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19 Leitmotiv of living planets

In which the entropy law brings a gift: a special optic for watching our moist blue planet mine structure from energy flows to keep herself exuberantly alive.

Earth eats low-entropy sunlight, poops high-entropy infrared radiation and hosts a myriad of versatile, multifaceted and sometimes even intelligent entropy producing factories. Still, except for the "sometimes intelligent" part, every planet does much the same. [1] So let's zoom to what's unique about Earth and, almost certainly, about any living planet we might someday discover.

During an afternoon on a hillside we were transported to the image of relaxing in a space capsule somewhere between our moist blue planet and its moon [1]. In that fantasy, we watched the sun throw energy toward Earth at the rate of some 178,000 TW. But not all the sunlight made it. Earth's upper atmosphere immediately reflected about 53,000 TW back into the universe. [2] Still, some 125,000 TW survived, avoided reflection and travelled on to be absorbed within Earth's epidermis (see for example Figs. 4–11 in [2]).

Then we realized that *all* this absorbed energy would eventually be pitched back into the universe as infrared radiation. Earth exports an equivalent 125,000 TW into the universe. So Earth enjoys an import–export trade balance in energy. That led to the suspicion that Earth must be extracting something-of-value from the *flow* of energy as it wends its way through Earth's innards. Which is why we embarked on this odyssey in search of "exergy"—the name we've given that something-of-value. Having found entropy [3], we're getting much closer to exergy.

We've learned that one of the best ways to ship entropy from one place to another is to have it piggyback on heat. And we've learned that the *amount* of entropy carried by heat is proportional to the amount of energy in the heat divided by the heat's *absolute* temperature. And because the temperatures of Earth's incoming and outgoing energy streams are very different they carry very different entropies. We can bundle these ideas like this:

- The temperature of the sun (which sets the temperature of Earth's solar energy import) is much greater than the temperature of the Earth (which sets the temperature of Earth's infrared energy export).
- Thus, solar radiation delivered to Earth carries much less entropy than does the infrared radiation leaving Earth. (Earth accepts low-entropy streams from the sun and throws out entropy streams to the universe.)
- Therefore, because Earth's entropy is constant, Earth must *produce* entropy at a rate equal to the difference between the rates of outgoing and incoming entropy.

Cartoons can help. Fig. 19A shows Earth's incoming and outgoing energy flows. Energy entering via sunlight is equal to the energy leaving via infrared radiation. Fig. 19B shows Earth's incoming and outgoing entropy flows. Incoming entropy is carried by low-entropy sunlight. Outgoing entropy is carried by high-entropy infrared radiation, so much more entropy leaves via infrared than enters via sunlight.

By comparing Fig. 19B with Fig. 19A it's obvious that although Earth hosts no energy consuming (or producing) factories, she must host a myriad of entropy producing factories.

I like the image of Earth consuming structure and sending its entropy excrement off on a high-speed trip through the universe. [3] Still, my *real* fascination is with Earth's intriguing, eclectic tricks for *producing* entropy. That's what distinguishes Earth from Mars…and from Mercury…and from Saturn…and from any other heavenly body we've come to know.

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[1] I've been asked, "How do you know every planet must behave much the same?" Well any planet, anywhere in the universe, must be cooler than the star it's orbiting, but not as cold as deep space. So the planet will be receiving low entropy (high temperature) radiation from its star and (in order to maintain constant temperature) *must* be exporting higher entropy (cooler) radiation to the cold universe.

[2] These numbers for incoming and reflected sunlight differ slightly from those given in Ref. [1]. In Ref. [1], we noted that the contributions from geothermal and tidal energies are trivial by comparison. The solar energy Earth receives also varies slightly throughout the year as Earth follows its elliptical orbit. There is also the influence of sunspots, atmospheric conditions and the like. But none of these phenomena change either the macro levels of incoming outgoing energy—and certainly not the principles we're discussing here.

[3] The speed of light.

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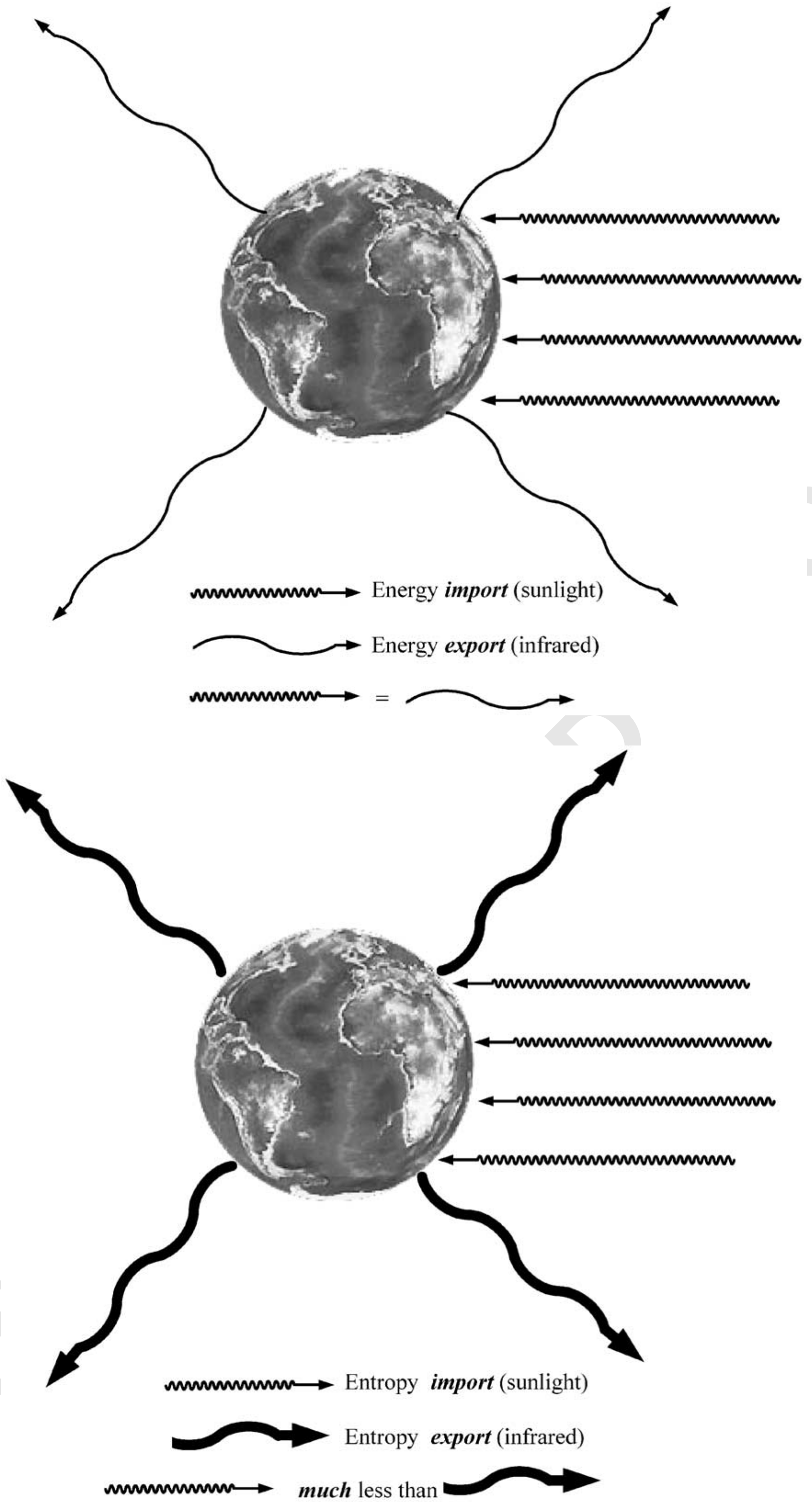

Fig. 19. (A) Earth's *energy* import/export. 19(B) Earth's *entropy* import/export.

Now, we must pause to speak about words. Earlier, we said entropy was an unfortunate name because what we want is not entropy but rather low-entropy. We likened our problem to the difficulty we'd have describing beauty if we could only use the word "ugly"—suggested that "a low-ugliness sunset" would hardly captivate lovers [3]. In "Conservation, Confusion and Language" we were struck by the Chinese admonition, "The first step to wisdom is getting things by their right names" [4]. So we're faced with the question; how can we escape this problem of having named a property we don't want—and not having named the property we do want?

Turns out that thermodynamicists *do* have a word for the *opposite* of entropy, it's *neg*entropy. Negentropy is frequently used in advanced thermodynamic studies, especially when applied to large systems like cities, civilization or Earth. Applied to civilization's energy systems, one of the best presentations in terms of "negentropy" is given in Energy in a Finite World [5]. And applied to living systems, I think it's impossible to top Schrödinger's What is Life? [6]

I originally used the scientific word "negentropy" in these articles. Then some non-technical readers who had kindly reviewed my drafts—especially a draft of "From Steam Engines to Symphonies" [7]—pointed out that, try as they might, they couldn't expunge the *neg*ativity that was imbedded in the word *neg*entropy. Damn! I thought, why hadn't I realized that? So I began searching for a suitable word that wouldn't be off-putting, negatively.

After discussing this with my German friend, Wolf Häfele, I was tempted to use the German words for entropy, *unordnung*, and negentropy, *ordnung*. They rattled about nicely within my English-trained ear-of-the-mind. *Unordnung* seemed to suggest disorganized—and *ordnung*, organized. But did I really want in introduce even more new words? The answer was no! So I decided to stay with "structure". Although, technically not as precise as negentropy—or *ordnung*—the inference is surely right.

Now back to *leitmotiv.*

Unlike some people think: Life does *not* violate Nature's entropy law.

Amazing how the myth has persisted. Should have been nipped-in-the-bud when Schrödinger's beautiful little book, What is Life? [6] was published back in 1944. Even the great writer Isaac Asimov, who I doubt was misled himself, may have misled others when he said about life: "In apparent deviance of the second law of thermodynamics" [8].

Let's treat ourselves to an out-of-body experience. Just as we had an out-of-world experience when looking down from our imaginary space capsule watching how Earth works, let's look down upon ourselves to watch how *we* work.

Gazing down upon ourselves we're struck by the fact that whatever we're doing—eating or fasting, sleeping or waking, one thing is consistent, one thing never stops; we're continuously producing entropy throughout our innards. Blood circulating produces entropy. So do muscles twitching, stomachs digesting, lungs breathing, brains thinking, hormones percolating. All these activities dump disorder into *us*, break down defined molecular structures, grind neat arrangements of atoms into random distributions. All are working to turn us into mush.

So to *stay* alive we must rid ourselves of the entropy we produce by *being* alive. We must flush out disorder or we'll croak.[4]

People have two ways to flush entropy. One way dumps it in batches. The other pushes it out continuously—using a process that, within limits, can be speeded up or slowed down to match the rate we're producing entropy. So the two mechanisms are synergistic.

We shed entropy in batches when we leave material waste behind in rooms marked "Gents" or "Ladies"—or, as the Brits say, in "the loo". The stuff we leave behind is more disordered, contains more entropy, seems more like mush than the food we ate. Our excrement is entropy rich. The food we eat is entropy poor, structure rich.

To augment batch shedding, we continuously flush entropy by excreting heat. Of the two mechanisms available for heat transfer—conduction and radiation [9]—conduction (supplemented by convection[5]) is the most important for people. Radiation, which has sole responsibility for carrying entropy to and from Earth, is usually less important for you and me.[6] Earlier, we set out the relationship for entropy transport by conduction heat transfer as: $\mathbf{J}_s = \mathbf{J}_q/T$—where $\mathbf{J}_q$ is the energy flowing with heat, T is the absolute temperature of the heat as it leaves your body (the temperature of your skin), and $\mathbf{J}_s$ is the entropy transported with the heat [10].

[4] To die is to loose our entropy shedding ability. After death, our remaining structure becomes attractive to micro organisms. By mining structure from our corpse, they keep *themselves* alive and speed the process of turning us to mush—"dust to dust" and all that.

[5] Internally by blood flow.

[6] Although normally of less importance for people, radiation *towards* people can be unfortunate—like thermal radiation from a molten steel splash in a steel mill. Of course there can be happier circumstances, like when roasting marshmallows by a campfire. Radiation *from* people sometimes helps when scanning for lost hikers or, during war, for snipers. And on a still, clear night; you can radiate energy to the universe—especially if you forgot your hat. During winter, folks living in places like northern Canada or Minnesota are wise to close the curtains to block nighttime radiation *from* their homes.

When we are especially active—running, fighting, making love—we're ratcheting-up our entropy production. So, we better ratchet-up our entropy shedding. During these activities we don't want to call "time out"—to visit the loo. But we *can* increase the rate heat leaves our bodies. Sweating helps.

Back in high school, I recall my teacher explaining that we are genetically programmed to sweat when fighting because it made us slippery, more difficult for our enemy to get a good grip. Well that may be true for fighting. But what about sweating when climbing a mountain or a tree, or chopping wood? What good does having a slippery body do then? I'd prefer be much less slippery when, rolling in a seaway a thousand miles from land, I'm trying to free a jammed halyard while clinging to the top of *Starkindred*'s mast. I expect it's the same for rock-climbers who don't want to slide from a rock wall, or woodchoppers who don't want the axe to fly from their grip. Slippery bodies may be advantageous during some vigorous activities, but for most I expect it's a disadvantage. Yet, what always helps, any creature, is being able to shed entropy faster than normal when it's being produced faster than normal. Sweat brings evaporative cooling. And evaporative cooling substantially increases heat rejection and therefore entropy flushing.

We mine our structure from food. Food brings structure, energy and material to our lives. But of these, I expect structure is the most important—material the least. Few adults need food for its material content. (I would benefit from less material round my middle, when lunging after a cross-court tennis shot.)

Of course, aside from structure we also need energy. First, we need flows of energy from which we can mine structure. (Earth mines structure from the energy flow called sunlight. We mine it from the energy flow called food.) Second, we need energy to do the mining. Third, we use streams of energy to cart away entropy—just as infrared radiation carries entropy away from Earth. So by the coupled processes of eating and excreting we both import energy for doing things and shed the entropy produced by doing things.

If that's what keeps us alive, what is *being* alive? What *is* life? An easy question without an easy answer. But what about asking, what is *unique* about life? In his book The Strategy of Life [11], Grobstein wrote:

> "Life—macromolecular, hierarchially organized, and characterized by replication, metabolic turnover, and exquisite regulation of energy flow—constitutes a spreading centre of order in a less ordered universe."

Seems to me this gets close to the core of it—especially that bit about "constitutes a spreading centre of order in a less ordered universe". Merging Grobstein's statement with the fact that the entropy of the universe is growing, we can add one word so the last clause becomes "*constitutes a spreading centre of order in an* **increasingly** *less ordered universe*".

Life swims upstream against the arrow of time. And it uses a wonderful two-stage propulsion system: absorbing structure and disgorging entropy.

I think of a living tree as a kind of factory whose product is more tree—and sometimes fruit and seeds that, perchance, will grow to more trees. The factory metaphor leads us to ask things like: What are the factory's material inputs? What are its energy inputs? What are its manufacturing technologies? What are its waste products and, of course, its products?

Water (H_2O) and carbon dioxide (CO_2) are the primary material inputs—from which the tree mines hydrogen and carbon. (Of course it also mines trace elements, but hydrogen and carbon are the big guys.) The energy input is sunlight, which the tree uses to do the mining. Photosynthesis is the mining technology. Oxygen is the waste product—the tailings from mining hydrogen and carbon from water and carbon dioxide. The product, as we said, is more tree and next generation trees.

That's a preliminary look at our tree. It's similar to the look we took when we began "Smelling land" [12]. Yet now, having reached our entropy waypoint, something seems missing. Mining hydrogen and carbon is one thing. But a tree is much more complicated, much more *structured*, than just a flock of hydrogen and carbon atoms (which could be merely a bag of methane or a lump of coal). So we must ask: where does the tree get the structure it uses to arrange the carbon and hydrogen into the exquisite molecular assemblies of walnuts or maple leaves? Bet you know. The tree harvested structure from sunlight.[7] So while sunlight brought energy to the tree, even more importantly it brought the *structure*, the tree used to assemble the wonderful molecular arrangements of its roots, trunk, branches, leaves, flowers and fruit.

To keep itself alive, our tree uses its photosynthesis technology to mine *both* energy and structure from sunlight. Both are essential. Yet to me, structure seems the more important. Energy is a means to an end. Structure is the end.

Let's return to the space capsule for another look at our moist blue planet.

Looking down, we watch petunias and apple trees, forests and blue-green algae *all* dipping into the incoming sunlight, all scooping out structure using a scoop called photosynthesis. Petunias and forests pour this structure into themselves—where it appears in the exquisite architecture of leaves, stamens and all the floral magic you see about you. Then what happens? Let's turn our binoculars to lions and eagles, termites and people.

[7] The route is via hydrogenation of carbon, oxidation of the hydrogen and then (with a little phosphate and nitrogen) the formation of the energy currency of life, ATP (Adenosine Triphosphate).

Herbivores eat flora to get their energy, material and structure. Carnivores eat herbivores to get theirs. Omnivores and maggots eat them all. Then there are the fungi, bacteria and protoctists…and the whole canopy of life that envelops our Earth. Lynn Margulis and Dorion Sagan wrote a wonderful book showing the extraordinary interconnections between all these life forms giving it, out of respect, the same title as Schrödinger's seminal contribution, What is Life? [13] Building on Schrödinger's overarching truths and placing them in the context of the GAIA (see for example [14]) optic, they enrich these earlier concepts with five decades of expanding scientific knowledge; use wonderful artistic layouts and graphics, bequeath thrilling insights.

All life's species, from bacteria to tigers, work much as we work—consuming structure and shedding entropy. The conveyor belts for incoming negentropy and outgoing entropy can be different. The sources of structure can be different. The technologies for harvesting negentropy can be different. Flora scoop structure from sunlight. We take it from where it has been stored in the flora, or in fauna that ate flora—or from mushrooms. We don't so much have conveyor belts delivering our structure as we move about hunting or scavenging for it, or—for at least the last ten thousand years—staying put and farming it. And now, shipping it round the world via trains, trucks and ships.

We—you and I—are structure *parasites*.

We thrive by parasitically consuming structure originally mined from sunlight by photosynthetic life. We are merely one of the "sometimes even intelligent entropy factories" that distinguish Earth's entropy production mosaic from the dull entropy production of lifeless planets, like Mars. On Earth, life is chemicals having fun.

Of course, life must shed its entropic waste, cannot survive within an increasingly entropy-fouled nest. So it seems to me that every living system must develop strategies to place itself where there are *both*,

- Sources of structure from which to graze.
- Conveyor belts for removing entropic waste.

Therefore, for life to thrive on *any* planet, I expect such a planet will have fluid (gas or liquid) conveyor belts. Fluid conveyors haul away life's entropic waste and spread it over the living planet as a first step towards pitching it out to the universe as infrared radiation. On the other hand, planets don't require fluids to deliver structure, although fluids can surely help. Local starlight can always deliver structure, as it does on Earth.

On Earth, the hydrosphere and atmosphere are our fluid conveyors. They result in more uniform planetary temperatures than would exist without fluid conveyors—more uniform than if the *entire* planet were solid. In turn, these more uniform temperatures aid the process of throwing high entropy infrared out into the universe.

These same conveyors also deliver the trace ingredients for life support, like material nutrients. But I'm not persuaded these are as fundamental to life as the need for entropy shedding. What is, or is not, a material nutrient is *specific* to a particular form of life.

I see an analogy with Nature's fundamental laws and her constitutive relations that we discussed back in "Engineering and Classical Physics" [15]. For living systems, the fundamental law is to eat structure, shed entropy and thereby to swim upstream against the arrow of time. But what are or are not material nutrients are, by analogy, constitutive relationships for particular planets—in some cases even for different locations on our own planet.

On Earth or any other living planet, all life must remove its entropy excrement from its home. From this perspective, Earth's two colossal conveyor belts, the oceans and atmosphere with all their tributaries, take on mystical proportions—if they aren't already mystical.

For a final image, imagine a world some folks might consider utopia; a world of constant 24 h blue skies, uniform temperatures of 22°C everywhere (~ 71°F for Americans)—and no sun to blind you should you accidentally glance towards the wrong corner of the sky. Of course, to keep everything uniformly delightful, the sky must be the same temperature as the beach on which you're lollygagging. Everywhere, unvaryingly wonderful.

Oops! A *big* problem.

If the sky, beach and everything else were at the same comfortable temperature, Earth would have neither a negentropy supply nor a place to export its entropic waste. Our lovely imaginary planet would be as dead as dead can be. So next time you wish it weren't as quite as cold, or as hot—be careful for what you're wishing.

With these ideas burbling, I'm drawn back to the GAIA hypothesis developed by Lovelock, Margulis and others. The GAIA perspective argues that there is great value in viewing Earth as alive. Two of GAIA's insights are:

1. A living planet is unlikely to be merely weakly alive—having only tiny bits and pieces of life scattered over an otherwise dead ball in the sky. If life develops on a planet it will almost certainly bloom, quickly in geological time, to be robustly alive, spreading to every nook and cranny of that planet, like on Earth.
2. A robustly alive planet will, almost certainly, have an atmosphere that is *not* in chemical equilibrium with the planet's bulk material. Rather, its atmosphere will be held out of equilibrium by life's gaseous waste products.

Now, I wonder if a third requirement for living planets might be:

3. A living planet will, almost certainly, have an extensive network of fluid conveyor belts for structure delivery and *especially* for removing entropic wastes. Moreover, I think it best if one conveyor is liquid and the other gaseous. Because then synergies blossom.

All planets have one ingredient for life: incoming low entropy (high structure) starlight from their neighbourhood star—although for outlying planets it might be a pretty weak stream. And all planets have a second ingredient: a location within a cold universe into which the planet can pour its entropic waste. But now a third, complementary, requirement for life seems to be an extensive network of fluid conveyors to vacuum out entropy-fouled nests. So, if we ever find another living planet, anywhere in our universe, I expect a robust network of fluid conveyors will course through its epidermis.

Exploring the *leitmotiv* of living planets may seem to have taken us off our odyssey's great-circle route to exergy.[8] Well, it may have taken us a few degrees off the quickest route to technological applications, but we're bang on course for how the entropy law applies to everything in our universe—including life. And since our technologies must be intimately tied to improving the quality of life, methinks we're not far off course for applications.

The next leg of our odyssey will bring us to exergy, the goal of our odyssey. In-the-finding we'll better understand the energy systems of today, and be better able to design the energy systems we'll need tomorrow.

Finally, after a few more landfalls and with the tough sailing behind us, we'll climb a promontory overlooking the oceans we've crossed. There we'll find a little bistro called "From Steam Engines to Symphonies" [16]. We'll sit back, order up tall drinks, relax, tell stories, laugh, smugly reflect on what we've accomplished, chuckle over our adventures—humbled by what it could mean.

This is the nineteenth in a series of articles by c

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[8] A great-circle route is the shortest distance to traverse Earth's surface between two points on the surface. It's more direct than a rhumb line course.