher, or a first exposure to the fundamentals.

B.1 Moles 375
B.2 Stoichiometry 376
B.3 Chemical Energy 379
B.4 Ideal Gas Law 381

B.1 Moles

Chemistry deals with atoms and molecules and the interactions between them. Atoms and molecules[1] are irreducible nuggets of a substance—the minimum unit that carries the essential properties of that substance. Water, for instance, is comprised of two hydrogen atoms bonded to a single oxygen atom, which we denote as H_2O.

1: Molecules are made from a handful of atoms.

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Ni	28 Co	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	103 Lr	104 Rf	105 Dg	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Ca	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

Figure B.1: Periodic Table of the Elements. This version is too small to permit names, so that only symbols are given. The more familiar elements are highlighted. Numbers represent the number of protons in the nucleus of the associated atoms.

Figure B.1 presents a stripped-down version of the periodic table. Additional exploration of more fully-featured versions is encouraged.[2]

2: Perhaps at least identifying the highlighted elements would be worthwhile.

It is natural to imagine that a first step in dealing with piles of atoms and/or molecules is being able to *count* them. But since individual atoms are fantastically small, the numbers can be overwhelmingly large. This is where the mole[3] comes in. A mole is *just a number*, and that number is called Avogadro's number, having a value of $N_A = 6.022 \times 10^{23}$, or 602,214,076,000,000,000,000,000, if written out.[4]

3: . . . the word *molecule* begins with *mole*.

4: Unfortunately, it can be hard to remember if it is supposed to be 6.022×10^{23} or 6.023×10^{22}. For this reason, it may be wise to forget about the 22 and just remember 6.0×10^{23}, or even 6.023×10^{23} as something that is *very slightly* wrong but much better than being 10 times off!

The way the mole is defined, essentially, is that 12.000000 grams of neutral carbon atoms (of the isotope having 6 protons and 6 neutrons in its nucleus) will constitute one mole of atoms. In this way, the masses of

other elements—being comprised of an integer number of protons and neutrons[5]—will tend to be close to an integer number of grams.[6] For instance, a mole of hydrogen atoms is very close to 1.00 grams. A mole of helium is very nearly 4.00 grams, nitrogen 14, oxygen 16, etc.

So the concept of the mole is pretty straightforward: just a number—albeit a very large one.

5: . . . and associated light-weight electrons equal in number to the protons

6: Blends of different isotopes can mess up this convenient arrangement in natural (mixed) samples, however.

Box B.1: Moles to Mass

Incidentally, the inverse of Avogadro's number becomes the definition of the atomic mass unit (a.m.u.). The a.m.u. can be thought of as the average mass of an atom per nucleon.[7] In other words, carbon-12 (6 protons, 6 neutrons) has a mass of 12 a.m.u. In fact, this is how the a.m.u. is defined. This means that hydrogen (a single proton) has a mass very close to 1.00 a.m.u., and oxygen-16 (8 protons, 8 neutrons) has a mass close to 16.00 a.m.u. Chapter 15 delves into the subtle reason why these are not exactly 1.00000 and 16.00000 in these cases.

Since one mole of 12.00000 a.m.u. carbon-12 atoms is defined to have a mass of 12.00000 g, one mole of 1.000000 a.m.u. particles[8] would have a mass of 1.000000 g. Therefore, a *single* 1.000000 a.m.u. particle would have a mass of 1.000000 g divided by Avogadro's number, $N_A = 6.02214076 \times 10^{23}$, which turns out to be $1.66053907 \times 10^{-24}$ g, or $1.66053907 \times 10^{-27}$ kg. This is the number you will find if looking up the atomic mass unit (also called a Dalton).

7: A nucleon is either a proton or a neutron: the two types of particles that occupy the nucleus of an atom and are responsible for almost all of the atom's mass.

8: . . . if such a thing were to be found/created

B.2 Stoichiometry

Chemistry starts by counting atoms and molecules. Since molecules are comprised of integer numbers of atoms of specific types, the counting fun does not stop there. When atoms and molecules react chemically, the atoms themselves are never created or destroyed—only rearranged. This means that an accurate count of how many of each atom type are present at the start, a proper count at the end should yield *exactly* the same results.

Before we get into balancing chemical reactions, we need to know something about the scheme for labeling chemical compounds. A compound is an arrangement of atoms (representing pure elements) into a molecule. For instance, water is made of three atoms drawn from two elements: hydrogen and oxygen. Two atoms of hydrogen are bonded to an atom of oxygen to make a molecule of water. We denote this as H_2O.

Examples of a few familiar atoms and molecules are presented in Figure B.2. Each one is named at the top. Below each one appears the bond structure in the case of molecules and the chemical "formula" in all cases. Notice that hydrogen atoms always have a single bond (single

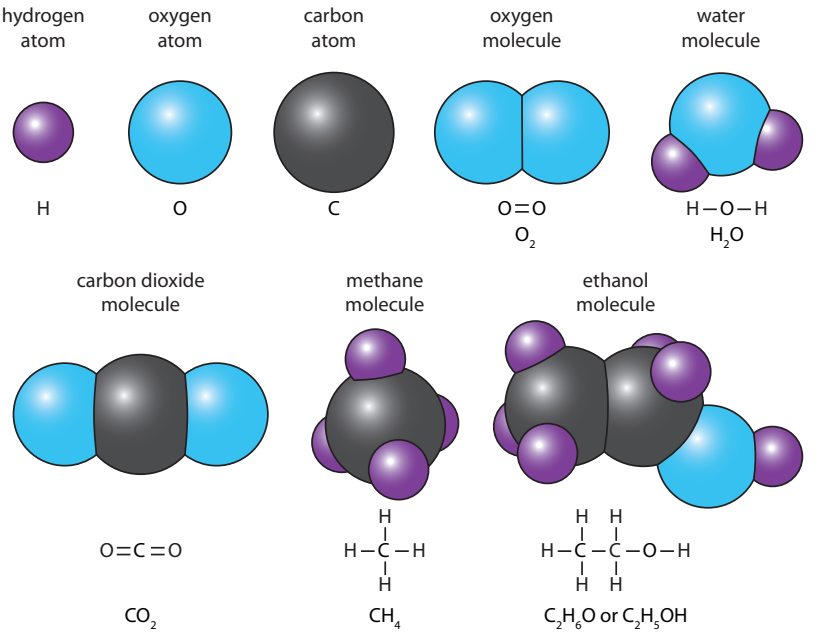

Figure B.2: Representing atoms as colored spheres for schematic purposes, we can depict the general appearance of molecules as bonded collections of atoms. Here, we have three elements—hydrogen, oxygen, and carbon—combined into familiar molecules. Oxygen in the air we breathe is self-bonded into a "diatomic" molecule. Two representations appear below each molecule: a diagram indicating bonds (including double-bonds in some cases), and the chemical formula.

electron to share), oxygen has two (wants to "borrow" two electrons to feel good about itself), and carbon tends to have four (either donating four in the case of CO_2, or accepting four when bonding to hydrogen). The chemical formula for each uses elemental symbols to denote the participants and **subscripts** to *count how many are present*.[9]

Now we come to a bedrock practice in chemistry called stoichiometry—which boils down to counting atoms in a reaction to make sure no atoms are missing or spontaneously appear. To get a sense of this, see Figure B.3 for two examples. The graphical version captures the physical reality, so that simply counting the number of spheres of each color on the left and right had better match. Below each graphical reaction is the associated chemical formula. Each formula contains an arrow indicating the direction of the reaction (separating "before" and "after"). Numerical factors (coefficients, or prefactors) in front of a molecule indicate how many molecules are present in the reaction. To get the total number of atoms represented, we must multiply the subscript for that atom (implicitly 1 if not present) by the prefactor.[10]

Example B.2.1 Let's figure out a tougher formula, pertaining to the combustion of ethanol (depicted in Figure B.2). In this situation, we combine a C_2H_6O molecule with some number of oxygen molecules (O_2), and the reaction products will be CO_2 and H_2O (carbon dioxide and water). Our job is to figure out how many molecules are needed to balance the reaction:

$$C_2H_6O + ?O_2 \rightarrow ?CO_2 + ?H_2O$$

9: Two variants are shown for ethanol. The first is a no-nonsense census of the atoms, while the second pulls one of the H symbols to the end to call attention to the OH (hydroxyl) tagged onto the end of the molecule. In either case, the formula specifies 2 carbons, 6 hydrogens, and 1 oxygen, in total.

10: For example, $2H_2O$ has a total of 4 hydrogen atoms and 2 oxygens.

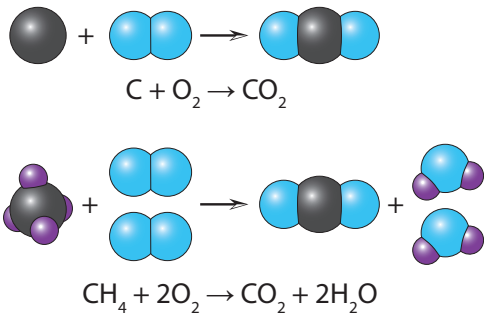

Figure B.3: Two example fossil fuel reactions (combustion) are shown here. The first is coal and the second is natural gas (methane). Both cases simply rearrange the input atoms without creating or destroying any, so that the count is the same on both sides of the arrow (which denotes the direction of the reaction). In other words, four purple hydrogens on the left in the case of methane must all appear on the right somewhere. The formula version also just counts instances of each atom/molecule, in which pre-factors (coefficients) indicate how many molecules are present.

where question marks indicate what we need to figure out. Three unknowns and one equation? It may seem hopeless, but the formula is *not* the equation. The equations are that the total number of carbons on each side are equal, the total number of oxygens are equal, and the total number of hydrogens are equal. So we actually have three equations.[11]

Start by noticing that the left side has 2 carbons and 6 hydrogens. We don't know how many oxygens yet, but it's good enough to start. On the right, carbon only shows up in CO_2, so getting 2 carbons on the right requires $2CO_2$. Likewise, hydrogen only shows up in water, and ethanol has 6 hydrogen atoms to stuff into water molecules that hold 2 hydrogens apiece. It will obviously take 3 water molecules to account for 6 hydrogens.[12] So now the right side is hammered out:

$$C_2H_6O + ?O_2 \rightarrow 2CO_2 + 3H_2O$$

The only thing left to figure out is how many oxygens are on the left. To balance the reaction, count the number of oxygen atoms on the right. Four come from the two CO_2 molecules, and 3 from the water for a total of 7. One oxygen was already present in the ethanol molecule on the left, so only need 6 in the form of O_2, thus requiring three of these:

$$C_2H_6O + 3O_2 \rightarrow 2CO_2 + 3H_2O$$

The job is done: the reaction is now balanced. That's stoichiometry.

The treatment above cast chemical reactions at the most fundamental level of individual molecules reacting. In practice, reactions involve great numbers of interacting particles, so it is often more convenient to think in moles. In fact, common practice is to look at the prefactors[13] in chemical reaction formulas as specifying the number of *moles* rather than the number of individual molecules. Either way, the formula looks exactly the same,[14] and it's just a matter of interpretation.

Thinking of the chemical formulas in terms of moles makes assessment of the masses involved more intuitive. Recall that one mole of carbon

11: Equations are just statements of truth that we can create on our own. They are just a way to express what we know about a problem.

12: What if the starting point had an odd number of hydrogens on the left? We'd need to double the number of hydrogen-containing molecules on the left to produce an even number and start over.

13: . . . also called coefficients

14: To be explicit, if a formula is balanced for individual molecules, then it should also be balanced if doubling the "recipe," or tripling, multiplying by 10, or even by 6×10^{23}.

atoms is exactly 12 grams, that hydrogen is 1 g, and oxygen is 16 g. That means one mole of water molecules (H_2O) will be 18 g (16 + 1 + 1), one mole of carbon dioxide (CO_2) is 44 g (12 + 16 + 16), and one mole of ethanol (C_2H_6O) is 46 g (12 + 12 + 1 + 1 + 1 + 1 + 1 + 1 + 16). We refer to this figure as the molar mass, and standard periodic tables display the molar masses for each element: the mass of one mole of the substance. The unit is typically grams per mole, or g/mol.

Example B.2.2 How much mass of CO_2 will emerge from the burning of 1 kg of ethanol? We start with the formula we worked out in Example B.2.1:

$$C_2H_6O + 3O_2 \rightarrow 2CO_2 + 3H_2O$$

This problem can be approached in Two equivalent ways: either figure out how many moles of ethanol it takes to amount to 1 kg and then scale the formula accordingly; or just work it out for one mole to get a ratio and then apply to 1 kg. We'll do it both ways.

Since ethanol has a molar mass of 46 g, one kilogram corresponds to 21.7 moles. So we could re-write the formula as:

$$21.7C_2H_6O + 65.2O_2 \rightarrow 43.5CO_2 + 65.2H_2O$$

where we have multiplied each prefactor (coefficient) by 21.7. CO_2 has a molar mass of 44 g/mol, so 43.5 moles will come to 1.91 kg.

The other approach is to note that 2 moles of CO_2 are produced for every one mole of ethanol combusted. So 88 g of CO_2 (44 g/mol) results for every 46 g of ethanol supplied. This ratio is 1.91. So 1 kg of ethanol input will make 1.91 kg of CO_2 out, as before.

B.3 Chemical Energy

Atoms (elements) can bond together to make molecules (compounds). The bond—formed by outer electrons within the atoms—can be strong or weak. It takes energy[15] to pull apart bonded atoms. It stands to reason that when two atoms form a new bond, energy is released—usually as vibrations that we know as heat. In a typical reaction, some bonds are broken and other new ones formed. If the balance is that the new bonds are stronger than the broken bonds, energy will be released. Otherwise, energy will have to be put into the reaction to allow it to happen.

15: Recall that energy is a measure of work, or a force times a distance.

In the context of this book, chemical energy is typically associated with combustion (burning) a substance in the presence of oxygen. This is true for burning coal, oil, gas, biofuels, and firewood. In a chemistry class, one learns to look up the energetic properties of various compounds in tables, combining them according to the stoichiometric reaction formula

to ascertain a net energy value. We're going to take a shortcut to all that, by introducing the following *approximate* formula for combustion energy.

This empirical formula can serve as a general guide, but should not be taken as a literal truth from some profound derivation. It captures the main energy features and produces a useful, approximate result.

The *approximate* energy available from the compound $C_cH_hO_oN_n$—where the subscripts represent the number of each atom in the molecule to be burned—is:

$$100\frac{c+0.3h-0.5o}{12c+h+16o+14n}\ \text{kcal/g}. \tag{B.1}$$

For instance, sucrose has the formula $C_{12}H_{22}O_{11}$, so that $c = 12$, $h = 22$, $o = 11$, and $n = 0$. The denominator in the formula is just the molar mass,[16] or 342 in this case. The numerator adds to 13.1, so that the result is 3.8 kcal/g—very close to the expected value around 4 kcal/g for a carbohydrate like sugar.

16: The coefficients in the denominator reflect the fact that carbon is 12 units of mass, oxygen is 16, etc.

The numerator of Eq. B.1 tells us that we get the most energy from each carbon atom, 30% as much from each hydrogen atom, and take a 50% hit (deduction) for each oxygen atom. Nitrogen is energetically inert and does not contribute to the numerator—while degrading the energy density by adding mass in the denominator. The negative coefficient for oxygen tells us something important. Since combustion is a process of joining oxygen to atoms in the fuel, the presence of oxygen *already* in the fuel means it is already partly "reacted" and has less to offer in the way of new oxygen bonds.

We can explore the sensibility of Eq. B.1 by testing it on some known boundary cases.[17] Since one ubiquitous end-product of combustion is CO_2, calculating for CO_2 should offer no energy to us, since it's a "waste" product at the end of the energy process. H_2O, as another common combustion product, is likewise effectively neutralized in the formula (the result is at least made to be very small). Table B.1 provides some examples of what Eq. B.1 delivers for familiar carbon-based substances. Note that oxygen content (last column) drives energy down, while hydrogen offers a boost.

17: This is a generically useful practice: it helps integrate new knowledge into your brain by validating the behavior in known contexts. Does it make sense? Can you accept it, or does it seem wrong/suspect? Experts often apply new tools first to familiar situations whose answers are known to build trust and competence using the new tool before applying it more broadly.

Try it out, using $c = 1$ and $o = 2$.

Try this one, too, coming up with your own values for h and o.

substance	formula	Eq. B.1 kcal/g	true kcal/g	% C	% H	% O
glucose	$C_6H_{12}O_6$	3.7	3.7	40	7	53
typ. protein	$C_5H_{10}O_3N_2$	4.4	~ 4	41	7	52
coal	C	8.3	7.8	100	0	0
typ. fat	$C_{58}H_{112}O_6$	9.8	~ 9	77	12	11
octane	C_8H_{18}	11.8	11.5	84	16	0
methane	CH_4	13.8	13.3	75	25	0

Table B.1: Example approximate chemical energies. The results of the approximate formula are compared to true values (favorably). Fractional mass in carbon, hydrogen, and oxygen also appear—emphasizing the penalty for molecules already carrying oxygen.

The resulting calculated energies are definitely in the right (expected) ranges. Notice that the "winners" have little or no oxygen as a percentage of the total molecular mass. The lower-energy entries in Table B.1 are more than half oxygen, by mass.

B.4 Ideal Gas Law

Another topic covered in chemistry classes that strongly overlaps physics is the ideal gas law. This relationship describes the interactions between pressure, volume and temperature of a gas. In chemistry class, it is learned as

$$PV = nRT, \tag{B.2}$$

where P stands for pressure (in Pascals[18]), V is volume (cubic meters), n is the number of moles, T is temperature (in Kelvin), and R is called the gas constant, having the value

$$R = 8.314 \frac{\text{J}}{\text{mol} \cdot \text{K}}. \tag{B.3}$$

To get degrees in Kelvin, add 273.15 (273 among friends) to the temperature in Celsius.[19] Standard atmospheric pressure is about 10^5 Pa.[20]

Example B.4.1 Let's say we have a gas at "standard temperature and pressure" (STP), meaning 0°C (273 K) and 1.013×10^5 Pa. How much volume would one mole of gas[21] occupy?

We have everything we need to solve for volume, so

$$V = \frac{nRT}{P} = \frac{(1\text{ mol})(8.314\text{ J/K/mol})(273\text{ K})}{1.013 \times 10^5\text{ Pa}} \approx 0.0224\text{ m}^3 = 22.4\text{ L}.$$

Okay; lots going on here. After the three values in the numerator are multiplied, the only surviving unit is J (Joules of energy). The unit in the denominator is Pascals, but this is equivalent to Joules per cubic meter. So the answer emerges in cubic meters, as a volume should. Since a cubic meter is 1,000 liters, we find that a mole of gas at STP occupies 22.4 L—a number memorized by many a chemistry student!

Physicists prefer a variant of the ideal gas law that derives from the study of "statistical mechanics," which is practically synonymous with thermodynamics and relates to the study of interactions between large ensembles of particles. The form looks pretty familiar, still:

$$PV = Nk_\text{B}T. \tag{B.4}$$

Pressure, volume, and temperature are all unchanged, and expressed in the same units as before. Now, N describes the *number* of particles (quite large, usually), and k_B is called the Boltzmann constant, having a value

$$k_\text{B} = 1.3806 \times 10^{-23} \frac{\text{J}}{\text{K}}. \tag{B.5}$$

Notice that N, the number of particles, and n, the number of moles, differs simply by a factor of Avogadro's number, $N_\text{A} = 6.022 \times 10^{23}$. Indeed, if we multiply N_A by k_B, we get 8.314, and are back to R.[22]

18: A Pascal (Pa) is also a Newton of force per square meter, which reduces to more fundamental units of J/m^3 (Joules of energy per cubic meter).

19: And $T(°\text{F}) = 1.8 \cdot T(°\text{C}) + 32$.

20: 1 atmosphere is 101,325 Pa.

21: It may be surprising, but the ideal gas law does not care what element or molecule we are considering!

22: The units work, too, since N_A effectively has units of a number (of particles) per mole.

Example B.4.2 Gas is stored at high pressure at room temperature in a metal cylinder, at a pressure of about 200 atmospheres.[23] The cylinder is designed to meet a safety factor of 2, meaning that it likely will not fail until pressure reaches 400 atmospheres. If a fire breaks out and the cylinder heats up, the pressure will rise. How hot must the gas get before the cylinder may no longer be able to hold the pressure (assuming no fire damage to the cylinder itself)?

We *could* start throwing numbers into the ideal gas law, but we don't know the volume or number of moles (or particles). Heck, we're not even given a temperature. Ack! Students hate this sort of problem, because it does not appear to be algorithmic in nature. No plug and chug (an activity that does not engage the brain heavily, and thus its appeal).

But we're okay. What is room temperature? Something like 20–25°C, so that's 293–298 K. Whatever the volume is, or the amount of gas in the cylinder, those things don't change as the temperature rises.[24] What we're left with is a straightforward scaling between temperature and pressure (because the numerical factors are all constant for our problem). Therefore, if temperature doubles, pressure doubles.[25]

Hey, it's doubling pressure that we are interested in, which will happen if the temperature doubles. So if the temperature goes up to about 600 K, we may be in trouble. It is easy to imagine that a fire could create such conditions. Notice that we are not bothering to say 586–596 K, but just said about 600 K. Do you want a precise temperature when the thing will rupture? Good luck. The point at which it explodes may be 405 atmospheres or it may hold on until 453. Also, how likely is it that all the gas throughout the cylinder is at exactly the same temperature when being heated by a nearby fire? So let's give ourselves a break and not pretend we're totally dialed in. There's a fire, after all.

23: . . . means 200 times atmospheric pressure

This is an example where internalizing the ideal gas law for what it *means*, or what it *says* is more important than treating it like a recipe for cranking out problems. Don't just treat equations as mechanical objects: learn what it is they have to *say*!

24: The gas is not leaking out, and the cylinder does not change size—at least not significantly—as it warms.

25: That's one of the things Eq. B.4 is trying to say, beneath all the bluster.

Selected Answers C

Numerical answers are given as ranges or other hints, meant to facilitate checking for gross departures from the right track, without revealing the precise answer so that shortcuts are discouraged. Questions for which the answer is already known (questions asking to verify an answer), easily validated in the text, or that are a matter of original thought or opinion may not be included here.

The ranges sometimes may be annoyingly large, but think of them as guard rails to prevent a tragic miscalculation or to catch a fundamental misunderstanding of the underlying concepts. It can help catch errors like dividing the wrong things or swapping numerator and denominator, or multiplying when division is called for. In many cases, intuition, or guessing, might lead you already to similar answers or ranges. With practice, students may be able to anticipate what they think are reasonable ranges for answers. In fact, it is a great practice to think about expectations before working on the problem.

This appendix, then, might be thought of as an "intuition implant" that simulates how problems are for experts. Real life does not provide "answers at the back of the book," so experts rely on experience, intuition, and a sense for "reasonable" results to help them understand when they've taken a wrong turn. A successful use of this appendix would help train students to develop their own "common sense" guard rails.

Chapter 1

4. Between 250 and 300 years

5. Between 250 and 300 years

6. Between 10^{18} and 10^{20}

7. Between 100 and 150

8. More than 10^{40}

9. Between 5 and 500

10. Later than 23:50

11. Before 12:10 AM

12. Between 10 and 40 years

14. Between 75 and 100 years

15. Between 300 and 500 billion

16. It's not 100 times longer

17. A few millennia

19. Between 50 and 100 W

20. A smidge higher then boiling

21. Between 200 and 250 K

22. Between 150 and 250 K

23. Between 100 and 275 K

Chapter 2

1. Nearly $100 billion

2. 4%: ~$1 trillion; 5%: more than $100 trillion

4. On the low end of advanced countries

5. Between 25 and 100 MJ/$

6. Between 5% and 50%

7. The text had trading art, singing lessons, therapy, and financial planning

8. Between 100 and 1,000; Less than 10 to go

9. Between 20 and 100 years

10. May help to think of something once prevalent, now rare

11. Especially fruitful might be biological dependencies

14. It can't all be free of material substance

Chapter 3

1. Less than a third

3. Comparable to U.S. population today

4. Comparable to world population 200 years ago

5. Table 3.2 offers a rough check

6. Over 16 billion; less than half the time we now experience

7. Pretty close to Table 3.2 except for first two entries

8. Answer *must* be less than 14 billion; whereas Problem 6 was in excess of 15 billion

9. Two are negative; three are positive

12. Between 1 and 5%

13. Add almost a half million; more than half million born; less than half million died

14. Answers should round to the table values

16. Only one country in the table creates more total demand, and only two have higher per-citizen contributions

17. Correct results are in the table

19. See Figure 3.15

20. This is why Africa gets attention, while North America is perhaps a greater concern.

21. It nearly triples

23. Area is key

25. Lesotho is relevant

Chapter 4

1. Earth: smaller than peppercorn and basketball-court distant; Moon: sand grain a hand's width away

3. Comparable to the actual Earth radius

5. 1 AU = 1 km; Earth 1/12,000 km

6. A fast walk or slow jog

7. Think about the subtended angle

8. Multiply sets to get accumulated scale factors

9. A good deal farther than the moon, but still well short of the sun/Mars

10. Ratio is more than a billion, and would take more than 4 lifetimes

16. Think in terms of area as fraction of plot space

17. Text has climbing Mt. Everest, supersonic commercial flight, squirrel obstacle course, and economic decoupling

18. Will take 15–20 tanks of gas, and achieve a fuel economy a factor of 30 or so below typical cars

19. Double the gasoline from previous problem; gasoline mass almost as much as the car itself

Chapter 5

1. Several inches

2. About the length of a typical room

3. A few kJ total, most in sliding

4. You've got this

6. Nearly 1 GJ

7. Two of the points in Example 5.2.1 offer guidance

8. Figure 5.1 offers hints

9. Roughly half human metabolic power

10. Less than 5 seconds

12. Between 50–100 kcal (200–400 kJ)

13. Sensibly, a little less than 2 minutes

14. Results should be roughly consistent with Figure 5.2

15. A bit less than 10% of household electricity

16. They're actually close, within 10%

17. More than two

18. Several kWh; less than $1

19. On the low end of the human metabolism range; the equivalent cost of 10–20 burritos

20. A few hundred W

21. Comparable to running a clothes dryer (Fig. 5.2)

22. Several hundred MJ

23. Over 100 kWh; 2–4 burritos-worth

24. Several Therms; cost of fast-food lunch

25. Several gallons; cost of fast-food lunch for two

26. One is about twice the other

27. A little in excess of 10 kW

28. Less than a quarter of estimated

29. Between 1 and 2 hours per day

30. The largest number is near 10^8

31. Six of the entries are inverses of six others

32. A little over an Amp

33. Nearly 10 kW; will cost over $1,000; don't do this!

34. Will last 2–3 hours

35. In line with most chemical reactions, in the 50–200 kJ/mol range

36. Between $3–5\times10^{-19}$ J per photon; get more than 10^{18}/sec

37. In the neighborhood of 1 μm or 1 eV

Chapter 6

1. Approx. 200 kJ, depending on mass

2. Several minutes

3. Several minutes

4. About 5 minutes

5. A few hours

6. Not below freezing

7. Not quite up to "room" temperature

8. Not quite half the time

9. The cost of two burritos per day

10. Instances of heat/flame causing movement

11. See Table 6.2

12. Roughly 30 kJ and 100 J/K

13. Between 5–10%

14. A couple dozen percent, roughly

15. Pushing 100%, but not quite there

16. Achieves about 1/3 of theoretical

17. $\Delta T > 50°$C; environment not that cold

18. Close to a dozen kJ

19. Twice, twice

20. Just short of 5 years

Chapter 7

1. a) between 30–40%; b) almost all; c) close to 2/3; d) roughly a quarter

2. Coal is near 12 qBtu, for instance

3. Nuclear is about 22%, for instance

4. Residential is about 5 qBtu, for instance

5. Industry is a little over 30%, for instance

6. About 14% is renewable, for instance

7. Less than 10%

8. Between 5 and 10%

9. It is one of the fossil fuels

10. Well over 100 years

11. Surprisingly soon: maybe before student loans paid off

12. Nothing to see here

13. Nothing to see here

14. Pay attention to the dashed line

15. Pay attention to the dashed line

Chapter 8

1. All lines overlap the up-slope

2. Likely vs. hopeful?

3. Many features unchanged

4. Won't be zero into future

5. What enabled, then disappeared?

6. Opposite of ideal

7. Did not behave like U.S.

8. Based on energy density

9. Roughly one-third

10. 2 H per C plus 2 more

11. In the neighborhood of 20 bbl/yr

12. Should be appropriate fraction of 10,000 W total

13. A little over 100 MJ and a few dozen kWh

14. Sum to about 15 kg, which would fill a refrigerator shelf in the water-bottle equivalent.

15. drinking glass

16. A few dozen times more volume, and about 10^2 in mass

17. $> 1,000\times$ more expensive

18. Will cost nearly $1,000

19. Between 10–15%

23. Approximately half-century

24. Roughly a third

25. If the rate of production increases. . .

26. What have you wanted that was all gone?

27. Shorter than R/P suggests

28. Opposite of virtual

29. Can't have what's not there

30. Reasons could fill a book

Chapter 9

1. A single integer works okay for all three

2. Nearly 100 kg

3. Between 10–15 kg

4. Approaching 1 GJ, and human-mass scale

5. Total is like small adult or large child

6. More than a factor of two

7. Get about 50 years; rate not constant

8. The numbers basically match

9. Between 1–2 ppm_v, in agreement with Figure 9.3

10. What is it we *know*?

11. Seems deserving of high marks

12. Historical vs. current activity levels

13. About 10°C cooler than actual

14. Two pure cases and one partial

15. Several degrees warmer

16. Very good for us at the right level

17. Numbers are not far from realistic

18. Triple pre-industrial and almost 5°C

19. End ~3°C high; almost linear, but not quite

20. No need to balance: Nature doesn't bother

21. It's no game-changer

22. Student's choice

23. E.g., 390 − 152 = 238 for a match

24. Use 290.6 K; looks like continuation of panel progression

25. A few millimeters

26. A little over a century

27. A year or two

28. A couple of degrees

29. Sum to about 700 years; almost all in ice and ocean

30. A few hundred meters

31. A finger's breadth per year

32. Keen to hear your thoughts

33. Keen to hear your thoughts

Chapter 10

1. Mostly clean; not all, though

2. Nothing is free

3. What would unlimited mean?

4. Table 10.2 has some help

5. Can't rely on any sun-driven energy

6. Between 200–250 W/m^2

7. Photosynthesis supports essentially all life

8. Comparing numbers in TW

9. More than half

10. A little less than 1%

11. Not far from 1,000 W/m^2

12. Nearly 10 degrees

13. Look for crazy-big input

14. Between 0.5–1 gallon

15. More than 4,000×

Chapter 11

1. Roughly 20 kJ
2. About 10 stories of a building
3. Close to 0.1 kJ
4. About 4 times higher than airliners travel
5. About two-thirds Earth radius
6. Try using half the mass and half the energy
7. Cube is roughly as big as height from ground
8. About 6 times typical nuclear plant
9. Nearly 200 m
10. A little shy of 500 m^3/s
11. Between 50–75%
12. Roughly 50%
13. About a million homes
14. Approaching 10,000 cubic meters per second
15. You've got a little over an hour
16. Less than 1 TW in the end
17. Between 1–2 meters

Chapter 12

1. A few Joules
2. Roughly 1°C
3. Something like 10 m/s
4. Mass shows up in both mgh and $\frac{1}{2}mv^2$
5. In the neighborhood of 1,500 m/s
6. About 5–10 humans–worth of mass!
7. Comparable to the height of Mt. Everest
8. Around about 8 times
9. Follow the cube. . .
10. Runs approximately 10 kW to 1 MW
11. Roughly two-thirds the original speed
12. Close to 10 MW
13. Closer to 10 m/s than to 15 m/s
14. Almost double freeway speeds
15. Between 5–10 m/s
16. In the ballpark of 70 kW
17. Recover 0.65%
18. Unpack W/m^2 to confirm kg/s^3
19. Outer box area corresponds to running at 100%, full time
20. Definitely less than 50%
21. Looks like a factor of 8
22. Approaching (American) football field length
23. Approximately 1 MW
24. They may not have equivalent energy needs

Chapter 13

1. How big are the packages?

2. Something times 10^{21}

3. Roughly 10^{16}

4. About 1,000

5. About 4,000 times

6. Use Eq. 13.3 to guide your reasoning

7. Should match Figure 13.1

8. One micron for each finger?

9. Think about spill-over into UV and/or IR

10. Peak around 2.5×10^8, about 1 μm wide; matches up well

11. Think energetics and depth

12. Is the answer transparent?

13. Just comparing two energies

14. Several hundred km/s

15. Condense the saga to that of a winner

16. Answer might involve physics, biology, rooftops

17. Inversely: larger in one means smaller in the other

18. Already extremely similar

19. Think of current as a rate of electron flow in the circuit

20. Get very close to 1,360 W/m^2

21. Sweltering is not preferred

22. Between 5–6 kWh/m^2/day; between 200–250 W/m^2

23. Involves interpreting kWh/m^2/day as full-sun-hours

24. Not far from 200 W/m^2

25. Range straddles 200 W/m^2, varying about 10%

26. Best at latitude; almost 15% better than flat

27. Approaches 6 kWh/m^2/day

28. Large house (and just the PV for one person)

29. Square is about as wide as Arizona or California east-to-west

30. Cost, surely—but other challenges and mismatches as well

31. A little over 200 W

32. Roughly the size of a bedroom

33. Will spend a little over $4,000

34. A little over a decade

35. Even lower than ~20% from insolation vs. overhead

36. About $2-worth of sun

37. Hint: study Figures 13.23 and 13.24

38. In absolute terms. . .

Chapter 14

1. About a dozen tons of CO_2

2. Between 0.1–0.5%

3. Almost 100 logs per person per year

4. In the neighborhood of half-dozen logs per day

5. Won't be exactly 15 years, but close

6. Almost 1.5 L of ethanol

7. Roughly consistent with Table 14.1 for coal

8. Net is one-third production

9. Extra land is twice the yield-land

10. A bit longer than a U.S. Presidential term

11. Nothing to spare

12. Corn now approximately 15% as much as this; still more than total arable land

13. Box barely fits north–south in U.S.

14. Personal preferences play a role

Chapter 15

1. A blueberry

2. $N = 8$

3. Use $Z = 26$ to get there

4. Should match quite well

5. Two diagonals have no gray squares

6. One has a half-life longer than a million years

7. Roughly twice as old as agriculture

8. Between 1–2%

9. One is about 3% of the other (both decay)

10. Step right

11. That last step might take a while

12. Two decays do it

14. Sand does the job

15. Somewhere between a car and a bus?

16. Close to 1 kg

17. Around a couple-dozen micrograms

18. Table should match

19. Energy has a mass, via $E = mc^2$

20. Adds about 1% to the mass

21. Not far from 1,500 MeV

22. Not much

23. Figure 15.14 is relevant

24. It's a strontium isotope

25. A is twice a prime number

26. Stick to $80 < A < 110$ and $125 < A < 155$ to respect distributions

27. Mid-20s of MeV

28. From steam onwards, it's basically the same

29. Between 3 and 5 cents per kWh

30. A few per week!

31. Around 20 tons per year (more in reality)

32. Almost 2 million tons

33. A few hundred tons

34. Less than a decade

37. Two stand out

38. Centuries

39. More often than once every two years

41. A nearly exact match!

42. Worked out in text: no calculation necessary—just interpretation

43. Energy jump size

44. Like a milk jug

Chapter 16

1. Shortfall is more than a factor of 200

2. A bit farther than the record

3. About as thick as a six-story building is tall

6. Ranges about 55–85%

7. Geothermal is a bit less than 1% of alternative electricity

8. A little shy of the 8 m design height, sensibly

9. Works out

10. Diameter like a small house's footprint

11. Comparable to human metabolism; 1% of American demand

12. A little more than 6 times that in Example 16.4.1

Chapter 17

3. Algae who?

5. Two words almost say it all

6. Fine if it is a little shy: transfer rates vary

7. Think about what a house *can* access, and steam plants

10. May be up there with solar (4 to 6, likely)

Chapter 18

1. 16 equal portions

2. Predicts largest well; not *too* far on smallest

4. Gaping disparities on opposite poles is no random fluke

6. Brilliant future if you can figure out effective ways

7. How else will change happen? (but elaborate. . .)

8. Will contribute 2–3% of the annual total

9. A bit over half the global energy budget!

10. Two approaches: cynical or hopeful; make either pitch

11. In the hundreds

12. I was hoping you had some ideas

Chapter 19

1. Still could be a parasite, even if larger than a flea

3. Easier to break than make

4. What things are dependent on growth to operate normally?

5. What limits?

7. Does it bear on humanity in some way?

8. Wait; who has my. . .

9. Focus on what has mattered until now

10. What's the alternative?

13. Please figure out how it can work!

14. Is this the movie version, or the real-life one?

Chapter 20

2. What needs to happen to avert?

3. Focus on demonstrable new conditions that likely push limits

4. Obligations of reality?

5. Some things are out of our control

7. What type of activity tends to consume a lot of power?

8. Duty cycle

9. Proportional to ΔT

10. Gasoline is about 4 times the other two

11. Just a bit less than average in all categories

12. Close to twice the gas is used in the form of electricity

13. Both in the same neighborhood

14. Big disparity; which is more likely?

15. S.U.V. might not make the cut, but smaller cars will

16. Surprisingly far: almost two-thirds of the way

17. Is six-sevenths a coincidence?

18. As if one day a week is all dairy/eggs

19. Is it directed or emergent?

20. Think frivolous or huge resource demand

21. Do your best: might prevent the worst

22. Can you even tell the needle isn't at full?

Alluring Tangents D

This Appendix contains tangential information that may be of interest to students, but too far removed from the main thread of material to warrant placement within chapters. Many of these items were prompted by student feedback on the first draft of the textbook, wanting to know more about some tantalizing piece mentioned in the text. Pick and choose according to your interests.

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D.1 Edge of the Universe

Sec. 4.1 (p. 54) built a step-wise scale out to the edge of the visible universe, which a margin note clarifies as the visible horizon of our universe. This fascinating and deep concept deserves elaboration.

Two foundations of experimental physics and cosmology are that the speed of light is finite, and the universe began in a Big Bang 13.8 billion years ago. Ample evidence supports of both claims. It should be noted that these notions were not at all accepted by scientists until the preponderance of evidence left little choice but to adopt them as how the world really appears to work.

The finite speed of light means that looking into the distance amounts to looking back in time. Here, Imperial units have a brief moment of glory, in that every foot of distance (0.3 m) is one nanosecond of time. We see the moon as it was 1.25 seconds "in the past," the sun as it was 500 seconds (8.3 minutes) ago, and the nearest star 4.2 years back. The "nearby" Andromeda Galaxy is 2.5 million years in the past, and as we peer farther into the universe we look ever farther back in time. Indeed, at great distances we see infant galaxies in the process of forming as gravitational vacuum cleaners collecting materials from the diffuse gas that came before.

So what happens when we look 13.8 billion years into the past, when the Big Bang is alleged to have happened? Shouldn't we see the explosion? And shouldn't it—perhaps confusingly—be visible in all directions?

The answer is a resounding, though qualified, YES. Yes, we see evidence of the Big Bang in all directions, as a glow that appears in the microwave region of the electromagnetic spectrum. The Cosmic Microwave Background, or CMB, as it is called, represents the glowing plasma when the universe was just 380,000 years old and about 1,100 times smaller than it is today. We cannot see earlier than this because the hot ionized plasma

that existed before this time is opaque[1] to light travel. The universe only became "clear" after this time, when the plasma cooled into neutral (mostly) hydrogen atoms. So we can see *almost* back to the Big Bang, at least 99.997% of the way before the scene becomes opaque.

1: . . . much as the sun, another plasma is opaque: we only see light from its outer surface

So that's the limit to our vision, based on the idea that light has not had time to travel farther since the universe began. This is what we mean by the edge of the *visible* universe.

But is it a real edge? All indications are that it is certainly not. When we look 13.8 billion light years away, we just see this glowing plasma (the CMB). But in the intervening years, galaxies and stars and planets have formed in that region of space, and would appear "normal," or mature today. So imagine a being on such a planet looking at us today, 13.8 billion light years distant. But they see us 13.8 billion years ago, when our neighborhood was still a glowing plasma well before the formation of galaxies, stars, and planets.

Let's say the distant being is directly behind you and you are both looking off in the same direction—the alien essentially looking over your shoulder as you look directly opposite the direction to the alien. You (or the primordial gas that will someday become you) are at the limit of their vision, and they can't see anything beyond you. You sit at their edge. But to you it's no edge. You have no trouble seeing more "normal" universe stretching another 13.8 billion light years beyond what our distant friend can see. It's only a perceived edge, based on the limit of light travel time.

A nice way to think of it is familiar scenes of limited vision, like in a fog or in the ocean, or even on the curved surface of Earth. All cases have a horizon: a limit to the distance visible. Yet moving to the edge of vision reveals a whole new region that was before invisible. Keep going and your starting region will no longer be visible, or within your horizon. But it has not ceased to exist.

Similarly, the universe would seem to be much larger than our visible horizon. Measurements of the "flatness" of the geometry of space suggest a universe that is *at least* 100 times larger than our horizon, and may in fact be *unfathomably* larger. We may never know for sure, as limits to light travel seal us off from direct observation of most of the universe.

D.2 Cosmic Energy Conservation

Sec. 5.2 (p. 69) discussed the foundational principle of the conservation of energy, claiming that the principle is never violated except on cosmic scales. Besides elaborating on that point, this section follows the story of energy across vast spans of time as our sun forms and ultimately delivers energy to propel a car. We also clarify what it means for energy to be "lost" to heat.

D.2.1 Cosmological Exception

Emmy Noether was a leading mathematician in the early twentieth century who also dabbled in physics. In a very profound insight, she recognized a deep connection between symmetries in nature and conservation laws. A *symmetry*, in this context, is a property that looks the same from multiple vantage points. For instance, a sphere is symmetric in that it looks the same from any angle. A cylinder or vase also has symmetry about one axis, but more limited than the sphere.

The symmetries Noether considered are more subtle symmetries in time, space, and direction.

Definition D.2.1 *Symmetry in time means that physics behaves the same at all times: that the laws and constants are the same, and an experiment cannot be devised that would be able to determine absolute time.*

Symmetry in space means that the laws of physics are the same no matter where one goes: fundamental experiments will not differ as a function of location.

Symmetry in direction is closely related to the previous one. It says that the universe (physical law) is the same in every direction.

The insight is that these symmetries imply conservation laws. Time symmetry dictates conservation of energy. Space symmetry leads to conservation of momentum. Directional symmetry results in conservation of angular momentum.

Great. As far as we know, the latter two are satisfied by our universe. To the best of our observational capabilities, the universe appears to be *homogeneous* (the same everywhere) and *isotropic* (the same in all directions). Yes, it's clumpy with galaxies, but by "same," we mean that physics appears to act the same way. Therefore, substantial observational evidence supports our adopting conservation of momentum and conservation of angular momentum as a fact of our reality.

But time symmetry is a problem, because the universe does not appear to be the same for all time. It appears to have emerged from a Big Bang (see Section D.1), and was therefore much different in the past than it is now, and continues to change/evolve. An experiment to measure the effective temperature of the Cosmic Microwave Background is enough to establish one's place on the timeline of the cosmic unfolding.

As a consequence, conservation of energy is not strictly enforced over cosmological timescales. When a photon travels across the universe, it "redshifts," as if its wavelength were being stretched along with the expansion of the universe. Longer wavelengths correspond to lower energy. Where did the photon's energy go? Because time symmetry is broken in the universe, the energy of the photon is under no obligation to remain constant over such timescales. Deal with it, the universe says.

On timescales relevant to human activities, conservation of energy is extremely reliable. One way to put this is that the universe is 13.8 billion years old, or just over 10^{10} years. So in the course of a year, physics would allow an energy change by one part in 10^{10}, or in the tenth decimal place. Generally, this is beyond our ability to distinguish, in practical circumstances.

But violations are even more restricted than that. A photon streaming across the universe is in the grip of cosmic expansion and bears witness to associated energy changes. But a deposit of oil lying underground for 100 million years is chemically bound and not "grabbable" by universal expansion, so is not "degraded" by cosmic expansion. In the end, while we acknowledge that energy conservation is not strictly obeyed in our universe, it might as well be for all practical purposes. Thus, this section amounts to a tiny asterisk or caveat on the statement that energy is always conserved.

D.2.2 Convoluted Conservation

This section follows a chain of energy conversions that starts before our own Sun was formed, and ends in a car wreck as a way to flesh out the manner in which energy is conserved, in practice. Don't worry about understanding every step, but absorb the overall theme that energy is changing from one form to the other throughout the process.

A gas cloud in space collapses due to gravitational attraction, exchanging gravitational potential energy into kinetic energy as the gas particles race toward the center of the cloud. The cloud collapses into a tight ball and all that kinetic energy in the gas particles "thermalizes" through collisions,[2] generating a hot ball of gas that is to become a star. As the ball of gas contracts more, additional gravitational potential energy is exchanged for thermal energy as the proto-star gets hotter.

Eventually, particles in the core of the about-to-be star are moving so fast as they heat up that the electrical potential barrier[3] is overcome so that protons can get close enough for the strong nuclear force to take over and permit nuclear fusion to occur, at which point we can call this thing a *star*. Four protons[4] bond together, two of which convert to neutrons to form a helium nucleus. The total mass of the result is *less* than the summed mass of the inputs, the balance[5] going into photons, or light energy.

The photons eventually make it out of the opaque plasma of the star, and stream toward Earth, where a leaf absorbs the energy and cleverly converts it to chemical energy by rearranging atoms and electrons into sugars.[6] The leaf falls off and eventually settles at the bottom of a shallow sea to be buried by sediments and ultimately becomes oil, preserving most[7] of its chemical energy as it changes molecular form.

2: Thermal energy is nothing more than kinetic energy—fast motion—of individual particles at the microscopic scale. Thermalizing means transferring energy into heat, or into randomized kinetic energy of particles in the medium.

3: . . . charge repulsion of two protons as their collision course brings them close to each other

4: . . . hydrogen nuclei

5: . . . via $E = mc^2$; see Sec. 15.3 (p. 246)

6: We call this photosynthesis.

7: To the extent that energy is "lost" in any of these exchanges—operating at < 100% efficiency—we should recognize that the missing energy just flows into other paths, generally into heat.

One day, a silly human digs up the oil and combusts it with oxygen, converting chemical energy to thermal energy in a contained fireball explosion. The thermal energy is used to produce kinetic energy of a piston in a cylinder, transmitted mechanically to wheels that in turn propel a car along a freeway.[8]

8: . . . kinetic energy

The car climbs a mountain, converting chemical energy in the fuel into gravitational potential energy via the same thermal-to-mechanical chain described above. Along the way, kinetic energy is given to the air, thermal energy is given to the environment by the hot engine, and brakes get hot as the kinetic energy of the car is converted to heat via friction as the car comes to a stop. But the car does not fully stop in time before tipping over a cliff and giving up its gravitational potential energy to kinetic energy as the car plummets and picks up speed.

At the bottom, the crunch of the car ends up in bent metal[9] and heat. It does not explode, since this is not a movie. All the heat that was generated along the way ends up radiating to space as infrared radiation (photons), to stream across empty space—probably for all eternity.

9: . . . a form of electric potential energy

Tracing the energy we use for transportation back far enough, passes through oil, photosynthesis, sunlight, and nuclear fusion in the sun's core. Going back further, we recognize nuclear energy as deriving from gravitational energy of the collapsing material. What gave the atoms in the universe gravitational potential energy? The answer would have to be the Big Bang, truly arriving at the end (beginning) of the story.

D.2.3 Lost to Heat

The sequence in Section D.2.2 terminated in heat and infrared radiation. But let's flesh this out a bit, as heat is an almost-universal "endpoint" for energy flows.

Since energy is conserved, whatever goes to heat does not truly disappear: the energy is still quantifiable, measurable energy. It is considered to be "low grade" energy because it is hard to make it do anything useful, unless the resulting temperature is significantly different from the surroundings. Sec. 6.4 (p. 88) discusses notable exceptions, wherein we derive substantial useful work from thermal energy in heat engines.[10] For now, we just note that it is entropy that limits the use of thermal energy.

10: In this way, we can make an explosion or fireball do useful work as in dynamite, internal combustion, or a coal-fired power plant.

When a book slides across a floor, it gives up its kinetic energy to heat caused by friction in the floor–book interface. When a car applies brakes and comes to a stop, a very similar process heats the brake pads and rotors. As a car speeds down the road, it stirs the air and also experiences friction in the axle/bearings and in the constant deformation of the tire as its round shape flattens on the road continuously. The stirred air swirls around in eddies that break up into progressively smaller ones

until at the millimeter scale viscosity (friction) turns even this kinetic motion into randomized motion (heat).

Human metabolism converts chemical energy from food into exportable mechanical work (lifting, moving, digging, etc.) at an efficiency of 20–25%. The rest is heat, which is conveniently used to maintain body temperature in most environments. But even most of the external work performed ends up as heat. The primary exception may be lifting masses to a higher location. Even this is temporary in the very long run,[11] and the stored energy will ultimately flow into heat.

11: The "shelf" we place the mass on eventually collapses or is otherwise disturbed.

Light from our artificial sources and screens survives for a few nanoseconds as photon energy, but eventually is absorbed onto surfaces and turns to heat. Some small fraction of our light escapes to space and carries non-thermal energy away, but this is incidental and could be said to represent poor design (not putting light where it is useful).

Even devices whose job it is to *cool* things are net generators of heat. The air pushed out the back and bottom of a refrigerator is warm, as is the exhaust from an air conditioning unit. Virtually all energy pulled out of an electrical wall socket ends up as heat in the room in some way or another. A fan actually *deposits* a little bit of energy (heat) into the room, but feels cool to us only because the moving air enhances evaporation of water from our skin (perspiration), carrying energy away.

Essentially the only exceptions to the heat fate of our energy expenditures is anything that we launch into space, like electromagnetic radiation (radio, light). This is a very tiny fraction of our energy expenditure, and can be quantitatively ignored. Most of our energy is from burning fossil fuels, which is an inherently thermal process. The part we salvage as useful energy itself tends to end up as heat after serving its intended purpose.

In the end, most of the heat we generate on Earth's surface finds its way back to space as infrared radiation. All objects glow in the infrared, and once the radiation escapes our atmosphere it is gone from Earth forever.[12] At this point, the energy is pretty well spent, so that we would not be able to profit from its use should we try to capture it.[13] The energy that came from the universe returns there, as part of the dull, fading glow that lingers from the Big Bang.

12: . . . except for some improbable paths that reflect off the moon, for instance, and return to Earth

13: The temperature of the radiating entities is so close to ambient temperature that its efficiency to perform useful work would be nearly zero.

D.3 Electrified Transport

This section aims to answer the question: Why can't we *just*[14] electrify transportation and be done with fossil fuels? It turns out to be hard. Rather then rely on external studies, this section applies lessons from the book to demonstrate the power of first-principles quantitative assessment.

14: . . . beware of the word "just," often hiding lack of familiarity

Box 13.3 (p. 212) indicated that direct drive of cars and airplanes from solar energy is impractical: while it may work in limited applications, solar power is too diffuse to power air and car travel as we know it.

Thus electrified transport becomes all about **storage**, generally in batteries. Several times in the book, the energy density of gasoline was compared to that of battery storage. In rough numbers, gasoline delivers about 11 kcal/g, working out to ~13 kWh/kg in units that will be useful to this discussion. Meanwhile, lithium-ion batteries characteristic of those found in cars[15] have energy densities about one-hundred times smaller.

15: The larger Tesla battery pack, for instance, provides 265 miles (425 km) of range and holds 85 kWh at a mass of 540 kg for an energy density of 0.16 kWh/g.

This section will use the most optimistic energy density for lithium-ion batteries—around 0.2 kWh/kg—which is about 65 times less than for gasoline. Offsetting this somewhat is the fact that electric drive can be as high as 90% efficient at delivering stored energy into mechanical energy, while the thermal conversion of fossil energy in large vehicles is more typically 25%. The net effect is roughly a factor of twenty[16] difference in delivered energy per kilogram of fuel vs. storage.

16: The math goes: 13 kWh/kg divided by 0.2 kWh/kg times 0.25/0.90, yielding a factor of 18. For the sake of estimation, 18 is close enough to a factor of 20 to use the more convenient and memorable 20× scaling factor in what follows.

The enormous mismatch in energy density between liquid fossil fuels and battery storage is the crux of the problem for transportation, the implications of which are explored here. We will start at the hard end, and work toward the easier.

D.3.1 Airplanes

Box 17.1 (p. 290) already did the work to evaluate the feasibility of powering typical passenger planes electrically. The result was a reduction in range by a factor of 20, consistent with the premise above: the best lithium-ion technology—not yet achieved in mass-market—at 90% efficiency delivers about 5% as much mechanical energy per kilogram as do liquid fossil fuels.

Keeping the same 15 ton[17] "fuel" mass, but now at 0.2 kWh/kg results in a 3,000 kWh battery capacity. The factor-of-twenty energy reduction per mass results in ranges down from 4,000 km via jet fuel to 200 km on battery, which is a two-hour drive, effectively. Charging a 3,000 kWh battery in the 30 minutes it typically takes for a plane to turn around—in efficient operations, anyway—would consume 6,000 kW, or 6 MW of power, which is about the same as the average electricity consumption of 5,000 homes.

17: One metric ton is 1,000 kg, and is often spelled tonne. Here, ton is used to mean metric ton, which is only 10% larger than the Imperial "short ton."

We will keep track of kWh per kilometer as a useful metric for transportation efficiency, putting it all together at the end (Section D.3.7). In the case of air travel, it's 3,000 kWh to go 200 km, or 15 kWh/km. On a per-passenger basis, 150 passengers in the airplane results in 0.1 kWh/km/person.

D.3.2 Shipping

Large container ships ply the seas carrying stacks of shipping containers over very long stretches of open ocean. A typical ship operating between Shanghai and Los Angeles travels 10,400 km carrying 10,000 20-foot equivalent[18] containers each bearing an average of something like 10 tons of cargo. Thus, the full (maximum) load is 100,000 tons.[19]

18: . . . TEU: 20-ft-equivalent units

19: . . . called DWT: dead-weight tonnage

At normal cruising speed, the ship takes 10 days to make the journey, consuming about 325 tons of fuel per day. A battery large enough to replace 3,250 tons of fuel would be 20 times more massive, at 65,000 tons, displacing two-thirds of the cargo capacity, and requiring triple the number of ships to carry the same cargo. The resulting 13,000,000 kWh of storage[20] to travel 10,000 km results in 1,300 kWh/km.

20: This is 13 GWh, which would take the equivalent of an entire 1 GW power plant 13 hours to charge—or longer considering imperfect charge efficiency.

The open ocean has no refueling stations. Even a refueling ship/platform would have to get the electrical energy from *somewhere*. Thus, shipping would be radically changed if electrified. Electric ships may not be able to cross open ocean, instead hugging the coast dotted with power plants[21] to supply frequent and lengthy charge stops for the ships.

21: . . . and from what source do *they* get energy? . . . picturing outposts on the remote Aleutian Islands

D.3.3 Long-haul trucking

Typical "big rigs" on the highway achieve a fuel economy around 6 miles per gallon (40 L/100 km) of fuel, while the most aerodynamic ones achieve 8 mpg (30 L/100 km). Long haul rigs carry two fuel tanks, each holding about 150 gallons (570 L; 425 kg). The range for the more efficient trucks therefore becomes about 2,000 miles (3,200 km).[22] Cargo capacity is about 20 tons.

22: . . . not using 100% of capacity to leave some prudent reserve

Total fuel mass is 300 gal times 2.85 kg/gal,[23] or about 850 kg. The same mass of battery would hold 170 kWh and deliver a range of 100 miles (160 km; roughly 1 kWh/km). Ugh. Lots of recharging stops.

23: . . . density, in unusual units; equivalent to ~0.75 kg/L

But wait, trucks are big, right? Surely a larger battery can be accommodated. Unlike airplanes, where mass is critical, trucks can afford to pack on a larger battery. Some of the cargo space could be devoted to energy storage, surely. What fraction of the space would be acceptable?

To achieve comparable range as is presently realized, the battery mass would need to be about 20 times the gasoline mass, or 17,000 kg. Oh dear—the maximum cargo load was about 20 tons. So 85% of the cargo capacity is taken up by battery, which would seem to be unacceptable.

A solution would be smaller batteries and more frequent charging stops—possibly in the form of forklift-loaded pre-charged modules that are owned by the trucking company and can be interchanged among the fleet. Otherwise a substantial fraction of time would be spent charging: very possibly more time than is spent driving.

It is not impossible[24] to electrify long-haul trucking, but neither is it free of significant challenges. Certainly it is not as easy and convenient as fossil fuels.

24: Indeed, Tesla offers a Semi capable of 500 mile range, but see this careful analysis [129] on the hardships.

D.3.4 Buses

Like cargo ships and long-haul trucks, public transit buses are on the go much of the time, favoring solutions that can drive all day and charge overnight. Given the stops and breaks, a typical bus may average 30 km/hour and run 14 hours per day for a daily range of approximately 400 km. At an average fuel economy of 3.5 mpg (70 L/100 km), each day requires about 300 L or 220 kg of fuel—no problem for a fuel tank. The equivalent battery would need to be 4,500 kg (900 kWh; 2.3 kWh/km), occupying about three cubic meters. Size itself is not a problem: the roof of the bus could spread out a 0.15 m high pack covering a 2 m × 10 m patch. Buses typically are 10–15 tons, so adding 4.4 tons in battery is not a killer.

Electrified transit is therefore in the feasible/practical camp. What makes it so—unlike the previous examples—is slow travel, modest daily ranges, and the ability to recharge overnight. Raw range efficiency is low, at 2.3 kWh/km, but this drops to a more respectable 0.2 kWh/km per person for an average occupancy of 10 riders.

For charging overnight, a metropolitan transit system running 50 routes and 8 buses per route[25] and therefore needs to charge 400 buses over 6 hours at an average rate of 150 kW per bus[26] for a total demand of 60 MW—equivalent to the electricity demand of about 50,000 homes.

25: A one-hour one-way route operating on a 15 minute schedule needs 4 buses in service in each direction of the route, for instance.

26: . . . 900 kWh capacity and 6 hours to charge

D.3.5 Passenger Cars

Passenger cars are definitely feasible and practical for some uses. Typically achieving 0.15–0.20 kWh/km, the average American car driving 12,000 miles per year (about 50 km/day, on average) would need at least 10 kWh capacity to satisfy average daily driving, but would need closer to 100 kWh to match typical ~500 km ranges of gasoline cars.

At a current typical cost of $200–300 per kWh, such a battery costs $20,000 to $30,000, without the car.[27] The most basic home charger runs at 120 V and 12 A,[28] multiplying to 1,440 W. A 100 kWh battery actually takes closer to 110–120 kWh of input due to 80–90% charge efficiency. Dividing 115 kWh by 1.44 kW leaves 80 hours[29] as the charge time. Table D.1 provides similar details for this and two other higher-power scenarios.

27: Thus, long-range electric cars roughly double the price.

28: . . . satisfying the 80% safety limit for a 15 A circuit

29: . . . 3.3 days!

The middle row of Table D.1 is most typical for home chargers and those found in parking lot charge stations, resulting in an effective *charge speed* of about 10 miles per hour, or 16 km/hr. This is a convenient way to

Volts	Amps	circuit	kW	hours	mi/hr	km/hr
120	12	15 A	1.44	80	4	6
240	16	20 A	3.8	30	10	16
240	40	50 A	9.6	12	25	40

Table D.1: Approximate charge times and effective speeds (in miles per hour and kilometers per hour) for charging a 100 kWh battery at three different household power options. Such a battery delivers a range of about 300 miles, or 500 km.

characterize charge times. Adding enough charge to cover an average day of 30 miles or 50 km will take about 3 hours for the middle-row case, or just over an hour for the high-power charge.

Imagine now making a long road trip, driving at 100 km per hour. Even the fastest charge rate[30] in Table D.1 is 2.5 times slower. Every 400 km driven will take 4 hours on the road plus 10 hours at a charger for an average rate of 28 km/hr,[31] or 18 mi/hr.

Special fast-charge stations can provide a staggering 250 kW[32] of power, cutting charge times dramatically. But this is neighborhood-scale energy delivery that households cannot expect to supply themselves. It is also informative to compute the temperature rise of a battery from a fast charge. If charging is 90% efficient, the other 10% turns to heat in the battery. Each kilowatt-hour of battery capacity has an associated mass around 5–10 kg, and receives 0.1 kWh (360 kJ) of thermal energy when charged. At a specific heat capacity around 1,000 J/kg/°C, a 360 kJ deposition increases the cell's temperature by 36–72°C, depending on energy density.[33] This is not a small rise (reaching boiling temperatures on warm days), and can contribute to shorter battery lifetime.

So electric cars are not simple drop-in replacements for the gasoline machines roaming the roads today, that effectively refuel at a rate of 10 MW[34] given the fast delivery of an extremely energy-dense liquid. On performance and convenience measures, it would be hard to characterize them as *superior* substitutes. But they can *certainly* suit well for local travel when given ample time to recharge—overnight, for instance. And in the long run, it seems we will have little choice.

For all this, several things still are not clear:

1. Will large scale ownership of electric cars become affordable, or remain cost prohibitive? Battery prices will surely fall, but enough?
2. If widespread, how will residential areas cope with tremendous increases in electrical demand during popular recharge hours?
3. How could night-time charging utilize solar input?
4. Will enough people willingly give up long-range driving capability? Will dual-system cars (like plug-in hybrids) be preferred to maintain gas capability for the occasional longer trip?
5. Will people sour over costly battery decline and replacement?

Electric cars are a growing part of transportation, and will no doubt grow more. It is too early to tell whether they will be able to displace fossil cars in the intermediate term. If not, personal transportation is likely to decline as fossil fuel use inevitably tapers away.

30: . . . which is much higher than typical parking lot chargers that are more in line with the middle row

31: . . . 400 km in 14 hours

32: . . . like 200 homes

33: . . . higher energy density (better) batteries will experience a larger temperature rise based on less mass to heat up per amount of energy injected

34: . . . the equivalent electricity consumption of 10,000 homes or a medium-sized college campus

D.3.6 Wired Systems

To finalize the progression of hardest–to–easiest electrified transportation, we leave the problematic element behind: batteries. Vehicles on prescribed routes (trains, buses) can take advantage of wires carrying electricity: either overhead or tucked into a "third rail" on the ground. Most light rail systems use this approach, and some cities have wires over their streets for trolley buses. High-speed trains also tend to be driven electrically, via overhead lines.

The ease with which wired electrical transport is implemented[35] relative to the other modes discussed in this Appendix is another way to emphasize the degree to which storage is the bottleneck.

35: Wired electrified transport has been a steady contributor to transportation for over a century.

D.3.7 Collected Efficiencies

Each transportation mode in the previous sections reported an efficiency, in terms of kilowatt-hours per kilometer. Not surprisingly, mass and speed play a role, making container ships very hard indeed to push along, followed by airplanes. In some cases, it makes sense to express on a per-passenger or per-ton basis, distributing the energy share among its beneficiaries. Table D.2 summarizes the results, sometimes offering multiple options for vehicle occupancy to allow more fruitful comparisons among modes. Note that air travel looks pretty good until realizing that the distances involved are often quite large, making total energy expenditure substantial for air travel.

Mode	context	kWh/km	load	kWh/km/unit
Ship	cargo	1,300	100 kton	~0.01/ton
Air	passenger	15	150 ppl	0.1/psn
	cargo		15 ton	1/ton
Bus	passenger	2.3	10 ppl	~0.2/psn
	passenger		30 ppl	~0.07/psn
Truck	cargo	~1	20 ton	0.05/ton
Car	passenger	0.18	1 psn	~0.18/psn
	passenger		2 ppl	~0.09/psn

Table D.2: Energy requirements for various modes of transportation (lower numbers are more efficient). Total energy is distance times the measure in kWh/km. Loads are expressed contextually either as people (ppl) or tons (1000 kg). Per-passenger/ton efficiency depends on occupancy—expressed as kWh/km per person (psn)—for which multiple instances are offered in some cases. While trucks have a far better kWh/km measure than ships, ships are about four times more efficient per ton, carrying 5,000 times more cargo. Air freight is 100 times more energetically costly than by ship!

D.4 Pushing Out the Moon

Some forms of alternative energy are tagged with asterisks in Table 10.1 (p. 166), indicating that they are not *technically* renewable, but will last a very long time so might as well be considered to be renewable.

Tidal energy, covered in Sec. 16.2 (p. 280), is one such entry that honestly does not deserve much attention. The text mentioned in passing that

aggressive use of tidal energy has the power to push the moon away from Earth, providing the mechanism by which we could "use up" this resource. Curious students demanded an explanation. Even though it's not of any practical importance, the physics is neat enough that the explanation can at least go in an appendix.

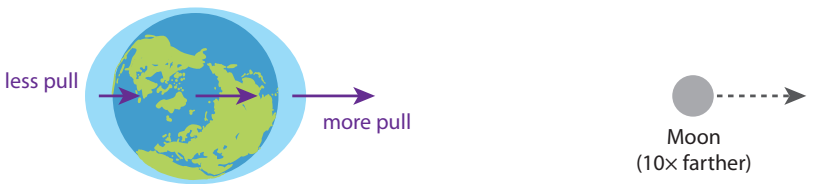

Figure D.1: The moon pulls harder on the near side of the earth, and less hard on the back side. Relative to the earth as a whole (medium force), the near side advances toward the moon and the back side lags the rest of the earth, creating a bulge on both sides that is aligned toward the moon. Note that a drawing to scale would put the moon well off the page.

The first step is realizing that Earth and Moon each *pull on each other*[36] via gravitation. Since the strength of gravity decreases in proportion to the square of the distance between objects, the side of the earth closest to the moon is pulled more strongly than the center of the earth, and the side opposite the moon is pulled less strongly. The result is an elongation of the earth into a bulge—mostly manifested in the oceans (Figure D.1).

36: In fact, equally, per Newton's third law.

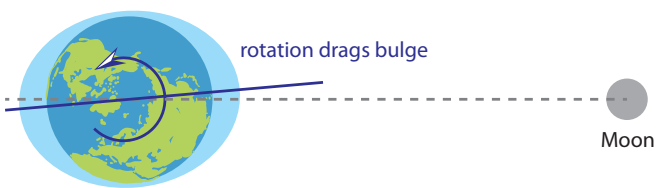

Figure D.2: The rotation of Earth and it continents "underneath" the tidal bulge creates a friction, or drag, that pulls the bulge around a few degrees (somewhat exaggerated here), so that it no longer points directly at the moon.

The second step is to appreciate that the earth rotates "underneath" the moon, so that the bulge—pointing at the moon—is not locked in place relative to continents.[37] But friction between land and water "drag" the bulge around, very slightly rotating the bulge to point a *little* ahead[38] of the moon's position (Figure D.2).

37: This is why we experience two high tides per day and two low tides: the earth is spinning underneath the opposite bulges, so that a site on the surface passes under a bulge (high tide) every ~ 12 hours.

38: The angular shift is around 1–2°.

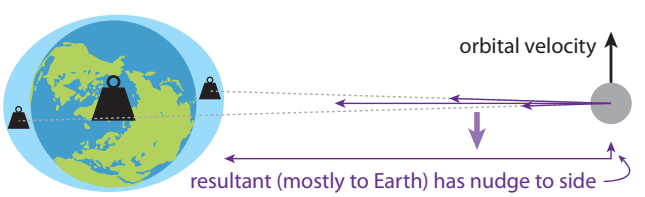

Figure D.3: Gravitationally, the earth looks like a big central mass and two bulge masses displaced from the connecting line. The closer mass pulls harder than the more distant one, so the addition of all the force vectors (not to scale) results in a little asymmetry, leaving a small sideways component of the force along the same direction as the moon's orbital velocity (up in this drawing).

Now think about how the moon sees the earth, gravitationally. It mostly sees a spherical earth, but also a bulge on the front side, slightly displaced, and a bulge on the back side, also displaced in the opposite direction (Figure D.3). While the bulge masses are equal, the closer one has a greater gravitational influence and acts to pull the moon a little forward in its orbit, speeding it up.[39]

39: It may help to think of this bulge as being like a carrot dangled in front of a horse, encouraging it forward.

Accelerating an orbiting object along its trajectory adds energy to the orbit and allows the object to "climb" a little farther away from the

central body. So this displaced tidal bulge on Earth is tugging the moon forward and causing it to climb about 3.8 cm per year away from Earth. That's one-ten-billionth of its orbital radius per year, so it's not going away for a very long time, indeed.[40]

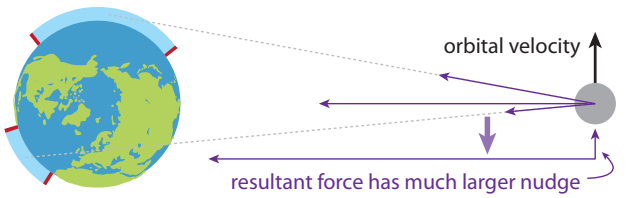

Figure D.4: If we built some inconceivable global-scale tidal capture structure the size of oceans and let them drain for six hours or so, the artificial bulges we created would travel farther around with the earth's rotation, enhancing the sideways "kick" and encouraging the moon to climb away from earth at a faster rate.

If we built global-scale structures (Figure D.4) to capture tidal energy in a big way,[41] we would effectively increase the lag angle of the tidal bulge. This is because we would likely release the captured stack of water over a period of many hours,[42], rotating this stack of water around the planet farther than it would naturally go. Now the gravitational pull in the forward direction would increase and the egress would speed up. If we managed to extract 18 TW[43] out of tides, this would be six times larger than the current 3 TW of tidal dissipation, and we might expect the egress to increase to about 23 cm per year.

It's still a slow rate, and would not drive the moon away faster than hundreds of millions of years. So technically tidal energy is a one-time resource whose use diminishes its long term capacity.[44] But the timescales are so ridiculously long that we may as well think of tidal energy as inexhaustible.

40: All the same, total solar eclipses will no longer occur after several hundred million years because the moon will be farther and too small to entirely block the sun.

41: Don't count on this happening: it's a truly ludicrous idea plagued by a giant list of practical problems, and all for such a small gain.

42: . . . like the ~6 hours between high tide and the next low-to-high tide cycle

43: . . . our current energy scale; not feasible, but used to illustrate

44: This is why it is not strictly renewable

D.5 The Long View for Humanity

Sec. 8.1 (p. 114) took a sweeping view of humanity's timeline as a useful lens through which to appreciate the very short age during which fossil fuels impart a substantial energy benefit. This section revisits this time-warping perspective in a slightly different way as a means to reflect on humanity's far future.

D.5.1 Success vs. Failure

We start by noting that human civilization is about 10,000 years old, to the nearest order-of-magnitude.[45] Consider this question:

> Is human civilization still in its infancy, or are we closer to the end than the beginning?

Wow. Heavy question. Of course, we do not *know* the answer, but most of us would prefer to believe the first—that we are only beginning. So let's roll with that and explore the consequences.

45: This roughly marks the start of agriculture, and in any case is far closer to the truth than the adjacent order-of-magnitude figures of 1,000 years or 100,000 years.

In order for human civilization to be in its infancy, it would have to continue for *at least* 10,000 years more, if not far longer. What would it mean for us to still be operating "successfully" 10,000 years from now? Our physics and math approach actually allows us to place constraints!

This discussion is limited to living on Earth. Chapter 4 laid out reasons why imagining a space-faring future may be misguided. But even ignoring these arguments, Chapter 1 illustrated that human growth ambitions would be brought to an end long before 10,000 years pass. In this light, it is most straightforward to concentrate on what it would take to succeed on Earth itself.[46]

46: Even if extending to other planets, the same logic will apply.

If we manage to carry our civilization into the far future,[47] we can comfortably call this **success**. If we don't, well, that would be **failure**. Can we sketch out what success looks like? One easy way to get there is to start enumerating the things that *can't* be carried into the far future.

47: A useful definition might be uninterrupted preservation of the knowledge and history gained thus far, without some apocalyptic collapse forcing a start-from-scratch revival—to the extent that's even plausible.

1. Fossil fuels will not power civilization: a large fraction of the initial inheritance has been spent in a short 200 years,[48] so that 10,000 years in the future it is safe to say they will be long gone.
2. No steady annual decline of natural resources like forests, fisheries, fresh water, or species populations can be brooked. Allowing any component to decline would mean eventually losing that resource, which may be critical to our survival.
3. Human population will not be allowed to grow. Even small growth rates will step up pressure on natural resources, and Earth can only support so much, long-term. Independent of what the "right" number is,[49] once settled, we will not be able to dial it up without imperiling the hard-won success.
4. Even under steady human population, any increase in resource use per person will also not be compatible. In general, growth leads to a dead end: to failure.
5. Mining materials from the Earth will not continue at anything near the current pace. In the last few hundred years, the best deposits of copper, gold, aluminum, etc. have been found and exploited. Even if only 10% of the attainable resource has been consumed thus far,[50] continuing for tens of thousands of years (and beyond) cannot be expected.
6. Ultimately, any activity that draws down a finite natural resource will be impossible to sustain if the extraction rate is modest or high in relation to the initial resource abundance. Anything that can't last for well over 10,000 years is not a viable long-term solution and should not be exploited if success is the goal. Likewise, any pollutant that can build up to dangerous levels on even these very long timescales cannot be tolerated, if failure is to be avoided.
7. We can use the rule of 70 to say that anything having a doubling time (or halving-time in the case of depletion) shorter than 10,000 years is a no-go for success on these timescales, meaning that any activity impacting resources would have to be held to a growth rate

48: . . . most of this in the last 50 years

49: . . . unlikely as high as 10 billion, and it could even be well less than a billion, depending on living standards

50: . . . author's conjecture; it could well be higher

or depletion rate of less than 0.007% per year, which is essentially zero-growth.

It becomes clear that long-term **success** is practically synonymous with the word **sustainable**. Any practice that is not long-term sustainable will fail to continue.[51] We therefore cannot *depend* on any non-sustainable resource if we strive for success.

51: Any activity today not geared to contribute to ultimate success (true sustainability) is therefore likely only contributing to failure. Most activities today are in the latter category, alarmingly.

D.5.2 Sustainable Living

Imagine that you have a stash of $100,000 tucked under your mattress, and that you have figured out a way to live on $20,000 per year. You *could* decide to live on this fund for five years, and then figure out later how to keep going. Perhaps this is not the wisest move. A smarter move would be to figure out how long you expect to live—maybe 50 more years—and ration out the fund, allowing $2,000 per year. You'll still need a job earning $18,000 per year to meet the $20,000 annual goal. Maybe the smartest move would be to *ignore* the money under the mattress and get a job for $20,000 per year.[52] Now you have the safety of resources should you need it, and can even pass it along down the generations to kids and grandkids who have also been taught not to use it, but to survive on their annual income.

52: . . . hardly different from $18,000 per year, so if you're going this far already, why not?

The analogy is clear, and perhaps it is also clear why we did not allow interest accumulation, as many of Earth's resources are one-time endowments that do not spontaneously grow larger.[53] If our human civilization succeeds at surviving uninterrupted for 10,000 years, it will necessarily be *because* we figured out how to live on the **annual income**[54] provided by Earth's natural renewable flows, rather than on the **inheritance** in the form of finite resources that are not replenished. In other words, humanity needs to learn to refrain from any dependence on one-time resources (the inheritance).

53: Interest is an artificial construct made possble by accelerating resource use.

54: Annual income would be in the form of solar energy delivered and biomass that has grown in the course of the year, for instance.

Success, therefore, puts humans as *a part* of nature, not *apart* from nature. Anything else is failure. The closer we are to nature, the more likely we are to succeed.

Nature prepared a biosphere that has stood the test of time. Natural selection has operated to eliminate non-viable solutions and create interdependencies cleverly balanced in a stable equilibrium of sorts. Elements of modern human civilization—our cities, agricultural practices, fossil fuel dependence—have *not* withstood the test of time, nor can they. Which system would be the wiser bet for long-term survival: the well adapted natural world, or the artificial world humans have erected and operated for a few dozen decades—without attention to sustainable principles? The answer seems obvious.

D.5.3 Time to Grow Up

In a sense, humanity is going through an awkward adolescent phase: growth spurts, a factory (pimple) strewn landscape, an attitude that we have all the answers—adults[55] can't possibly understand or tell us what to do. Conversely, nature is mature.[56] Ignoring recent human influences, it had already forged its complex, never perfect, but functional interdependencies and had settled into something resembling a steady state. Adolescents new to the scene may be hugely disruptive and destructive, and unless they change their ways, civilization drives straight into the jaws of failure. The adolescents lack the wisdom to build lasting systems that will have the privilege of co-existing with nature for very long.

55: . . . in this case hypothetical wise humans who have managed a successful transition through the adolescent phase

56: Note the similarity of the words!

In human society, most adolescents become adults who learn to live within their means. Sometimes this involves sacrifices or perhaps selecting a diet based on nutrition and health rather than what might be most tasty.[57] Likewise, humankind needs to define a scale for its activities that fits within nature's capacity to replenish, so that each subsequent generation is not deprived of resources the previous ones enjoyed. At present, civilization is *nowhere close* to this operating principle.

57: . . . opting out of the plan to eat ice cream for dinner

D.5.4 Frameworks

Humanity needs to develop a framework by which to evaluate its activities and ask whether each helps or hurts ultimate human success. Sometimes this might produce jarring results. Consider, for instance, a cure for cancer or other advances that might extend human lifetimes. Only if balanced against a smaller population or a smaller resource utilization per capita could such seemingly positive developments be accommodated once a steady equilibrium is established. Otherwise, total demand on Earth's resources goes up if the same number of people live longer at a fixed annual resource utilization per living person. In a successful world, any proposed new activity would have to demonstrate how it fits within a sustainable framework. Ignoring the issue would irresponsibly imperil overall long-term human happiness.[58]

58: In such cases, the outcome may ultimately settle on longer lives for fewer people.

At some level, humans need to realize that success means the thriving of not only themselves, but all of Earth's precious irreplaceable species and ecosystems. Without them, humans cannot be successful anyway. This is another part of maturing: many adolescents have difficulty considering the impacts of their actions on anyone other than themselves. Humans need to realize that hurting any component of Earth is hurting humans, long-term. Our legal system affords rights to humans, but gives no agency to plants, animals, or even non-living features of our planet. A successful future must give voice to every element of our world, lest we trample it and rue the day.

Can it work? Can humans create the institutions and uncorrupted global authority to regulate the entire biosphere—or at least the human interface—to prevent unsustainable disruption to the rest? Is human nature compatible with such schemes? Do we have the discipline to deny ourselves easily reached resources for the good of the whole? Individual desires for "more" may always work to subvert sustainable practices. Individual lifetimes are so very short compared to the necessarily long-term considerations of success that it will be very hard to universally accept seemingly artificial restrictions generation after generation. Also unclear is whether it is possible to maintain a technological society preserving knowledge and history while living on the annual renewable resources of the planet. We simply have no guiding precedent for that mode of human existence.

It is therefore an open question whether a technological society is even *compatible* with planetary limits. Are modern humans just a passing phase whose creations will crumble into oblivion in a geological blink, or can we stick it out in something other than a primitive state? We again have no evidence[59] one way or another. The current state of *apparent* success cannot be taken as a meaningful proof-of-concept, because it was achieved at the expense of finite resources in a shockingly short time: an extravagant party funded by the great one-time inheritance. The aftermath is only beginning to appear.

59: See Sec. 18.4 (p. 312) on the Fermi paradox for a worrisome—albeit inconclusive—lack of evidence of success in the universe.

We have a choice: work toward success—hoping and assuming that it is indeed possible; or acquiesce to failure. It seems that if we are not wise enough to know whether long-term success is even *possible*, the responsible course of action would be to *assume* that we can succeed, and do what we can to maximize our chances of arriving there. When should we start? Again—without knowing any better—the sooner we start, the more likely we are to succeed. Any delay is another way of driving ourselves toward a more likely failure.

D.6 Too Smart to Succeed?

This section pairs nicely with Section D.5, taking a slightly different perspective on the prospect of future success.

Evolution works incrementally by random experimentation: mutations that either confer advantages or disadvantages to the organism. Advantages are then naturally selected to propagate to future generations,[60] while disadvantages are phased out by failure of afflicted organisms in competition for resources and mates. Evolution is slow, and hard to spot from one generation to the next. When a common ancestor of the hippo evolved into whales, the nose did not suddenly disappear from the face to end up behind the head as a blow-hole, but took a tortuously long adaptive route to its present configuration.

60: After all, advantages make survival and procreation more likely.

Intelligence confers obvious advantages[61] to organisms, able to "outsmart" competition to find resources, evade dangers, and adapt to new situations. It also has some cost in terms of energy resources devoted to a larger brain. But multiple organisms from across the animal kingdom have taken advantage of the "smart" niche: octopuses, ravens, dolphins, and apes to name a few. Experiments reveal the ability of these species to solve novel, brainy puzzles in order to get at food, for instance.

Like other attributes, intelligence would not be expected to arrive suddenly, but would incrementally improve. Humans are justified in appraising themselves as the most intelligent being yet on the planet.

So here's the thing. The first species smart enough to exploit fossil fuels will do so with reckless abandon. Evolution did not skip steps and create a *wise* being—despite the fact that the *sapiens* in our species name[62] means wise. A wise being would recognize early on the damage inherent in profligate use of fossil fuels[63] and would have refrained from unfettered exploitation.

Put another way, the first species entertaining the notion that they are able to outsmart nature is in for a surprise. Earth's evolutionary web of life is dumb: it has no intelligence at all. But it exists in this universe on the strength of billions of years of tested success. All the random experiments along the way that were unworkable got weeded out. The vast majority of species around today have checked the box for long-term viability.

Modern humans—those who have moved beyond hunter-gatherer lifestyles, anyway—represent an exceedingly short-lived experiment in evolutionary terms. This is especially true for the fossil fuel era of the last few centuries. It would be premature to declare victory. The jury is still out on whether civilization is compatible with nature and planetary limits, as explored in Section D.5.

Evolution does not avoid mistakes. In fact, it is built upon and derives its awesome power precisely *because* of those few mistakes that somehow escape the more likely failed outcomes and find advantage in the mistake.[64] Maybe humans are one of those more typical evolutionary mistakes that will culminate in the usual failure, as so often happens. The fact that we're here and smart says nothing about our chances for long-term success. Indeed, humankind's demonstrated ability to produce unintended global adverse consequences would suggest that success is less than a safe bet.

It seems fairly clear that hunter-gatherer humans could have continued essentially indefinitely on the planet. And the brains of hunter-gatherer *Homo sapiens* are indistinguishable from those of modern humans. So intelligence *by itself* is not enough to cross the line into existential peril, if continuing to operate within and as a part of natural ecosystems. But once that intelligence is applied toward creating artificial environments[65] that no longer adhere to the ways of nature—once we make our own rules

61: Intelligence is not the only sort of advantage, and can easily lose to tooth and claw, or even mindless microscopic threats: nature has devised many ways to "win."

62: . . . self-assigned flattery

63: Not only is climate change a problem, but building an entire civilization dependent on a finite energy resource and also enabling a widespread degradation of natural ecosystems seems like an amateur blunder.

64: Since mutations are random mistakes, and some actually, surprisingly, turn out to be advantageous, one might say that life is a giant pile of mistakes that failed to deliver the expected bad outcomes, snatching success from the jaws of failure.

65: . . . e.g., agriculture, cities

as we "outsmart" nature—we run a grave risk as nature and evolution cease to protect us. In other words, a species that lives completely within the relationships established by the same evolutionary pressures that *created* that species is operating on firm ground: well adapted and likely to succeed, having stood the test of time.[66]

66: Since evolution is slow, any species has a reasonably long track record of success behind it.

Once we part ways with nature and create our own reality—our own rules—survival is no longer as guaranteed. Even 10,000 years is not enough time to prove the concept, when human evolution works on much longer timescales. This is especially true for the fossil fuel world, being mere centuries old. Nature will be patient while our fate unfolds.

The situation is similar to establishing a habitat on the lunar surface: an artificial environment to provision our survival in an otherwise deadly setting. The resources that were available to construct the habitat are not continually provided by the lunar environment, just as the fossil fuels and mined resources and forests are not continually re-supplied[67] as we deplete them. Just because the habitat *could* be built does not mean it can be maintained indefinitely. Likewise, the world we know today—being rather different from anything that nature prepared—may be a one-off that proves to be unsustainable in the long run.

67: Forests can grow back, but not at the rate of their destruction at present.

Since evolution is incremental, we cannot expect to have been made wise enough to avoid the pitfalls of being *just* smart enough to exploit planetary resources. And being slow, it seems unlikely that wisdom will evolve fast enough to interrupt our devastating shopping spree. It is *possible*[68] that we can install an "artificial" wisdom by using our intelligence to adopt values and global rules by which to ensure a sustainable existence. Probably most smart people assume that we can do so. Maybe. But living in a collective is difficult. Wisdom may exist in a few individuals, but bringing the entire population around to enlightened, nuanced thinking that values nature and the far future more than they value themselves and the present seems like a stretch.

68: What hope we have lies here, and provides the underlying motivation for writing this book. The first step is appreciating in full the gravity of the challenge ahead.

One way to frame the question:

> Are humans collectively capable of leaving most shelves stocked with treats, within easy reach, while refraining from consuming them, generation after generation?

Do we have the discipline to value a distant and unknown future more than we value ourselves and our own time? Successful non-human species have never had to answer this question, but neither has any species been smart enough—until we came along—to develop the capability to steal all the goodies from the future and, in so doing, jeopardize their own success.[69]

69: Success here means preserving civilization. It is far easier—and perhaps more likely—to at least survive as a species in a more primitive, natural state.

D.6.1 Evolution's Biggest Blunder?

As a brief follow-on, we framed evolution as a mistake-machine, sometimes accidentally producing functionally advantageous incremental improvements. Countless species adapt in ways that are not able to survive long term, and die off. So those "blunders" are inconsequential failed experiments. Evolution is indifferent to failure, being a mechanism rather than a sentient entity.

But most of the time, these failures are isolated, bearing little consequence on the wider world. Did anybody notice the three-dotted bark slug[70] disappear? If the human species turns out to be another of evolution's failed experiments—having made a creature too smart to stay within the lanes of nature—is it just another inconsequential blunder?

70: . . . totally made up

Unfortunately, it may turn out to be a rather costly blunder, if the failed species creates a mass extinction as part of its own failure. By changing the climate and habitat on the planet, we have already terminated or imperiled a number of species, and are nowhere near finished yet. Mass extinctions have happened many times through history, but seldom due to an evolutionary blunder. We may yet distinguish ourselves!

It is true that cyanobacteria transformed the climate starting about 2.5 billion years ago by pumping oxygen into the atmosphere. Called the Great Oxygenation Event, this precipitated the first-known mass extinction on the planet—essentially poisoning the simple anaerobic lifeforms that existed until that time. But we would hesitate to call it an unmitigated disaster, as it paved the way for multi-cellular life[71] in all the richness we see today. So accidental? Yes. Blunder? Okay. Disastrous? Let's say no, on balance.[72]

71: . . . although it took over a billion years to get there: no instant gratification

72: The anaerobic life would disagree, but when do we ever listen to them anymore? In any case, the result was tremendous biodiversity, which ultimately may be a decent figure of merit for value in this world.

The most recent mass extinction, 65 Myr ago, was caused by an asteroid impact, and the two before that appear to be connected to volcanic activity. The two prior to these are mixed: the first appears to have been caused by geological processes, and the next by a changing climate likely connected to diversification of land-based plants. And that's it, since the much earlier cyanobacteria oxygenation event. Only one of the five is likely attributable to evolution itself—and in this case not the fault of a single species.

A human-caused mass extinction *could* pave the way to whole new modes of lifeforms. But it was much easier in the early days to break new ground. It seems much less likely that a human-induced mass extinction will unleash a fantastic evolutionary richness hitherto unexplored. That leaves only downside, and the ignominious distinction of being the one species that evolution would most regret, if ever it could.

Please, please, please—let this tragic fate not come to pass!

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Notation

This list describes several symbols that are commonly used within the body of the book.

c	Speed of light in a vacuum inertial frame: 2.99792458×10^8 m/s $\approx 3 \times 10^8$ m/s
ε	Efficiency; typically $0 \leq \varepsilon \leq 1$; unitless
g	acceleration due to gravity: 9.8 m/s^2 or $\approx$10 m/s^2
h	Planck's constant: 6.626×10^{-34} J $\cdot$ s
k_B	Boltzmann's constant: 1.38×10^{-23} J/K
N_A	Avogadro's number: 6.022×10^{23} particles per mole
ΔQ	Change in thermal energy, in Joules
$R_\oplus$	Radius of Earth: 6,378 km
$R_\odot$	Radius of Sun: 695,700 km
$r_{\oplus\odot}$	Earth–Sun distance (1 AU): 149.6 million km
σ	Stefan-Boltzmann constant: 5.67×10^{-8} W/K/m^2
ΔS	Change in entropy, in J/K
ΔT	Change in temperature, typically in °C or Kelvin (K)
ΔW	Change in energy—work performed, in Joules

Scale Factor Prefixes

Factor	Letter	Prefix	Factor	Letter	Prefix
10^{-21}	z	zepto	10^{21}	Z	zetta
10^{-18}	a	atto	10^{18}	E	exa
10^{-15}	f	femto	10^{15}	P	peta
10^{-12}	p	pico	10^{12}	T	tera
10^{-9}	n	nano	10^{9}	G	giga
10^{-6}	μ	micro	10^{6}	M	mega
10^{-3}	m	milli	10^{3}	k	kilo

Greek Letters, with Pronunciation

Character	Name	Character	Name
α, A	alpha *AL-fuh*	ν, N	nu *NEW*
β, B	beta *BAY-tuh*	ξ, Ξ	xi *KSIGH*
γ, Γ	gamma *GAM-muh*	o, O	omicron *OM-uh-CRON*
δ, Δ	delta *DEL-tuh*	π, Π	pi *PIE*
ϵ, ε, E	epsilon *EP-suh-lon*	ρ, P	rho *ROW*
ζ, Z	zeta *ZAY-tuh*	σ, Σ	sigma *SIG-muh*
η, H	eta *AY-tuh*	τ, T	tau *TOW (as in cow)*
θ, Θ	theta *THAY-tuh*	υ, Υ	upsilon *OOP-suh-LON*
ι, I	iota *eye-OH-tuh*	ϕ, Φ	phi *FEE, or FI (as in hi)*
κ, K	kappa *KAP-uh*	χ, X	chi *KI (as in hi)*
λ, Λ	lambda *LAM-duh*	ψ, Ψ	psi *SIGH, or PSIGH*
μ, M	mu *MEW*	ω, Ω	omega *oh-MAY-guh*

Glossary

AC
: alternating current. 77, 215

AER
: Annual Energy Review. 102, 103, 105–107, 109, 170

alpha decay
: (α) happens when a nucleus emits an alpha particle, otherwise known as a ^{4}He nucleus. 243, 422, 435

alpha particle
: (α) is a ^{4}He (helium) nucleus, ejected from a larger nucleus in an alpha decay It therefore consists of two protons and two neutrons. 243, 245, 422

Amp
: (A) is short for Ampere. 77, 293, 422, 425

Ampere
: (A, or Amp) is the SI unit of current, defined such that one Ampere is the same as one Coulomb per second (1 A = 1 C/s). 77, 422

a.m.u.
: atomic mass unit. 241, 246–248, 253, 254, 265, 376, 422, 432, 433, 435

Annual Energy Review
: is compiled by the U.S. EIA, capturing energy use and trends for all sources and sectors [34]. 102, 170, 422

Astronomical Unit
: (AU) is a unit of distance, equal to the average Earth–Sun distance of 149.6 million kilometers (1.496×10^{11} m). 56, 422

asymmetric risk
: describes a condition where given the choice to pursue action B for fear of some future condition instead of the normal action A, the downside of being correct about the threat and *not* taking action B is *far* more disastrous than being wrong about the threat and pursuing route B unnecessarily. 345, 351

atomic mass unit
: (a.m.u.) is defined so that a single neutral carbon atom, consisting of 6 protons, 6 neutrons, and 6 electrons has exactly 12.00000 a.m.u. In other units, it is 931.4941 MeV or 1.66054×10^{-27} kg. This unit sometimes goes by the name: Dalton. 241, 376, 422, 433

AU
: Astronomical Unit. 56, 206, 420, 422

Avogadro's number
: is $N_A = 6.022 \times 10^{23}$, pertaining to one mole of particles (e.g., atoms, molecules). 375, 376, 381, 433

band gap
: is the energy difference between the conduction band and the valence band, determining how much energy is needed to promote an electron out of an atom and into conduction. 203, 204, 223

barrel
(bbl) is a unit of volume used primarily for petroleum. It is exactly 42 U.S. gallons, amounting to 159 L of volume. A commonly used measure of energy is barrels of oil equivalent (b.o.e.), amounting to 6.1 GJ of combustion energy. 112, 120, 126, 129–131, 135, 141, 211, 266

beta decay
(β) happens when a nucleus emits either an electron (β^-) or a positron (β^+). 243, 245, 265, 435, 438

Betz limit
is a theoretical maximum amount of kinetic power that can be removed from wind without slowing the wind too much. It computes to 19/27, or 59%, and is independent of technology [71, 72]. 188, 189, 195

Big Bang
is the name given to the start of the universe, about 13.8 billion years in the past. 9, 55, 239, 257, 392, 394, 396

biofuel
describes a liquid chemical fuel derived from biologically grown plants: algae, sugar, corn, rapeseed, etc. The two most common forms are ethanol and biodiesel. 165, 227, 230, 231, 428

biomass
is a generic term for biological matter, but in the energy context usually means firewood or dung that may be burned for thermal energy. 170, 227, 229–231

birth rate
quantifies the number of births per 1,000 people per year, typically. Numbers tend to be in the 5–30 range. 38, 426

blackbody
is a term describing the radiative qualities for thermal emission of light (infrared radiation for "normal" temperatures, becoming visible for very hot objects). A perfect blackbody is not reflective (i.e., "black" at the wavelengths of interest) and emits energy as a function of wavelength according to the Planck spectrum. 145, 199–201, 203, 223, 434, 438

boiling water reactor
is a type of nuclear fission reactor in which water surrounding the fuel rods acts both as a moderator and as the means of transporting heat away from the nuclear fuel. 255, 256

Boltzmann constant
is a fundamental constant of nature associated with thermodynamics. In SI units, it has a value of $k_B = 1.38 \times 10^{-23}$ J/K. 89, 199, 381

breeder reactor
is a nuclear fission reactor that transforms non-fissile nuclei into ones that are fissile by means of neutron capture and subsequent radioactive decay. 250, 262, 264, 296, 423

breeding
see breeder reactor. 259

British thermal unit
(Btu) is a unit of energy in the Imperial unit system, defined as the amount of energy required to heat one pound of water by 1°F. It is equivalent to 1,055 Joules. 75, 423, 427, 435, 437

Btu
is short for British thermal unit. 75, 97, 98, 335, 372, 423

Calorie
(Cal, or kcal) is a unit of energy, defined as the amount of energy required to heat one kilogram (1 kg, 1 L, 1,000 cm^3) of water by 1°C. It is equivalent to 4,184 Joules, and is the exact same

thing as a kilocalorie. Note the capital C differentiates it from the calorie, which is 1,000 times smaller, making this the dumbest unit convention around, and strongly favoring the use of the equivalent kcal instead. 73

calorie
(cal) is a unit of energy, defined as the amount of energy required to heat one gram (1 g, 1 mL, 1 cm^3) of water by 1°C. It is equivalent to 4.184 Joules. 73, 85, 177, 194, 424, 431

capacity factor
is the fraction of energy delivered by an installation compared to what it would deliver if operating continuously at peak operating ("nameplate") capacity. 176, 179, 180, 182, 183, 190, 191, 196, 212, 216, 217, 226, 256, 267, 279, 281, 282, 288

caprock
is a geological feature of impermeable rock that can trap oil, gas, or steam below it. 120, 278

carrying capacity
refers to the limiting population that can be supported long-term by the environment. No consensus exists for Earth's carrying capacity for humans, though standards of living have a large influence. 34, 432

CFL
compact fluorescent light. 21

chain reaction
is a self-feeding process that keeps itself going. In the context of nuclear fission, neutrons released by the fission precipitate the next fission event, and so on. 251, 252, 255, 262, 425, 432

charge
is a measure of the degree to which a particle or object is influenced by electromotive forces. Electric charge can be positive or negative, so that like charges repel and opposites attract. The unit for electric charge is the Coulomb. 77, 240, 241, 246, 395, 425, 427, 429, 433

Chart of the Nuclides
is a Periodic Table on steroids, listing the properties of every known nuclide including mass or energy, abundance (if stable), half life (if unstable), decay mode, neutron cross section, nuclear spin, and other salient properties; see `https://people.physics.anu.edu.au/~ecs103/chart/`. 240–242, 244, 245, 248, 251, 253, 259, 266, 270

chemical energy
is energy stored in chemical bonds, like gasoline or wood that might be burned, or in the food we eat. 70, 117, 121, 182, 227, 228, 234, 379, 395, 396

climate sensitivity parameter
relates a change in radiative forcing to the net temperature change once all the feedback mechanisms have acted. The units are °C per W/m^2, and a typical value is 0.8. 147, 160

coefficient of performance
(COP) refers to the energy gain by a heat pump, usually in the context of heating rather than cooling. It is identical to $\varepsilon_{\text{heat}}$, as defined in Eq. 6.11 (p. 95). 97, 425

compound
describes a particular combination of elements that construct a particular molecule. For instance, H_2O is the compound we know as water. 376, 379, 432

concentrated solar power
(CSP) refers to a form of solar thermal (ST) energy, employing troughs or "power towers" or any technique that focuses solar power to create high temperatures, often then used to generate electricity. 220, 425, 436

conduction band
is the energy level a step up from that of electrons in the valence band. Electrons in the conduction band are very loosely bound and freely wander about the crystal, hopping from one atom to the next, and therefore able to contribute to a current. 202, 203, 422, 435, 438

confinement
in the context of fusion refers to the trapping and holding of a high-temperature plasma, usually by magnetic means. 265

conservation of energy
says that energy is never created or destroyed, only shifting from one form to another. 70, 91–93, 95, 246, 393, 394, 425

conservation of mass-energy
extends conservation of energy to include mass, so that the *combined* mass-plus-energy of a closed system is never created or destroyed, only shifting from one form to another (mass-energy exchange via $E = mc^2$). 246

control rod
is used in a nuclear fission reactor to absorb neutrons so that the chain reaction does not get out of control and cause a meltdown. 251, 255, 256, 432

COP
coefficient of performance. 97, 99, 335, 424

Coulomb
(C) is the SI unit of electric charge. An electron has a charge of -1.6×10^{-19} C and a proton has a charge of $+1.6 \times 10^{-19}$ C. 77, 422, 424, 427

coupled
refers to the tight connection often seen between energy/resource use and economic scale (as measured, for instance, by GDP). 18, 425

critical mass
is the mass of fissile material (assumed to be in spherical form) above which a self-sustained chain reaction will occur. Below this, the material poses no danger. Right at critical mass, the material will limp along in a slow chain reaction. Above this threshold—super-critical—an exponential runaway detonation will occur, and is the basis of nuclear weapons. For ^{235}U, critical mass is 52 kg (a bit smaller than a volleyball), and for ^{239}Pu, it is 10 kg, and about the size of an American softball. 262

CSP
concentrated solar power. 220, 424, 436

current
is a measure of charge flow, expressed in the SI unit of Amps. 77, 85, 202, 203, 205, 422, 425, 436

D–D fusion
uses deuterons (^{2}H nuclei) as the fuel for fusion, achieving an energy density of 137 million kcal/g. 265

death rate
quantifies the number of deaths per 1,000 people per year, typically. Numbers tend to be in the 5–30 range. 38, 426

decay chain
refers to a consecutive series of radioactive decays. 244, 245

decoupling
is the notion that economic activities need not incur a large energy or resource cost, breaking the tendency for economic scale to be tightly coupled to physical goods. 20

demographic transition
refers to the process in which an undeveloped country initially having high birth rate and high death rate transitions to low death rates followed by low birth rates as medical and resource conditions improve. 39, 44

deuterium
is an isotope of hydrogen, in which the nucleus (called a deuteron) contains one proton and one neutron. 248, 265, 266, 272, 274, 299, 426

deuteron
is the nucleus of deuterium, consisting of one proton and one neutron. 265, 425, 426

dietary energy factor
is the quantitative energy impact of a set of dietary choices compared to a vegetarian diet. A typical American diet has a dietary energy factor around 2, meaning it takes twice as much energy as would a vegetarian diet. This term is not in universal use. 339–341, 349, 428

differential equation
is an equation that relates functions and their derivatives. The subject is often sequenced after calculus within a curriculum. 33, 34

doping
is a process by which deliberate impurities are introduced into a semiconductor in order to change its properties with respect to transport of electrons or holes. 202, 431

doubling time
is how long it takes a system or collection to double its amount under conditions of growth, such as in exponential growth. See also the rule of 70. 2, 6, 23, 31, 32, 405

D–T fusion
combines a deuteron (^{2}H nucleus) and a triton (^{3}H) as the fuel for fusion, achieving an energy density of 81 million kcal/g. 265, 267

duty cycle
refers to the percentage of time something is "active." For example, a refrigerator may be on 40% of the time to maintain internal temperature, in which case its duty cycle is 40%. 88, 334

Ecological Economics
is a field that builds economic theory on top of the notion that the planet offers finite resources and flows. A principle aim is that of a steady-state economy capable of indefinite planetary compatibility. 323, 324

EER
energy efficiency ratio. 97–99, 427, 430

EIA
Energy Information Administration. 7, 75, 102, 103, 106, 107, 131, 170, 215, 422, 426

Electric Power Monthly
(EPM) is compiled by the U.S. EIA, capturing electricity production and usage at the state level from all energy sources [85]. 215, 427

electromagnetic radiation
refers to any transport of energy by electromagnetic waves, which include light, ultraviolet, infrared, X-rays, microwaves, gamma rays, and radio waves. 10, 198, 397, 426, 431, 435

electromagnetic spectrum
refers to the sweep of wavelengths or frequencies of electromagnetic radiation, including light, ultraviolet, infrared, X-rays, microwaves, gamma rays, and radio waves. 79, 392

electron
: is a fundamental particle typically found in the outer parts of atoms, surrounding the nucleus. Electrons have negative charge equal and opposite to that of protons, but are 1,836 times lighter than the proton, at 0.511 MeV. 77, 78, 198, 202, 239, 244, 245, 255, 395, 422, 423, 425, 426, 429, 430, 433–435, 438

electron-volt
: (eV) is a unit of energy, defined as the energy (work) it takes to push a charge of one fundamental charge unit (see entry for Coulomb) through an electric potential of one Volt. 1 eV is equivalent to 1.6×10^{-19} Joules. 78, 198, 223, 248, 428, 432

element
: pertains to a single atom on the Periodic Table. For instance, hydrogen, helium, and carbon are all elements. 376, 379, 424, 432

energy
: is defined as the capacity to do work. The SI unit is the Joule. 68, 73, 77, 174, 334, 379, 423–425, 427, 431, 434, 437, 438

energy density
: describes how concentrated energy is in a substance, quantified as energy per unit mass. In chemical contexts, anything around 10 kcal/g or higher is considered energy–dense, while substances at about 1 kcal/g or lower are poor. Carbohydrates and proteins are middling, around 4 kcal/g, while fat is 9 kcal/g, and therefore among the more energy–dense substances. 121, 122, 175, 228, 230, 231, 236, 237, 254, 256, 264, 277, 290, 380, 398, 425, 426, 428

energy efficiency ratio
: (EER) refers to the energy gain by a heat pump, usually in the context of cooling rather than heating. Its units are odd, defining how many British thermal units (thermal energy) may be moved per Watt-hour of input energy, but relating to $\varepsilon_{\text{cool}}$ (defined in Eq. 6.10 (p. 95)) by a simple numerical factor: EER = $3.41\varepsilon_{\text{cool}}$. Sometimes seen as SEER to represent a *seasonal* average EER value. 97, 98, 426

energy intensity
: measures the energy use of a society relative to its economic scale. A typical value may be about 5 MJ/$. 19, 336

energy trap
: refers to a phenomenon in which energy shortage motivates aggressive pursuit of alternative energy schemes, but that pursuit requires substantial energy investment—forcing an even more acute but voluntary energy shortage, which is politically difficult. 132, 301, 310, 311

enriched
: see enrichment. 258, 262

enrichment
: refers to the process of increasing the concentration of a particular isotope within a sample of an element. Usually, this term is applied to the concentration of ^{235}U from its natural 0.72% to 3–5% for power plants or >20% (typically ~85%) for weapons. 258, 427

entropy
: is a measure of how many ways a system can be configured for some fixed energy level. The entropy of a closed system cannot decrease. 90, 396, 420

Environmental Economics
: is an offshoot of neo-classical economics that adds a layer of pricing to capture "externalities," or environmental costs not normally included in market price. 323

EPM
: Electric Power Monthly. 215, 426

EROEI
: Energy Returned on Energy Invested: a measure of how profitable an energy source is in terms of energy, expressed as a ratio. For instance, a 9:1 EROEI means 9 units were extracted or produced for an investment of 1 unit, leaving a net gain of 8 units of energy. 1:1 is break-even, deriving no net energy benefit. 231, 235, 236, 278, 295, 297, 301, 302, 310, 311, 315, 339

estimated total resource
: is an educated extrapolation of proven reserves trying to characterize the amount of resource that may be ultimately found and extracted. 127, 131, 258

ethanol
: (C_2H_5OH) is a liquid alcohol frequently produced as a biofuel having an energy density of ~7 kcal/g. 108, 230, 297, 377, 423

eV
: electron-volt. 198, 203, 248, 427, 432

exponential growth
: happens when the rate of growth—as a percentage or fraction—is constant. 2, 4, 31, 33, 61, 319, 426, 434

feedback
: is the response of a system when a change is made that itself influences the change: either counteracting it as in negative feedback or amplifying it as in positive feedback. 145, 147, 424

fill factor
: is a generic term describing the fraction of total area occupied. For instance a polka-dot pattern of circles on a piece of fabric might have a fill factor of 15%. 189

fissile
: describes a nucleus that is prodded into fission by a (slow) thermal neutron. The three fissile nuclides of interest are ^{233}U, ^{235}U, and ^{239}Pu. 255, 259, 262, 423, 425, 428

fission
: is a nuclear process in which a heavy nucleus splits into two lighter nuclei. Only ^{233}U, ^{235}U, and ^{239}Pu are usually considered as accessible nuclides that are fissile in the presence of slow (thermal) neutrons. 85, 239, 249, 264, 289, 296, 423–425, 428, 432

flexitarianism
: is the practice of pursuing dietary choices based on *quantitative* assessment of energy costs in an effort to keep the dietary energy factor low, without enforcing complete strictness, enjoying the occasional deviation on special occasions or just to avoid being a pain to others. 342

fossil fuel
: refers to an energy source buried in the ground, in the form of coal (solid), petroleum (liquid), or natural gas (gaseous). Fossil fuels represent ancient solar energy captured in living matter, processed and stored underground over millions of years. 7, 22, 27, 31, 61, 103, 104

fracking
: is slang for **hydraulic fracturing**, a technique used to extract "tight" oil and gas resources locked up in less permeable rock formations. High-pressure fluids are used to create cracks in the rock that the allow oil and/or gas to flow. 120, 124, 128, 130, 232

frequency
: characterizes the number of cycles per second in a periodic phenomenon (often in wave phenomena). The units are Hertz, or 1/s. 79, 198, 426, 430, 434, 436

fuel rod
: is a long cylinder having a high-enough concentration of fissile material to be used in a nuclear fission reactor. 255, 256, 260, 263, 272, 423

fusion
is a nuclear process in which two light nuclei merge to form a larger nucleus. Repulsion of the charges in the nuclei make it exceedingly hard to achieve, requiring temperatures of many millions of degrees. 85, 239, 249, 265, 289, 299, 395, 425, 426, 437

galaxy
is a collection of stars held together by mutual gravitational attraction, generally numbering in the billions of stars. 9, 54, 55, 312, 394, 438

gamma decay
(γ) is when a nucleus in an energetically excited state emits a high-energy photon. 244, 429, 435

gamma ray
(γ) is a high-energy photon, as may be generated by a gamma decay or by annihilation of an electron and positron. 244, 251, 255, 434, 435

GDP
Gross Domestic Product, effectively representing the total monetary flow of goods and services within a society, typically over a one year period. 18, 24, 39, 425

generator
converts mechanical motion (rotation, typically) into electrical current, generally by the relative motion of wire loops and a strong magnetic field. 89, 99, 164, 165, 175, 184, 185, 190, 250, 279, 280, 282, 285, 430, 436

geothermal
refers to thermal energy within the earth, both from the original heat of formation and from radioactive decay. 85, 99, 108, 166, 275

GHG
greenhouse gas. 146, 151, 152, 155, 160, 161, 429

Gppl
is a short-hand unit for giga-people, or billion people. 32, 37

gravitational potential energy
is the energy stored in a mass, m, lifted a height, h, above some reference in the presence of gravity, $g \approx 10\,\mathrm{m/s^2}$. The energy amounts to mgh, and will be in Joules if the inputs are in kg, m, and s. 66, 69, 70, 77, 89, 167, 173, 174, 177, 184, 275, 280, 283, 395, 396, 438

Green Revolution
refers to the modernization of agricultural practices worldwide beginning around 1950, when fossil fuels transformed both fertilization and mechanization. 31, 37, 123, 124, 234

greenhouse gas
(GHG) absorbs infrared radiation and acts as a thermal blanket in a planetary atmosphere. H_2O, CO_2, O_3, and CH_4 are powerful greenhouse gases. 11, 12, 144–146, 151, 429

grid tied
refers to a photovoltaic system connected to the local electrical utility grid, enabling export of solar production by day and use of utility electricity by night. 213, 222

half life
is the time after which half a sample of radioactive nuclei will have undergone radioactive decay. After N half-life periods, the remaining fraction will be $1/2^N$. 242, 243, 257, 259, 261, 262, 270, 276, 424, 435

heat capacity
is the amount of energy it takes to raise an object's temperature by 1°C. The *specific heat capacity* is the heat capacity divided by mass, becoming an intrinsic property of the material. Water's

specific heat capacity is 4,184 J/kg/°C, intimately tied to the definition of the kilocalorie. 74, 85, 99, 147, 153, 168, 194, 271, 277, 372, 401

heat engine
is a device that converts thermal energy into another form, usually mechanical motion. Automobile engines are a common example, as are power plants that create steam from a thermal source that itself drives a turbine and generator. 89, 92, 165, 239, 267, 276, 277, 286, 294, 298, 348, 396, 433, 436

heat loss rate
as used in this book is the power per ΔT (in °C) required to maintain a temperature differential. Units are W/°C, and typical houses might be a few hundred W/°C. 87, 99, 100, 334

heat of fusion
is the energy barrier associated with either forming (fusing) or melting a solid from a liquid. In the case of water (ice), the heat of fusion is 334 J per gram. 152, 153

heat of vaporization
is the energy barrier associated with turning a liquid into gas. In the case of water going to water vapor, the heat of vaporization is about 2,250 J per gram. 177

heat pump
is a device that moves thermal energy from a cold environment to a hotter one, against normal flow. Some energy input is required to drive this reverse flow, but thermodynamic principles permit a small amount of input energy to drive a larger amount of thermal energy transfer. 85, 95, 297, 335, 427, 430

heating seasonal performance factor
(HSPF) refers to the energy gain by a heat pump in the context of heating, but in the same units as the EER so that HSPF is COP times 3.41, numerically. 97, 98, 430

heavy oil
refers to oil that is very viscous—closer to tar than to gasoline. Heavy oil is more difficult to extract, process, and obtain gasoline via refinement. 131

Hertz
(Hz) is the SI unit for frequency, and is equivalent to cycles per second, or 1/s. 198, 428

hockey stick
is a term used to describe plots that suddenly shoot up after a very long time of relative inaction. Plots of human population, atmospheric CO_2, energy use, all tend to show this characteristic—which resembles an exponential curve. 31, 115

hole
in the context of semiconductors is the absence of an electron—or an electron vacancy. When another electron fills the hole, it leaves behind another hole, and it is as if the hole moved—effectively like a positive charge able to roam through the crystal. 202, 204, 426, 435

HSPF
heating seasonal performance factor. 97–99, 430

HST
Hubble Space Telescope. 59

hydrocarbon
is a chain of carbon and hydrogen atoms such as the alkanes (methane, ethane, propane, butane, octane, etc.) having chemical formula C_nH_{2n+2}, where $n = 1$ for methane, 2 for ethane, 8 for octane, etc. 119, 121, 131, 229, 436

hydrological cycle
is the solar-driven process by which evaporation of water from the surface (bodies of water or moist land) forms clouds, and the clouds deliver rain back to the surface. 166, 168, 177

infrared radiation
is the property that all objects glow in light, or electromagnetic radiation. For objects that are not "red hot," the emission is invisible to the human eye, at longer wavelengths than the visible spectrum. The power radiated obeys the Stefan–Boltzmann law. 10, 84, 143, 147, 151, 161, 169, 396, 397, 423, 429, 435, 437

insolation
is the annual average solar flux reaching flat, level ground for a particular location. A typical number is 200 W/m^2, but can range from half that at high latitudes to about 350 W/m^2 for arid areas at lower latitudes. 168, 178, 189, 206–208, 228, 276, 285

inverse function
is a mathematical operation that "undoes" its counterpart, like the square root undoes the square, or the natural logarithm undoes the exponential. 5, 32, 367, 370

isotope
is what we call atoms that have various nuclear configurations for the same element. That is, variants of a nucleus having the same number of protons but differing numbers of neutrons, and therefore differing mass number. See also nuclide. 240, 242, 252, 261, 266, 296, 375, 376, 426, 433, 437

ISS
International Space Station. 58–60

Jevons paradox
is named after early economist William Stanley Jevons, and describes the backfire of efficiency improvements leading to *increased* usage of the associated resource due to greater demand for the more attractive, efficient technology. Also called the rebound effect. 23, 435

Joule
(J) is the SI unit of work or energy, and is equivalent to Newtons times meters (N·m), or kg · m^2/s^2. 19, 69, 159, 309, 371, 420, 423, 424, 427, 429, 431, 432, 434, 435, 437, 438

junction
describes an interface between two semiconductors that have different doping. Junctions are the basis of photovoltaic, diodes, light emitting diodes (LEDs), transistors, and many light detectors. 202, 204

kcal
kilocalorie. 74, 85, 99, 118, 121, 122, 136, 140, 228–230, 233, 236, 237, 246, 253, 254, 258, 265, 277, 290, 334, 335, 339, 340, 380, 398, 423–428, 431

Kill-A-Watt
is the name of a relatively inexpensive device that can measure instantaneous power in Watts and accumulated energy in kWh of electrical appliances. The name is a pun on units. 334

kilocalorie
(kcal) is a unit of energy, equivalent to 1,000 calories, defined as the amount of energy required to heat one kilogram (1 kg, 1 L, 1,000 cm^3) of water by 1°C. It is equivalent to 4,184 Joules. 73, 84, 254, 334, 339, 424, 430, 431

kilowatt-hour
(kWh) is a unit of energy, constructed as a power (kilowatts) times time (hours). It is equivalent to 3,600,000 Joules, or 3.6 MJ. 72, 159, 172, 209, 214, 226, 343, 401, 402, 432

kinetic energy
is the energy of motion, given by $\frac{1}{2}mv^2$ for a mass, m, at velocity, v. If input units are kg and m/s, the resulting unit will be Joules. 69–71, 89, 174, 184, 185, 223, 275, 282, 284, 395, 396, 437

kWh
kilowatt-hour. 76, 159, 214, 272, 334, 335, 337, 338, 342, 348, 398, 431, 438

LED
light emitting diode. 21, 29, 78, 83, 431

life-cycle CO_2 emission
is an assessment of how much CO_2 is released from an energy source when considering the entire enterprise—including manufacture/construction, operation, etc. See the Wikipedia page on List of life-cycle greenhouse gas emissions. 181, 194, 218, 221, 264

liquefied natural gas
(LNG) is cryogenically-cooled natural gas (methane) at −160°C that can be stored much more compactly than the gaseous form, making it suitable to transport. 432

LNG
liquefied natural gas. 121, 432

logistic
describes a mathematical model in which rate of growth depends on how close the population is to the carrying capacity. The resulting population curve over time is called the logistic function, or more informally, an S-curve. 34

macro-economics
concerns itself with the allocation of goods and services across the marketplace, optimizing supply and demand, aiming to minimize surplus or deficits. 323, 324, 433

mass number
(A) is simply the total number count of protons and neutrons (nucleons) in a nucleus. For example, a carbon atom having 6 protons and 6 neutrons has $A = 12$. 240, 431

meltdown
refers to a failure mode of nuclear fission reactors, in which the chain reaction becomes uncontrolled due to too many neutrons triggering new fission events (as may happen if control rods are absent or insufficiently deployed). 262, 263, 425

MeV
is a mega-electron-volt, or 10^6 eV. In Joules, it is equivalent to 1.6×10^{-13} J. Nuclear masses are often expressed in MeV/c^2 terms, where 1 a.m.u. is equivalent to 931.4941 MeV. 78, 246–248, 253, 265, 422, 427, 433, 435

micro-economics
concerns itself with the production of goods, including raw resources, marketing, and distribution. 323, 324, 433

micron
(μm) is 10^{-6} meters, or a micro-meter. 198, 200, 438

moderator
in the context of nuclear fission is a material used to slow down neutrons speeding out from the break-up so that they can become thermal neutrons and stimulate subsequent fission events in a chain reaction. Light atoms like water are a good choice for absorbing the neutron impacts. 251, 255, 256, 423

molar mass
is the mass of one mole of an element or compound. The molar mass for carbon, for instance, is 12 grams. The number is often found on a Periodic Table, in addition to the proton number for the element. 121, 138, 241, 379, 380

mole
is a *number* of atoms or molecules, tuned so that one mole of the carbon-12 isotope is exactly 12.000 grams. It takes 6.022×10^{23} atoms for this to happen, which is called Avogadro's number. 78, 83, 375, 376, 378, 422, 432

negative feedback
involves a reaction to some stimulus in the direction opposite the stimulus, performing a corrective action and leading to stability. Systems in equilibrium must have negative feedback keeping them there. 33, 123, 147, 428, 433

neo-classical economics
is the prevailing economic regime practiced today, driven by supply and demand, fueled by growth, market investment, and focus on micro-economics and macro-economics. 323, 427

neutrino
is a fundamental particle associated with the weak nuclear force that has almost no mass, travels near the speed of light, and interacts so weakly with matter that it could pass through light-years of rock before being likely to hit anything. Neutrinos from the sun stream through our bodies constantly, day and night, since Earth is transparent to them. 243, 244, 438

neutron
is one of two basic building blocks of atomic nuclei, the other being the proton. Neutrons have no electric charge, and a mass of 939.565 MeV, or 1.008665 atomic mass unit (a.m.u.). Neutrons are made up of three quarks: 1 up and 2 down. 240, 243, 244, 255, 299, 375, 376, 395, 422–426, 428, 431–433, 435, 437, 438

Newton
(N) is the SI unit of force, and is equivalent to $\text{kg} \cdot \text{m/s}^2$. 68, 371, 431, 438

nuclear binding energy
is the energy associated with the strong nuclear force that holds a nucleus together against charge repulsion. Typical levels are 8 MeV per nucleon. 247, 248

nuclear energy
derives from reconfiguring the nuclei of atoms, releasing tremendous thermal energy that can be harnessed in a heat engine. 103, 104, 239

nucleon
is either of the two building blocks of a nucleus, meaning that it is either a proton or a neutron. 240, 247, 248, 251, 376, 432, 433, 437

nucleus
is at the center of an atom, composed of protons and neutrons and spanning $\sim 10^{-15}$ m. The vast majority (99.97%) of an atom's mass is in the positively charged nucleus, which attracts a cloud of negative-charge electrons to complete the neutral atom. 239, 375, 376, 422, 423, 425–429, 431–433, 435, 437

nuclide
is any bound arrangement of protons and neutrons. Every nucleus of every isotope is one of the possible nuclides, designated, for instance as C12, C-12, or ^{12}C. 240, 242, 243, 424, 428, 431, 435

overshoot
occurs when the negative feedback in a system is delayed. After surpassing the equilibrium, oscillation may ensue. 36

parts per million
(ppm) is a unit used to measure small contributions. One ppm is 0.0001%. 61, 139, 141, 434

parts per million by mass
(ppm_m) is a parts per million measure in terms of fractional mass. For instance, a gram is is 1 ppm_m of a metric ton (1,000 kg). 141, 258

parts per million by volume
(ppm_v) is a parts per million measure in terms of fractional volume occupied. For instance, a cubic millimeter (1 μm, or micro-liter) is 1 ppm_v of a liter. 140–142

payback time
is how long it takes to recuperate an investment by removing a chronic cost. For example, spending $1,000 to no longer pay an annual $100 charge has a payback time of 10 years. 215, 226

photon
is the smallest indivisible particle of light: a minimum quantum packet of energy. Each photon has a well defined energy, which can also be expressed as a wavelength or frequency. 21, 70, 78, 79, 198, 199, 202, 227, 243, 244, 251, 394–396, 429

photosynthesis
is the process by which living matter captures sunlight and stores some of it as chemical energy. Effectively, it takes CO_2 out of the atmosphere, combines the carbon with water to make sugars, releasing oxygen back into the air. 227, 395

photovoltaic
(PV) is a semiconductor technology by which light directly drives an electrical current by interacting with electrons in the material. 165, 197, 201, 217, 218, 239, 267, 289, 292, 315, 350, 429, 431, 435

Planck spectrum
describes a mathematically precise spectrum of light emission from a blackbody, fully defined by the temperature of the blackbody. 145, 199–201, 423, 436, 438

Planck's constant
is a fundamental constant of nature associated with quantum mechanics and the world of the very small. In SI units, its value is $h = 6.626 \times 10^{-34}$ J · s. 79, 198, 199

plasma
is a gas hot enough to strip electrons from atoms to create a highly-ionized medium, such as the gas comprising the sun. 265, 267, 268, 392, 393, 395, 425, 437

positive feedback
involves a reaction to some stimulus in the same direction as the stimulus, thus amplifying the effect. Positive feedback leads to an unstable, runaway process—like exponential growth. 33, 123, 147, 428

positron
is an elementary particle of anti-matter, and specifically an anti-electron, having the same mass and opposite charge as the electron and will annihilate with an electron into gamma rays. 243–245, 255, 423, 429

power
is the *rate* of energy, or change in energy per change in time. The units are Joules per second (J/s), or Watts (W). 7, 10, 11, 30, 43, 71, 73, 77, 86, 110, 118, 146, 151, 171, 176, 187, 205, 280, 334, 335, 368, 373, 431, 435–438

ppm
parts per million. 61, 139, 141, 433, 437

predicament
describes a seemingly intractable situation: more than a *problem*, but possibly a tangled set of interconnected problems. Predicaments require responses rather than tidy *solutions*. 332, 436

proliferation
is used to describe widespread distribution of dangerous nuclear materials, which becomes difficult to control if they exist in abundance due to increased reliance on nuclear energy. 239, 260, 262, 264, 269, 296, 297

proton
is one of two basic building blocks of atomic nuclei, the other being the neutron. Protons have positive charge, equal and opposite to that of the electron. Protons have a mass of 938.272 MeV, or 1.0072765 a.m.u.. Protons are made up of three quarks: 2 up and 1 down. 77, 240, 243, 244, 375, 376, 395, 422, 425–427, 431–433, 437, 438

proven reserve
pertains to the amount of resource known to exist, having been discovered and surveyed to estimate the economically recoverable amount. 126, 127, 131, 257, 258, 267, 269, 428

PV
photovoltaic. 165, 197, 201, 205, 217, 220, 221, 267, 269, 281, 292, 293, 434

qBtu
is short for a quadrillion (10^{15}) British thermal units, and is equivalent to 1.055×10^{18} Joules. 28, 75, 103–105, 170, 214, 229, 230, 234, 236, 277

R/P ratio
or reserves-to-production ratio is a means to assess time remaining for a resource of quantity R units, being used (produced) at a rate of P units per year. The result is years available at the present rate, absent discovery of additional resources or change in rate of use. 126, 129, 131, 133, 136, 267

radiation
is a broad term that can can describe light (e.g., electromagnetic radiation, infrared radiation, gamma rays) or particles from radioactive decay or cosmic origin. High-energy radiation of any form can cause damage to materials and biological tissues (DNA being perhaps most critical). 263

radiative forcing
is used to describe the areal power (in W/m^2) of absorbed solar energy and infrared radiation to space. In equilibrium, a balance exists so that the net radiative forcing is zero. 146, 147, 151–153, 155, 160, 424

radioactive
describes a nucleus, or nuclide that is unstable and will undergo radioactive decay with some half life. 241, 257, 260, 261, 263, 268, 276, 296, 297, 299, 429

radioactive decay
involves a change in the nucleus of an atom, most commonly in the form of alpha decay, beta decay, or gamma decay. 239, 242–244, 262, 275, 297, 423, 425, 429, 435, 437

rebound effect
describes the counterintuitive process by which efficiency improvements lead to *greater* use of the resource as the enhanced appeal and lower cost results in more widespread adoption and use. Also called the Jevons paradox. 23, 431

recombination
is when an electron in the conduction band of a semiconductor finds a vacancy (hole) for it to settle into. By disappearing from the conduction band, it is no longer available to contribute to current, and the energy it had becomes unrecoverable. 202, 204

refinement
is the process by which crude oil—as it comes out of the ground—is separated by approximate hydrocarbon chain length. In order of lighter/shorter to heavier/longer chains, crude oil yields propane and butane, gasoline (around octane), kerosene, diesel, heating oil, lubricating oil, and tar. 119, 430

renewable
forms of energy are not necessarily depleted by their use. In other words, the resource is replenished naturally at some rate. The sun will still shine and wind will still blow even if we harness some of the energy. Firewood will grow back, but at a limited rate. 103, 104, 106

response
is an appropriate reaction to a predicament, which may fall well short of a *solution*, but still represents a reasonable compromise approach. 332, 434

rule of 70
tells us that the time it will take a system or collection to double in size is 70 divided by the percentage growth rate. The time units depend on how the time over which percentage growth is expressed—like 2% *per day* or 2% *per year*, for instance. The rule works most accurately for smaller growth rates, under 10%. 2, 5, 6, 28, 31, 405, 426

R-value
describes the thermal resistance, or insulating quality of a wall or similar barrier. It is an inverse to the U-value, numerically $5.7/U$. Units are $^\circ\text{F}\cdot\text{ft}^2\cdot\text{hr/Btu}$, and larger numbers translate to better insulation. 87, 438

sea level rise
is one of the inevitable consequences of climate change, as land-bound ice melts and ocean water thermally expands. 151, 155

sector
refers to a domain of activity, typically dividing into residential, commercial, industrial, and transportation. 104, 165, 193, 337

semiconductor
is a material poised between being a good conductor of electrical current and an insulator (not passing current). Silicon is the most commonly used semiconductor. 201, 202, 426, 430, 431, 435

SI
Système International. 68, 71, 85, 88, 422, 423, 425, 427, 430, 431, 433, 434

solar constant
measures 1,360 W/m^2, and is the power flux of the sun at the top of Earth's atmosphere. It is not technically a *constant*, but is very stable. 11, 144, 167, 203, 206, 211

solar system
refers to our own star, the sun, and the planets that surround it, including Earth. 54

solar thermal
(ST), also called concentrated solar power (CSP), typically refers to troughs or "power towers" or any technique that focuses solar power to create high temperatures, often then used to generate electricity via a heat engine and generator. 165, 197, 219, 221, 424, 436

spectrum
describes a distribution, often associated with light. In this context, a light spectrum specifies how much light is present as a function of wavelength or frequency. The Planck spectrum is a good example. 145, 200, 434

ST
solar thermal. 219–221, 269, 424, 436

Stefan–Boltzmann constant
(σ) has a value of $5.67 \times 10^{-8}\,\mathrm{W/m^2/K^4}$ and is used in the Stefan–Boltzmann law relating to infrared radiation. 10, 144, 199, 437

Stefan–Boltzmann law
says that the power emitted from a surface of area, A, and temperature, T will be $P = A\sigma T^4$, where σ is the Stefan–Boltzmann constant. 10, 144, 199, 431, 437

stoichiometry
amounts to the counting of atoms and balancing formulas in chemical reactions to reflect the survival of every atom in a reaction: none created or destroyed. 377, 378

strong nuclear force
is the force that binds nucleons together in a nucleus, overcoming the electrical repulsion of protons. 240, 245, 247, 395, 433, 438

substitution
refers to interchangeability between goods and services, so that an unavailable or inferior resource can be replaced by an alternative, possibly superior one. 21

terraforming
is the speculative idea of transforming the atmosphere and environment of a planet hostile to human life into one that is suited to human needs. 60, 61

Therm
is a unit of energy defined as 100,000 British thermal units, and is equivalent to 1.055×10^8 Joules. 76, 335, 337, 348

thermal energy
is the energy of heat, and is really just randomized kinetic energy (motion) of atoms and molecules vibrating and zipping around. 70, 71, 84, 86, 89, 99, 165, 194, 203, 227, 246, 275, 277, 294, 334, 335, 373, 395, 396, 401, 420, 423, 427, 429, 430, 433

thermal equivalent
is a construct used to compare thermal energy sources like coal, oil, and natural gas to sources like solar, wind, and hydroelectricity, which do not derive from thermal sources. Usually in the context of electricity production, multiplying by about 2.7 puts non-thermal sources into thermal-equivalent terms. 106–108, 170, 256, 279

thermal expansion
describes how materials expand, or swell, as temperature increases. Typical rates of expansion are in the range of 5–100 ppm per °C. 155

thermal neutron
is a neutron whose kinetic energy (speed) is no greater than it would naturally possess based on the temperature of its surroundings. Sometimes it is called a "slow" neutron because it is not traveling faster than thermal jostling would establish. 250, 428, 432

tokamak
is the name of a donut-shaped chamber in which high-temperature plasma can be confined, and potentially used to generate fusion. 267

transmutation
describes the transformation of a nucleus into a different one, usually via neutron absorption—possibly followed by radioactive decay. 259, 268

tritium
is an isotope of hydrogen, in which the nucleus (called a triton) contains one proton and two neutrons. 265–268, 299, 438

triton
is the nucleus of tritium, consisting of one proton and two neutrons. 265, 426, 437

turbine
is essentially fan blades on a rotating shaft, which can be compelled to move by a flow of air, water, or steam through the blades. 89, 99, 164, 175, 185, 190, 250, 279, 280, 282, 295, 430

universe
refers to the entirety of our physical realm, including all galaxies. 9, 54, 55, 257, 312, 392, 423

U-value
describes the insulating quality of a wall or similar barrier, in terms of how many Watts move through each square meter of surface area for each 1°C difference in temperature across the barrier. Units are $W/m^2/°C$, and smaller numbers mean better insulation. The U-value is an inverse measure to the R-value, numerically $5.7/R$. 87, 436

valence band
is the energy level of outer electrons bound to an atom. Valance electrons stay home, as opposed to electrons in the conduction band. 203, 422, 425

Volt
(V) is a unit of voltage, or electric potential, and can be thought of as the electrical analog to gravitational potential energy, and is also somewhat like pressure in a fluid system. 77, 198, 427, 438

voltage
is a measure of electric potential energy, expressed in units of Volts. 77, 438

Watt
(W) is a unit of power, defined so that 1 W is 1 J/s (one Joule per second). 7, 18, 21, 43, 71, 77, 118, 169, 196, 267, 309, 371, 431, 434, 438

watt-hour
(Wh) is a unit of energy, constructed as a power (watts) times time (hours). It is equivalent to 3,600 Joules, or 0.001 kWh. 73, 77, 97, 110, 176, 427, 438

wavelength
measures the length of a wave from crest to crest or trough to trough, and can apply to waves in water, air (sound), or electromagnetic waves (light). The symbol λ (lambda) is often used to denote wavelength. The units are length (m), often expressed in microns (μm). 79, 144, 198, 283, 394, 426, 431, 434, 436

weak nuclear force
joins gravity, electromagnetism, and the strong nuclear force as one of nature's four fundamental forces, responsible for beta decays and neutrino interactions. 244, 245, 433

Wh
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Wien law
describes the wavelength for which the Planck spectrum is at maximum brightness. It is roughly 2.9 mm divided by the blackbody temperature, in Kelvin. 199

work
is a mechanical expression of energy, defined as a force (Newtons) times distance (meters) through which the force acts (along the same direction). The resulting unit is the Joule. 68, 84, 89, 174, 248, 379, 427

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