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Evolution and World-Systems:
Complexity, Energy, and Form[1]

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Abstract

World-Systems Theory and Complexity Theory are siblings from the same parent of Von Bertalanffy's foundational work on general systems theory. But they were ideologically separated at birth. World-Systems emerged out of dependency theory, itself a product of and reaction to neocolonialism after World War Two. Wallerstein's historical analysis of the origins of unequal exchange in the "long" 16th C., first within Europe, and then encompassing its colonies, extended dependency theory's exposure of exploitation by demonstrating the systemic consistency of geopolitical parasitism well before the modern era. Christopher Chase-Dunn has furthered that insight by using empirical research on the unequal exchange between the earliest known polities. His work has additionally shown how the methods of cross-polity parasitism have changed over time, both creating and undermining the empires of history in response to changing ecological and climatic constraints. His work also shows how systemic change often starts in the creative conditions unique to semiperipheries. The other child of general systems theory evolved in the worlds of physics and computer science, becoming known first as Chaos and later Complexity theory. It too expanded, demonstrating that positive causal feedback loops of energy and information could explain the life-processes of biology and evolutionary theory. Given their common ancestry and attention to the flows of energy and information, their re-connection was inevitable. This paper seeks to merge them. The approach will be to use complexity to explain how entropy builds structures on a physical level, then how those same dynamics created life, drove evolution, and continue to drive social complexity from our nomadic roots to our current global strife. The work of Chase-Dunn will be shown as logically consistent with complexity theory, and ideally a marriage of the traditions completed. As a former student and life-long colleague of Chase-Dunn's, the author is also paying homage while pointing a way forward.

Keywords:

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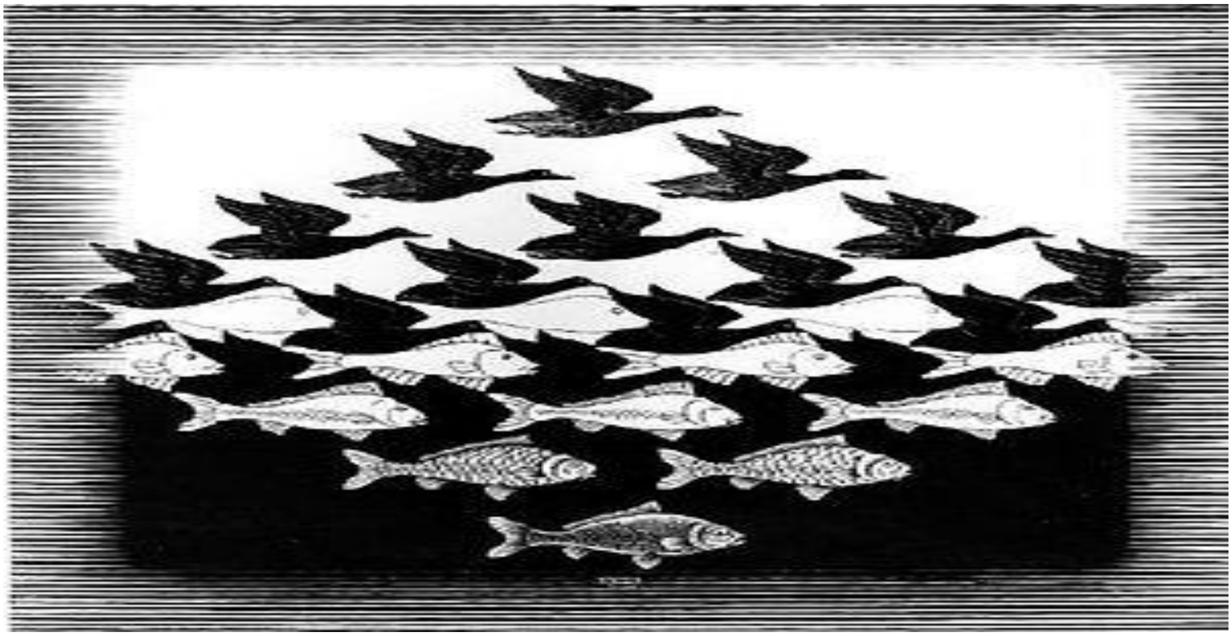

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Complexity Theory: The Next Step Of World-Systems Theory

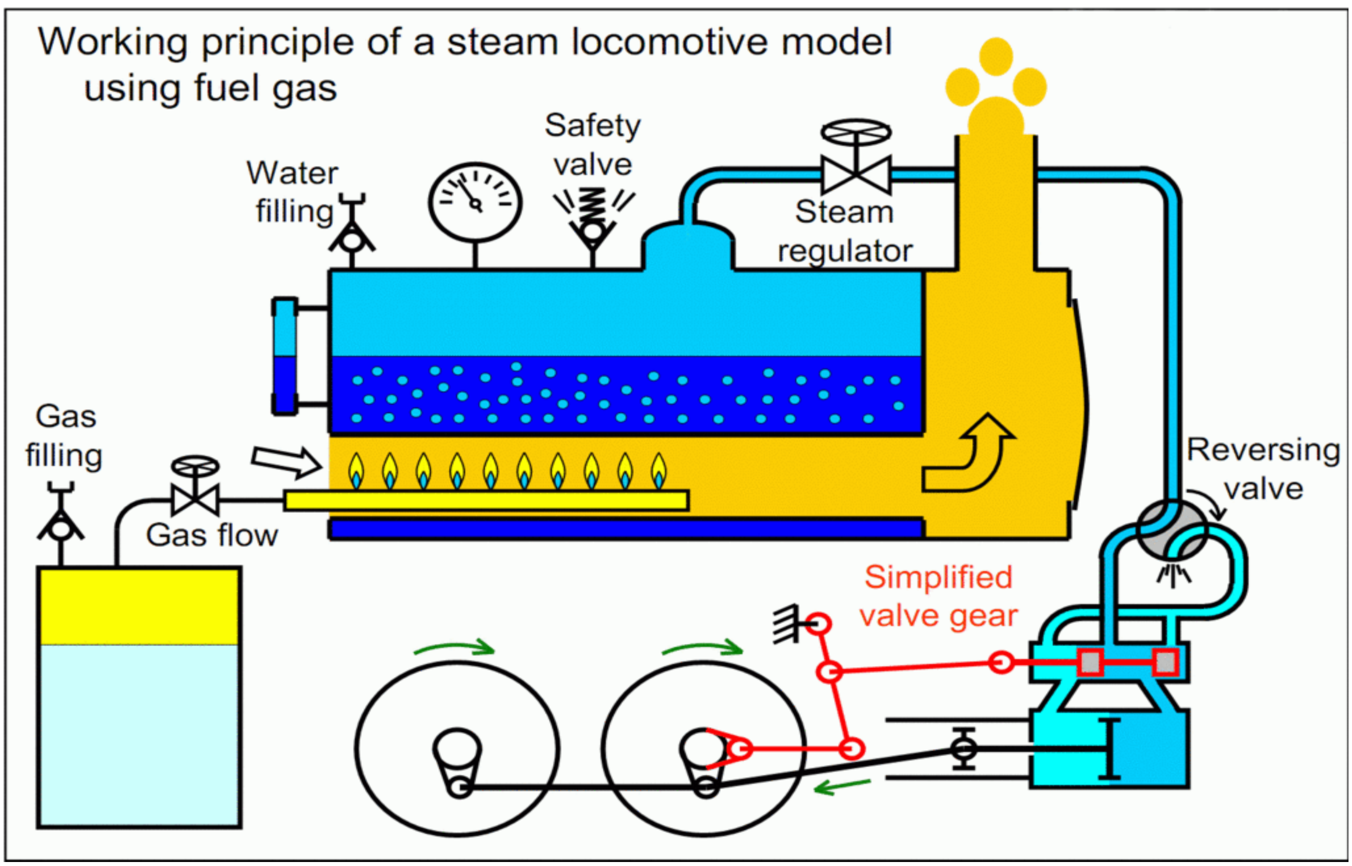
We are now several decades into another scientific revolution. Chase-Dunn's extension of Wallerstein's categories of the core, semiperiphery, and periphery into the distant past highlighted the continuity of unequal exchange since the first human settlements.[2] This theoretical expansion opened the door to connecting unequal exchange to energy flows, enabling us in turn to link history to complexity theory. This essay seeks to extend this link and explore the potential for complexity theory to further the promise of an ultimate scientific unification of the social, historical, and ecological findings of Chase-Dunn and colleagues with the simultaneous breakthroughs of complexity in physics and biology. To do so we must first explain what complexity theory is, and why the theory itself appeared. What follows will be a sketch of its history, along with selected examples chosen to illustrate its principles. We will begin with the simple example of the steam engine: how it worked, yet also how its limitations changed our understanding of physics, opened the door to thermodynamics, and exposed the path toward complexity.

[2] (Bertalanffy 1968).The entire list of sources by Wallerstein and Chase-Dunn is too lengthy to be included within this sentence, but can be found in the bibliography. Specific works will be cited within the text.

The Steam Engine: Power, Efficiency, And Thermodynamics

The schematic engine in Figure 1 strips the concept to its essentials. The steam engine was initially applied to pumping water out of English coal mines, then to powering textile looms, and only later to locomotives in the 1820s. But all used the same logic as in Figure 1, which happens to be a locomotive. A fuel source--here in the diagram natural gas, but initially wood, coal, or anything else that burned— would be placed under a horizontal hermetically sealed cylinder (the boiler) filled partially with water. When the water boiled into a gaseous form as steam, the steam would quickly fill the area within the boiler above the water, displacing and pushing the original air out via the safety valve pictured above the boiler in the diagram. Once the steam pressure had reached a critical value sufficient to overcome the inertial mass of the entire machine (indicated by the pressure gauge atop the boiler), the "steam regulator" valve would be opened. Super-heated and extremely energetic steam would race through the pipes to fill up the piston mechanism (lower right).

Figure 1. Schematic View of a Steam Engine



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The result was the transfer of the steam to the piston chamber, which could only release that enormous pressure-power by pushing the piston to the left (in the illustration). That piston-push transferred the steam pressure energy to the steel rods bolted to the rims of the wheels. The movement of the wheels released the hot steam inside the piston into the air while restoring the piston to its original position, enabling the next cycle. Sufficient energy from fire (***FORCE***) was generated, converted, and channeled into overcoming ***(MASS)*** to result in movement ***(ACCELERATION)*** hence overpowering ***(INERTIA)***. The entire apparatus was a practical application of Newton's law **F=MA**, and another triumph of physics (Atkins 1994; Summers 1971).

Once a steam engine had been purchased at great expense, it needed constant maintenance by skilled mechanics, another cost. Further, it needed a steady supply of fuel, preferably coal, because coal packed the greatest amount of combustible energy into the smallest volume of any fuel then known. In the early 19th Century coal was mined in crude tunnels vulnerable to flooding and collapse, at great cost in labor and lives. It was expensive, so every effort to minimize its use was deployed by successive improvements in the design of the steam engine to increase its energy efficiency and minimize its fuel consumption. As with all learning curves, initial design changes yielded a rapid increase in efficiency, beyond which further changes seemed to approach a ceiling that could not be broken. Exploration of this stubborn barrier would reveal an entirely new realm of physics called **Thermodynamics**, in turn opening the door to complexity theory. Starting with the study of gasses and later fluids, thermodynamics explained why **all** energy transfers in form (like those from the flame in the steam engine to the boiling water, or from the steam in the boiler to the piston, and ultimately the wheels) **must** cost energy at every step of conversion. This recognition of the necessity of energy loss was the core gift of thermodynamics, and its crown jewel. It is generalized as the second law of thermodynamics[3], the law of ***ENTROPY***—the requirement that all sources of energy must ultimately lose that energy to their environment, in the process creating an equality between any energy source and that environment (Atkins 1994). Phrased another way, ***all differences in the distribution of energy in space must disappear over time, such that all areas achieve energy equality, or thermal equilibrium.*** To understand this on a practical level, let us return to the steam engine and more closely examine its parts, starting with the flame.

[3] The first law of thermodynamics is that energy cannot be created or destroyed. Hence the energy supplied by the "big bang" has remained constant ever since (Atkins 1994).

Figure 2. The Candle Flame Is A Common Dissipative Structure

Source: https://duckduckgo.com/?q=free+use+download+candle+flame+pictures&t=ffsb&ia=images&iax=1

Careful examination of the flame in Figure 2 reveals some of the key insights of complexity theory drawn from studying everyday gases. First, the *shape of the flame* is the same as all candles everywhere in space and time. That constant shape is determined by the rate at which the surface area can shed the heat inside the volume of the flame. The shape of a flame will always approximate a "teardrop" because that is the most **efficient** way that the heat within the core can achieve thermal equality with its environment, obeying the law of entropy. Yet the entropic process of shedding its excess energy compels the flame to conform to a predictable **shape**, or ***STRUCTURE***. The flame illustrates a fundamental principle of complexity: in the process of "seeking" thermodynamic (energy) equilibrium with its environment and thereby conforming to the law of ***ENTROPY,*** the flow of energy can ***SELF-ORGANIZE matter into entirely new structures.*** Hence there is no contradiction between the law of entropy and the creation of new structures. Because they emerge as efficient methods of ***DISSIPATING*** spots of high energy into their environment, complexity theorists call the emergent structures ***DISSIPATIVE STRUCTURES*** (Grimes 2012, Lehn 2002, Nicolis 1989, Prigogene 1996, Prigogene, Ilya; Isabelle Stengers 1984)**.**

Another aspect of the flame's service to entropy lies in its colors. The photograph in figure 2 captures many of them, but not all. Once the wick is ignited, the energy creates a flame as it raises the temperature of the wick high enough to begin combining it with oxygen, high enough also to melt the "wax" below the wick into a liquid, which is in turn drawn via osmosis up the wick to meet the flame, replacing the fuel of the wick with the gas boiling off of the wax. It is the oxidation of both wick and gas that releases its chemical energy as light. The energy is high enough at that meeting at the bottom that the light it releases is ultraviolet, beyond human perception. So to the human eye it looks clear. But hidden from our eyes, the high-energy ultra-violet photons of light emitted at the base of the flame are themselves boiling the wax liquid, generating yet more super-heated gas. It is a positive feed-back loop of energy: a mutually causal cycle of (gas +UV photons)➔(liquid wax) ➔(more gas)➔(UV photons). Usually run-away energy feed-backs like this lead to explosions, unless there is a complementary negative feed-back releasing the energy. Here there **is** a negative feed-back—**the flame itself**, which is the escaping hot gas made visible as it shoots upward and cools, dissipating the energy as it rises. The next step down in energy release is the deep blue captured in the image, sequentially shifting through the color spectrum as one's eyes move toward the top of the flame, fading off into deep orange and infrared (uncaptured in this image) as each molecule in the gas passing through the flame releases photons of declining energy, ultimately perceptible only as residual smoke that has ceased glowing at all in the realm of human perception. These colors within the flame are as predictable as its shape, another aspect of the structure imposed by the dissipation of entropy.

What is actually happening inside a flame reveals three observations of complexity theory that apply to every system studied:

(1) The Law of Entropy requires that pockets of space with more energy than their surroundings will release that energy until the entire environment has the same energy and has thereby achieved thermodynamic equilibrium.

(2) The material medium through which the energy passes will self-organize into a structure that is shaped to maximize the speed of achieving equilibrium, a dissipative structure persisting until general energy equilibrium is achieved.

(3) The structure's energy circulates in a balance of positive and negative causal feed-back loops. If either loop is disrupted, the structure will collapse (Holland 2014, Mitchell 2009, Lineweaver, Charles H.; Paul Davies, Michael Ruse 2013).

Throughout the examples below we will encounter these rules frequently, and build upon them additional rules which, taken as a whole, will provide us with some of the tools to understand their application to human socio-cultural evolution.

But let us first return to the steam engine to watch how these rules apply to it in ways unknown to its first designers. Recall that the flames beneath the boiler in figure 1 are the source of the energy for the entire engine. That flame energy is a gas glowing in a dissipative structure as it emits photons while shedding energy. The gas flow does not stop at the boiler, but shoots beyond, up, and out through the chimney in front. So we have already lost energy twice—in photons that never strike the boiler at all but leak out the sides, and again when the flames quickly caress the boiler while speeding to the chimney. Hence the water inside the boiler does not—indeed it cannot—receive all of the energy in the fuel. Assuming we are initially working with a cold engine, the water in the boiler starts at the same temperature as the steel and air around it—thermodynamic equilibrium (Atkins 1994).

Before the fuel beneath the boiler is ignited, the equilibrium of the water inside with the surrounding steel and air has some qualities important to complexity theorists. The water itself is of course made of H_2O molecules in fluid form, which means that the molecules share some bonds (swapping electrons) but are much freer to move around than they would be as solid ice. All are able to bounce around and off of each other, reflecting the energy of the overall temperature of the environment. If one could imagine the water *as if one were a water molecule inside the cold boiler*, everywhere you "looked" you would see the same view: other water molecules bouncing about randomly. The view would be the same in the front section of the boiler as in the back, bottom, top, or sides. All views would appear **identical**, meaning that all locations would be **symmetrical**. All would be a fog of ***SYMMETRY***. In this sense **space itself** would be symmetrical, so the very concept would lack meaning. Further, as long as the energy (temperature) remains the same, so are the views of the same fog over time. **Hence time also is symmetrical, lacking meaning** (Nicolis 1989). This quality of space-time symmetry, sameness, and homogeneity is true of all circumstances lacking energy differences (such as the vacuum of inter-stellar space).

However, once the fuel beneath the boiler is ignited, ***the symmetry of the water is broken because shapes emerge within it***. As the water at the bottom eventually warms, the warmer molecules bounce more vigorously and take up more space. That also means that the molecular density of that warmer water decreases, allowing the denser and heavier cooler water above to fall into the empty space created by the warmer area below, displacing the warmer water and compelling it to rise. As the warmer water rises, it dissipates its energy to the cooler water surrounding its path to the surface, where it releases its remaining energy into the air. Sluggish at first, the constant injection of the energy from the fire below gradually accelerates the circular flow of cooler water to the bottom and warmer to the top. Once the average temperature within the boiler has breached a ***critical threshold***, the water "boils." The effects throughout the water are immediate and dramatic: vertical columns from the bottom to the surface spread to immediately consume the entire chamber, snapping into adjacent spaces. Along one side of every column the water races to the surface, ejecting water molecules in gaseous form to release energy, while the opposite side of every column is violently sucking (cooler) water back to the bottom. This instant reorganization of matter is a ***PHASE-CHANGE*** (Atkins 1994, Nicolis 1989). The former symmetry of the water is broken by the appearance of the columns, collectively self-organized into tightly packed dissipative structures shaped to maximize the efficient dispersion of the concentrated fire-energy into the environment, in the service of entropy. As with the flame, these structures contain causal feed-backs, circulating columns of water from hot to cold. Finally, as with the flame, the new structures shatter the symmetry of space and time. Our hypothetical observant water molecule can now determine its location (whether it is in an up or down flow in, say, the third column from the back, fifth row), as well as time (by traveling horizontally at the same speed across columns while marking the time between traversing the equally spaced column locations) (Nicolis 1989).

Close examination of the flame and the water in the boiler not only ratifies the first three rules of complexity listed above but now allows us to add another. ***The spontaneous appearance of self-organized dissipative structures marks a "phase-change" within the affected matter*** (Nicolis 1989). In the case of the flame, its ignition imparts enough energy to a stable solid (wick and wax) to break its molecular bonds and combine them with oxygen, yielding enough energy to force them into a phase-change (liquid ➔ gas). In the case of the boiling water, the tightly packed adjacent columns of vertically circulating water also reflect the transition of the phase-change from fluid to gas. In each case the spontaneous appearance of a dissipative structure marks a phase transition. Below, we will see this pattern repeated within natural processes and even echoed in human social forms.

To complete our improved understanding of the steam engine in the light of complexity, let us follow the energy of the steam in the boiler to the wheels. The pipes from the boiler provide an escape for the super-heated steam. Along the way, the now-hot boiler is also freely radiating its heat to the air around it, as are the pipes leading to the piston chamber, and even that chamber itself (with more energy loss). Even so, enough hot steam enters the piston chamber to force the piston to move, in the process converting the gaseous energy of the steam into mechanical movement of solid metal, ultimately moving the wheels. Solid metal does not change shape with energy (unless it melts); instead it can move in space with time. As it does so, the bolted connections between the piston and wheels lose yet more energy in friction, as do the wheels grinding against the rails (Atkins 1994).

In summary, it is now clear that every change from one form of energy into another necessitates an energy loss, and no engine re-design could eliminate that loss.[4] The failure to do so during the 19th C.—the failure to break the ceiling of energy efficiency—ultimately gave birth to the field of thermodynamics and its second law, the law of entropy. Ironically, a close examination of the steam engine—the iconic materialization and triumph of Newtonian

[4] The peak efficiency of modern steam engines used today for electric power generation is about 40% (Summers 1971). That is the energy captured from the initial fuel. The remaining 60% is lost to the environment.

mechanics—yields the very flaws of energy leakage generating the discovery of thermodynamics, entropy, dissipative structures, the self-organization of nature, and even life itself (Brooks & Wiley 1988; Kauffman 1993; Kauffman 2013).

Emergence And Self-Organization

The full implications of the law of entropy did not receive much attention until the 1970's and 1980's and the study of chaos (Gleick 1987, Waldrop 1992). The most profound insight from the renewed pursuit of entropy was that it was not just a ***law of decay***, but also a law of ***creation and emergence.*** The realization that entropy required that the energy loss through matter must reorganize that matter into new shapes, creating new structures along the way, introduced a revolutionary new view of nature (Atkins 1994; Bertalanffy 1968; Ford 1989; Gleick 1987; Holland 1995; Mitchell 2009; Waldrop 1992). The mechanisms creating gaseous flames and structures within boiling water were just the beginning. Once they were also coupled with phase changes in matter, other examples of self-organization were found in nature. One simple example is the role of entropy in creating a tornado.

Tornados

Storms are disruptions of a stable atmospheric environment at rough energy equality, like all other dissipative structures. Unlike steam engines, they are spontaneously produced by entirely natural forces, yet they also replicate many of the same mechanisms of entropic dissipative structures first noticed in the steam engine. To understand weather, a good place to begin is the moon, which illustrates solar absorption and release in its simplest form, without the complications of an atmosphere. The moon's surface is exposed directly to the sun, whose radiation quickly raises its naked surface to 117^0 Celsius. When that baking surface rotates into lunar night, the heat is quickly released into the absolute zero of deep space as infrared photons, plunging the night surface back again toward equilibrium with the surrounding vacuum. However, the earth has an atmosphere dragging behind its surface, absorbing (while protecting the surface from) the high-energy solar photons in daylight, and retaining the blanket of the daylight heat during the night, even as its surface and atmosphere also emit infrared energy out into space and back down to the surface. Complicating matters are the vast oceans, themselves retarding solar absorption and night-time release.[5] In addition, the annual wobble of the earth around its axis produces dramatic temperature oscillations with the shifting seasons (Burroughs 1992, Graedel, T. E.; Paul J. Crutzen 1993). As we saw with the steam engine, energy differences below a critical threshold do not change the local environment in an obvious way—warmer areas convey their energy into cooler areas quietly

[5] To simplify this story, many important causal influences must be minimized, skimmed, or ignored altogether, such as Hadley Cells, ocean currents, and the influence of mountains and vegetation (Graedel, T. E.; Paul J. Crutzen 1993).

and effectively. Yet we also saw that when the energy **difference** achieves a critical level, a ***PHASE-CHANGE*** in matter occurs: solids become liquids, liquids gases, or even the reverse (e.g.—a gas becoming liquid as rain; or a gas becoming a liquid and then a solid as hail).[6]

Every ordinary spot on Earth experiences breezes, cloudy days, and rain. These events represent the quiet efficiency of the equilibration of minor temperature differences. A violent storm can only occur under the rare conditions of large energy differences--differences between closely adjacent areas exceeding the ***critical threshold value of a phase-change***, the value required to create a dissipative structure.

Across the seasons the equator always receives the most solar energy. The warm ocean evaporates, and the hot humid air rises. But it does not leak out into deep space. That path is retarded by gravity: 90% of the mass of earth's atmosphere lies within the first mile above the surface. A portion of the tropical air will follow the tropospheric ceiling toward the nearest pole. When it moves far enough away from its tropical birth it will encounter colder air, compelling it to release its heat via rain. This is a routine dynamic that happens all year. But when the closest pole is approaching winter, the encounter can expose energy differences approaching the critical threshold, creating the violent dissipative structures we call tornados. It is this clash that makes us correctly associate violent weather with seasons (Robinson 1993).

Temperature is molecular motion within any material medium, regardless of its phase (solid, liquid, gas). The shift from one phase to another is just an outward sign of the reorganization of the bonds between molecules and their speed. As in the case above of the steam engine boiler, cooler forms of water have less energetic molecules that are more densely packed and heavier per volume. The hotter a phase, the more vigorously the molecules collide and create more space between them, making hotter media more loosely packed and lighter. Yet, paradoxically, in hotter and less dense atmosphere *more water molecules can be suspended and retained per volume than in cooler and denser air*. A good metaphor reconciling this paradox is to imagine the hotter air molecules as enthusiastic volleyball players, where the volleyball is the H_20 molecule, and the energetic players the high temperature atmosphere. The rarity of the molecular distribution of the hot air molecules is compensated for by their speedy juggling of the water. This contrasts with the denser cooler air, whose atmospheric molecules are sedated and unresponsive, constantly dropping the ball and allowing it to bounce straight down as rain or dew, allowing the water to clump into clouds blocking the sun.

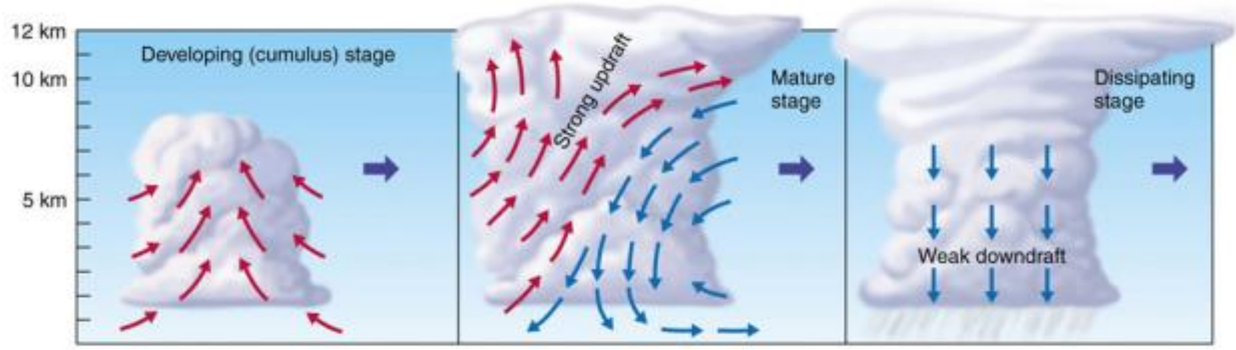
Such is how an ordinary rain-storm develops. Even during seasonal clashes when the energy differences are at their highest, the encounters between cold/dry and hot/humid air masses only

[6] Unnoticed by us in daily life, such phase transitions are always happening around us, but at rates so slow we ignore them: ice evaporates into water vapor, dead wood oxidizes without flame, etc. It is the speed of these phase transitions that creates the dissipative structures addressed here.

rarely produce tornados. Why they are rare remains unclear, but complexity theory suggests a direction to look: As with the steam boiler, there probably are conditions within the atmosphere that create some kind of boundary**,** enclosing, channeling, and ***forcing*** the violent thermal clash creating these dramatic dissipative structures. One such boundary is between the troposphere and the stratosphere, with gravity along with widely separated molecules constraining the height that clouds can typically go. But this ceiling can be broken with enough energy. Clouds bearing tornados have been observed as high as 50,000 feet, deep into the stratosphere (Robinson 1993). There may also be other similar ground forces at work pushing divergent air masses to clash. For example, the mountains in the west of the United States channel cold air south during the fall into the warmth of the Mississppi valley and tropical Caribbean basin, while the reverse movement of humid air flows north in the spring (Robinson 1993). Whatever the exact circumstances, it would be consistent with the observation from complexity theory that ***dissipative structures emerge under compulsory bounded and channeled constraints***; and that ***the complexity of the resultant structure(s) reflects the volume of the energy*** being forced to clash. What remains unknown is *not why tornados appear,* ***but rather why they are so rare***.

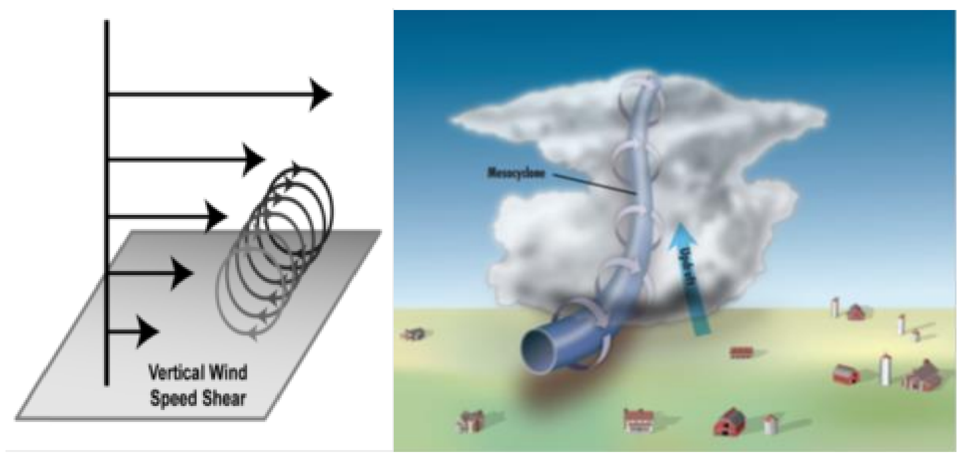
Figures 3, 4, and 5 below illustrate the special conditions producing a tornado. The three schematic images in Figure 3 (below) start on the left with the upward hot air flow typical of all thunderstorms, producing visible water vapor in the form of a cumulus cloud as it cools. The middle image illustrates how sufficiently hot air can punch up to 35-50,000 feet, forcing the cloud to flatten at the top, producing an "anvil" shape. Not shown here is that at such heights the cloud often changes color from dark blue to greenish yellow, because the water droplets at the top level have frozen into hail (phase-change), refracting the sunlight at the top downward through the cloud. What **is** shown in the second image is the beginning of a thermal circulation (*the same as in a boiler*) caused by the displacement of the cold air at the top by the hot air from the bottom, sucking cold air from high altitudes back toward the warm ground, where a portion is ***pulled back up with the hot air*** even as another portion spills across the surface as high-speed cold winds. If the energy clash is sub-critical, the outcome is a thunderstorm as in the third image on the right. If, however, the energy *breaches the critical value*, ***the cold downdraft in the middle image curls back up to create a self-amplifying cylinder***, as illustrated by the forces of wind shear in creating supercell mesocyclones in Figures 4 & 5. Also see photos in Figures 6 &7 below.

Figure 3. Three Stages Of Thunderstorm Development



Source: Image courtesy NOAA http://www.photolib.noaa.gov/

Figures 4 & 5. Wind Shear Creates Spinning Cylinder And Mesocyclone



Source: Image courtesy NOAA http://www.photolib.noaa.gov/

The enormous speed of the dissipated energy in a tornado tends to make their life-span short (3-10 minutes). Multiple “**daughter**” tornados are created when the **central storm has too much energy to shed efficiently with just one vortex**. These demonstrate how enough energy compels the creation of ***additional forms of increasing complexity***. The ability to spontaneously add new shapes is one reason dissipative structures are inherently unpredictable (Prigogene 1996). This ability is like speciation, or the division of labor within societies.

Figure 6. Tornado

Source: Image courtesy NOAA http://www.photolib.noaa.gov/

Figure 7. "Daughter" Tornadoes

Source: Image courtesy NOAA http://www.photolib.noaa.gov/)

To create and sustain complex structures far-from-equilibrium, external power is most effective when it is augmented by *amplifying causal feed-back loops recycling that power* ***within*** the new structure, like the circulating cells within a boiler or tornado. **These loops capture and prolong the influence of the external energy, retarding its release and enabling the construction of new structures**. Further, the causal loops not only help construct the structure, but are sustained by it. Once a complex structure emerges, it becomes an active agent in its own recreation (as in a mesocyclone, or the UV-wax-gas-UV cycle at the base of a candle). A central contribution of complexity theory is that every component of a complex structure plays a role in its own reproduction: there are no **"epi"-phenomena**. Once created, every new form shapes the future of the entire structure. ***The integrated whole is more than the sum of its parts,*** *and collectively recreates the simpler elements from which it emerged* (Holland 2014).

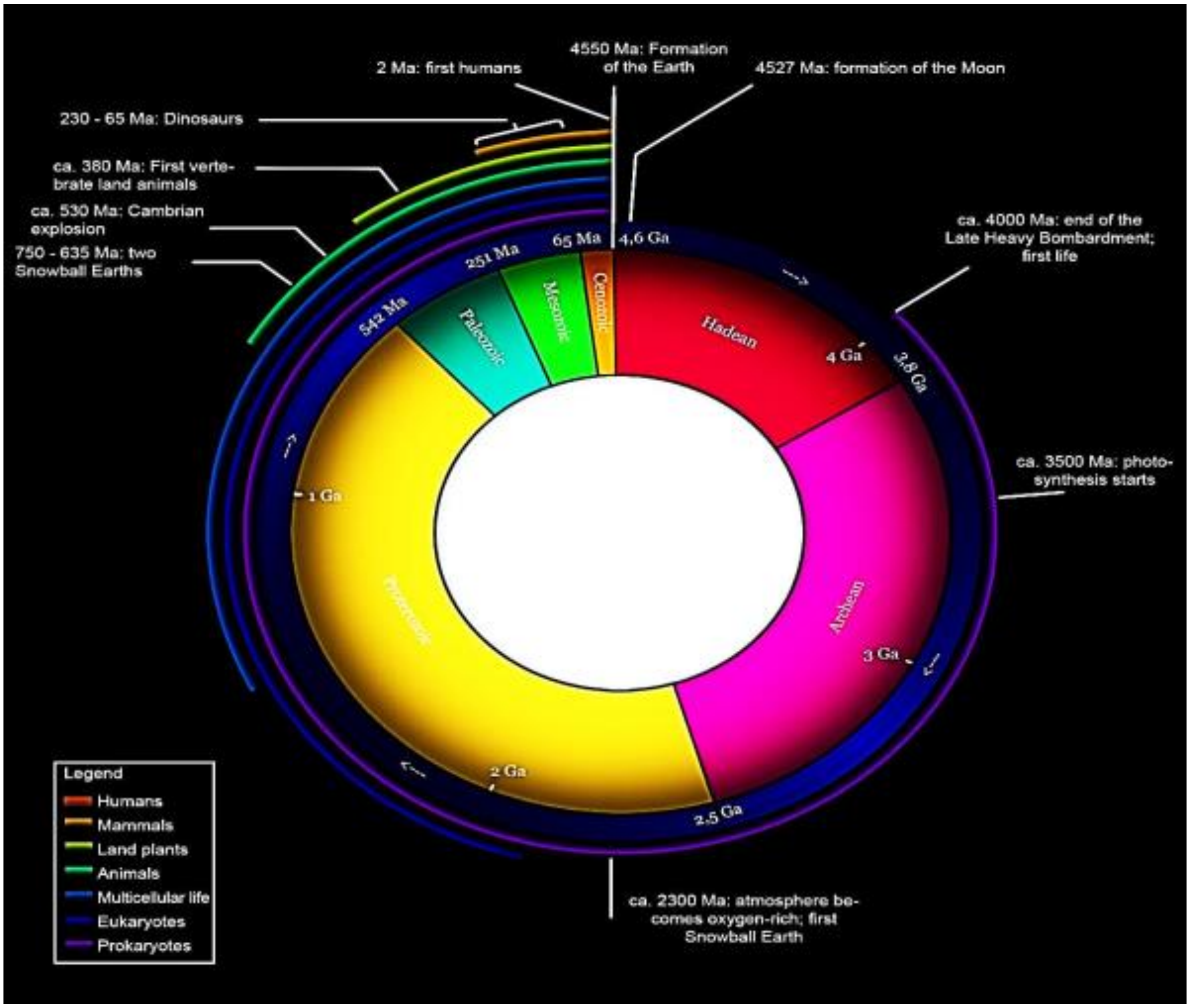
When any structure is compelled to develop new forms (like the "daughter" tornados in Figure 7 above) to dispel more energy, complexity theorists call this jump a ***BIFURCATION***. The result is unpredictable in advance. Since the precise qualities of the new forms created by bifurcations are shaped by their environment at a particular instant, they each reflect their own unique history (Holland 2014, Nicolis 1989, Prigogene 1996).

Life as a Dissipative Structure: The View from Complexity

The ability of dissipative structures to create unpredictable new shapes through bifurcation also extends to the speciation of life and to development of increasingly complex societal forms. The entire history of life itself is historically conditional, making it impossible to predict in advance. A corollary is that while extraterrestrial life may be abundant, its particular expression on earth is probably unique.

The circular visualization of the sequence and timing of different life-forms appearing on earth illustrated in Figure 8 serves as a map of evolution. It is a clock-face representing life forms since the initial formation of our planet up to the present (from 4.6 billion YA [here Bya is noted using the British notation Giga year or GA] to the present). The colored sections radiating out from the white circle at the center indicate major geological epochs and eras, while the in-most blue line enclosing the entire circle marks specific dates. Starting at 4 GA, asteroid bombardments drop off, allowing the first life to develop, indicated by the violet line just outside the blue circle. The side comments around that circle point to the emergence of the first photosynthetic life appearing around 3.5 GA. The color-coded legend on the lower left inside Fig. 8 indicates that these earliest life forms were Prokaryotes, cells lacking nuclei enclosing DNA. Just before the 2 GA mark during the yellow Proterozoic era, a blue line appears marking the evolutionary jump to

Figure 8. Schematic view of the evolution of life on Earth.



Source: Courtesy woudloper, 9/07 https://commons.wikimedia.org/wiki/File:Geologic_clock.jpg

Eukaryotes, cells with sealed nuclei containing DNA—the same cell design that built all later life forms and continues to do so today. Thereafter, an accelerating feed-back builds upon prior forms to sequentially create multicellular life, plants, animals, mammals, and humans: each represented by an additional band of a new color of shorter length. Clearly the emergence of new life forms is accelerating, as is complexity itself.

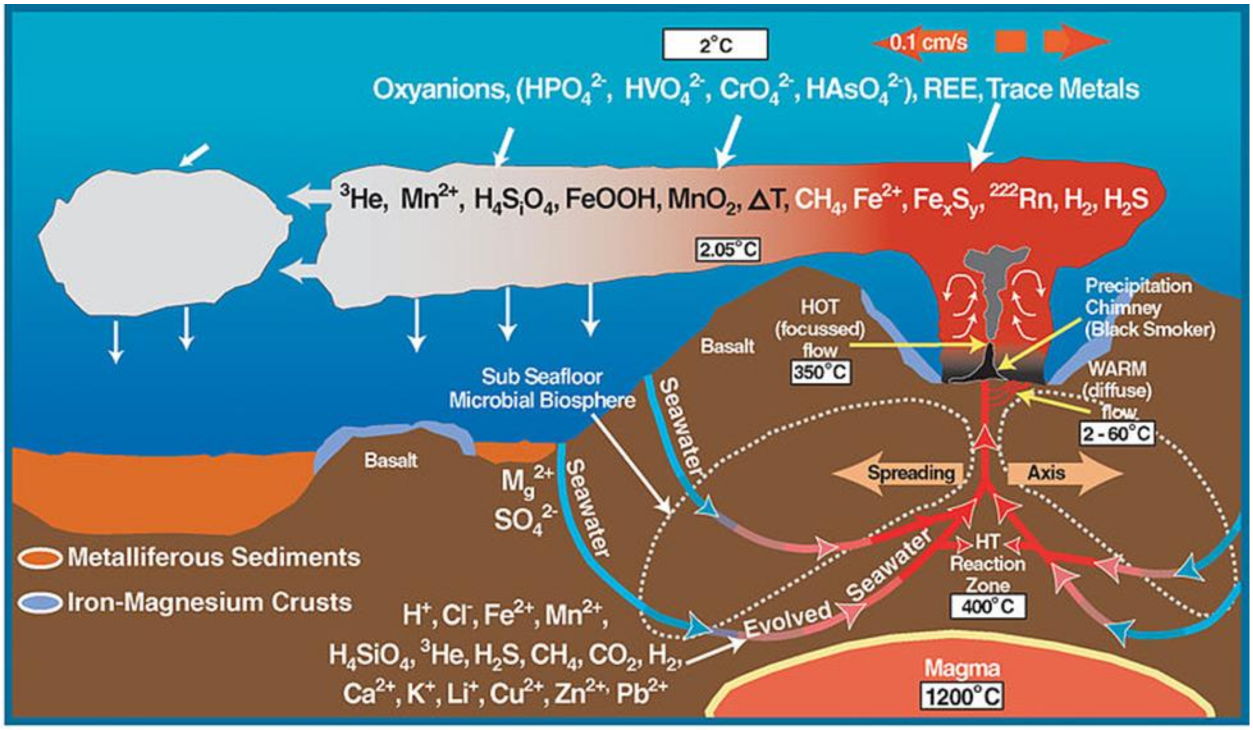
When new structures emerge from, yet augment, prior structures, they create more total complexity and internal hierarchy. When they do so at an accelerating rate it is a type of cumulative positive feedback called a "deviance amplification." Here the "deviation" is away from thermal equilibrium, the building of structures whose complexity requires the capture and retention of ever-greater energy, creating yet newer structures even farther away from equilibrium (as with the "daughter" tornados). The "amplification" refers to the self-reinforcement of the processes creating that "deviance."

The emergence of life happened at the tiny scale of molecules, but the causal feedbacks of deviance amplification are independent of scale. The chemistry of the process of self-reinforcement still relies on cycles of circular causation, where the initial materials are ultimately reproduced. Typically, this cycle is accelerated by one or more chemicals produced during the process that increase the probability that the appropriate molecules in the causal chain will link more quickly than by chance alone. These guiding molecules are called "***catalysts***." Their presence within the cycle accelerates it, giving it the label of "***auto-catalytic***," or self-accelerating. **Figure 8** illustrates this process over the long term: once life began, its development of complexity was both cumulative and accelerating, hence ***autocatalytic***. This is precisely the process that complexity theory addresses, and is uniquely equipped to explain (Schwartz 2010, Virgo, Nathaniel; Takashi Ikegami, Simon McGregor 2016).

As with tornados, the building blocks of what might have become living structures on earth likely started as efficient ways of dissipating the intense heat from the young planet's interior to the cooler initial seas and via them to the surrounding vacuum of space. Since the energy difference between the magma just beneath the surface and the vacuum just beyond the atmosphere was so very great, the physical and chemical structures that first emerged to equalize that difference could have quickly became highly complex (See Figure 9 below) (Marshall 2016).

Figure 9 illustrates the chemistry and energy flows of a deep sea vent. Vents like this power continental drift, as the magma in the core pushes up through cracks in the mantle and crust. Maps of the seafloor show these "spreading centers" as lines like zippers running through the center of all of the oceans. Even after the 4.6 billion years since earth's creation, the bulk of the interior is still magma. The solid ground beneath our feet is a crust a few miles deep at most, compared to the nearly 8,000 miles of the planetary diameter. The mantle beneath the crust itself is a semi-liquid, gradually melting with increasing depth into the pure fluid of the molten core inside, allowing the crust (powered by these spreading centers between crustal plates) to slide across the slippery mantle. Like boiling water in extremely slow motion, this inexorable pressure pushing up through the mantle breaks through the surface crust, prying tectonic plates apart, allowing the vents to out-gas. These spreading centers are compensated by complementary continental collisions where one plate rides atop another, forcing the bottom plate to curve inward and melt back into the mantle (Robinson 1993).

Figure 9. The Dissipative Structure Of A Sea Vent On The Ocean Floor



Source: Back smoker (deep sea vent) http://oceanexplorer.noaa.gov/explorations/02fire/background/hirez/chemistry-hires.jpg Template:PD-USGov-Interior-NOAA)

The chemistry surrounding these deep sea vents is clearly complicated. When combined with the large energy differences between the magma and the sea, it is obvious that this is a complex dissipative structure. The energy of the magma serves as a catalyst accelerating the circulation of the water and with it the flow of molecules, themselves forced to interact in unlikely ways by the high pressure, heat, and the tight quarters of the rocks. This natural complexity is an attractive candidate for the emergence of life (L. E. Orgel 1995, L. Orgel 2004). It already has several requirements: an external power source, natural boundaries confining the reactions, and a circular flow.

Today deep sea vents are indeed surrounded by life forms using a chemical metabolism rather different from our own, using some of the same chemicals illustrated. These creatures use sulfur to assist in storing energy, and appear as tubes several meters high. They also have DNA and can reproduce. Comparison of their DNA with that of all other life forms has identified enough genetic overlap to suggest that we share a common ancestor. This ancestor has been called LUCA, an acronym for "Last Universal Common Ancestor" (Boussau, Bastien; Samuel Blanquart, Anamaria

Necsulea, Nicolas Latillot, Manolo Gouy 2008). The precise sequence of events leading to its emergence remains contentious, but research during recent years has itself been accelerating toward a convergence (Marshall 2016, L. E. Orgel 1995, L. Orgel 2004, Smith, John Maynard; Eors Szathmary 1995). Among the breakthroughs have been how naturally abundant amino acids could have combined to create many forms of RNA, including a subset that could indirectly self-replicate, govern metabolic cycles, and eventuate as DNA; how cell boundaries could have developed out of naturally occurring lipids, liberating cells from the need for rock boundaries; and how metabolic cycles themselves could have developed around external energy sources as diverse as meteor impacts, volcanism, sea vents, or sunlight (Marshall 2016). Once begun, by any or only some of these means, the key capacity was self-replication, which has also been solved.[7] With replication, selection becomes possible, enabling adaptation and with it evolution. Even RNA alone can carry an instruction set remaining dormant and isolated (L. Orgel 2004), yet harness a range of metabolic cycles, as in a modern virus.[8]

The map of the evolution of life in Figure 8 teaches us that the first life began no later than one billion years after earth's formation (or 4Bya). One half of that time later (3.5Bya) anaerobic cyanobacteria had already started pumping oxygen into the atmosphere while dwelling near the ocean surface. Immediately that implies two critical developments: first, that photosynthesis had developed, converting solar energy into a chemical that can be used as a storage battery; and second, that **some kind of boundary enclosing the cellular life-form existed** to protect it from dangerous radiation.[9] Cells using solar energy needed boundaries to contain their metabolism,

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[7] Spherical cells can be stretched by natural forces into cylindrical strings with the molecules of metabolism and the DNA to govern them spread equally along the string, so if the spaghetti-like string is severed, its components can continue to function. For reproduction to become routine, the external forces creating elongation must have become internalized, perhaps by the initial cells absorbing too much energy to remain internally organized, requiring a sub-division to avoid bursting the cell walls (Marshall 2016).

[8] All of these attributes are found in viruses today. A virus is just an RNA instruction set coated with proteins. Absent a host, it can retain its structure indefinitely. When it is within a suitable host, its protein jacket can fool a target cell into gaining entry, upon which it quickly inserts itself into the host's DNA, altering the cell instructions to convert its energy into generating more viruses until the host cell explodes, dispersing daughter viruses like dandelion seeds. Hence the virus can assume control over the functions of metabolization and replication of alien life without needing to carry those functions with it. It is a brilliant parasite, and a plausible model for the first life forms. The simultaneous development of anaerobic Cyanobacteria c. 3.5 Bya supports the segregation of RNA instruction sets from specific metabolic paths.

[9] We must also think about what was happening to the sun itself during this time. The current view is that our star formed around 5 Bya, not long before the inner planets. Its capacity to fuse hydrogen into helium within its core would have only just begun, manifested externally first by an increasing output of relatively low-energy infrared photons as viewed from afar. The fusion reaction $\mathbf{H_1 \rightarrow He_2}$ is negatively dampened by its expansion against the intense gravitational pressure of the interior, and by the energy released to the surrounding vacuum of external deep space. Initially the external radiation was low. Interior expansion pushed against gravity, slowing fusion. As the rate of fusion dropped, gravity pulled matter inwards again, re- igniting fusion. Hence the young sun would have oscillated in diameter until fusion had reached equilibrium with gravity, and the surface temperature would have risen to radiate fast enough to balance the fusion inside. This time lag between interior fusion and external radiation allows for an

protecting its chemistry from diffusion into the surrounding water; and also to control the wavelengths of sunlight allowed in. By 2.3 Bya, photosynthetic life had proliferated enough to have altered the earth's atmosphere by the addition of massive amounts of oxygen (the waste from photosynthesis). By then the sun's radiation would have maximized, reflecting the generalized spread of the fusion of hydrogen throughout the star. Correspondingly, the surviving cell walls of existing life forms must have both toughened and become more selective about which wavelengths to allow inside.

The common core unifying the most generically adaptable portions of RNA became the central operating system of DNA. Conversely, DNA seems to have eventually absorbed and combined the most specialized aspects of RNA that could be "switched on" when useful. Hence DNA became a metaphorical Swiss army knife able to deploy job-specific RNA. The appearance of cells containing a protective boundary around DNA (Eukaryotes) dates to around 2.3 Bya, long after the first life 4 Bya. It was an evolutionary leap enabling cells to expand their habitats and energy sources across all of the oceans.

Living Complexity:
Boundaries, Channeled Information Flows, And Hierarchies

The leap to Eukaryotes containing DNA protected by a separately enclosed membrane in the cell was also an expansion of complexity, the internal division of labor[10], information processing, and hierarchy. The key lies in the sophistication of how information is handled. On a physical level recall that we are dealing with molecules and chemistry, units so small that even the largest proteins containing many tens of atoms remain governed by the micro-scale forces of electromagnetism. At these scales, the three-dimensional shapes of molecules are controlled by the shape of their fuzzy electron clouds and the weak nuclear forces binding atomic nuclei. Likewise, the boundaries of the exterior cell walls, as well as the internal boundaries surrounding the cell nucleus and mitochondria, are themselves chambers built of interwoven molecules. These interior chambers within the cell protect the specialized "labor" within them from external interruption, maximizing productivity. Yet if they were completely sealed they would be useless, exhausting their energy supply and unable to "export" their molecular product(s)—their function. The solution is for the cell itself and the chambers within it to have boundaries that are permeable

early period of a "dim" sun, during which the bulk of the earth's temperature would have been governed by the heat from internal compression combined with the radioactive decay of heavy elements contributing to the earth's formation such as uranium & its isotopes, plutonium, etc. (each having been produced by earlier stellar explosions) (Longair 1989).

[10] All functional specializations are "divisions of labor". It could be argued that every atom involved in metabolization has its own specific task, hence any interaction between even two atoms is a primitive division of function.

to some molecules but impermeable to others—***semi-permeable*** (Holland 2014). The key is molecular shape and charge. Like a lock and key, if the molecule satisfies certain criteria, the boundary will be ***transparent***; if not, **opaque**. [11]

Semi-permeable boundaries selectively allow or exclude molecules. This enables them to act in an "on/off" fashion: if (molecular shape fits), then (allow entry). After a molecule is allowed entry, it does not just sit there. Like a guest allowed into a horticultural village, the inhabitants (here molecules) interact with it. In a village, the human inhabitants talk to the guest, determine its intentions, and then guide it to the appropriate authority. Inside a cell, the functional equivalent of the human interaction with the guest in the village is the molecular shape. If the molecule conforms to one of a particular range of shapes, it will eventually bump into and bind with another molecule, forming a new combined shape capable of interaction with yet another molecule (which might break the combination into entirely new parts), leading to a long series of molecular interactions. The net result is that the new molecule or its by-products get "delivered" to the appropriate cellular "authority" (perhaps as molecular food energy to the mitochondria, or information stimulating switches in the activation of DNA). Hence every molecule allowed entry into the cell comes with a specific "address" guiding it to a particular location, just as in the village where the guest was admitted because of the acceptable tattoos or identifying "tags," And just as inside computers whose binary strings "tag" and address machine code. The cell, village, and computer all use analogous processes to accept/reject outside input in a Boolean if/then sequence. Complexity theorists perceive these as separate examples of the same underlying ***information processing***, different ways of gaining new inputs from and about the local environment and responding to them. Note also that in the case of the cell, the molecule gaining entry may be food, so that for cells our distinction between energy and information disappears. The same distinction dissolves in computers, where the channeling of the power supply governs the running programs. However, among humans the members of the village do not typically eat their guests.

Hierarchy is another feature intrinsic to complex systems (Holland 2014, Ghysen 2003, Holland 1995). To understand this, we must clarify the meaning of the word. Human power hierarchies are populated by individuals with their own wants and needs, so we are accustomed to confusing power with both ego and greed. But for complexity theorists hierarchy is divorced from ego. Cells have hierarchies, but molecules lack ego. Here hierarchy is meant simply as differences in the power to affect the system. For the delivery system inside a cell, a good metaphor is a

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[11] In this "lock and key" metaphor, current viruses have a "master key" allowing entry into multiple "locks" common across multiple cell types. Yet the fact that no virus can infect (enter) all cells across all species of organisms reveals the counter-evolution of defensive cell walls. Another evolutionary change since the earliest RNA is that today's viruses are exclusively parasites invading pre-existing complete cells, whereas the notion of an "RNA world" relies upon the capacity of the earliest RNA to construct entire cells "from scratch."

railroad network. When rails diverge, a switch determines which path is taken. The switch is a point of disproportionate power compared to any other section of rail. The switch position directs the train to the pre-programmed location, just as molecules do within a cell. So the molecules with "switch" functions have disproportionate power, and the most powerful switches lie within the nucleus of the DNA. As with life itself, hierarchy is an emergent quality common to ***all*** *complex structures*.

Hierarchy, a segregated division of functions, and the capacity to channel information appear to be unique to life, although their precursors can be found in other far-from-equilibrium dissipative structures. Stars derive their energy from fusion, which is like a metabolism. But stars lack anything like a "switching" function for channeling either matter or energy, and ***it is that very capacity to direct "information" in a Boolean "if/then" way that seems to be unique to life. The emergence of that capacity within living cells along with the ability to "store"/preserve that information as RNA or DNA is the essential divide of complexity between living and non-living*.** The development of all dissipative structures can go through bifurcations that give each one a specific history, making their futures impossible to predict precisely. ***But only life can record and replicate that history. It does so every time it reproduces.***[12]

Evolution and the Acceleration of Complexity: The Cambrian Explosion

The circular presentation of Figure 8 shows the compound acceleration in complexity. Like compound interest, ***compound acceleration of self-organization produces exponential growth***. This quality is unique to life, because life can chemically store and draw upon both energy and information as needed.[13] During a 50 million year-long period, from 550 Mya to 500Mya, life diversified and built shells and teeth that were preserved in the fossil record for the first time. This recent and rapid acceleration in the diversity and complexity of the forms life is called the "**Cambrian explosion**" (Cowen 1995). Its appearance in the fossil record can best be explained by the ability of life to use RNA➔DNA to store and build on its own past construction, enabling it to use existing energy and to channel that energy within its walls and between life forms. Its timing and appearance remain mysterious (Jermilin, Lars S.; leon Poladian, Michael A. Charleston

[12] Note that the development of a human embryo is governed by a sequence of DNA switches that collectively "recapitulate" the developmental forms of life across evolutionary time. Not only is life conservative, but the fact that embryos briefly develop and then eliminate gills and tails, for example, shows that the capacity to reproduce ancient forms has not been lost, merely switched on and quickly off during the launch sequence. The evolutionary information is retained in the DNA, and its recapitulation during the construction of an embryo implies that the genetic sequence built over evolutionary time must be followed in programmatic step-wise precision to construct the final life form. No steps can be by-passed (Ghysen 2003, Smith, John Maynard; Eors Szathmary 1995).

[13] Contrast that capacity with a storm. The continuity of storm forms is merely a passive reaction to the same forces encountering the same barriers as the last time, just like waves crashing onto a beach. No information is either stored within or used by such structures. Once the storm energy is exhausted, there is nothing left to build upon.

2005), but complexity theory suggests that we look for solutions in changes in the construction of and interactions between organisms—the balance of positive and negative causal feed-back loops—as they developed new structures. Further, we must include how their environment changed in response to the emergence of neighboring life.

The First 3.5 Billion Years of Life: The Peaceable Kingdom Before the Cambrian

Initial life started around 4 Bya, followed by Cyanobacteria and similar Prokaryotes governed by RNA around 3.5 Bya, then Eukaryotes with DNA protected by a segregated chamber around 2.3 Bya. The "Cambrian explosion" did not even start until at most 600 million years ago. That leaves over 3 billion years of simple pre-Cambrian life forms. Compared to developments since, it was a stable period, verging on stagnation. But behind that quiescence, a set of processes was at work that would eventually converge into the explosion of the Cambrian.[14] Three processes led to that convergence: *Reproduction, Oxygenation, And Respiration.*

One of the processes quietly working during those first 3 billion years was the ***reproduction of life***, and its growth in abundance (see note 7 above). The advent of reproduction, combined with the capacity of single-celled life (or even just RNA) to go dormant when energy was withdrawn, allowed for the ocean currents and storms to spread the seeds of life on a global scale. This was one of the quiet changes happening during the long 3.5 billion years before the Cambrian explosion, and an essential precursor. The capacity of life to reproduce near energy sources and go dormant when deprived of them translated into a gradual population increase. During the quiet 3.5 billion years between 4 and .5 Bya, life could have colonized every favorable location throughout all of the seas on the planet.

One fossilized remnant of the proliferation of life is a stromolite (Cowen 1995), now thought to be the fossilized remains of massive colonies of cyanobacteria, densely packed cells clustered around favorable energy sources, collectively building "apartment towers" containing innumerable inhabitants. Stromolites are those towers in fossilized rock form, dating back nearly 3 Bya, and found wherever the rocks are old enough.

Cyanobacteria are photosynthetic, and use chemicals for their cycle of energy storage like their cousins on the sea floor. But modern plants use photosynthesis in an entirely different way to

[14] The ratio produced by dividing the .5 billion years of rapid evolution by the preceding 3 billion years of apparent stability is 5/30 or 1/6 or (roughly) 15%. This ratio can be compared to the length of human settlements as a ratio of the time anatomically modern humans have existed. Human settlements proliferated between 6➔10 Kya, whereas "modern" humans may have existed as early as 200 Kya. 8/200=1/25=4%. I suspect that the speed of human social complexity compared to the more prolonged burst of complexity across all of life reflects the efficiency of cultural knowledge via language, vs. adaptation via genetic change.

create carbohydrates as an energy battery. The chemistry of that cycle consumes carbon dioxide to create carbohydrates (a form of sugar) and releases oxygen as a waste product.[15] When the sun sets, modern plants consume that sugar by reversing photosynthesis--using oxygen to break the chemical bonds--in the process releasing carbon dioxide and water as waste, allowing the plants to take the released energy to power the building of new structures such as roots and leaves. This night phase is called respiration, and its chemistry is the same generating power for animal life. But entropy requires that the ***amount of solar energy needed to construct the carbohydrate battery is greater than the energy it can release***. Hence the CO_2 used in building a carbohydrate is greater than the CO_2 released during respiration, and the O_2 released in building a carbohydrate is likewise greater than that consumed in respiration. The net result of photosynthesis + respiration in a plant is the creation of more O_2 than CO_2.

It is a complementary cycle where the waste from each phase becomes the fuel for the next, although its energy efficiency is retarded by entropy. This two-cycle metabolic engine is relatively modern, emerging long after the photosynthetic cyanobacteria built stromolites. Cyanobacteria produced oxygen, but lacked the capacity to respire. Oxygen was a poison to them. Instead, they used other chemical paths to access their stored energy. The result was a gradual build-up of atmospheric oxygen on a planet that originally had none. Oxygen is a dangerous atom—promiscuously reactive and highly volatile. The colonies of cyanobacteria that left behind stromolites were prodigious producers of oxygen. For a long time this toxic waste would not have been a local threat, because the tides would have absorbed the oxygen and swept it away, eventually releasing it to the atmosphere. In either sea or air, most of the free oxygen would have quickly reacted with and been locked up into ferrous rocks, leading some to speculate that for a time the rivers would have turned blood-red with iron oxides (Cowen 1995). But eventually these reactive sinks would have become exhausted, allowing free oxygen to enter the atmosphere unimpeded, with nothing left to bond with. Since oxygen is clear to infrared photons, its increasing abundance in the atmosphere would have accelerated global cooling. The oxygen content of our atmosphere today is 20%, all of which was created by photosynthesis**.**

At the local scale of stromolite colonies of cyanobacteria, the oxygen saturation of the sea and air began to become a problem (ultimately forcing them to retreat into anaerobic areas). A new life form emerged: novel cells capable of using the concentrated oxygen surrounding and within the colonies of cyanobacteria to develop respiration (Cowen 1995). This was perhaps the ancestor

[15] The basic chemical equation of photosynthesis is: $CO_2 + H_2O$ + hi-energy photons → $[CH_2O] + O_2$, or, more precisely: $6CO_2 + 6H_20$ + hi-energy photons → $6H_{12}O_6 + 6O_2$ [In words, Carbon Dioxide + water + light energy → Carbohydrate and Oxygen]. When the sugar battery is used during respiration, the equation is run backwards: Carbohydrate + Oxygen → low-energy photons + water and Carbon Dioxide. Note the energy difference between the photons absorbed during photosynthesis compared to those released during respiration, another appearance of entropy (Cowen 1995).

or cousin of mitochondria (Niedzwiedzka, Katarzyna Zaremba; et. al. 2017). It harnessed the volatility of oxygen in its own novel metabolism. Starting initially as a parasite confined to the tight quarters between stromolite cells, it too linked with RNA to find new niches eventually, some of which would unfold as symbionts with the first proto-modern plants (creating carbohydrates, unlike cyanobacteria) to enable those plants not only to photosynthesize carbohydrates but to respire as well.[16]

So we have now seen the processes that would eventually converge to create the Cambrian "explosion." The first was the invention of reproduction. That invention preserved accumulated information as RNA/DNA, while eventually populating all favorable underwater environments with life. Second, the gradual accumulation of oxygen protected the earth's surface from UV light,[17] after it had saturated the oceans. Finally, the emergence of respiration, allowing life to harness the volatile energy of oxygen, and ultimately to leave the seas altogether.

The Cambrian Explosion:
The Accelating Flow of Energy Between Organisms

The cumulative result of these innovations by life, along with their environmental effects of oxygen saturation prompting yet more innovations, is a ***classic positive feed-back loop***. Without compensatory negative loops, run-away feed-backs culminate in exponential outputs and violent collapse. For life, the negative loop lay in materials. The molecules required by photosynthetic life floating in the oceans were limited. Today the oceans appear blue in part because they are largely sterile. Except for oxygen, the molecules necessary for life are larger and heavier than water, and thus drift to the bottom. Yet photosynthesis requires a solar intensity only available near the surface. Modern algae can only live where the two intersect: where ocean currents collide with continents creating a turbulence that draws bottom sediments up to the surface (Colinvaux 1978). The obvious corollary is that the abundance of photosynthetic life has always been constrained by the number of locations near continents where the right molecules were exposed to the right energies. Indeed fossilized stromolites are only found in ancient rocks that were once on the coasts of ancient seas. The limit on the number of locations where the necessary materials were connected

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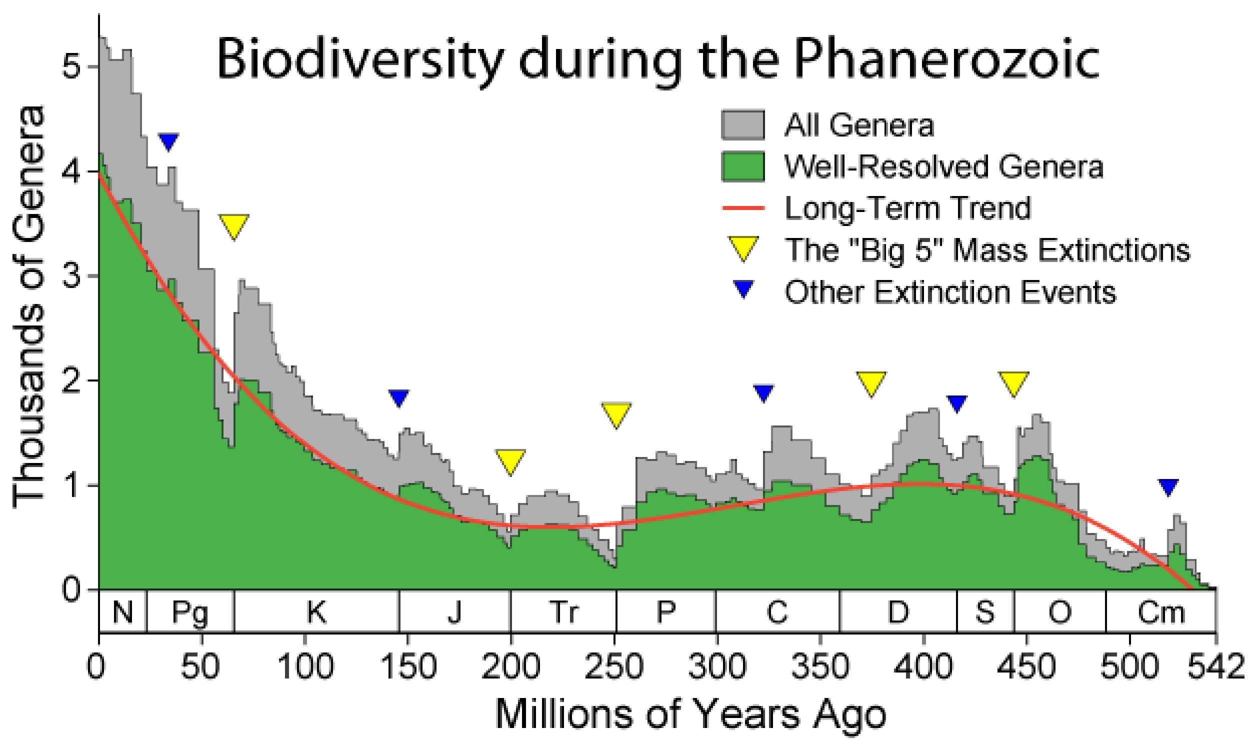
[16] Photosynthesis can power many different chemical cycles. Cyanobacteria and algae are both photosynthetic, but use quite separate chemical paths. Algae and modern plants can tolerate and even respire using oxygen, whereas it is a toxin for cyanobacteria that can only thrive in its absence, in refuges within mud or eutrified ponds and lakes.

[17] The high energies of UV light can break atomic bonds. That is why humans get burned by it, yet can also harness it to create vitamin D. In the atmosphere, when a UV photon strikes O_2, it splits it into two separate O_1 atoms, which often re-combine into O_3—ozone. Ozone itself is unstable (and toxic to humans), quickly returning to the more stable O_2 form in the reaction $O_3 + O_3$ ---> 3 (O_2) atoms. Yet the ozone layer in the upper atmosphere is recreated by solar UV fast enough that the layer has remained roughly constant until recent times (Graedel, T. E.; Paul J. Crutzen 1993).

with the required energies was a selection pressure, favoring life forms that could either survive prolonged dormancy separated from "food" (matter or energy); or forms that could push competitors aside to acquire favorable locations. Doubtless both strategies were deployed. The aggression of the latter forms would have favored predation (Bonner 1988).

Likewise, the "prey" were equally pressured to generate new defenses quickly. The arms race was frenetic (albeit in slow motion), generating creatively bizarre extensions of animal forms never observed before or since. It was an "all-out war" of Hobbesian proportions involving all life. Within a relatively short 50 million years (550-500 Mya), the mutually accelerating clash between a growing population of rapidly changing life forms with a finite chemical food supply created a new ecosystem of organisms. It was a ***bifurcation*** that dramatically and quickly reorganized the internal design of most organisms and the relations between them. Once again, the ***phase-change*** of boiling water comes to mind: after some billions of years of imperceptibly increasing population of life, a critical threshold (the limited chemical food supply) was finally breached, and a phase-change occurred (Kauffman 1993).

Figure 10. Global Biomass Since The Cambrian



Source: https://commons.wikimedia.org/wiki/File:Phanerozoic_Biodiversity.png

The **Phanerozoic Eon** in **FIGURE** 10 includes all of the Eras and Periods beginning with the Cambrian. From right to left, the periods abbreviated in letters are: **Cm=Cambrian, O=Ordovician, S=Silurian, D=Devonian, C=Carboniferous[18], P=Permian, Tr=Triassic, J=Jurassic, K= Cretaceous, and Tertiary (Pg=Paleogene + N=Neogene).** Fossils from the Silurian period suggest temporary land use for eggs; the Devonian suggests arthropods, animals, and some plants; the Carboniferous, full plant adaptation to land along with the emergence of fully adapted tetrapods. Note that with the exception of the end of the Permian (in which up to 90% of all life died),[19] the great extinctions only retarded—**but did not stop**--the *exponential growth of life*. From this we can infer that even then the core information of DNA was sufficiently retained to allow for a rapid rebound and renewal of self-organization (Hallam, A.; P.B. Wignall 1997, Sepkoski 1986, Raup 1991).

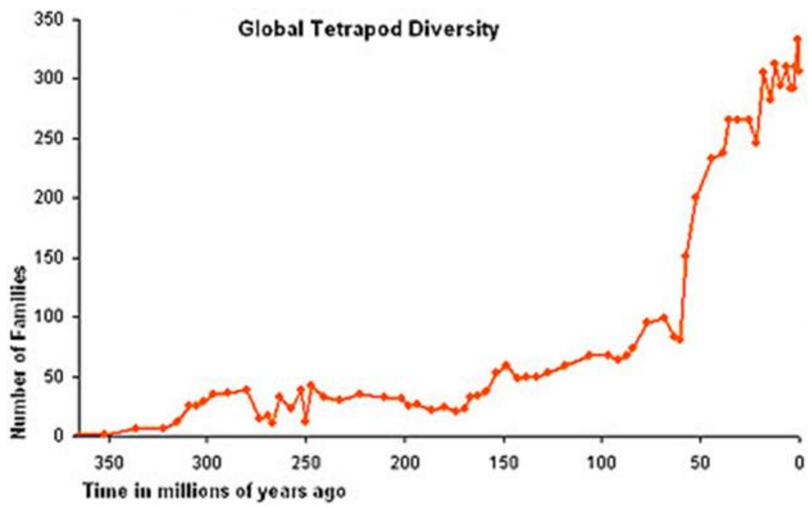
Within the surviving life forms, many became actively mobile, interactive, and interdependent--requiring a coordinated internal high-energy multi-cellularity. Every multi-celled organism was pushed by selection to develop an exponentially increasing number of sub-sections containing many specialized divisions of molecular labor—the precursors to modern organs. External protective shells appeared, along with the first true neurons. ***It was an explosion of internal regulatory hierarchy, as well as an explosion in organismic size and diversity***. The growth in size conferred advantages to the predator, but also to the prey. One common method of escape from predation used by the prey was "***pioneering***" into entirely new and unfamiliar areas (including size). During the periods immediately following the Cambrian, some of these newly complex life forms would make it just a few feet out of the water to bury their eggs safe from predators (Bonner 1988, Cowen 1995). Pioneering onto land to escape predation could not have been possible without the prior innovation of entirely new multi-cellular life forms using the oxygen needed for the respiration of carbohydrates. The evolution of respiration itself required a saturation of the oceans with oxygen, a saturation created by the perpetual production of cyanobacteria during the billions of years before. It was respiration that fueled the growth of fish and their capacity to build internal organs, skeletons, and the brains to coordinate them. It was respiration that also built the battle-ready external armor surrounding the arthropod ancestors to the lobster, spider, and crab. It was respiration that powered the creation of the bulk of skeletons and shells forming all of the fossils ever discovered: all because the evolutionary burst of new

[18] The Carboniferous period derives its name from the abundance of fossil fuels deposited then—the oil and coal powering modern machinery. From the volume of these un-decomposed deposits we can infer that the biodiversity of decomposers on or underground lagged behind the diversity of plant life above ground.

[19] Estimates of percent of species extinguished during "mass" extinctions cannot be definitive, because they rely on assumptions about the abundance of species lacking fossils. But based on fossil evidence, the end-Permian extinction seems to have been unique in devastation, with typical estimates of 90% or more. Even the most conservative estimate of 50% still places it as the worst ever experienced (Hallam, A.; P.B. Wignall 1997).

creatures involved in Cambrian combat had previously acquired the capacity to harness the power of oxygen and carbohydrate metabolic respiration. Respiration powered the arms race between predator and prey.

Figure 11. Global Tetrapod Diversity



Source: Courtesy http://fishfeet2007.blogspot.com/2007_05_01_archive.html

Despite extinctions, the division of labor within and between life forms continued throughout the Phanerozoic Eon (the time from the Cambrian to the present). The Cambrian explosion has never stopped. The Pre-Cambrian "Ancestral Chordate" was a worm using neurons to sequentially squeeze muscles along its digestive tract to burrow through the mud (Ghysen 2003). By the beginning of the Cambrian, some of its descendants had acquired protective vertebrae surrounding the neuronal trunk line. The existence of neurons already implies a coordinated multicellular and specialized division of labor within the organism. Also, all of the major generic divisions among the animals with spinal columns (except for the birds) preceded the massive Permian extinction 245 Mya.[20] The profusion of life after the Permian extinction was due to the resumption of mutual competition continuing the (interrupted) series of bifurcations both internally and externally:

[20] Mass extinctions eliminate the largest and most complex life forms, both because of their reliance on a larger food web necessary for such life, and because their gestation times are longer (Neutel, A; Heesterbeek, J. A. P. and de Ruiter, P. C. 2002, Simberloff 1994). The cessation of chordate differentiation with the Permian extinction (except for the birds) may reflect that. The chordates that survived were probably small, yet still preserved the DNA instructions for protected neurons, enabling the renewed growth of competitive complexity. Also, it should be noted that the devastation of every extinction is at best an educated guess, so the most reliable comparisons must remain relative for now.

internally as a division of labor among cells becoming organs governed by neurons and ganglia of increasing sophistication, and externally as ecosystems of specialized organisms using some combination of photosynthesis, predation, parasitism, or mutualism.

Pioneering: The Growth in the Size of Organisms

n any physical conflict between organisms, size matters.[21] That is why carnivorous predators seek out smaller prey, unless they hunt in groups. Over time, this selection pressure generates larger prey, in turn generating larger carnivores. The entire cycle of selection favoring larger size is one example of pioneering over time, another way that competition literally breeds complexity (Bonner 1988). Even though basic body designs and the DNA regulating them only change incrementally with growth in size,[22] every increase requires complementary changes in anatomy and physiology. So a gradual doubling or even tripling of size implies an exponential growth of the number of cells and the complexity of coordinating them (Bonner 1988). Yet the fossil record during the age of the dinosaurs demonstrates that process continuing across the entire Mesozoic Era (sequentially embracing the periods of the Jurassic, Triassic, and Cretaceous). The result was the emergence of the largest land animals ever recorded.

Entropy and the Limits to Size

The largest animal ever known to have existed continues today: the great blue whale. Its enormous bulk is possible because it is supported by water. Were it on land, it would immediately collapse. Hence for a land animal lacking external watery support, its own mass would crush it if it were large enough.

The other limit to the size of any organism is far more subtle, but equally decisive. It lies in the *availability of energy and the* ***law of entropy***. Recall that entropy caps the amount of input energy that can be used, and that the most efficient modern steam engines use only 40% of their fuel doing their work. The rest is lost as heat (Summers 1971). The same caps apply to life forms. The maximum measured efficiency in a young corn plant is 8% of the sunlight received, and across its life-span is a paltry 5% (Colinvaux 1978). So 95% of the sunlight received by corn is not or cannot be used. Plant efficiencies doubtless vary, but it is safe to assume that with abundant sunlight even low efficiencies have sufficed to allow plants to colonize most land areas since the Carboniferous period. Instead, the constraint on plant growth has been the abundance of materials,

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[21] For the moment I am ignoring microbial infections.

[22] See, for example, the dramatic growth sequence of Theropod and Tyrannosaurid fossil sizes using identical skeletal designs from the Triassic through the Cretaceous, as illustrated in Bonner (1988, p.29, Fig. 6).

particularly rainfall and CO_2, each of which has been gradually dropping since at least the Mesozoic, a point to which we will return shortly.

Plants are the gate-keepers of life, the doorway governing the size and diversity of all organisms feeding on them. Their unique ability to acquire all of their energy from sunlight makes them act as a valve regulating all of those downstream. Yet entropy adds its own toll to that downstream flow, like leaks in an irrigation canal. Plant-eaters are more energy-efficient than plants, but not much. They average 10-15% efficiency, losing 85-90% of the energy in the plants that they eat (Brooks and Wiley 1988, Carbone C 2002, Marquet 2002). Hence, a 70-ton Sauropod would have potentially required **700 tons** of plant matter to build itself. This plant volume would not be a daily requirement, of course, but the cumulative sum needed for its growth to full maturity. Thereafter its daily intake—like our own—would only be that necessary for organ maintenance, injury repair, or energy storage. *Logic requires that the entire biomass of herbivores could not be much greater than 10-15% of plant biomass for very long*. If we extend the same logic to carnivores, the same rigorous limits apply. They too seem to be around 10-15% efficient today, and were presumably during the Mesozoic also. So even the fearsome T-Rex, like all big fierce animals, would have been rare: thin on the ground. Once again, the collective weight of all carnivores could not have long survived above 15% of the herbivores, themselves constrained to 15% of plant biomass. Despite such inefficiencies, existing metabolic cycles have still adequately powered the increasing complexity of life, and natural selection may yet compel further improvements to the efficiency of those cycles. But entropy imposes an ultimate ceiling on their efficiency. It is a ceiling as rigorous as gravity and, like gravity, blocks the pioneering pathway of size for both predator and prey (Raffaelli 2002).

Finally, the construction of bone uses carbon, derived from carbon dioxide. Bone proliferated in the seas during the Cambrian, and it has since accumulated in vast deposits of calcium carbonate on the sea floor. An example can be found in the "white" cliffs of Dover, which were once an ancient seabed. Even on land, bone is not a food source. The result has been a gradual drop in atmospheric CO_2, bringing with it global cooling and drying (Graedel, T. E.; Paul J. Crutzen 1993). Hence vegetation (requiring both CO_2 and H_2O for photosynthesis) has contracted in abundance, requiring parallel contractions in the sizes of herbivores and carnivores. So, even if the asteroid ending the Cretaceous had never struck, the dinosaurs of the Mesozoic would have still held pride of place as the largest land organisms that ever existed. Their hypothetical descendants would have been compelled to shrink to the sizes of the plants and animals typical today.

Pioneering: Biodiversity, Chemical Defense, and the Roots of Human Language

Beyond pioneering in increased size, another way of escaping predation was also available: a colonization of new ways of getting energy via highly specialized behaviors, dwellings, and metabolisms. Plants also tried pioneering using size; ***but their primary pioneering lay in environmental specialization, symbiosis, and chemicals***. Plants could not instantly move sideways in space, but they could do so over time via their spores and, later, seeds. By adapting to higher, colder, and drier areas, they could escape insect and animal predators requiring the lower, hotter, and more humid areas. In a co-evolutionary parallel, their predators themselves would have followed, thereby limiting their own capacity to live in the lowlands. The net result of this cat-and-mouse game eventuated in increasing specialization, symbiosis, and even mutualism among subsections of life. Plants today are sometimes pollinized by specialized insects, so that the shape of a plant's flower has evolved to allow only some co-evolved insects to access the nectar, creating a symbiotic relation of mutual co-dependence (Holland 2013). Another example is that some insects are only able to live on the specialized sap of a particular tree, so that if the tree is attacked the resident insects will defend it. It was the coevolution of symbiotic and mutualistic relations like these that served as one mechanism producing new ecological niches, and with them the profusion of biodiversity, despite falling levels of carbon dioxide, rain, and temperature across the entire Phanerozoic Eon. As with the initial Cambrian "explosion," ***the accelerating cycle of the diversity of life has been autocatalytic****, one giant positive feed-back loop generating an expanding number of niche-specialized sub-loops like eddies in a stream, all governed by the negative limits of available energy, materials, gravity, and entropy*.

Information Flow Among Organisms

A by-product of the increased diversity of energy flow was a growth in the flow of chemical information. One source was from plants: the development of molecules toxic to animals is a common plant defense against predation. Modern examples include plants with poisonous fruit, bark, leaves, or thorns. These compounds are not by-products of core metabolism, but instead require specialized production. Beyond self-defense, chemicals also serve as information signals between plants. Recent research has demonstrated that if a forest of many plant species is attacked by a fungal or insect parasite or predator, the affected plants will produce chemicals alerting all of the other flora inhabitants across considerable distances. The method is via root systems connected by underground fungi collectively comprising a complex communications network similar in both structure and function to a neural net—an underground "brain," as it were. The recipient plants respond by diverting their energy toward the production of appropriate chemical defenses.

Adjacent plants also lend and borrow carbon as needed via that system (Gorzelak, Monika A.; Amanda K. Asay, Brian J. Pickles, Suzanne W. Simard 2015, Rees, Mark; Rick Condit, Mick Crawley, Steve Pacala, Dave Tilman 2007, Song, Yuan Yuan; Suzanne W. Simard, Allan Carrol, William W. Mahn, Ren Sen Zeng 2015, Vivaldo Gianna; Elisa Masi, Camilla Pandolfi, Stefano Mancuso, Guido Cadarelli 2016).

Ant colonies have taken the chemical-neural net of plant communication to a higher level. They are entirely organized by the exchange of pheromones between individuals. Like forests, ants can communicate threats, marshalling entire divisions of specialized soldiers to pour out for defense. Sections of ant nurseries have embryos guided in their development, via titrated chemical inducements from supervising adults, to mature into specialized shapes pre-destined for their roles, anticipating Huxley's *Brave New World* by at least 80 million years (Moreau, Corries S.; Charles D. Bell, Roger Vila, Bruce Archibald, Naomi E. Pierce 2006). Taken as a whole, ant colonies replicate entire animals, complete with specialized organs, governed by a distributed neural net in which all individuals participate. Every individual acts like both a cell and a neuron at the same time. Bees have extended the ant model of coordinated chemistry by the addition of movement: the "dance" of a forager inside the hive. Hence, the volume of information exchanged among bees is greater than that among ants, and both are a great leap beyond the sophistication of plants.[23]

Visual signals among bees and animal groups augment chemical signals, but do not replace them. An additional layer is sound. Birds in the corvid family (ravens, crows, blackbirds) have been shown to recognize individual humans, and crows seem to have a call vocabulary of 70 distinct sounds communicating specific information. Among other birds, the songbird males "sing" in the spring to claim specific territories to warn off competing males, guaranteeing enough geographic dispersion to allow their future young to survive, much like the howling of male wolves. Molecules, movement, and sound comprise a suite of media used in sophisticated combinations by all chordate life forms with brains living in groups. Taken together, they are a powerful "alphabet" with an infinite set of possible arrangements, enabling a wide range of information potential (Holland 2013). Human language is unique only in its complexity. These core components emerged during the Mesozoic era (Bonner 1980).

Non-Genetic Energy and Information Flow Across Generations: The Origins of Culture

The land colonized by the first plants was warm and moist. Both the warmth and the moisture were products of high levels of greenhouse gases, particularly CO_2 and methane. In this soppy world, plants could successfully reproduce like their fungal cousins (and sometime symbionts) using

[23] Leaf-cutter ants also use movement to alert their colonies.

spores. Around 220 million years ago, close to the end of the Triassic period, spores were gradually replaced by seeds as the atmosphere cooled and dried. The hard shells of seeds enclosed a starter pack of water, some food, and DNA—like a packed lunch with instructions. Later innovations were seeds adapted to survive digestion by herbivores, spreading their dispersion. But it was with animals that the young stayed near to and dependent upon their parents for food and protection. This seems to have started with dinosaurs. Certainly we see it today in most animals. The dependence of the young on their parents is a far more complex method of transferring energy from parents to offspring than is true for the seed of a plant. That energy transfer is also accompanied by a transfer of information—instruction by the parent about appropriately adaptive behaviors. The intergenerational transmission of information after hatching or birth is in addition to genetic transmission, and its volume rises with brain intelligence. ***It is the origin of culture***, according to Bonner (1980). His point was that the growth of brains gradually favored behavioral instruction over genetic, because it could respond to survival challenges in "real time."

Humans mastered linguistic non-genetic transmission in another ***exponential inflection point***[24] some unknown time ago (Anderson 2016, Corbalis 1999, Fisher, Simon E,; Matt Ridley 2013). But like all of the prior inflections of increasing complexity – the origins of life, life's ability to reproduce, and life's diversity during the Cambrian – human language itself was a ***phase-change*** rooted in ancient trends breaching a critical value; trends quietly gathering momentum from the accumulating media of chemical, vision, and sound communication across life forms starting in the Permian period. External chemicals, movement, and sound collectively co-evolved into a communications network spanning and informing large areas of ecosystems populated by a myriad of specialized species: portions of these elements became potentially interpretable to every life form within that ecosystem. We have already confirmed this to be true across different plant species within a forest. It is also true of chemical and visual communication between plants and insect pollinators. Likewise, mosquitos distinguish among humans for selective attack; mammalian carnivores smell chemicals indicating fear, and mammals share many sexual pheromones in common. These observations exemplify the existence of signals, but are at best only the component alphabet of a potential language (Holland 2013).

The hominid➔human use of language was a profound breakthrough far beyond anything before. It drew from media first developed in the Mesozoic, but did so in a revolutionary new combination, enabling an explosive volume of information to be delivered in an extremely compact and efficient way. Given our disproportionate intellect, it included how to interpret a high proportion of the signals from the rest of the ecosystem.

[24] Exponential curves (such as compound interest) start out rising slowly, then bend like an elbow sharply upward. The location of this bend is called an "inflection point."

Human Language and Social Compexity

Human language eased group living. Presumably it started slowly and grew exponentially from selection pressures (Anderson 2016). Among some large mammals, sexual relations are of the "harem" form, in which a dominant male has exclusive sexual access to several females (e.g., rhinos, lions, walruses, and gorillas).[25] One indicator of this strategy is a significant size difference between the sexes, preserved in their fossil remains. Among the fossils assigned to the hominid line(s), the few found within the millions of years between 4+ and 1 or less show a clear drop in sexual dimorphism, a trend toward an equality of size (Gibbons 2002). This trend might have accompanied a growth in the sophistication of a proto-language, for two complementary reasons: (a) females could negotiate sexual access ("no means no"); and (b) male competition for access to females could itself have shifted from violence to verbal negotiation. Both would have enhanced group survival. Language would have reduced competition among all and enhanced reciprocity. In turn, this would have boosted group survival chances, favoring groups with greater language skills via lower infant mortality and higher rates of food acquisition. Parallel with the drop in dimorphism was a growth in brain size faster than body weight (Merkel-Bobrov, Nitzan; Sandra L. Gilbert, Patrick D. Evans, Eric J. Vallender, Jeffrey R. Anderson, Richard R. Hudson, Sarah A. Tishkoff, Bruce T. Lahn 2005).

The proliferation of hominids over the past one million years contrasts with the fates of the other great apes, all but three of which are now either extinct or soon will be.[26] Gorillas, orangutans, and chimpanzees[27] continue only because of tenuous human sufferance. The sheer weight of gorillas compels them to live on the ground, leaving them vulnerable to ground-based carnivores like humans, cats, baboons, and the large snakes that also prey on monkeys. This weight/prey problem might have been another selection pressure that operated on hominids, favoring group cooperation and a potential acceleration of language.[28] All we know for certain is that during the past 4 Million years some hominids survived during a period that others died out (Gibbons 2002, White, Tim D.; Berhane Asfaw, Yonas Beyene, Yohannes Haile-Selassie, C. Owen Lovejoy, Gen Suwa, Giday WoldeGabriel 2009).[29]

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[25] Elephants use a different strategy, in which the females and young males live in herds supervised by a senior matriarch, while the adult males are banished after maturity. Among Orcas, adult males are allowed to stay in the pod, but they remain subordinate to the matriarchs.

[26] See Chase-Dunn and Lerro, 2014, Chapter 3.

[27] Chimps and bonobos are close cousins, although the substitution of the male aggression typical of the former by the sexual promiscuity of the latter is fascinating. Yet both remain human prey and are headed for extinction.

[28] On the other hand, Colinvaux (1978) reports that large mammalian predators do not control the number of their prey, because they select the easiest catch, typically the infirm or young, the former of whom are already unlikely to reproduce and hence are ecologically "dead" anyway.

[29] The Neanderthals also died out during this period.

Size Limits on Hominid Bands and Kinship

Energy flows limit the number of organisms that occupy any niche. Herbivores are typically 10-15% efficient in energy use; carnivores also. Further, let us consider that the long-term growth in biodiversity in a world of gradually declining CO_2 can only be explained by a compensatory growth in niche specialization. Logic dictates that the more specialized the niche, the less energy available to it and the fewer the number of individual organisms able to populate it. Yet there is also a minimum size: too few organisms and they risk extinction. One of the paths to extinction is inadequate numbers of viable young, and one entrance to that path is inadequate genetic variation. So the size of surviving hominid bands must have negotiated between these limits. Too few individuals risk inadequate genetic variation and/or inadequate mutual defense and aid when attacked, while too many risk starvation. A thought experiment may give us a general range for possible band sizes.

Let us hypothetically assume one hominid with a strictly vegetarian diet needing only 2 Kilocalories/day, located in an area receiving the average solar energy for a square meter of earth of 1,161 K calories/hr. Calculating a 5% efficiency of solar energy use by the local plant life, 5% of 1,161 = 58.05 K calories of generated plant mass/meter^2/hr. The maximum day-length is 12 hours at the equator, so 58.05 * 12 = 696 Kcals/meter^2/day. Hence, our hypothetical equatorial hominid would be required to consume roughly 3 meters^2 of all of the plant matter therein per day to survive. Like other herbivores, however, it could use at best only 15% of the energy contained in the plants: 0.15 X 696= 19 usable Kcals/meter^2/day –increasing the necessary land area per hominid ten-fold, to 30 meter^2/day. But this 1:30 ratio assumes 12 hours of sunlight, and it ignores the more realistic constraints of the human inability to digest cellulose, the need to avoid plants with toxins, and the need to vary diet. Even in an ideal environment, the number of band members would be limited by how fast they could move.[30] These simple calculations suggest a geographic range of roughly 1km/day/individual to survive (if the meters required were all in one line one meter wide). This range, combined with the probable rate of movement on foot, limits the number of individuals per band to 10~40+, continuously on the move (less than 30 members risks extinction). Over the course of a year, the search for accessible plant food alone would have necessitated travelling several hundred kilometers. A maximally efficient spiral search pattern could have enclosed those kilometers into a much smaller area; but even then, the territory required would have been large enough to have made hominid bands rare, thin on the ground.[31]

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[30] Another example of the same point is provided by locusts. Their vast numbers require even vaster energy from huge areas of crops, which they can only acquire by flying at great speed.

[31] This crude average ignores the uneven distribution of edible plants, clumps of abundance segregated by areas of scarcity.

Among our nomadic ancient ancestors, band survival depended upon equality and reciprocity. Food was shared among all, just as times without food were endured by all. The band was not "like" family, it *was* family. All were genetically related, unless encounters with another band enabled sexual exchange (negotiated or coerced) (Millassoux 1975). Even then, the nearest band might have been composed of cousins only recently compelled to separate. The cultural expectation of reciprocity among kin would have persisted well into the Neolithic era and its settlements.

Territorial competition motivated migration, sometimes beyond Africa. The alternative was warfare, dangerous and painful (emotionally and physically) (Curry 2016). Evidence of early migration dates back 2Mya. In European Georgia, the skull of a forty-year-old toothless man was unearthed and dated to 2Mya. The tooth sockets had healed before death, implying social support and social bonds. Homo Erectus emerged 1Mya and left remains at an outpost in southern England dated to 700Kya, along with the horses they'd eaten. But these migrations were limited to certain "launch windows" by the "Sahara Pump"—climatic phases in which the area now occupied by the Sahara desert was well-watered and verdant. During the Pleistocene era (a time enclosing the "Paleolithic"), cycles of glaciation dating back to 700Kya were punctuated by warmer inter-glacial intervals; these cycles governed the ability to cross the Sahara, limiting migrations out of Africa. This explains why the ancestors of Neanderthals left Africa perhaps several 100Kya, whereas our nearest relatives could not leave until perhaps 60Kya. However, once they did so, they survived migrations that spread quickly: Australia and Eurasia by 55Kya, and the Americas by at least 13Kya, more likely 20Kya. The expert sailors of Polynesia had settled Hawaii by 1500 CE.

Over a few tens of thousands of years, humans had successfully occupied every continent. Like the planetary diffusion of the first life forms, new environments required new adaptations. However, unlike the first life, the most important adaptations were not genetic[32] but cultural, social learning communicated by language. Further, cultural knowledge was treasured for its survival value. It was passed down intact through generations using methods protecting its accuracy and continuity. Elders of nomadic bands were relied upon for their knowledge and experience. Cumulative group knowledge was passed along via histories memorized by the young before marriage, supervised by those elders.[33] Among the traditions retained from the nomadic life (even

[32] Of course, there were genetic changes also—lactose tolerance, skin color balancing UV protection with vitamin D generation, and perhaps others—but these had no clear consequence on the creation of social bonds or complexity.

[33] Michel-Dolmatoff reports that hunters in the Amazonian jungle living as recently as the 1960s were not encouraged to bear children until they had successfully demonstrated their knowledge of tribal history and cosmology to the satisfaction of the shaman. We find these passage rites of puberty faintly echoed in every major religion today (Cambell 1988, Reichel-Dolmatoff 1971). Portions of the initial books of the Bible (Leviticus) shared by all of the Abrahamic faiths were clearly memorized, given the repetitive frequency of the phrasing, using the same "book-marking" function as the repeating chorus in songs.

up to and beyond settlement) was shamanism, a vocation assigned to or chosen by a particularly gifted child. Shamanism required years of specialized training, because it combined the skills of an herbal doctor (requiring extensive plant knowledge), an historian, a teacher, a psychologist, a mystic seer, and a medium to the ancestors (Plotkin 1993). Such a person would have commanded respect, so his/her blessings would have been politically valuable.

Within Africa, human geographic diffusion and climate change over time had compelled us to shift niches/food sources. Starting with a diet perhaps like that of chimpanzees – plant roots, fruit, insects, and the occasional monkey – humans might have encountered some environments which had dried out to become grasslands; and/or some groups may have migrated into drier areas that were already savannah. Either scenario would encourage a dietary shift to meat and a lifestyle shift to hunting. In South Africa, human remains dating to 70 Kya have been found with rock beads whose color required exposure to sustained high temperatures (Chase-Dunn, Christopher; Thomas Hall 1997). So fire was in use, and meat could have been cooked. This is an example of ***a niche-shift (bifurcation) that was cultural***, something unique to humans. Further, the development of hunting did not stop the continued development of gathering elsewhere. The two niches were not exclusive. Nor did either **<u>require</u>** (either biologically or energetically) any major change in the division of labor by gender or age, although all hunting groups observed to date assign hunting to males. Energetically, in both hunting and gathering societies, the aged, the very young, and pregnant/nursing women would have been the least productive; but all could have participated in each activity. Division of labor aside, in hunting the prey would be wounded and tracked, then periodically re-wounded until it bled out. Once dead, all could have participated in the rendering and assisted in the transport of the body parts. As our ancestors learned how to hunt, so their prey learned how to avoid them; this is why large animals today still survive in Africa. But by the time humans started populating Eurasia and the Americas, they had developed spear-throwers able to deliver a payload of razor-sharp rock at high speed over a considerable distance (Nielsen, Rasmus; et. al. 2017, Alroy 2001). Simultaneously, the global climate was shifting as the last ice age ended, raising the question of what combination of climate and human invasion destroyed the Megafauna. Whatever the causal sequence, large animals quickly went extinct in the Americas and Australia around the same time as the arrival of humans, bringing in turn extinctions of the carnivores that had preyed on them. In Eurasia, the last wooly mammoths, shrunken by island dwarfism, died out in the Aleutians around 5Kya.

Circumscription, Division of Labor, and Hierarchy: The Human "Cambrian Explosion"

To "circumscribe" something is to draw a boundary around it, to enclose it, and restrict it. As with the Cambrian before, the growth and spread of human life began to collide with the boundaries of its food sources. The last glaciation ended around 11Kya. By then humans had spread around the globe. Their migrations had brought them into previously unfamiliar environments, forcing them to adapt to new niches, to "speciate"/bifurcate culturally, a uniquely human trait. Just as in the Cambrian era, a growing population density was constrained, not just by a limited food supply, but by one now actually shrinking. But that shrinkage was uneven and slow. The "megafauna" (mammoths, mastodons, rhinoceros, giraffes) required large grazing areas to survive, areas with suitable plants that in turn prospered in geographic shifts with the seasons, latitudes, and altitudes. The last glaciation did not end abruptly, so climate shifts were as patchy then as is warming today. Plants would themselves have relocated in latitude or altitude, compelling all herbivores to follow. Further, successful plant movement depends on their pollinators, methods of seed dispersal, and the seeds landing in the right soils exposed to the right amounts of sunlight. Necessarily these linked contingencies must have often failed, reducing the total herbivore food supply even as they forced new patterns of migration upon them, yet another survival challenge. Changing megafauna migration routes also challenged their predators. Following the scent and scat of the herbivores, human and animal carnivores could no longer rely on ancient routines (large cats) or received wisdom (humans). In this competition among carnivores, the big cats had to lose. Yet the inevitable human victory was Pyrrhic, because the humans were already competing among themselves as their numbers grew. Once again, conflicts among competing bands of hunters would have increased. However, the extensive peopling of the planet precluded migration to resolve conflicts. A new solution emerged: trade between bands. Instead of all hunting bands pursuing all game everywhere they went, they worked out a territorial division of labor where trade in meat and goods allowed survival during the periods that the herds were absent. The most important unintended consequence was the ability to settle in one location, in effect substituting trade for migration. The megafauna still went extinct, but humans had begun the process of settlement, a first step toward cities (Chase-Dunn, Christopher; Hiroko Inoue, Teresa Neal and Evan Heimlich 2015).

Hunters also "down-shifted" to smaller game with shorter breeding times (e.g., rabbits). Some eventually became herders or, as in North America, set fires to clear forests for grass land to feed the deer they would hunt later ("fire-stick farming") (Mann 2006). Meanwhile, those humans who'd remained reliant on gathering were themselves compelled to shift gradually to horticultural gardening, also using their own variation of "fire-stick farming" (see below).

Under the stress of foreclosure in ancient hunting life-styles and rapid fluctuations in climate, many humans found themselves responding in the same way as our simpler ancestors during the Cambrian. Within a few thousand years after the last glaciation, settlements had become common where the food supply allowed. Those settlements that would incubate the first true cities and surrounding polities had also emerged, typically along rivers with fish running through lands that could be cultivated, and began to develop social hierarchies. This Neolithic wave of settlements seems to have eventually become global, beginning first in Eurasia some 4,000 years after the last glaciation, and then in the Americas after an additional 4,000 (Mann 2006). The content of the social changes among humans was strikingly similar to the genetic changes of the Cambrian: the ***emergence of conflict, hierarchy***, ***reorganization of energy flow*** from the weak to the strong, an ***increasingly complex division of labor***, ***and social regulations*** designed to coordinate labor and keep the flow of energy reliable. The Cambrian explosion was recapitulated by reorganizing the relations among human beings using language, but the qualities that emerged were the same: a specialized division of labor controlled by a hierarchy of authority coordinating the creation and distribution of food (Chase-Dunn, Christopher; and Bruce Lerro 2014, 75-148).

The most famous settlements creating the pristine[34] (or first) states were generally located between 20^0 and 40^0 north of the equator. Mesopotamia, illustrated in Figure 12, was closer to 40^0. This was no accident. The climate within that latitudinal band 10Kya was cool enough to have winters allowing some deciduous hardwoods to grow, dropping leaves during the cool months. Winter leaf decomposition was retarded by microbes, themselves either greatly slowed or forced into hibernation. These are the conditions producing the fastest growth of the most fertile topsoil able to feed wheat, maize, and rice for generations (Colinvaux 1978, P. Grimes 1999). It was these soils produced by temperate climates that made the eventual intensity of agriculture possible in the downstream alluvial river deltas, generating the food required for high populations and pristine states.

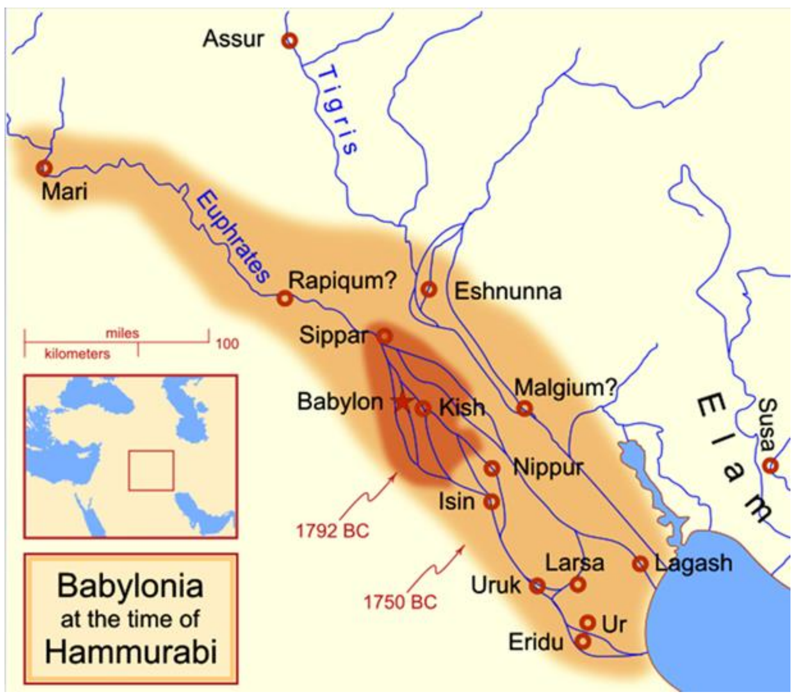
This can be contrasted with the soils nearer the equator beneath tropical rainforests. There, the intense solar energy supports the greatest biodiversity (Jablonski, David; Kaustuv Ray, James W. Valentine 2006), including abundant species of animal, insect, and microbial herbivores and decomposers, collectively preventing dead plant matter from storing nutrients in the soil. Absent winters, dead leaves drop evenly over time and are immediately eaten. In addition, frequent heavy rains quickly wash lose topsoil into the nearest river. Hence tropical soils cannot support the agricultural re-use available in the north (Colinvaux 1978). Instead, tropical farmers must re-fertilize their intended cropland by burning sections of forest.[35] After a few seasons the burned

[34] “Pristine” states were the ***first*** states, not the “cleanest.”

[35] Another form of “fire-stick” farming, more typically called swidden, and/or “slash and burn.”

and fertilized land is exhausted, compelling the process to be repeated in another section. Even if the pattern of sequential burning is optimally organized in a circle around the central village, such that the original area is renewed, the net energy available to the human villagers is less than that available to the agricultural occupants of the temperate zones. The tropics limit human population density, capping social complexity at the level of chiefdoms emerging from an alliance of villages. Without enough surplus food to support a standing army, even a simple kingdom would be impossible. The exceptions of the Khmer and Mayan kingdoms were possible because of massive river basins depositing upstream nutrients (P. Grimes 1999). Equally rigorous energy limits capped the polar hunters. In the Americas, the Eurasian experience was recapitulated, but retarded by 4K years by a lower population density which took longer to reach crisis levels.

Figure 12. The River Cities Enclosed By Hammurabi Over The 42 Years Between 1792 And 1750 Bce



Source: https://en.wikipedia.org/wiki/File:Hammurabi%27s_Babylonia_1.svg (Mapmaster)

Conflict, Food, and Armies

Settlements require a stable food supply. Early horticultural techniques in the temperate zones replicated the tools used in the tropics, such as digging sticks like spears applied to the soils, tools that were eventually improved to function like the modern hoe. Simultaneously, the former hunters in all areas would have been compelled eventually to become herders (Chase-Dunn, Christopher; and Bruce Lerro 2014, 75-104). Some of them also used horticulture to feed their animals, but not all, and not at once. Others still remained nomadic, travelling with their animals. Inevitably these nomadic pastoralists would have encountered the cultivated crops of horticulturalists, doubtless to the great delight of their animals. The ensuing human conflict would have favored the herders (because they retained the tools and cultural knowledge of hunting), leading to burned villages, kidnapped women, and many dead. Enough such conflicts created the walled villages typical of ancient chiefdoms, whose remains are scattered across the globe.

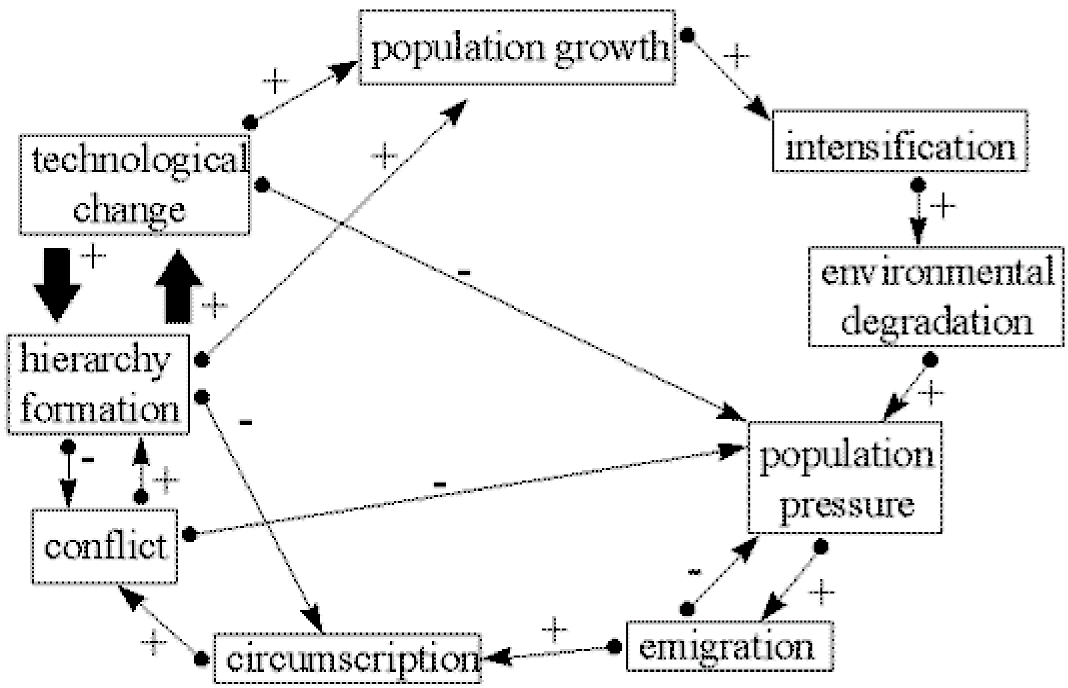
In the tropics, food supply limits population and the capacity for standing armies, so these niche-clashes would have likely ended by negotiation instead of victory. But in the temperate zones soil fertility eventually enabled the villagers to collectively support armed young men for defense, turning the tables and keeping the pastoralists at bay. The long-term result over thousands of years was a retreat of pastoralists into mere nuisances living in the mountains, peoples who would sometimes trade with or raid the settlements, but were otherwise consigned to semiperipheries, such as the Elamites living in the mountains in the map in figure 12. The semiperiphery continued to produce charismatic leaders who would sometimes be able to use their lineage connections to assemble large armies on horseback to conquer enormous areas in a blitzkrieg fashion such as the Mongols.[36] However, these amazing achievements did not stop the steady progression of agricultural production. Conquest and wars checked the proliferation of production and settlement, but with far less impact than any one of the extinctions during the Phanerozoic. As with the Phanerozoic, checks and set-backs were simply brief interruptions to an inexorable process powered, like the Cambrian, by the autocatalytic cycle described below.

The map in Figure 12 is a snapshot of this process, a snapshot taken late in the game (1.7 K BCE) over 2,000 years after the creation of the first settlements archeology has found 3.7 K BCE (see figure 14 below). The reason for its inclusion here is geographic. The rivers are always shifting their course, but the map shows the abundance of water and the fertile alluvial soil. It also shows some of the important early cities relying on those soils. Over time the city locations tended to move upstream as the best land was settled earliest. The occupants of "Elam" (lower right) were semiperipheral warriors, alternately trading with and raiding the inhabitants below. But the driving force of settlements in the Mesolithic and urban growth in the Neolithic was mutual competition

[36] Chase-Dunn's team have discovered that at least 50% of imperial geographic expansion during recorded history originated with organized semiperipheral armies, whose conquests were only put to an end with the invention of guns (Chase-Dunn, Christopher; Hiroko Inoue, Alexis Alvarez, Rebecca Alvarez, E. N. Anderson and Teresa Neal 2015, McNeil 2011).

between cities over land and trade routes. A model describing this process appeared in (Carneiro 1970), and a version by Chase-Dunn and Hall in 1996 is in figure 13 (The figure is also labeled 2 in the paper from which it is drawn.)[37]

Figure 13. The Iteration Model

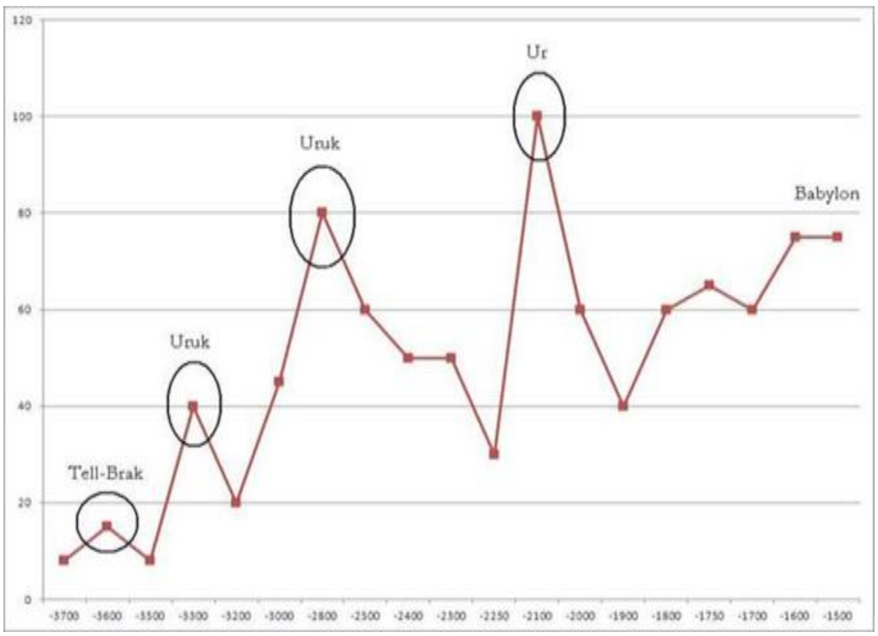


The "Iteration Model" in Figure 13 is ***essentially identical to the causal dynamics of the Cambrian: an autocatalytic cycle of self-amplification.*** It also resembles the cyclical causality of the origin of life (Virgo, Nathaniel; Takashi Ikegami, Simon McGregor 2016)**.** Starting from the top and moving clockwise through the model, we see that population growth intensifies the search for food, creating more population density, encouraging some to break out on their own while compelling others to become more tightly organized. Conflicts erupt between groups with greater frequency, promoting both social hierarchy and internal rebellions against it. Hierarchy and technology are mutually reinforcing, enabling further population growth. These processes replicate the Cambrian with one crucial difference: During the Cambrian, these changes were retarded because they happened within organisms via **genetic change**. Among humans **culture** compressed the process from millions of years to thousands.

[37] Environmental degradation is another important input to the cycle (Chase-Dunn, Christopher; Thomas Hall 2006).

Another parallel between the Cambrian and Neolithic periods was a growth in speciation (Cambrian); analogous to the growth of the division of labor within cities (Neolithic). The exponential growth of both are "outputs" generated by positive feed-back loops. In Figure 14 below, Chase-Dunn and colleagues have plotted the urban populations of the cities found near the mouth of the Tigris and Euphrates rivers mapped in Figure 12. It is a jagged line, a fractal echo of the growth of biomass during the Phanerozoic between extinctions.

Figure 14. Urban Population (In Thousands) Of The Earliest Cities Found Nearest The Mouths Of The Tigris And Euphrates, 3700 Bce –1500 Bce (Chase-Dunn Et. Al; 2014, Fig 2).



In Figure 15 below, the geographic size (in square mega meters) of the empires of the "Central Civilization" (basically the Mesopotamian, Egyptian, and Persian areas (Chase-Dunn 2015, Chase-Dunn, Christopher; Peter Grimes 1995)) is plotted, along with those of "East Asia" (China and surroundings). Hence there are two superimposed lines, one for each area. Imagine adding the two together into one combined line. Recall also that these lines omit the contemporary American states of the Yucatan, Central Mexico, and the Andes (collectively spanning 500 BCE to 1500 CE).[38] The cumulative result of including all known areas of conquest is another fractal echo of

[38] During its peak c. 14-1500 CE, the Incan empire alone is estimated to have approximated that of Rome (Mann 2006). If included here, that additional area would have extended the time and added height to the outlier dominated by the Khanate in figure 15, while its Yucatan predecessors would have smoothed the sharp variations found in the graph between 200 and 1200 CE. If these American data had been included, the result would have been a smoother upward line until 1500 CE. But the plummet after 1500 would have remained, perhaps reflecting the plague in Europe and smallpox in the Americas, each perhaps worsened by the "Little Ice Age."

the Phanerozoic. All of these graphs are the life-outputs of the same self-amplifying causal loops of matter and energy identified by complexity theorists. The commonality of these loops reflects their common source in autocatalytic deviance amplification.

The Division of Labor and Hierachy Within Core Areas: The Ideology of Social Control and Centralization of Resources

Within the fertile core areas of Mesopotamia protected by armies, walls, and mutual defense treaties, the populations could continue to fish, farm, and cooperate with settled (hence "domesticated") herders to produce food with a varied diet. The land productivity continued to rise with irrigation, extending the nutritious water ever further from the river courses, augmented by the use of animals to pull ploughs or power irrigation. Abundant food fed not only armies when needed, but also craftsmen and women creating pots, clothing, and jewelry. Food created the capacity for a division of specialized labor, but this did not require a power hierarchy. At the daily village level of barter, trade, and neighborly negotiation, political power would only be invoked to resolve disputes. Otherwise the exchange of goods could have been among equals (Kohl, Philip L,; Rita P. Wright 1977).[39]

The informal culture governing these exchanges did not arise out of a vacuum. Instead it retained the shadowy echoes of kinship reciprocity handed down from the enormous history of small-band living.

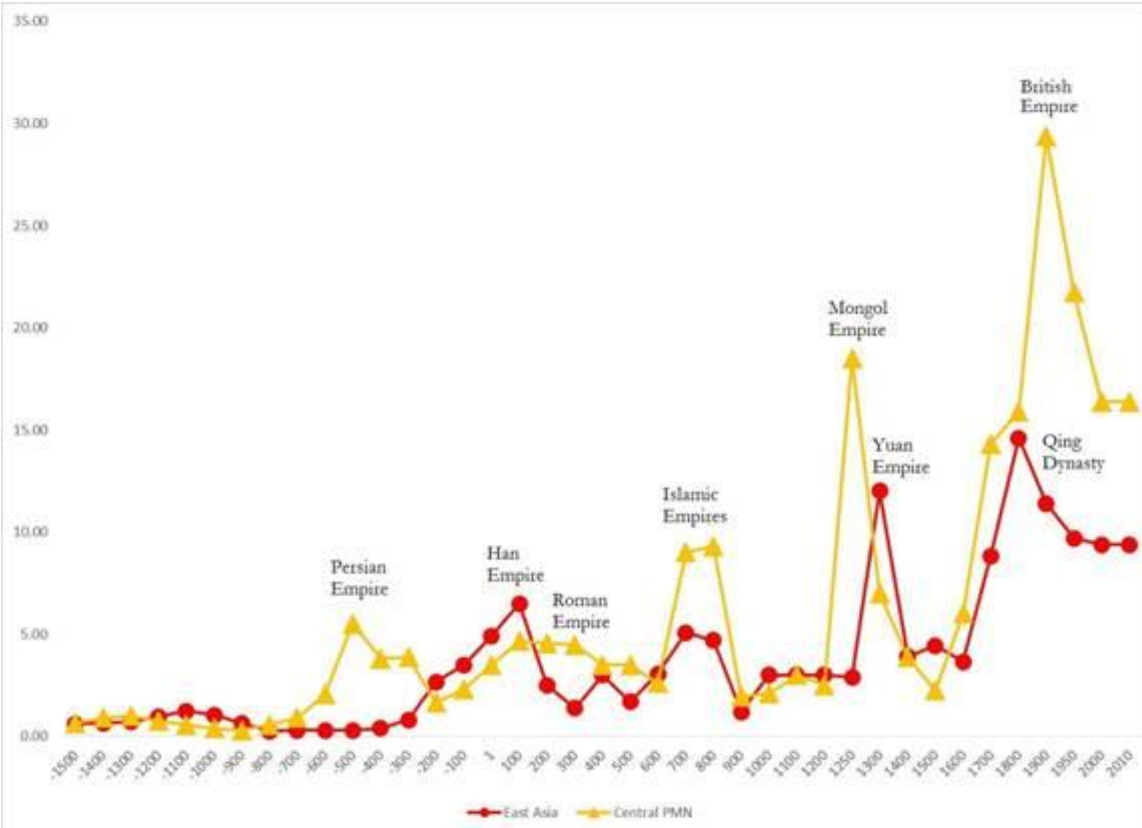
Reciprocal kinship ties would have provided a comfortable touch-stone legitimating all more distant ties.[40] So within settlements, kinship ties would have remained a foundational link, a unit allowing peaceful relations among adjacent villages. Disputes would have been resolved by respected elders.

An elder leading one village could have been acquainted with all, allowing individual "lobbying" by inhabitants, perpetuating at least the illusion of popular democracy and the morality of reciprocity. But a paramount chief responsible for a cluster of villages containing over 1,000 people—let alone 10,000--could not possibly have known them all, requiring the emergence of an ideology of legitimacy transcending personality and instead inhering in the office derived from religion.

[39] The caste hierarchy of India originated in the division of labor imposed on family trees. My point here is that divisions of labor do not *require* social hierarchies to function.

[40] Indeed it continues today as ritualized tributary gift exchange during holidays. This pattern is global, indicating its continued utility as a bonding ritual.

Figure 15. Eurasian Area Under State Control For 3.5 K Period 1.5k Bce—2.0k Ce (Figure 2 In Chase-Dunn Et. Al. 2015).



The Tributary System in the Pristine Cores: A Dissipative Structure

Weber's classic description of the transition from "charismatic" to "traditional" authority applies well to the gradual shift of authority which accompanied the increased complexity of human settlements from the Mesolithic to the Neolithic. Authority shifted from personal ties within one village to an individual or group of priests presiding over a population of multiple thousands. Another corollary development was the transformation of the reciprocal sharing of food and other necessities typical of bands and small villages into "gifts" expected by the gods (the "state") as ritualized expressions of gratitude. The frequency of these gifts, and their material forms as food or labor, became the acts of "tribute" giving the system its name.

The effect of these changes was to pass energy up and out of the villages via the village headman to the authorities in the ceremonial center, liberating them from direct labor. Yet once again, entropy via this parasitism necessarily contracted the amount of energy available across every transfer along each step to the top.[41] ***In this regard, society itself is a dissipative structure, like an ecosystem, with energy flowing from the plants to the farmers, thence via social layers to the most powerful.*** Even subtracting the necessary energy losses of entropy, the accumulation of a food surplus in the center allowed redistribution to craftsmen and warriors—or even back to the villages themselves during bad years. This system has had many variations, leading to scholarly debate over whether the flow of energy (via food or labor) was state administered, and/or bartered, and/or regulated by markets (Chase-Dunn et.al.; 2015; Smith 2004). I agree with Chase-Dunn that it was a combination that varied over scale and time. As today, kinship ties dominated at the "household" level. The parasitic flow of energy from mother to child during nursing is primordial and continues today, as do the social expectations of males to assist. But 6Kya, the definition of "household" was quite different, including perhaps an entire village, or at least dozens of individuals. Child-rearing was truly a social project, as were social instruction and sharing food. Reciprocity among kin continued as always at the village level, and most of the village were, in fact, kin (Zagarell 1986). The bulk transfer of energy as firewood, food, and labor to the centers of regional administration was likely perceived much like a "tithe" in churches today – an act of self-sacrifice to the gods, who were theological symbols of the common good. The accumulated energy from food, fuel, and labor indirectly (via the ruler) fed the families with specialized skills living in urban centers, families who in turn were creating items for village distribution. The energy created by the farmers and delivered to the manufacturing centers returned to their village origins as useful household goods, minus production and administration "costs" (military and priesthood).

The trade in bulk goods required for survival imposed practical limits on the geographic size of the exchange, forming a geographically close-knit economy (Chase-Dunn et. al.; 2015). Urban craftsmen also produced jewelry and other culturally valued scarce items for the king, enabling him to send some of them as goodwill gifts to neighboring kingdoms. These "prestige goods" were a form of diplomacy, covering a much larger area of political-military alliances. Recently, obsidian arrowheads from southern Mexico were unearthed in the Cahokia mounds near modern St. Louis, and copper from mines near Lake Superior was found in ancient pre-Columbian settlements surrounding the Chesapeake Bay (Mann 2006, Chase-Dunn, Christopher; and Bruce Lerro 2014, 111). Hence Chase-Dunn proposes an early model for the first multi-state "systems" with three concentric circles (Chase-Dunn, Christopher; and Bruce Lerro 2014, 20-21). The inmost circle is the area within the range of bulk goods transport of daily requirements; the second is the realm of overlapping power with adjacent states where shifting alliances and warfare occurred; while the largest circle overlaps with other "world-systems" centers connected by the exchange of

[41] Therefore, the social distribution of power and wealth is always pyramidal. Political stability is presumably related to the ratio between pyramid height and the area of its base.

diplomatic prestige goods. The realm of diplomacy and geopolitics enclosed the known "world-system" of that region into one "Political-Military-Network."

So the pristine states emerging in the most favorable areas during the Neolithic were built in cultural layers forming a dissipative structure. The first layer was village-level kinship obligations; the second, religiously mandated tribute supporting urban centers; and the third, the exchange of prestige goods for cross-polity diplomacy. So we have now come full circle, following the iteration model in Figure 27 above, as illustrated by Sumer. The very success of kinship reciprocity which enabled peaceful relations and tied many villages together unintentionally allowed (1) the emergence of a paramount chief➔chiefdom➔kingdom; (2) indirectly, the sweeping up of shamans into official priests employed by the state; and (3) a tribute requirement compelling farmers to support craft workers. The ultimate result was the creation of a powerful (social) dissipative structure with enough energy to spawn a division of labor like daughter tornados. It was a new form—a new complex structure—of self-organization emerging from the same dynamics that had produced life itself.

The self-amplification of the causal feed-back of the Cambrian has never stopped, despite mass extinctions. It continues to generate new life forms finding new niches. The same is true of its human form as exemplified in the "iteration model." It continues to produce new social formations today, generating the current global economy and the potential emergence of a global state (Chase-Dunn, Christopher and Hiroko Inoue 2012, Chase-Dunn, Christopher; and Kirk Lawrence 2011a, Chase-dunn, Christoper; and Kirk Lawrence 2011b).

Population pressure among the pristine states of Mesopotamia, Egypt, China, and India (Chase-Dunn, Christopher; Peter Grimes 1995)—collectively the first core areas of multi-state "world"-systems—found their leaders tempted or compelled to expand their areas. At the very least, expansion could increase the agricultural land they could draw from. Their well-fed armies could conquer ever-more distant areas. When successful, the newly conquered peoples had their own histories, ethnicities, and deities; making their enslavement more palatable. Slavery was endemic to conquest and an additional reward of new energy to the structure, allowing slave labor to be used for the construction of monuments like the pyramids of Egypt or, more practically, for mining and farming.[42] The code of Hammurabi has long sections addressing the treatment of slaves and the punishment for mistreatment, and these sections clearly imply that slaves were quasi-commodities subject to both sale and inheritance. The capacity for manumission and for

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[42] The peoples that could be enslaved were governed by a theology used to discriminate between "us" and "them," a theology that evolved in response to the increasing frequency of contacts with the "other" peoples enslaved and the realization of their common humanity. That recognition of common humanity broadened the theological concept of "us" and contracted the category of the "other," ultimately increasing the areas off-limits to slavery ("No Slaving Zones") and increasing the raids on the shrinking areas where slavery was permitted, such as the savage chiefdoms of northern Europe, the Balkans, and horticultural Africa, as brilliantly documented by (Fynn-Paul 2009).

anyone to be enslaved created the first true multi-ethnic empires: states large enough to encompass peoples of many ethnicities/cultures, indirectly promoting equal inclusiveness for religions (Fynn-Paul 2009).

Nearer the centers were the peoples of the semiperiphery. These were tribes living outside of core state control but aware of their existence. Their interactions would have perhaps begun as conflicts like those described above between pastoralists and horticulturalists. But over several millennia, conflicts would have fallen in frequency as the victories of the settled armies became increasingly assured. Their environment in the hills and mountains supported herding, but lacked the fertility necessary for agriculture, making their lands less attractive to core conquest. But those same rough conditions also made their lives dependent on a keen awareness of their environment, along with a skill with weapons that could be deployed in an instant. Their contacts with the initial cores were mutually useful trade (and occasional raids), exposing them to the latest technologies, beliefs, and prestige goods. The combination of their precarious lives with core technologies formed a perfect cauldron of creative innovation, enabling them to apply core technologies in unintended "off-brand" ways. One by-product was the development of novel weapons and military tactics. Chase-Dunn's team has discovered that about 50% of imperial expansion originated from the ***semiperiphery*** (Inoue, Hiroko; Alexis Álvarez, E.N. Anderson, Kirk Lawrence, Teresa Neal, Dmytro Khutkyy, Sandor Nagy, Walter DeWinter and Christopher Chase-Dunn 2016). While these geographical expansions were impressive in speed and size, they merely accelerated the land area under state control.[43]

The Semiperiphery and Capitalism

Another important contribution from the semiperiphery was its creation of city-states governed by capitalists. Capitalism itself emerged within the tributary mode, but was always carefully controlled lest it provided a source of revenue and power separated from state control. Initially, the prestige goods of diplomacy and symbolic communication could be acquired by semiperipheral nomadic peoples via negotiation with the core and then passed along as attractive small objects. Their proud recipients could display them as symbols of rank to their brethren, increasing their geographic demand.[44] News of this demand would trickle back to the producers and motivate more production. Complexity theorists have called this positive loop a "bucket brigade" and have

[43] It was this dance between intimidation and popular support that compelled the evolution of the state from a fearsome parasite to its modern form as the provider of last resort, a power with a "monopoly on the use of ***legitimate*** violence." The slogan of the United States Postal Service originated in the Persian Empire.

[44] This is how copper from Lake Superior found its way to the Chesapeake, and obsidian to the Mississippi.

observed it in life at all levels from the cell up (Holland 2014). As long as every member of the "brigade" is rewarded with more energy along the path, the path will expand in width and length and the original producers will differentiate and multiply.[45] The traders became the long-haul truckers of the ancient world. They were tolerated as transient migrants across the territories of the tributary states they traversed, both because their goods were useful and also because they themselves paid "tribute" for the crossing. It was in this fashion that the camel caravans of the Sahara emerged, as well as the "Silk Road." (Abu-Lughad 1989).

Trade itself gave birth to merchant capitalism, sometimes even production capitalism as well, especially along the relatively safe (from robbers) seafaring routes—another form of niche "pioneering." Chase-Dunn (2015) argues that merchant capitalists with full state power may have first emerged in the city of Dilmun (in modern-day Bahrain) during the Assyrian empire, and has sporadically re-emerged ever since, within politically independent island or port niches outside of tributary state control.[46]

The eventual displacement of the tributary mode by capitalism has not changed the fact that ***social structures at all scales are dissipative***; but it has completely re-arranged the social organization of energy flow creating that dissipative structure, and that on a global level that has come to envelope us all. Trade started with prestige goods and, with seafaring, shifted to bulk goods. As it did so, the goods traded went from luxuries to necessities. Even the Phoenicians were loading tin ore from Cornwall in today's England to be off-loaded in Egypt. Tin was then a strategic raw material for bronze weapons. When the Western Roman Empire collapsed, the population dropped, reflecting the necessity of trade for survival. By no later than 1700 CE, the entire planet was involved in mutual trade, and the depression of the 1930s was itself both marked and caused by a collapse in international trade. Trade has become the means of energy distribution on a planetary scale, a true circulation system.

Conclusion

Chase-Dunn's work took the concepts of core, semiperiphery, and periphery from Wallerstein's explanation of the early European inter-state system of capitalist imperialism. He then carried these concepts back in time to help us understand the emergence of the first urban centers. Complexity theory allows us to extend that backward push to the origins of life itself and even before, by

[45] One non-social example is the growth of neuronal pathways in the brain as it learns: neurons receive blood as needed, and more firing means more blood, while those not firing at all die. So the logic expanding neuronal pathways re-appears in the reinforcement of trade routes

[46] Phoenicians 3-2.5 Kya (Chase-Dunn, Christopher, E.N. Anderson, Hiroko Inoue, and Alexis Alvarez 2015), Venetians and Genoese c. 1400 CE.

identifying the common dynamics unifying all dissipative structures and demonstrating that social organization is merely another form of complexity bound by the same rules. Complex structures cannot be precisely predicted because their forms are so sensitive to their shifting environments and histories. But all generate additional structures creating greater complexity when supplied with more energy, and all simplify when energy is withdrawn. Complexity theory alerts us to the fact that social reorganization is a form of phase-change, and phase-changes (like boiling water) require ever-increasing energy inputs to breach their critical levels. Hence Chase-Dunn's vision of a global state is unlikely (Chase-Dunn, Christopher; and Kirk Lawrence 2011a, Chase-dunn, Christoper; and Kirk Lawrence 2011b), because more energy is either lethal (fossil fuels, nuclear fission) or inadequate (solar). Humans have shifted energy sources with increasing frequency with population, enabling an intricate global division of labor and competing centers of accumulation, each protected by an energy-expensive military shell. Current global violence indicates that humanity is facing another bifurcation, while complexity theory allows us to see the continuity between past bifurcations since the emergence of life itself and the current one generating the 6th mass extinction. All share in common an imbalance between self-amplifying cycles of exponential deviance versus compensatory mechanisms of dissipative energy release. Even without global warming, entropy alone mandates that increasing energy inputs must create increasingly hot outputs. As with all life before us, our social complexity is capped by the fundamental laws of physics. This adds urgency to the need to integrate the sciences, and mine the promise of the principles of complexity. Our future as a species may depend on it.

About Author

Dr. Peter Grimes specializes in the Earth as a total system. As an undergraduate at the University of Michigan, he studied ecology and political economy. His M.A. at Michigan State University was on the political economy of global population growth. His second M.A. and PhD at Johns Hopkins (under the direction of Dr. Chris Chase-Dunn) were on the role of economic cycles in the shifts of global hegemony. During that period he was also co-PI on an NSF grant to study global warming. His recent work has been to merge the historical and physical sciences using the tools of complexity theory.

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Any conflicts of interest are reported in the acknowledge section of the article's text. Otherwise, author has indicated that she has no conflict of interests upon submission of the article to the journal.

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