REVIEW: There are 4 sub-regions in this course:
1. energy in nature,
2. the global environment
3. human energy use
4. life and energy at the rim of the Arctic

Introduction. This review is not meant to describe everything of importance in the course, but may help pull some of the ideas together. The four ‘sub-regions’ above are related in many ways; indeed that is the reason for studying them together. Here are some of these relationships.

In looking for basic principles that lie at the basis of life on Earth, energy, as it is described in physics and chemistry, is a strong candidate. There are certainly others: the structure and replication of the spiral DNA molecule provides a principle that underlies life in all its forms. There are other candidates for ‘basic principles underlying the environment’, for instance Darwin’s model of evolution of species. DNA is the engine that drives evolution and the books Richard Dawkins argue that evolution is a nearly universal idea governing life; it tries to answer the question, “why are we here?”; I think it better to ask “how did we come to be here” instead, so as not to go beyond questions of science. Others (not Dawkins, particularly James Lovelock and his Gaia description of Earth) argue even further that evolution and natural selection answer even greater questions, like “why is the Earth the way it is, a blue planet with its rocks and seas and ecosystems, in some reasonably stable state, rather than a parched, lifeless planet like Mars or Venus”.

Compared to DNA and evolution, energy seems a bit ‘dumb’, as in the difference between studying a great oil painting and studying the petrochemicals that make oil paints. Yet we physicists persist. Biology is great, and it paints rich pictures. But it paints them with energy. And, our recent understanding of the microscopic world of molecules makes energy cycles understandable.

At the same time we introduced energy, we started reading environmental/cultural history (Bill McKibben’s The End of Nature, J.R. McNeill’s Something New Under the Sun, an Environmental History of the 20th Century, Jared Diamond’s Collapse: How Societies Choose to Succeed or Fail, and Knud Rasmussen’s journals of Artic ethnology seen in the 1920s Thule Expeditions, in Gretel Ehrlich’s This Cold Heaven: Seven Season’s in Greenland, Harald Sverdrup’s ‘Among the Tundra People’ of the Siberian Chukchi Coast). Vaclav Smil’s Energy and John Harte’s Consider a Spherical Cow provided more of the science core.

1. Energy in nature. We followed energy from its generation in the sun (by fusion of the simplest element. – hydrogen – into the next simplest element, helium. This is a nuclear reactor, which physicists have reproduced in the H-bomb, and now are trying to tame to generate useful energy. Most of the energy used on Earth comes from this source, with a bit extra welling up from the Earth’s core. Gravity plays a central role in concentrating mass in stars like the sun, and making these energy events possible.

Energy arrives here after spreading out across space –thinning out—so that its power (rate of energy flow, across a square meter or Earth) is much less than at the sun’s surface. Not only the spreading in space affects this, but passing down through our atmosphere, some solar radiation is reflected and some absorbed.

Because the Earth’s energy (held in its land surface, atmosphere and oceans) is changing only very gradually, we can think of a ‘steady state’ in which incoming solar energy (an average of 342 watts/m²) is balanced entirely by outgoing energy. This is definitely not true during a single season (as for example the northern hemisphere heats up in summer) but after averaging over a year, things should be nearly in balance.
The incoming radiation is largely visible light, appearing fairly white because that is how our eyes respond when all the wavelengths are present together…from the longest (red), at about 650 nanometers \((6.5 \times 10^{-9} \text{ m})\) to green, to blue to the shortest (violet) at about 450 nanometers. What is the outgoing energy, that must almost equal the incoming? It is the invisible ‘heat waves’ or infrared waves which radiate from the warmed Earth. These are longer wavelengths than those we can see. As with a wood fire, the hottest flames are blue/violet, and the coolest are red…then when even cooler they become invisible infrared radiation which you feel on your face but not see. This long-wave radiation occurs at a wavelength that varies \textbf{inversely} with temperature, so that different stars in the night sky have different colors, according to their temperature (don’t confuse this color with the sparkling of many colors that happens when starlight is distorted as it passes through the atmosphere).

\textbf{The power} (in watts or Joules of energy per second) in the infrared radiation varies as the \(4^{\text{th}}\) power of the absolute Kelvin temperature. Using this (Stefan’s Law), and balancing the incoming and outgoing radiation gives us our first estimate of Earth’s temperature.

But that estimate is too cold! It has not accounted for the ‘blanket’ of greenhouse gases that are part of what we call ‘air’. Water vapor, carbon dioxide, ozone, and methane are present in small amounts in air, but the upward-going infrared waves are absorbed by them. This warms the planet closer to the \(300^{\circ} \text{K}\) that we think of as comfortable. A simple model of the atmosphere (as one or more plates of glass that perfectly absorb the upward moving infrared heat waves) gave us a warmer Earth….but too warm! So we then included the atmospheric circulation that air-conditions the tropics, moving heat to the polar regions in Hadley cells and their extension farther toward the poles. Gradually we have seen many of the processes that make Earth’s climate what it is.

It is remarkable that electromagnetic radiation takes so many forms at different wavelengths—from ultraviolet to visible light to infrared, then to x-rays and microwaves and tv signals and radio waves. Einstein demonstrated that light has another, parallel nature, as if it were a stream of particles (called photons), and this becomes important in chemistry and the biology of photosynthesis. We can see light as ‘waves’ when we see white light split into its component colors by a glass prism (as when looking through a spectrometer) or when reflected from a CD (compact disk). The wavelength of light is small, but not impossibly small. The CD has tracks about 1 micron (micrometer, or \(10^{-6}\text{m}\)) apart, and the rainbow reflection of light from it is an ‘interference’ pattern possible because that wavelength is comparable, roughly \(\frac{1}{2}\) micron. Waves are characterized by their speed of propagation, which is the product of their frequency and wavelength. So, long wavelength infrared radiation is also a low-frequency wave, compared with visible light.

Energy is a story of
- generation,
- transmission (or movement),
- transformation from one form to another, possibly
  into a highly concentrated form
- storage
- use….by living systems; yet governing all this is
  conservation of energy*. The forms energy can take are:
- nuclear
- electromagnetic
- chemical
- thermal
- mechanical (kinetic and potential energies)
We looked at mechanical energy, derived from Newton’s 2d law of motion, **force = mass x acceleration**. Think of a mass being pushed by a force. This led to a relationship between the change in kinetic energy, KE and the work done by the force, which is the force exerted x the distance traveled by the mass. If the force is due to gravity, we can think of the source of kinetic energy as coming from a second form of mechanical energy, the potential energy, PE. Summed together, the total mechanical energy, or **KE plus PE** is a constant provided no other forces are acting. This relationship tells us how fast a waterfall will be moving as water falls from a given height, or how high you will swing on a swing, provided we know your speed at some point in the arc of the swing.

**Thermal energy** in a basic ‘ideal’ gas is simply the kinetic energy of the gas molecules. Before molecules were discovered, thermal energy was a mystery, and empirical laws were developed from touch and feel, and thermometers constructed. But we now see thermal energy as a special form of mechanical energy. Because individual molecules in a gas like air move so much faster than the speed of typical breezes (a few m/sec), the thermal energy usually is much greater than the kinetic energy of the average air motion.

A theme running through the science core was that the properties of individual atoms, molecules and light waves, while microscopic in our view, can be understood surprisingly easy using simple observations: specific heat capacity (gives the speed of molecules flying around in an ideal gas), size of a film of oil on water (Benjamin Franklin’s experiment which gives the size of a molecule..see Spherical Cow Ch.1), rainbow patterns when light is bent by a prism or the tracks on a CD (gives wavelength and spectrum of energy in light), chemical energy released by burning an oil or digesting a Hershey bar (potential energy in the bonds with which atoms form molecules).

**Chemical energy** is related to the potential energy. Recall that potential energy is built up as a mass is moved against a force like gravity (gravity is a force pulling two masses together). When electric charge is present, the forces between masses can be very much greater than gravity forces, at short range. Atoms are made of positively charged protons in their nucleus and negatively charged electrons spinning round the nucleus, like satellites in orbit. Two atoms can bond together by sharing electrons, in ‘covalent’ or ‘ionic’ bonds (depending on how equal the sharing of electrons is). If the two atoms are pulled apart, it requires a force to do so. The ‘work done’ by this force in splitting the molecule apart is called the bonding energy (if the atoms come back together, the same energy is given back). Chemical reactions depend on breaking some bonds (separating molecules) and making new bonds. The net energy change is the making minus the breaking, or the bond energy on the righthand side of the chemical reaction minus that on the lefthand side. This is the energy given off in explosions or, in other chemical reactions, the great heating (addition of thermal energy) to required to make the reaction happen. In the lab one can study a candle burning, watching it become lighter on a precision scale (reading to 0.0001 gram!) and see it heat water in a soda can; this is a way to measure the chemical energy content, for the specific reaction of ‘burning’ or oxidation. Oily substances, from wax to gasoline have energy content in the range 20 - 45 million J/kg.

Some substances have extreme chemical properties. Oxygen particularly attracts electrons from other atoms (it has high electronegativity), making it very reactive substance. Oxidation...as in burning...refers generally to the acceptance of electrons in a reaction.

Water molecules have a bent shape in which the electrons spend more time around the oxygen nucleus, giving the molecule positive charges near its two ‘hydrogen’ ends. This property makes water a ‘polar molecule’ which bonds with other water molecules in a hydrogen bond. Water is thus hard to break apart...to boil, or melt, and easy to react with other molecules. It is the ‘universal solvent’. These ideas of physics and chemistry have enormous information for life on Earth...biology of the water planet.

The potential energy in each kind of chemical bond has been worked out (for very simple molecules, by theory; otherwise by experiment). This gives us the building blocks to study the energy given off or taken
up to make a reaction happen. The many bonds between atoms are broken and the atoms re-bond with other atoms. We add up the bonds broken, and the new bonds created, and the difference in energies is the net energy change. In this way we evaluate the energy produced by burning fossil fuel, for example, or by digesting food.

The important chemistry of nature and physics of heat and of moving bodies thus fits into a neat pattern, with much of it explained in part by basic ideas of kinetic energy, potential energy and forces. There is of course much more to study, for example the structure of electron orbits and the bonding energies are not easy to calculate for larger molecules and some new physics (quantum physics) is involved.

We described how energy can transform from one type to another, subject to conservation of the sums of all the energies. We rub our hands together and they are warm (mechanical => thermal, in equal amounts); we light a candle and it drives a Stirling engine (thermal => mechanical).

The introduction of the idea of an *engine* is important. You might say we are all engines or clusters of many engines. In simplest form, a ‘heat engine’ divides a stream of heat flow into mechanical energy output plus a heat flow output. There is an ‘efficiency’, the ratio of mechanical energy output to heat energy input, which is generally much less then 1 (since total energy is conserved, most of the heat input goes to heat output, with a smaller fraction shunted off to mechanical energy output).

Heat engines work through the force x change in distance formula for producing mechanical energy, which there appears as ( pressure x change in volume of the gas). By heating the gas when its pressure is high and cooling it when the pressure is low this ‘Pv’ cycle produces mechanical work. A glass bulb of air shows the temperature change when a volume of air is squeezed or expanded. These represent two of the four parts of the repeating cycle of a heat engine. The other two are heating and cooling of the air. Plotting the pressure and volume of a cylinder of gas being heated led us to the 4-stage repeating cycle, and a quantitative picture of work output. It was a ‘thought experiment’ in which the heated gas could lift weights. Engines are, in practice, built as ‘oscillators’ that would like to cycle round and round, and need just a little heat input to make them go.

Biology is using these laws in its own clever ways. Photosynthesis uses radiant solar energy to drive a chemical reaction in which carbon dioxide is split apart and combined with water to give carbohydrate plant material and oxygen gas. In this way plants store sunlight and convert air into green leaves and wood…as in Richard Feynmann’s poetic statement that “ a tree is made of air, mostly…”. Digestion of food is not a simple process of ‘burning’ it (though that is usually how food’s caloric values are determined). Complex carbohydrates convert to simple sugars soluble in the blood stream. We are roughly 18% efficient in turning this chemical energy into mechanical work (the rest goes into heat and unused chemical energy).

Photosynthesis was described in some detail, through a discussion of the amount of energy, in the form of sunlight, required to combine carbon dioxide and water to make simple plant material, modeled as a sugar. The exact energy in sunlight is counted in photons and gives the detail needed to predict the energy needed to create plant biomass. This was greater than the energy released when the material is oxidized, either because it has been eaten or because it is burnt, or it decays slowly. The ‘appropriation’ of photosynthetic energy by humans is surprisingly large, as a fraction of the global cycle. 80% of our energy use is mined fossil fuels, being used much more rapidly than they are replaced. Smil (p 42) gives the maximum possible efficiency of photosynthesis (ratio of energy stored in plants divided by solar energy input) at about 4%, but the actual efficiency on land at 0.33% and at sea 0.1% . So, the energy of only 1 photon in 500 (0.2%) hitting the Earth’s surface is converted to bioenergy. How does this photosynthetic energy flow compare with human use of bioenergy? We know that about 342 W/m² are entering at the top of the atmosphere, 168 W/m² are absorbed at the Earth’s surface (see fig. at end of these notes or Lec2-3 notes). 0.2% of this is 0.34 W/m². Human energy use is 4 x 10^20 J/yr or (x 1/π x 10^7 sec/yr) = 1.3 x 10^13 Watts = 13 teraWatts….this is better
recalled as 2 kW per person. Divide by the area of the Earth \((5.1 \times 10^{14} \text{ m}^2)\) to get 0.025 W/m². This estimate is thus that humans have ‘appropriated’ 0.025/0.34 or 7% of the current photosynthetic energy of the entire Earth! Other estimates may differ but this is our spherical cow’s pronouncement.

In Marcela Ewert’s lectures we saw some of the detailed machinery of photosynthesis, for example the role of ATP (adenosine triphosphate, a simple molecule as biology goes) and ADP in storing solar energy and transporting it to the growing DNA, proteins, powering nerve impulses, typically at night-time. Biology is full of remarkable molecular machinery and catalytic reactions (as in enzymes) which enable key chemical reactions to occur. Thus the energy cycles and chemical bonding relationships are only one part of the story, just as human engines are ingenious applications of thermal physics, with built-in oscillators that make them into viable machines. Combined with her lecture on chemical bonding, we began to see the ‘physics’ in biology, for example with the energy of a photon of light causing a hydrogen atom to ionize if its frequency is high enough. Basic energy gain and release in making and breaking chemical bonds can be understood quantitatively, and thus the energy release in burning oxidizing…fuels, or energy requirement for splitting water into hydrogen gas and oxygen gas, are readily worked out. Throughout the history of life on Earth organisms have adapted to obtain and use energy, with ancient eukaryotic cells that did not use oxygen capturing and assimilating bacteria that could use oxygen.

\[\text{At every turn there is more to be said: here, physicists and astronomers are concerned that much of the energy in the Universe has gone missing...'dark energy', sounding like something that belongs to Darth Vader, accounts for something like 95% of all energy, if ideas about the expansion of the Universe are right. But here in the solar system energy is better behaved. In fact it is conserved.}\]

The mathematics of conservation of energy...or of conservation of other things like pollutants...involve 'box models' in which movement (or 'transport' or 'flux') of energy (or a pollutant) is expressed as the product of a concentration, \(E\) (like Joules/m³) multiplied by a velocity, \(V\) (m/sec), and multiplied by the cross-sectional area, \(A\), of the flow (m²):

\[E \times V \times A\]

This product \(EVA\) gives Joules/sec or watts of power flowing (as with kinetic energy flowing down a river). Similarly the flow of water into a bath-tub is the concentration of mass (the density, \(\rho\) in kg/m³) x velocity \(V\) x area, the product \(\rho VA\) being mass flow rate in kg/sec. The flow of dissolved arsenic pollutant in a river is its concentration, \(C\) (kg arsenic per kg of fluid) x velocity \(V\) x area \(A\), or \(CVA\).

Box models in steady state have a key property, the **residence time**, which is the ratio of the flow rate to the volume of the box,

\[\text{residence time (sec)} = \frac{\text{mass (kg)}}{\text{flow rate (kg/sec)}}\]

(or if this is a fluid of unchanging density we can use volume instead of mass:

\[\text{residence time (sec)} = \frac{\text{volume (m³)}}{\text{flow rate (m³/sec)}}\]
2. **Humans and the global environment.** In looking at Earth’s environment, a few key energy transformations tell us a great deal about this great heat engine. The flow of solar energy, its storage in plants and burial as fossil fuels, all give a quantitative picture of natural energy.

This physics background helps to understand the heat engine that is the circulation of the atmosphere and oceans. Sunlight hits the Earth most strongly near the Equator. It radiates back to space more evenly round the whole world, Thus heat flow must occur from Equator toward the poles. This is achieved by the ‘Hadley circulation’ in the atmosphere, which is not the most visible thing: we see westerly winds, jet streams and storms more readily. But the up-and-down, north-and-south movement of the air carries heat, making the high latitudes much warmer than they would be without this circulation. The ocean does the same, contributing to the movement of heat, but this time in slower currents. Warm south winds, cold north winds and warm Gulf Stream, cold southward flowing deep ocean currents achieve this heat transport. Europe and even the Arctic are kept warmer by these circulations than they would be otherwise. The atmosphere picks up moisture and heat from the oceans, augmenting its own warmth, and transmitting warmth to the polar latitudes.

Water is a key to living systems, yet also to the physical, global environment. When a substance changes phase, from solid to liquid or liquid to gas, chemical bonds have to be broken. The latent heat of melting tells us how much heat energy is needed to break the bonds that hold ice together. The latent heat of evaporation tells us how much heat energy is needed for separating the hydrogen bonds of nearby liquid-water molecules to make a much less dense gas: water vapor. Water vapor is invisible but somewhere above it condenses back to droplets of liquid….fog or cloud. Thermal energy moves from the liquid water to the gas, then is deposited as sensible heat you can feel, when the cloud droplets form. We have a ‘heat pipe’ that cools the ocean and warms the atmosphere. Moist air flowing toward the poles from the Equator in this way accounts for as much heat flow as the simple movement of warm air and cold air.

The natural environment is the background for the world as we now have it: the world of human dominance. For the first time in Earth’s history, one species is able to make rapid and radical changes in the biosphere, globally. Of course phytoplankton and green plants, by producing oxygen and taking up carbon dioxide, affect the comfort zones of the Earth. But they do not over-reach themselves and invade new territories at the rate we do; they are more a stabilizing force of nature than a source of upheaval.

Both Smil (in *Energy*) took us on a detailed trip through energy, with emphasis on both physics and human aspects, much like the rest of this course. While his rapid-fire statistics were difficult to digest, the historic accounts of humans and energy showed us how the Industrial Revolution happened because of coal: energy slaves suddenly were available.

Our alteration of the Earth has extended to the extinction of many species of life, to changing the chemical balance of carbon, to altering Earth’s winds and temperature. Are we ladybugs, intoxicated by an oversupply of aphids? Can we not use our intellect to look over the horizon and make repairs? Greenhouse gases (carbon dioxide, methane, ozone and of great importance water vapor itself) affect the strength of the greenhouse effect, by trapping, absorbing and then re-radiating infrared heat radiation. The CO₂ concentration in air has risen from 280 ppm (parts per million as measured by volume) to about 385 ppm At current concentrations, greenhouse gases cause an estimated 2.5 watts/m² extra heating of the lower atmosphere. This seems small compared with the mean (about 342 watts/m²) yet is enough to have caused the 10 warmest years in recorded history to have occurred since 1990. And, 2007 was gauged to be the 2d warmest of them all. [This is based on globally averaged surface air temperature; regional variations are substantial.] Some perspective came from comparison of Earth with our planetary neighbors, Mars and Venus: the one too small to hold on to its atmosphere, and hence cold with little greenhouse warming and the other (Venus) with a deep atmosphere dominated by CO₂, and intense greenhouse effect. The whole planet
system gets involved (as in the story of Gaia on Earth). If plate tectonics on the planet is not active to bury the carbon in the atmosphere, one can have a run-away CO₂ greenhouse.

Lomborg’s *Skeptical Environmentalist* which we did not read, yet I often quoted, points to many ways in which humans enjoy better air, cleaner water, less disease, more energy in a steadily improving world. A sort of Panglossian picture (from Voltaire’s *Candide*) of the best of all possible worlds. I believe that he is right in some ways, particularly in the exaggerations of environmental activists armed with a few facts and little understanding of the nuances of global environmental change. But he is hugely guilty of his own form of exaggeration, by selecting the ‘best of all possible’ indices of environment and health. Global fishing has peaked and is declining after one species of fish after another is brought close to extinction. Fish farming is keeping the numbers up but at great cost to the environment, even to altering the genetic makeup of wild fish. Across the score-board of the environment, the upward climbing curves are threatened or hollow or non-existent, and are more than matched by other downward trending curves. Environmentalists often overstate the imminence of danger, but their end-result is almost certain to occur. The triple engine of human impact on the global environment: population x affluence x technology (‘PAT’ of Paul Ehrlich), is hard to overcome, even if Ehrlich overstates the rapidity of the incoming threat. In the PAT equation, visualize for example the impact of bulldozer and backhoe on the form of the Earth. ‘Affluence’ describes our wealth, which is really our accumulated capital which we can use to do further damage. ‘Population’ is growing, as you know, at rates never before seen on Earth.

Human population, now in excess of 6.7 billion, has grown faster than exponentially over the period 1 A.D. to 2000 A.D. Looking closely at the growth rates, we expanded most rapidly (in the sense of % population increase per year) in about 1963. In the sense of number of people increase per year, rather than %, the peak was about 1989. Thenceforth a remarkable change in fertility rates have reduced both kinds of growth rate. If one plots the log of the population curve against time, it will reveal these growth rates; the slope of the log(P) curve is the growth rate (% per year/100). This semi-log plot is a good way to study data that ranges widely in size, and has some tendency toward explosive growth or decay.

Exponential growth can be summed up by its ‘doubling time’, the time for population to double. This is about

\[
\frac{69}{\text{growth rate in } \%}
\]

which is a very useful rule of thumb (sometimes called ‘the rule of 70’, using 70 instead of 69 for convenience). Our global population was doubling in as few as 31 years at its peak growth rate (close to 2.2 %) but has now subsided hugely to about 55 years doubling time (1.25% population growth rate). This decrease in fertility is a most remarkable and important statistic, and like so many other environmental
changes, was largely unpredicted. It must be related at least partially to the increasing level of education and independence of women, who can develop their lives outside the family unit. Also this ‘demographic transition as it is called, happens as a country becomes more prosperous. Some demographers think population will never double again...let us hope. Disease and infant mortality remain high in the developing world; the AIDS pandemic claims (2008: World Health Org.) about 2.8M deaths per year globally. Locally AIDS has erased public health improvements in other sectors.

Similar to the demographic transition, air quality and water quality degrade as a nation industrializes, and then tends to improve greatly with further growth of prosperity: rich people don’t like breathing bad air. We had lectures on air- and water pollution, which gave quantitative measures: air has 6 pollutants monitored by EPA (Environmental Protection Agency of the US), maybe CO2 will soon be added to the list. Sub micron particles in the air are one serious problem. Chemistry and biology involve reactions along the surfaces of particles (or...cells, membranes..) and so when you crunch soot into tiny particles its surface area increases vastly, and in places like the human lung, this is dangerous. Plastics in the global environment are going through a decades long transition to high surface area as they are ground to ever smaller bits. Water has so many forms of interaction with humans and environment that it is difficult to summarize. Humans are badly stressed if their supply of clean fresh water is less than 1000 m³ per year...2740 liters per day., per person. But, only 2 to 7% of this is for domestic use, most is for agriculture (see Lecture 12 for detail). With increasing population the current 3.7% of people now under stress with inadequate water will rise to 17.8% by 2050. Yet a hopeful sign is that conservation can reduce our needs, especially in agriculture, and desalination costs are as low as $0.50 per m³, beginning to make the ocean source useable. Perth Australia was described as living under prolonged drought, yet with remediation measures actively being developed: desalination, ground water mining, water recycling and conservation: Australians are clever people!

Global warming, or more completely ‘global change’ which includes human impacts other than through burning fossil fuels, threatens the very fabric our world. McKibban’s The End of Nature which I read from early in the term, argues that our built-in sense of slow change of the Earth has given us the false impression that something like fossil fuel pollution cannot change the world quickly. But it is doing so. A sense of history and time is very important in understanding the environment, and one wants to learn from our ‘elders’ and from written history about the pace of global change.

J.R. McNeill’s Something New Under the Sun: an Environmental History of the 20th Century described in rich detail, from an historian’s point of view, the predicament of the rapidly changing environment and its connection with cheap oil. His memorable metaphor of ‘rats’ and ‘sharks’ captures the ironical human predicament. We evolved as supremely adaptable animals (like rats), able to reshape our local environments beyond simple hunting and gathering; yet come the 20th Century, we were intoxicated by cheap coal and oil, and rested at the top of the food chain like sharks, well-adapted to a stable, unopposed evolutionary niche. Traced through the development of heavy industry and assembly line production, through invention of wondrous new chemicals and medicines, and through the unexpected perils of pollutants both obvious and subtle, our century of growth saw human dominance challenge the very idea of Nature.

Natural Capitalism by Lovins et al. and Pacala and Socolow’s ‘wedges of carbon reduction’ gave ‘can-do’ solutions for our future. There are many ways to can lead better lives and at the same time protect the Earth’s ecosystems.

3. Human energy use. McNeill’s text gave a history of human use of energy...as first fire, then animals, then other forms of energy mining gave us many ‘energy slaves’ each. Humans are the most powerful creatures ever to walk the Earth, judging by their ability to alter the world around them. We not only adapt to the environment but we have learned to move between widely contrasting environments by insulating ourselves... building our own micro-environments with clothing, housing, heating fuels. The history of environment in the 20th Century is one of cheap, readily available energy as oil become more and
more the source of choice. Oil is stored sunlight. We became like sharks, at the top of the ‘energy chain’, feeding on the plentiful pastures of oil. But in doing so we may have forgotten our heritage, which brought us through the past few million years of evolution successfully. We are still here after natural disasters, drought, deluge, crops that failed, and of course our own endless struggles with one another. Scarcity of environmental resources is so built into our genes that we forget the reasons for global conflict, ethnic, religious, political wars. For, through the dark days of history, we were less powerful, and unable to move readily from one pasture to the next. Technology to tap the energy resources of the global environment developed only slowly, and in the past 2 centuries. The connections between oil and geopolitics are everywhere. McNeill describes the 1910-20 revolution in Mexico which led to a huge development of oil exports, recasting the ecology and society of Veracruz. From Lake Maracaibo to Baku to Nigeria (the subject of the new film *Sweet Crude* at this year’s Seattle Int Film Festival, first showing Weds. 3 June at the Egyptian Theater, 7pm), the environment was left out of the equation as oil gushed forth, and the skewed pattern of western use of oil supplied by poorer countries began. Democracies faltered as casualties of this exploitation.

We are still here, yet we are intoxicated by oil, and, we hope only temporarily, unable to stand up to the shortages that lie ahead. The huge debate over the ‘end of oil’ is only ‘when’ not ‘if’. The optimists say we will give up oil, as the Stone Age humans gave up stones, not because they ran out but because they found something better. The problem with this optimism is that we are in uncharted waters, rising on the exponential curve of human population. There is no precedent in history, and the nature of exponential curves is that they ‘smolder’ quietly for a long time and then ‘ignite’ quickly.

The big numbers of global energy (e.g., the \(4 \times 10^{20}\) Joules per year of marketable energy used by the world’s populations) use translate into understandable numbers on a *per capita* basis...divide by the relevant number of people. Two kilowatts of power use per global citizen (24/7), and eleven kilowatts per US citizen. Cars that each burn *one hundred kilowatts* of fossil fuel (rate of energy use), with an efficiency of 1% or so, as a people mover. The *richness* of chemical energy (compared to thermal energy which in turn is richer than mechanical energy) is part of the source of our intoxication. It is expressed in the *1 million* Joules in a candy bar, compared with *4000* Joules of thermal energy stored in it for each degree C of temperature change and a mere \(\frac{1}{20}\) Joule of kinetic energy in the candy bar moving at 1 m/sec. A key diagram is the US energy ‘flow’ chart (on the class website and lecture 13, and appended below). The US uses about 100 exajoules (\(10^{20}\) J) per year. It is a masterpiece of graphic content, showing the 80% of our energy coming from fossil fuels, how 40.3 exajoules (40%) of our energy passes through electricity, how much is lost on the way to us (27.8 exajoules; all figures for the year 2002). The figure shows that ‘useful energy’ comes out to be 37% of the energy extracted, though one must examine how such numbers are calculated. For example the efficiency of electrical generation and transmission to us (31%) from the coal-fired power station: how does it account for the mining of the coal, and how far back in the chain and how much of the ‘system’ of energy extraction (and environmental degradation should be included. Work to be done, in the spirit of *Natural Capitalism*.

We explored ‘spherical cow’ ways of estimating the power requirements for a car by letting it coast to a stop, and using the rate of change of its kinetic energy as a rate of input of energy from the fuel when it is running at a steady speed (the slope of the curve KE versus time as it slows down is the power: the curve is not a straight line, but instead is a curve with diminishing slope, showing that less power is consumed at lower speeds.) The bicycle is more efficient than the car as a people mover. I can think of 4 independent ways to estimate the power consumption in bicycling, including ‘coasting to a stop’ as one. What are some others? (Hint: how many 1MJ candy bars would you consume to cycle 100 km?).

Beyond the arithmetic of oil ‘mining’ and use, there is the carbon cycle. Hydrocarbons have a ratio of hydrogen to carbon atoms ranging from about 2 in long chains like octane, to 4 in methane (natural gas). Coal has even more carbon content plus lots of sulfur. So, for each unit of energy released in burning hydrocarbons we have carbon dioxide production that has raised the CO₂ concentration of the atmosphere by
about 30% since the pre-industrial period. At current growth rates we could easily double the present CO₂ concentration of the atmosphere during the coming century. This drives the ‘blanket’ that traps outgoing infrared radiation and warms the Earth. We learned through a ‘spherical cow’ estimate the connection between our energy use (US: 1 x 10²⁰ Joules per year, globally 4 x 10²⁰ J/yr) and our carbon emissions to the atmosphere (roughly 8.5 x 10¹² kg C/year (8.5 gigatonnes carbon per year, globally)), based on the typical energy and carbon content of fuels.

Prof. Jim Murray showed us how uncertain are the predictions of future fossil fuel use, and hence even global warming, because of uncertainty in estimates of oil and gas reserves in the ground. His and David Rutledge’s (Cal Tech) examination of reserves suggests that we may turn out to be on the low end of the spread of curves for future use of these fuels...which could be good news for the environment. This was a great lesson in looking more deeply into science and technology underlying these environmental issues. A key discovery here was King Hubbert’s bell-curve, which predicted in the 1956 when the US oil production would peak (1970) and when global oil recovery will peak (about 2010). Hubbert’s curve is symmetrical, and idealized, and predicts that half of the total oil supply is exhausted when we reach the peak. His analysis would predict that in the year 2070 90% of all the Earth’s oil will have been burnt.

Recent history of the first energy crisis (1972-80) is a story of over-reaction on both sides. OPEC showing its muscles in responding not only to the market for oil, but also their view of the politics of US involvement in the Middle East. First a tightening of oil supplies, a rapid increase in price, followed by development of more oil fields, conservation and the market response of a drop in oil prices to a very cheap level. Conservation did itself in, however. With newfound efficiency and conservation and alternative fuels and diversity of oil suppliers, the energy crisis was declared ‘over’. In the US that is; European and Asian governments maintained a larger tax on oil, holding down demand and promoting further efficiency. An overwhelming fact in this is the relatively small fraction of our income we spend directly on energy. Phrased in terms of energy cost divided by GDP, the numbers range from 8% (1970) to 14% (1980) to 6% (1998). But we are fooled: the real cost of energy includes hidden subsidies, cost of armies and homeland security, cost of depleted natural capital.

There are many negatives in the story of human energy use and the global environment. But our genes may come to the rescue. If we waken from our 20th C. slumber and sense that our survival is indeed at stake, we can immediately seize on the opportunity in developing energy efficiency. The ‘factor-ten’ group visualizes a world using 1/10th the energy currently being used (per person). Conservation becomes not an image of shivering in cold, dark houses, but of living better lives with greatly increased efficiency, with more social justice, with less inter-tribal tension. These somewhat vague hopes are brought into focus by Hawkens and Lovins’, Natural Capitalism, who give much detail about the value-system for capital: human capital, environmental capital, as well as the traditional financial and manufactured capital of the economist. Industrial societies keep careful balance sheets but their own accounting principles are violated by ignoring the depletion of natural capital, and neglecting the best interests of human capital.

They give us principles for redesign of human activity around closed-cycle, near-zero impact manufacturing with ‘biomimicry’ which imitates nature. It argues that toxic, high temperature industrial processes now typical, can be replaced with modestly recycled natural materials of equal strength and efficacy. The authors of Natural Capitalism want to work through the modern industrial system rather than against it. They are ‘for profit’. Government regulation and environmental idealism, conversely, both act more slowly and often fail to achieve.

Natural Capitalism urges us to use of our ‘selfish genes’ to profit the global ecosystems, showing that it serves us best...too. In the 99% inefficiency of the modern automobile they see opportunity. Yet right now it is Europe that is building the wind-power machines and Japan that is building the hybrid automobiles.
Almost all of our sources in HAS222d argue (in Amory Lovins’ words) that ‘It is not the supplies of oil or copper that are beginning to limit our development but life itself. …progress is restricted not by the number of fishing boats but by the decreasing numbers of fish, not by the number of chainsaws but by the disappearance of primary forests….a forest provides not only the resource of wood, but also the services of water storage and flood management. (Natural Capitalism, p3).

In the great debate about the environment there is some surprising agreement. Even the ‘skeptical’ Lomborg advocates alternative energies, arguing that, right now the cost of wind-power generation of electricity is nearly the same as from building a new coal-fired electricity generating plant: “…the difference in cost between traditional fossil fuels and some of the cheapest renewable energy sources is so relatively slight. Moreover these economic costs do not include the negative social cost of fossil fuel use on the environment.” (p. 132, The Skeptical Environmentalist). Surprising? Truth has a way of bubbling up to the surface.

4. Life at the rim of the Arctic. We read of the Greenland Inuit in This Cold Heaven by Gretel Ehrlich, plus out-takes from H.A.Sverdrup (Among the Tundra People), Gerard Diamond’s Collapse about the success or failure of civilizations, a brief reference to Alaskan Inupiat natives (from Charles Wohlforth, The Whale and the Supercomputer) and a brief description of the Arctic ocean ecosystem by Richard Brown (Voyage of the Iceberg). Why? Because it puts a human face and an ecosystem-awareness on the hugely complex problems of the global environment, shows how strong and resilient humans can be in the most challenging environment on Earth, points us to a region in which global warming and modern influence are finally ending the successful 6,000 year isolation of these natives. Reading about the Arctic rim at the same time introduces us to a strange and wonderful part of the Earth, where night-time lasts for months, yet is bright with moonshine on white snow, aurora dances in the sky and in summer the sun moves horizontally round the sky but never sets.

Another reason for our Arctic focus is that global warming is happening more rapidly in the high northern latitudes than anywhere else on Earth. When you melt snow or ice, the soil, vegetation or sea surface thus exposed is darker. It absorbs more sunshine (as expressed in its lowered albedo…reflectivity). Arctic sea ice cover has been declining by 8% per decade since the 1970s, with late summer 2007 showing the least sea ice…down 20% from the previous summer…the most open ocean surface in recorded history.
The natives of Greenland and the other lands of the ‘Arctic rim’ have successfully lived since the last Ice Age in cold and storms that we find frightening. With no communication, no medicines, no ‘energy slaves’ but for sled dogs, without easy movement, with uncertain food supplies, and very modest energy supplies for warmth, they prospered. They moved easily on ‘ice highways’ in winter. Is this not a symphony of the human spirit? Until very recently we would say that they were the only native peoples on Earth to survive the colonization by Europe or Eurasians from the warmer latitudes.

Gretel Ehrlich was an artistic tourist in this scene, while Richard Brown was a skilled scientist. Both contribute to our understanding. Our readings about the lives of natives of the north, and Knud Rasmussen’s brilliant and resourceful gathering of their life stories show us some of the qualities bred in this cold environment. Sila, weather goddess, looms large. Dreaming is an active pastime in winter, and I am told that the natives like to be a bit chilly while sleeping, because it promotes active dreams (try it and see!). Like the sea creatures, humans must follow closely the food supply. Ehrlich’s descriptions of the nuts and bolts of long hunting expeditions show us how close to the edge of survival these people have lived. She gives us glimpses, as in

“It was on the ice that I saw the wild genius and second sight of the Eskimos traveling by dogsled and hunting every day to feed themselves and their families as well as their dogs—twenty or more of them. The complexities of the ice had taught the hunters to reconcile the imminence of famine and death with an irreverent joy of being alive…the landscape is …an ode to the beauty of impermanence. I saw how skillfully hunting families refused the impoverishment of materialism to opt for a life of natural communalism, sharing food, love, gossip, feuds, dogs, as well as weeks of weathered-in, do-nothing days. Fierce individualism is frowned upon.
The group matters more. They said: ‘everyone wants to be different. We carry our differences inside.’” (Preface, *This Cold Heaven*).

For contrast, compare Charles Wohlforth’s description of the Alaskan Inupiat natives, from the mid-term quiz:

“For the perspective of traditional Inupiaq norms of behavior most whites were rude: they talked too fast and didn’t give others a chance to say anything, they stared, they spoke too directly, contradicted others, and didn’t listen for meaningful nuances, they couldn’t sit still, and they didn’t reciprocate the gifts of knowledge and hospitality they received.” (from *The Whale and the Supercomputer*).

The complex interactions with Europeans or Americans have many sides. Native ownership of some of the natural resources of the Arctic has put them in a difficult position, being both environmentalists and yet living off the land. The scale of exploitation of oil, minerals, furs has been so great as to challenge their balanced relationship with nature. Global warming presents a huge challenge to their lives and to the whole Arctic ecosystem.

We spent some time looking at the diversity of the ‘necklace’ of Arctic communities extending from Siberia to Alaska, Canada, Greenland, Svalbaard, Iceland, Faroe Islands, Scandanavia. Modern day Norway is itself worth some study during the present global economic distress: they seem to doing fine. They have put much of the proceeds of North Sea oil into a trust fund, avoided risking bank investments, kept a healthy level of homeland industry. Neighboring Iceland meanwhile went from great stability and prosperity to near financial collapse, due to risky bank-related investments. Finally we visited ANWR, the Alaska National Wildlife Refuge and its precarious competition between ecosystem preservation and oil drilling. The native response has been mixed, yet seemingly dominated by resistance to giving up this rare wilderness to the oil industry (for a ‘mere’ 10B barrels of oil...33 barrels per US citizen). A strong focus here was the Tragedy of the Commons (Hardin) and various rebuttals (e.g.,Rowe). Class discussion was illuminating, showing how governance of the commons can occur in many ways, yet how ‘smallness’ really helps: a village may do better than a state. We find food and fuel in our environment, yet who owns these? How is the competition resolved, between rights of individuals or small ‘tribes’ to harvest a common resource, on the one hand, and the larger community on the other. Does this community include creatures other than humans? The Commons is an ideal focus for this course, and the subject of the final essay.

Sverdrup’s Chukchi natives in Siberia were nomads, like the natives of central Canada, following the caribou migrations. Someday read *People of the Deer* by Farley Mowatt, which describes life near Hudson Bay. The natives ate voraciously when the hunting was good, but were close to starvation at other parts of the year. When furs became popular in Europe, the Hudson’s Bay Company changed their lives with guns, sugar and alcohol. Eventual settlement of the nomadic inland natives of Canada and Siberia altered their lives forever, with a wealth of contradictions. Relieved of starvation and danger, and the responsibility of the hunter, what becomes the purpose of life? Today Greenland’s economy is dominated by shrimp exported to Europe, which gives Denmark a continuing interest in them. In the unusual warm period of the 1930s-1950s it was cod. Tomorrow will it be oil? But fishing was not the life that Greenland hunters remembered so vividly. Some native skills, lost for a time, have been recovered. Native kayaks are extremely efficient craft, and are now being built and used again in Greenland. They have evolved highly over time, and have different shapes depending on the local environment of waves and wind, and the need for carrying cargo.
The science core entered in the Arctic in several ways. We discussed the aurora, the brilliant, multi-colored, rapidly changing curtains of light in the night sky. The aurora is an icon for the spiritual life of the natives, with their intense set of beliefs in natural forces and ‘deification’ of Sila, the weather. Yet aurora is also a visible demonstration of the clash of intense solar flux of particles...the solar wind...colliding with the our magnetic shield: the Earth’s magnetic field. The field lines tip into the north and south poles, ducting those particles into the atmosphere where they interact with gas molecules, making different colors relating to oxygen and nitrogen at high and low altitude. The slow convection in the Earth’s core and mantle (which drive continental drift) is responsible for our magnetic field and its life-protecting shield.

A compelling role of the Arctic in science is through global warming which is amplified in the far north. The albedo of snow and ice...strongly reflecting sunlight...is greatly reduced when ice melts and dark ocean is left bare. This amplifies the greenhouse effect, making the observed and predicted warming several times greater there than in the lower latitudes. Once ice and snow are gone in summer, other effects (melting permafrost releasing frozen methane deposits, changing interaction of atmosphere and the upper ocean, changing ocean circulation) may greatly affect global warming.

Bill McKibben’s book *The End of Nature* introduced us to our own perception of time...the rate at which the environment changes, and how really brief the span of human civilization on Earth has been (some 300 generations: there are individual trees still standing which are older than human civilization!). In ‘Deep Time’, that is over time intervals of a hundred million years and greater, the Earth has been cooling down since the dinosaur era...the Cretaceous, roughly 100 M years ago. Coal mines in Svalbard, the islands near northern Greenland, attest to a once warmer Earth (Smil taught us that coal is fossilized land plants, whereas oil is the liquid remains of plankton of the seas). Recently (in Deep Time) the cooling started huge oscillations of climate: Ice Ages. These are now spaced about 100 thousand (100K) years apart. The warm periods are relatively brief and start up ‘suddenly’ whereas the Earth is usually descending into long colder periods. Astronomical forcing (the slight changes in phasing of the sun’s radiation with season, changes in the tilt of the Earth’s axis and the eccentricity of its elliptical orbit) is known to be the ‘pacemaker’ of ice ages, but why they are so huge in magnitude is not yet known: it is a vital demonstration of the sensitivity of global climate to small changes in radiative forcing, which is why the small (7.5 gigatonnes per year) human input of carbon in the atmosphere is worrisome. The ‘direct’ effect on the greenhouse is roughly 2.5
Watts/m² change in radiation, but this seems to amplified by the dynamics of the atmosphere and oceans. Thus the Arctic is a focal point for global warming. The effect of this warming on ecosystems and native populations with their winter highways on the frozen sea and tundra, is great (Arctic peoples still largely rely on the bounty of the sea…shrimp being more than 90% of Greenland’s GDP; blue whiting, a fish you may not have heard of, being the dominant GDP of the Faroe Islands).

In Smil’s *Energy*, concentrated discussions relevant to Arctic ‘human energy’ can be found, for example animals’ somatic energy at rest: BMR (basal metabolism rate). His plot of BMR versus body weight shows, from mice to elephants, a weight⁰.⁷⁵ power law. (Somatic: relating to the body as opposed to the mind, from somatikos, Greek for ‘body’). We humans fall at about 100 Watts of BMR. The proverbial light bulb. So, Harald Sverdrup’s (*Life Among the Tundra People*) account of the sleeping room of Chukchi Coast natives in winter suggests a spherical cow calculation: at 100 Watts per person, how well insulated must a native sleeping room be to keep, say, 10 people warm at night. In the spirit of *efficiency* of use of energy, insulation is a big player. We waste a large part of global energy budget on heating and cooling (estimates anyone?). Another Smilian idea relating to the Arctic: we have an idea how much food (in kg. or kilocalories or Joules) we eat per day…something near 1% of body weight. See how this corresponds to typical energy content of foods (roughly 10 MJ/kg) and typical caloric intake (2500 kilocalories or 10⁷ J per day) (Smil p 129). This is itself a statement about our efficiency at rebuilding tissue and bone.

If the 1% rule holds for all animals (does it?), then the great whales of the Arctic (reaching 100 tonnes .. 10⁵ kg..or more) must eat something like 1 tonne of food per day. The great blue whale, the largest animal to have lived on Earth, and once very numerous, had a population estimated by whalers and biologists at 200,000 to 300,000. They must have eaten so much krill (shrimp-like animals, dominating the Southern Ocean) that the krill biomass could have itself fed perhaps 1/5 of the current human population. An estimate of 3.6 tonnes of food/day is found at [http://www.extremescience.com/BlueWhale.htm](http://www.extremescience.com/BlueWhale.htm) which is more like 3% of body weight. The tongue of a blue whale weighs as much as an elephant. The whole whale weighs up to 170 tonnes, with length 33m. These whales now number less than 15,000 (in a single year, 1931, 30,000 blue whales were taken. The largest current group of 2000 great blue whales cruises the California coast.). As with all energy issues we then are urged to look at ‘dietary transitions’…from vegetables to fish to red meat…and their impact on the global environment. *Who Will Feed China* (Lester Brown) is a poignant plea to consider the effect of the world’s largest nation as it raises its standards of living and eating. We saw that prediction is difficult however: the transition to massive wheat imports to feed a growing appetite for meat in China has been halted abruptly, yet transformed into soy imports.

Marcela lectured on the ecosystems of the Arctic, which have to deal with extreme conditions of cold and isolation. Living near the phase change of water/ice is tricky, and in the freezing of sea-ice the pockets of brine (water which concentrates the salt from neighboring freezing regions) algae can develop and access sunlight. These brine channels can have a surface area of 10⁶ m² in a single cubic meter of ice: remember the role of surface area in chemistry/biology. All trophic levels are found in these pockets, from viruses and bacteria to small invertebrates. The intense food chain in springtime is a sight to behold, with great whales at one end (or perhaps humans hovering above them), and the riot of fish, seal, sea-bird life that is intimately linked. Global warming is affecting these ecosystems rapidly, leading to major shifts of species (typically the boundaries between cold- and warm water fish are moving northward).

The short section of Brown’s writing is particularly valuable in describing the intensity of the Arctic food chain in springtime, where all sizes of creature explode with growth, beginning with ocean phytoplankton…the grass of the seas. The word gets out and birds migrate from as far as Antarctica, frantic to feed and breed and get out again before the end of the short Arctic summer. Brown tells us more clearly how immediate, compelling, energetic and varied is the cycle of life at high latitude. Somehow simpler than the ever-bearing ecosystems of warm latitudes, the Arctic spring is a laboratory of simple relationships. Kristin Laidre’s remarkable research with the narwhal in north Greenland gives us a first-hand picture of these large
mammals, living so effectively in Richard Brown’s Arctic spring. The narwhal dive deeper than a mile to forage for Greenland halibut, where the pressure is 150 times that of the atmosphere and compresses their bodies almost beyond recognition. The larger whales of the Arctic are very much a part of the native success story, for example Alaskan hunting of bowhead whales. The image of a native standing on top of a 100,000 lb mammal, 100 feet long, possibly 150 or even 200 years old, is unforgettable (lecture2 slides).

Greenland is a focal point in the global climate system. The warm Gulf Stream waters that transport heat toward the Arctic pass close by, and help to provide the setting for the explosive growth of the Arctic ecosystem. The sea does not freeze where this warm water invades from the south, and the open water provides the ‘window’ for intense growth of sea life (as in the North Water polynya of Baffin Bay, west of Greenland). In this region the harshly cold air from the Canada Arctic cools the ocean surface, and as the water becomes denser it sinks, driving an ‘overturning circulation’ akin to the Hadley cells of the atmosphere. Global warming is amplified in the Arctic, and to some extent the natives there are in the forefront of climate change. Even if the warming were slight, the effect on ice and snow would be large (near the freezing point). But it is not slight.

The first time I saw Greenland was on an oceanographic research ship, the R/V Knorr out of Woods Hole:

Prince Christian's Sound, Cape Farewell, August 1981.

The first sight of Greenland was a line of cloud on the horizon. We were working slowly inshore from the east, and a line of white hung strangely unchanging. It was not cloud after all, but ice. The glacial icecap of Greenland flows over the mountaintops toward the sea. An old fisherman’s song called 'Fiddler's Green' talks about the 'cold coast of Greenland' and I know why: as you approach the temperature of the air and water drop precipitously, and katabatic winds of heavy cold air slide off the continent at furious speed. This is iceberg alley, the East Greenland Current carrying both sea ice and icebergs rapidly south, in a boundary current just 20 miles or so wide. The light is strange and Norse explorers saw monsters now called the 'Norse Mermen'. They are mirages. An iceberg or an island, coupled with its inverted image appears as an hourglass shape. Sea ice lying low on the surface is elevated into a mighty white wall seemingly hundreds of m high.

Richard Brown, in The Voyage of the Iceberg wrote:

"After four Ice Ages Greenland is no longer green and it is not much of a land either. It is nothing more than an enormous mountain of snow 2 miles high, crushed into ice by its sheer weight, the land beneath forced down below the level of the sea. All that shows today of the largest island in the world is a ragged fringe of mountains and islands which creep out from under the edges. Greenland is the Ice Cap, a cold and barren waste of rolling white plains, deep crevasses and sharp ridges, with the everlasting winds roaring across it like screaming demons. It is a howling wilderness, and one of the few truly lifeless deserts on earth. ..."
The enormous weight of the Ice Cap bears down on the ice below, and squeezes it slowly into glaciers that come creeping out in tortoise rivers through the fringe of mountains.

"It is the middle of April. Suddenly the bleak winter is over. The sun is up, very low in the sky, but it will not set again until the end of August. The beluga whales which spent the winter as dim, hovering, white shapes moving only to breathe, press forward into every lead as soon as the ice opens up. The foxes bark and the ptarmigan cackle, and both of them moult out of their winter white into their summer camouflage, ready for the latest round in their endless mutual battle to survive. The Arctic is slowly beginning to come alive.

"Then the birds come: tight little flocks of yelping oldsquaw, long, low lines of grunting eiders and, very high up, the first skeins of snow geese. Thirty million dovekies pour along the edge of the ice heading for Thule, followed by tens of thousands of murres, kittiwakes and fulmars. Black-and-white snow buntings, just arrive from Europe, sing from every outcrop. All of them are driven on by the desperate need to get in and get breeding, then out again before the short arctic summer is over.

"When the sun comes back in the spring, the oasis of pen water grows even larger. The sea starts to nibble at the ice around it, and the more the ice melts, the more sea there is for the sun to warm. Now, in June, the North Water has spread far west into Lancaster Sound, and is pushing south toward Devil's Thumb, where Captain Adams is waiting patiently and hoping.

"With the ice gone now, nothing stops the sun's rays from reaching down into the depths of the sea to make the plants bloom. These are not the ordinary kelps and seaweeds of the shore, but phytoplankton, the real plants of the open ocean: tiny, drifting algae, no more than a cell or two long. Like the earthbound weeds, these need only sun, water and fertilizer to start growing, and there is plenty of each in the North Water in June. Their bloom lasts only a month, but more phytoplankton grows in that short arctic season than in a whole year in the barren tropics. This massive bloom sets off an equally massive swarming of the microscopic animals that graze on it, and of the higher predators in their turn. The shrimps are so hungry and abundant by July that their swarms can clean the bait out of a fish trap or the fat off a sealskin as neatly as any Amazon piranhas. Enormous schools of polar cod, hundreds of narwhal and belugas, tens of thousands of seals, murres and kittiwakes, and millions of dovekies, all gorge on the summer bounty of the North Water.

"The bounty also supports a tribe of men = the sierapaluk and the Saviqsivik. The white men {and southern natives} call them "Eskimos" but to themselves they are "Inuit" -{man} the true human beings. They are spread across the empty country from Thule to Cape York. But they do not think the land is barren at all. It is their Earthly Paradise, the only place in the world where real human beings can or ought to live. They
still half believe what they once knew for centuries--that they are the only people on earth.”

All this life, from microscopic plankton blooming when the sun returns, to the Inuit feeding on seal and inland caribou, are feeding on the ocean’s global overturning circulation. The upward and northward motion of the ocean brings the nutrients, melts the ice, and all of life follows.

**Conclusion.** What have we learned from the conjunction of these ideas? Was it worth the trouble to juggle spherical cows and global oil supplies and cold heavens? You will have to judge. Many feel that we industrialized peoples are following a growth trajectory that soon will take us beyond our ability to sustain life, in America and shortly the rest of the world. We have appropriated so much of the Earth’s fresh water and primary production that to raise the entire present population to US standard of living would require several Earths. To raise everyone of the doubled population expected this century would take twice this number of Earths.

Looking at northern people who have faced starvation, unimaginable cold, and isolation and yet somehow summoned the communal strength to survive and succeed and even prosper for so long, may be a worthwhile idea. One of several underlying themes, and a key to all of this, is the idea of efficiency; which we have looked at in great detail for engines, transportation systems, electricity generation, human beings and their energy slaves. Less technical thoughts of efficiency speak to our choices as humans, exemplified by the redesign of the city of Curitiba, Brazil (Hawkins, Lovins & Lovins). But efficiency also suggests an ‘economy’ of mind, a way of living that is simple, spare, elegant, self-reliant and eminently satisfying. Materially simple lives are dramatically different from the heavily consuming, numbing, frantically paced lives which many of us lead today. We may do and enjoy things that enhance and extend…and join in with…the ecosystems around us, or, on the other hand, we may act for other kinds of pleasure, short-sightedly enjoying the ‘last tree’ on an increasingly barren landscape. Lovins and collaborators show us ways to proceed.

J.R. McNeill urged us to take an historians view of the environment, and a human-centered one. We have seen in many ways how we are intertwined with the other living elements of the global biosphere. Finally, in *Natural Capitalism* and its more philosophical discussions we come to see that our future depends on accommodation of humans, plants and animals. We are greatly aided in this by new revelations of the subtle and highly evolved lives of plants and animals: Asian crows who make tools, cuttlefish who transform their skin patterns to become invisible next to piece of coral; fish whose color indicates their mood; dolphins who blow bubble rings and play with them. Great blue whales sing to each other with songs that are repeated over years, and they use the ‘sound channel’ of the ocean which carries their songs for hundreds of km (hear them at [http://en.wikipedia.org/wiki/Blue_Whale](http://en.wikipedia.org/wiki/Blue_Whale)). The tongue of the piliated woodpecker is long and efficient at grabbing insects from deep in a hole it has hammered in a tree trunk. The woodpecker listens with it as a stethoscope to locate the insects. Then, because hammering a hole in a tree involves very large forces (ratatatat sounds echo through the woods), the woodpecker wraps its tongue around its brains to cushion it while hammering.

Universities exist to teach students ideas and skills, preparing them for careers. They also exist for the production of new knowledge, new skills, new technologies, which will define new careers of the future. University of Washington has for many years had the 2d largest research grant income of any university in the nation (care to guess who is #1?). Students here can participate in this research stream through internships, part-time jobs, course-work, and reportorial (newspaper-) writing. Yet universities need to transform
themselves toward ‘greener’ undergraduate curricula. This means putting human environments and the global ecosystem (all that other living material) on an equal footing, in our science, arts, culture, economics, law, international relations…the whole list.

In July 2004, President Emmert of this university issued the following statement:

As the pre-eminent research university in Washington, the Evergreen State, the UW and its faculty, staff, and students recognize that we share a responsibility to act as a positive force for the enhancement of the local and global environment. The University of Washington embraces its important leadership role regionally and nationally to be an environmentally, economically, and socially responsible institution.

In July 2008 former Vice President Al Gore challenged the US to generate all its electricity from alternative, zero-carbon energy sources by 2018 (currently about 40% of our energy flow). (see his speech at http://www.youtube.com/watch?v=dt9wZloG97U).

In May 2009, President Obama issued new sets of standards for US cars and light trucks, large new programs for green energy research, in the midst of the greatest financial collapse since the Great Depression of the 1930s.

R/V Knorr  August 1981, Labrador Sea

Greenlander .. photo by John Rasmussen
northwest Greenland kayak: a triumph of thousands of years of design optimization, made of wood, skin or canvas, cotton thread. These 6 boats were built from scratch by 6 people in 6 days.
Greenlandic flag: midnight sun
below: energy balance from solar radiation: numbers are Watts/m² averaged over all seasons and all latitudes of Earth.

below: 2007 mean surface air temperature: the 2d warmest year in the past several centuries…this is the anomaly, the difference between 2007 and the average of 1951 to 1980.
Population density by country (source: Wikipedia): people per square km. Note the relatively low population densities of South America, Russia and much of Africa. Australia with ~ 19 million people in a country nearly the size of the US, is already overpopulated based on key environmental attributes like fresh water.
**Syllabus: energy, water, carbon symbiosis**

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<td>chemical bonding, chemical energy failure of civilizations handout and Arctic peoples</td>
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<td>heat engine Sverdrup Greenland’s success</td>
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<td>phase change: ice, water, steam Alaska’s natives and oil</td>
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<td>4 20/24 iv</td>
<td>energy in fuels Smil are we running out of oil?</td>
<td>lab 2: climate</td>
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| 5/27 | Review REVIEW handout solving | Earth Day 22 iv
| | PS1 handout | Storms, circulation |
| | Wohlforth | Movement in O & A |
| | | Air pollution; stratification; dilution |
| 4/8  | Quiz review REVIEW handout solving | Problem |
| | Read Sph Cow, Smil 4 | |
| | Energy in foods | Are we running out of food? |
| | The ‘eat’-engine | Traditional native diet, hunting and fishing |
| | Brown | Quiz |
| 11/15 | Photosynthesis Smil | Are we running out of environment? |
| | Carbon cycle | Arctic ecosystems and their future |
| | Global ecosystem: primary production biosphere: McNeill | Greenland: Ehrlich |
| | Water, ice, water vapor: The hidden climate engine | Global water use by humans ice highways, sea-ice, glaciers |
| | | Global warming and precipitation effect of global warming in Arctic |
| | | Environmental skeptics: do they have a point? |
| 18/22 | Review and problem solving lab | A can-do future: solutions: |
| | Lovins et al. Natural Capitalism working within the profit system | Lab 4: biology & ecosystems |
| | a visit to Curitiba | The Arctic Climate Impacts Assessment |
| 25/29 | Review & ps | An ice-free Arctic? (the Earth has not been free of ice for 35 million years) |
| 1/5 | Review & ps |

Exam week 4-8vi

**Final exam** Monday, June 8, 2009, 830-1020 Location: MGH 284