

Notes for Lectures – ENVIR 202 Earth, Air, Water winter 2003 9 i 2003
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1. INTRODUCTION

We will encounter several very different views of the environment: McNeill's history (which has considerable sociology and philosophy built in) which though inspired still leads to gloomy feelings; the up-beat can-do environmentalism of Amory Lovins (www.rmi.org); the skeptical conservatism (hey, no problem) of Bjorn Lomborg (www.lomborg.com) and the opposing views of scientists (www.anti-lomborg.com).

The early part of McNeill's book (up to p20) briefly reviews the historical trends that lead up to today. The combination of great increases in population, economic activity (related to 'wealth') and technological devices all multiply together to define the impact...the 'footprint'... of mankind on the environment. This trio of effects has often been described, for example by Paul Ehrlich in his book, *The Population Explosion* [McNeill only mentions the first two of these]. McNeill is one of a growing number of scholars trying to put both 'the planet's history' and 'the people's history' together, with the aim of improving our (and its) future. We will talk this term about some deep problems relating to life on Earth, and in the grandest notion of all, the life 'of' the Earth, described as a problem of evolution.

McNeill talks about 'rats' and 'sharks': versatile adaptability (rats) vs. supreme adaptation to one particular environment (sharks). 20th C. humanity is more shark-like: stable climate, cheap energy, but this is dangerous strategy. "In the 20th Century, societies often pursued a shark strategy amid a global ecology ever more unstable—and hence more suitable for rats....The same characteristics that underwrote our long-term biological success—adaptability, cleverness—have lately permitted us to erect a highly specialized fossil-fuel based civilization so ecologically disruptive that it guarantees surprises and shocks...we have created a regime of perpetual ecological disturbance.." (McNeill p xxiii).

"The human race, without intending anything of the sort, has undertaken a gigantic, uncontrolled experiment on the Earth. In time, I think, this will appear as the most important aspect of twentieth-century history, more so than world war II." (McNeill p 4). This 'experiment' has many aspects. One is global climate: the temperature, rainfall, winds, soil moisture, Arctic ice and so on. We will consider the greenhouse 'experiment' in the Air and Water units. Another is the development of diseases and epidemics: the combination of individual health and transmission and evolution of disease in crowded, fast-moving global populations. While we cannot study health issues in detail, they are much in our minds. However, it is the health of the planet and all its creatures that should concern us. Human beings are just one, dominant species.

"...in natural systems, as in human affairs, there are thresholds and so-called nonlinear effects." (p 4).

Numbers tell the story. Very roughly 80 billion humans have been born since we evolved a few million years ago, and more than 6 billion of these (7.5%) are now alive. The human body, viewed as an engine that converts chemical energy from food into glucose, then into mechanical work is about 18% efficient (This number would increase if we included our heat production as well...how would you measure this?).

We can put out no more than about 1 horsepower (=746 watts) and that only for very short periods (here I disagree with McNeill, p12, who argues for only 100 watts). Try this idea out on the bicycle-light in the lab. Over a work day we cannot put out much more than an average power of a puny 20 watts (take a 2500 kilocalories per day food diet, convert it to watts and multiply by the 0.18 efficiency factor above, using 4.185 Joules = 1 calorie). Yet by mining the photosynthetic energy of the deep past (fossil fuel) we have multiplied our strength. McNeill introduces the idea of ‘energy slaves’ ...the work done for us by fossil fuel, expressed in units of human power output. The ‘average’ citizen of Earth has about 20 such energy slaves (McNeill p.14). How many energy slaves does the average American employ? This rate of mining of energy has increased by a factor of 5 in the 19th Century and another factor of 16 during the 20th Century (McNeill p15).

The global use of energy from fossil fuels and renewable energies amounted to 3.8×10^{20} Joules per year in 1999 (Physics Today, April 2002). With about 6.3 billion (6.3×10^9) people now alive you can calculate what each of McNeill’s “20 energy slaves per person on Earth” is worth in watts of power. The rich nations (roughly 1.2 billion people) used energy at a rate about 7 times that of the poorer 4.1 billion people (1990 figures). That is, 2/3 of global energy supplies are used by the richest ¼ of the population. We will see quite a few energy numbers, but one I find particularly sobering is: driving along in your car a moderate steady speed, you are using 100,000 watts of power from burning gasoline. Your efficiency is about 1%. This is calculated by taking the roughly 20% efficiency (that is, 0.20) in turning the gasoline into mechanical work, multiplied by the ratio of your weight to the car’s weight, roughly 0.05 (we are talking about people-moving here). The 99% lost could be recaptured and sold for a profit. Actually, the efficiency is far worse than 1%, if you attempt to figure in the costs of mining the energy and bringing it to you gas tank. Economists might argue about this, but the *transmission, conversion and extraction* of energy is a long, complex chain. The efficiencies of each link in the chain multiply together to make a very small net efficiency. The ‘true cost’ of a gallon of gasoline is much greater than the \$1.20 we pay (far cheaper than fizzy drinking water). It leads directly to social-political costs involving wars, dictatorships and great inequality of health and happiness across the face of the Earth.

We begin to see conservation as a supremely valuable ‘hidden energy source’: a much more efficient and less polluting vehicle could be on the roads today (www.hypercar.com). Conservation throughout our lives could increase the likelihood of a happy future for everyone: people, insects, plants.

The problem is really not, as many people think, that we are running out of oil but that we are running out of environment.

ENERGY

In this course, Earth Air and Water (and we should add, Fire, since Energy is our first unit), we have a ‘science core’ of experiments and ideas, and we surround this with lectures and readings and essays on background and applications: environmental history of the past century and studies of environmental practice in specific geographical regions.

SOME ENERGY NUMBERS

Questions of Scale. Our lab experiments are small, yet the Earth is so big. In many cases we build ‘scale models’ of natural systems, just as you build a model airplane. With careful

design these can tell us a lot and can be poked and prodded and changed until we understand them. Understanding the natural world involves lots of exercise with powers of ten (there is a small picture book called Orders of Magnitude which is highly recommended). It is not easy to have a feeling for huge numbers or tiny ones. But living with the ideas and experimenting with them helps. That is why we have a bicycle connected to an electric generator: so you can feel what it means to light a light bulb with your own muscle. Some of our most important phenomena, like the ocean circulation, exist at many different scales, as if Nature were making her own models.

In our normal lives, *thermal* energy—the vibrations of atoms that make us feel warm—and *chemical* energy—the energy stored in bonds between atoms—are ‘rich’ or ‘concentrated’. *Kinetic* energy—energy of motion or potential for motion—is comparatively poor or dilute.

The energy output of the sun is about 10^{27} watts, radiating to space from its bright surface, which has a temperature of about 5900K. By the time it reaches Earth, 93 million miles away, it amounts to 1368 watts per square meter (watts m^{-2}), just outside the atmosphere. On a bright sunny day at noon you may have about 1000 watts (1 kilowatt) arriving at the ground: the rest is blocked or absorbed by the atmosphere. But averaging over night and day, summer and winter, tropics and poles, the Earth’s surface absorbs only about 120 watts m^{-2} .

The solar energy absorbed by growing plants on land and in the sea is enough to grow 6×10^{14} kg of glucose per year (glucose being a simple sugar, here used to represent the more complex biology of green plants), and the biomass energy produced contains about 10^{22} Joules of energy. This is 30 times bigger than the use of fuel energy by human beings (see below) However only a very small part of growing plants turn into future oil and coal and gas deposits, and we are now using them up far faster than they are being regenerated.

ENERGY: CONCEPTS

Forms of energy (*related to various kinds of physical forces*):

- *mechanical* – kinetic and potential
- *thermal* – internal thermal energy, radiation (hidden form of mechanical, electromagnetic energy)
- *‘electrical’* – electrostatic and electromagnetic
- *chemical* -- based on the bonds between atoms (often light...the lightest, hydrogen is the ‘best’) and within atoms (electrostatic, electromagnetic)
- *nuclear* – based on changing the nucleus of a heavy atom, splitting (fission) or combining (fusion) them. This is the ultimate source of almost all of Earth’s energy...fusion deep in the sun where hydrogen atoms combine to make helium, and in doing so give off tremendous energy.

Energy is conserved: yet it can change form. Conservation of energy is a keystone idea in physics. Energy is neither created nor destroyed, it just changes from one form to another, or is transferred from bit of matter to another. Symbolically, the 1st law of thermodynamics says

change in internal energy of a substance = net heating (or cooling) + mechanical work done on the substance

There may be energy ‘sources’ in which energy is stored, possibly in exotic forms like radioactive decay or radiation of light, but once these are accounted for energy is conserved. In this formula the internal energy is, for a simple gas, proportional to its temperature, in fact this warmth is mechanical energy in disguise (the vibration and translation of atoms). A more visible form of internal energy is the kinetic energy in the overall movement of the ‘substance’ ... as when you hit a baseball.

Forces are important to energy. The ‘work done’, in the 1st law of thermodynamics above, is defined as a force multiplied by the change in volume of the air sample. If we compress a bag of air by squeezing it, the work we have to do is force times distance our fingers move. Another way of expressing this is pressure times change in volume of the air [pressure is force per unit area, and change in volume is just distance compressed times the area of the surface of the bag]. We see that squeezing a bag of air should increase its temperature even though no heat has flowed into it. So, there are two ways to find the work done here: pressure times volume change or force times distance. The mechanical work and heat flow do not violate the conservation of energy: they just moves energy from one body (perhaps you) to another (the bag of air).

The sun is the ‘mother’ of most of our energy. It puts out roughly 10^{27} watts of radiating energy in all directions, based on nuclear fusion, where light hydrogen atoms fuse to make heavier helium atoms; energy of fusion has been created on Earth but not yet tamed. The power of arriving solar energy averages (over the year) 1376 watts/meter² at the top of the atmosphere, about 1000 watts/meter² at high noon, at the Earth’s surface and averages about 240 watts/meter² over day and night, summer and winter, at the surface (this is an average over both oceans and land). Note that this varies very greatly with latitude.

Energy flow from one place to another and conversion from one form to another is an organizing idea for the environment. That is why we began here. At all scales from microbial life to plants, animals and their machines, on to the Earth’s oceans and atmosphere, and the workings of the Universe, energy is working.

An engine is a device that converts energy from one form to another for example, internal thermal energy,

$C_v T$

of an ideal gas can convert to gravitational potential energy,

mgh

[C_v = specific heat capacity at constant volume, in Joules per kg, per degree Celsius; T = absolute (Kelvin) temperature, m =mass, g = acceleration due to gravity, h =height difference].

A heat engine converts heat to mechanical energy (in a 4 stage process of heating, expanding, cooling, compressing a gas to do work). The cycle can be drawn on a diagram of pressure versus volume of the gas, where it forms a closed curve. The area within this

curve is equal to the mechanical work done by the engine. The Stirling engine in the lab is such an engine, and works at quite high efficiency, converting candlewax into mechanical work (which then disappears back into heat as it is 'dissipated').

Power and energy: power is the rate of gain or loss of energy, or the rate of transmission of energy. 1 watt of power = 1 Joule (energy) per second (J sec^{-1}). Think of the analogy of filling a reservoir with water: the flow of water (in cubic meters per second, $\text{m}^3 \text{sec}^{-1}$) is the rate of filling it, analogous to power, and its volume (in m^3) is analogous to energy. Notice that dividing the volume by the flow rate gives a time (check the units: $\text{m}^3/\text{m}^3 \text{sec}^{-1} = \text{sec}$) which is the time it takes to fill the reservoir. This simple idea is surprisingly useful throughout this course. It helps in thinking about the flow and concentration of pollutants too. It is important to keep power and energy clearly in mind, and confusing when someone talks about kilowatt hours of energy and kilowatt hours per year of power.

Chains of energy conversion can be very long and inefficient, if the useful energy is for example 20% transmitted on at each stage (think of sun => plants => oil => gasoline => car) because 20% of 20% is $0.2 \times 0.2 = 0.04 \dots 4\%$ and ... and so on: $(0.2)^4 = 1.6 \times 10^{-3} = 0.16\%$ (actually the efficiency of photosynthesis is far less than 20%). And now we move to water, air (and earth): they should really seem simple by comparison. Our bodies and our cars are converting chemical energy into mechanical energy with about 20% efficiency. Since energy is not destroyed, we speak of the 'waste heat' that represents part of the remaining 80% (together with some unburned energy that is rejected as waste or 'exhaust'). Electricity moves through the power grid from generation plants to users. We need to work on these numbers, but an estimate of the efficiency of the power grid is 33% (J. Rifkin, E/The Environmental Magazine, Jan/Feb 2003). We will introduce the idea of the hydrogen economy: the hydrogen fuel cell is 40 to 65% efficient, in a local sense (just as with oil, producing and distributing the hydrogen involves additional losses).

Energy efficiency refers to the conversion of energy into a useful form plus an unused form: a heat engine takes thermal energy and produces mechanical energy + 'waste' thermal energy, with efficiency = mechanical energy/input thermal energy. The efficiency of an ideal heat engine is $(T_1 - T_2)/T_1$ based on the absolute (Kelvin) temperature scale ($T = \text{degrees Celsius} + 273$). One wants a big temperature difference between intake and exhaust to be efficient. As we have said above, human beings are about 18% efficient in converting food Joules to mechanical energy (the rest goes into heat and unused chemical energy); a 2500 kilocalorie per day diet is about 115 watts of intake, giving about 20 watts output (multiplying the efficiency times the input; (yet in short bursts we can do at least one horsepower of power output (=746 watts)...run upstairs, 5 meters in 5 seconds...calculate mgh/time). Other common engines also run at about 20% efficiency in converting energy: a car for example.

High quality, concentrated energy is often degraded by several conversions, each at low efficiency...with much of being wasted. Efficiency of an ideal heat engine at

producing mechanical energy, $(T_1 - T_2)/T_1$, rises with very hot intake of heat and very cold exhaust...but these are absolute temperatures. Of course the 'waste heat' can be put to use separately. By *concentrating energy (as with lenses and mirrors) this efficiency can be increased.*

There is a big contrast between 20 Joules of energy in a ton of water moving 20 cm/sec (in our water channel) and a million Joules in a candy bar: the chemical energy in the candy bar is a very 'rich' concentration of energy; mechanical energy of the flowing water is relatively 'low-grade' energy. Yet we do have hydropower because of the *scale*: the immense flow rates involved. A hydroelectric dam may be 90% efficient at converting the local potential energy of the reservoir water above to electricity; yet that water has descended thousands of meters from its source, losing almost all of its initial potential energy. In a river energy is constantly be dissipated into heat, and to do this the river must be turbulently whirling rather than smoothly flowing. You could estimate the power of a flowing river: it is the rate at which kinetic energy flows past a fixed point: essentially kinetic energy per cubic meter times rate of flow past a point, which is velocity times area. This is

$$\frac{1}{2} \rho V^2 \times AV \text{ or } \frac{1}{2} \rho AV^3$$

where A is the cross-sectional area of the river (depth h of the water x width w), V is its mean velocity, ρ is the mass density of water (= 1000 kg/m³).

{Note that the *units* of this formula are

$$\text{kg x meters}^2 \text{ /seconds}^3$$

which are the units of kinetic energy per unit time, or power. Whenever you write a formula think about its physical units, combinations of mass, length and time and also some energy related units like temperature. It is the easiest way to find a mistake.}

A river flowing at V=2 m/sec, h=5 m deep and w=100 m wide represents a power (energy-flow) equal to

$$\frac{1}{2} \rho AV^3 = \frac{1}{2} \times 1000 \times 2^3 \times 5 \times 100 = 2 \times 10^6 \text{ watts...} \mathbf{2 \text{ megawatts.}}$$

Note the cubic dependence on river velocity: at 6 m/sec the river will have 3³ or 27 times the power, 54 megawatts. While this sounds like a lot, a velocity v could come via 'free fall' of the river from a height $h = \frac{1}{2} v^2/g$. This comes from equating the potential energy ρgh (energy per kg of water) to the kinetic energy $\frac{1}{2} \rho V^2$ (per kg) that results from the fall. So for 6 m/sec velocity we would need a waterfall of height only 2 meters....except for the 'splash':

$$\rho gh = \frac{1}{2} \rho V^2$$

ignoring any loss of mechanical energy to heat. Hydropower dams are surprisingly efficient in a local sense (converting the mgh kind of potential energy of the reservoir above into kinetic energy, thence to electrical energy).

The Irish Energy Centre uses the formula:

$$\text{hydropower available in watts} = 8000 \times AV \text{ [volume flow (m}^3 \text{ /sec)]} \times h \text{ [head (m)].}$$

The 'head' is the vertical height through which the water falls. This is equivalent to an 82% efficiency since the formula with no energy loss would be (combining the above results): power = $\rho ghAV$ and g is equal to 9.8.

Grand Coulee Dam, which since 1941 helped to reshape the Northwest with cheap electricity, generates 6.5×10^9 watts..=6500 megawatts..=6.5 million kilowatts. It is also the largest concrete structure ever built. US households use on average about 2 kilowatts of electricity, so the Grand Coulee Dam can power 3.25 million such homes.

In the USA annual electric hydropower generation is about 2.8×10^{18} Joules, which is a small but important part of the national energy use profile: in total the USA uses about 10^{20} Joules per year, which is $\frac{1}{4}$ of the entire Earth's energy use! Solar energy amounts to 7×10^{16} Joules per year, very small in proportion, but growing rapidly each year.

Energy storage is essential to its use; and likely involves conversion from one form of energy to another. Gasoline, natural gas (mostly methane, CH_4), oil, candlewax all store energy at about 30 to 50 kiloJoules/gram (=megaJoules/kg), while hydrogen is the winner at about 145 kiloJoules/gram (yet by volume, it has less energy than methane, because it is so light). Foods range from 2 to 17 kJ/g (same as megaJoules per kg) in stored chemical energy. Hydropower can be stored by pumping water back uphill until it is needed. An electrical battery stores energy in chemical form, to be released by a chemical reaction (often involving an acid dissolving a metal electrode; sulfuric acid and zinc, say). The strong appeal of hydrogen fuel cells is that stored hydrogen is cleaner and simpler and less wasteful of other materials than is a chemical battery.

Energy transmission is essential to its use: movement in pipes, wires, radiation (light, heat (infrared radiation), uv (ultraviolet radiation), radio...all these are electromagnetic waves). When electrical energy is sold from Washington to California and then sold back, at least $\frac{1}{2}$ of it is lost on the way. Electrical transmission is done by stepping up a very high voltage, which reduces losses. It is in alternating current form (AC) usually though there are arguments in favor of high-voltage direct current (DC) transmission. During the electrical power shortage in California two years ago, electricity was 'borrowed' from the northwest, but transmitting it there and then back involves considerable loss.

We are largely carbon based creatures with hydrocarbon based energy. Decarbonizing our energy sources is happening and will clean the air. We move from wood to coal to oil to gas to alcohol to hydrogen: burnable fuels with fewer carbon atoms per hydrogen atom, and resulting decreasing output as carbon and generally increasing efficiency. 1 kg of hydrogen contains the same amount of energy as 2.1 kg of natural gas or 2.8 kg of gasoline. Although, hydrogen has just $\frac{1}{3}$ the energy per unit volume as natural gas at the same pressure (hydrogen being a very light gas). You could work this out using the atomic weights of carbon (12), hydrogen (1), with the formulas for methane (= CH_4) and hydrogen (= H_2).

Yet the carbon is also a waste byproduct of energy use that is creating the first global environment modification experiment that humans have ever carried out. The Greenhouse effect is what gives Earth moderate temperatures, but we are changing it and the result may be unpredictable.

Carbon is chemically unusual in forming long chain molecules: not only for hydrocarbon fuels but for as a basis for polymers: plastics. There are new developments: we have begun to observe and manipulate atoms and molecules. Nanotubes are carbon

cages that can act as flow conduits or trap other molecules. Bucky balls, fullerenes. Nature imitates us: *methane hydrates* exist in cold regions of moderately high pressure: these are methane molecules held in a cage of water molecules: ‘ice that burns’. Methane hydrates exist in natural icy deposits apparently far greater in total size than natural gases. Excess carbon dioxide, CO₂, could be pumped to the deep ocean where it freezes, and could be kept permanently out of the atmosphere. Molecular biology is just one form of nanotechnology, in which the molecular structure of life reduces to the laws of physics. As the Russian-born physicist George Gamow said to James Watson, one of several discoverers of DNA structure, ‘you have put biology on a sound physical basis’.

Technology of fuel cells is an example of manipulation of basic, rather simple chemical bonds to give clean, abundant energy conversion/transmission (storage, not production). Fuel cells are a sort of battery, carrying hydrogen from a generation site to where electricity is needed. So they do not by themselves cure the fossil fuel problem, but could vastly reduce it. We need to generate the hydrogen using energy from a traditional source. But even if fossil fuels are used, the carbon could be scrubbed from the smokestacks and stored underground or in the deep sea: wild visions but possible. Our cars could become mobile 25 kilowatt power generating stations, providing far more electricity than needed by a single household. What other science/technology developments are likely to have a major effect on the environment and on humans?

Many of the cycles of energy (natural and human-made) can run backward or forward. A heat engine (where heat generates mechanical energy...lifts weights or makes them move) run backward is a refrigerator...you use mechanical energy (derived from electricity with a motor-compressor) to move heat against its natural tendency...from cold to hot. Electrolysis uses electricity to split water into hydrogen and oxygen gases; run backward the hydrogen creates electricity. An electric motor can be turned by hand and it will generate electricity.

Energy slaves are the energy products based on fossil or other fuels, which we employ: with global energy utilization close to 400 exaJoules (400×10^{18} Joules) per year, each of the 6 billion (6×10^9) inhabitants of Earth account for about 2.1 kilowatts of power which is more than 100 times our own average power output (and Americans account for a disproportionate share of this).

Ironically, it takes energy to get energy. Building dams was itself a huge undertaking. If you have watched a back-hoe or steam-shovel digging, with each scoop a day’s work or many day’s work by a human, then you sense the power of energy! Yet somehow this transformed land, of dammed rivers and altered landscapes, has been labeled wild and pristine by many writers. The mythical abundance of the Willamette Valley perhaps shines out in comparison with the inland deserts of N America but it is not pristine (Robbins, *op. cit.*). In fact *it is elusive to think of the ‘natural state’ of the environment before this energy-transformation.* Before Europeans settled here natives had been reshaping the environment for thousands of years. Most of the large animals were extinct by then, the bison and mastadon and woolly mammoths, and often by human cause.

Geography shapes regional energy profiles. In the past through hydropower sites, through navigable rivers for trade, wood supplies for fuel and construction, and through hospitable agricultural soils and climate. In the future through wind-power sites, strong-sunshine sites and access to the sea, where transport will continue to be important.

Energy has reshaped society (in combination with increasing technology, wealth and population). The history of the US northwest involves in many ways: hydropower dams (1937 Hoover Dam ('FDR: I came, I saw, and I was conquered'; 1943 Grand Coulee; 2002... Three Gorges Dam in China) => cheap electricity => aluminum production => airplanes => Boeing => wartime buildup of Seattle.... Damming of rivers became a matter of lustful pride and ambition... the Willamette Valley in Oregon was badly polluted by the growing human occupation. The mood was human-centered and the human energy unstoppable: 'For a virtually raw area wherein man has done fairly well with the conditions as Nature left them, the valley will assume the polish of a regulated, planned region, designed by the ingenuity of man to provide the best possible living conditions for human beings' (Eugene Register-Guard). The dam-building frenzy, for irrigation, power, sanitation (smoothing out the river flow over the seasons), recreation... continued until the 1970s. This technocratic optimism also peaked after WW-II, a period when 'human genius could overcome all physical limits'. (Wm Robbins in *Northwest Lands, Northwest Peoples, Readings in Environmental History*, Goble and Hirt Eds. UW Press, 1999).

Energy is closely tied to wealth, power and economics. Examples: Enron, all the mergers of energy companies, and the World Bank's support of huge dam projects in underdeveloped countries. McNeill's discussion in Chap 10 of the clusters of energy, industry and population centers suggests energy as a driving force in shaping civilizations (of course, it is just one of the basic requirements for life: water, food, shelter, energy, and derivative needs like ease of transportation, animal or vegetable sources of clothing, and 'new' needs like *clean* air and water). The cluster coal-iron-steel-railroads and smokestack cities is a prime example. Energy recovery, oil wells and coal mines, has had particular impact on developing civilizations, from Venezuela which was the largest oil exporting country in 1946, but at the price of degrading Lake Maracaibo (the largest lake in S. America)... to Nigeria, where oil provides 80 to 90% of government revenue, and indigenous rebellion followed the fouling of fisheries and farmland by colonial oil companies (Royal Dutch Shell and British Petroleum in particular).

This leads directly to what we once suspected, and now know: *Energy is a driving force in global terrorism.* Oil has both brought both prosperity and unbearable strain and inequality across the face of the Earth.