

Advanced Track, Epoch 1

Particle Evolution

This Advanced Track provides a technical supplement to the introductory web site on cosmic evolution, produced by Eric Chaisson and based on courses taught mainly at Harvard University for the past few decades:

http://www.cfa.harvard.edu/~ejchaisson/cosmic_evolution/docs/splash.html

Currently, this Advanced Track is abbreviated while addressing mainly the concept of energy rate density—a numerical quantity proposed as a useful complexity metric for an underlying, unifying process that guides the origin, evolution, and destiny of all organized systems across the arrow of time, from big bang to humankind. In the summer of 2014, this supplement will grow dramatically, providing much more pertinent technical material at an advanced, quantitative level (suitable for colleague scientists and graduate students) well beyond that presented in the above-linked introductory web site (which is meant for non-scientists and beginning students).

A summary of this Advanced Track is here:

http://www.cfa.harvard.edu/~ejchaisson/advanced_track_sitesum.pdf

Further material related to the subject of cosmic evolution is available at:

<http://www.cfa.harvard.edu/~ejchaisson>

including a collection of recent research papers easily accessed and downloadable at:

http://www.cfa.harvard.edu/~ejchaisson/current_research.pdf

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Cosmic Evolution

Particle evolution is a subset of the larger category of physical evolution, which is itself part of the grand scenario of cosmic evolution:

Cosmic evolution = **physical evolution** + biological evolution + cultural evolution.

During this first, particle epoch, energy rate density, $\Phi_m \approx 0$ erg/s/g for complex systems, largely because no ordered, organized systems had yet emerged in the early Universe.

Thermodynamic Time

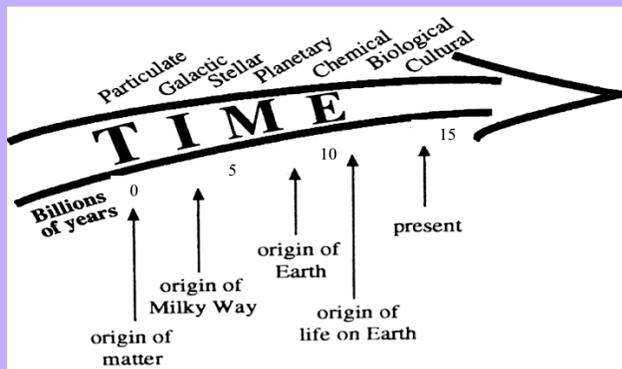
Unlike events in classical, deterministic (Newtonian) physics, which are time-independent, reversible, and ahistorical, in evolutionary models the past histories of systems contribute to their subsequent properties. Expressed thermodynamically, time moves in whatever way entropy increases: "Entropy is time's arrow," said Eddington.

The arrow of time is manifest in:

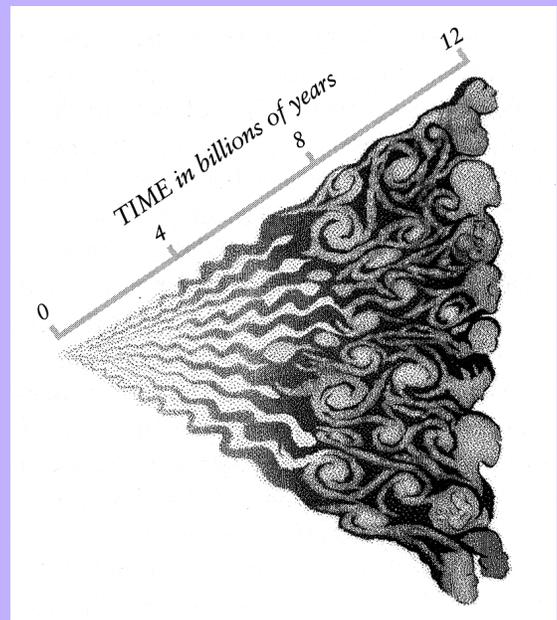
- expansion of the Universe; galaxy recession and the cosmic background radiation imply earlier times when the cosmos was hotter and denser
- fossil record; old rocks harbor fossils of simple life whereas younger rocks show more complex remains
- structure of stars and planets; stars develop greater thermal and chemical gradients from core to surface, and some moon's uneroded, cratered surface yield a history of their past
- irreversibility of some sub-microscopic events; proton-proton collisions produce neutral kaons (K^0), which then in microseconds decay into antikaons, $K^0 \rightarrow \bar{K}^0$, yet when the opposite, time-

reversed process occurs, $K^0 \rightarrow K^0$, it does so with nearly 1% less probability, implying that time is asymmetric, *ie*, has a preferred direction.

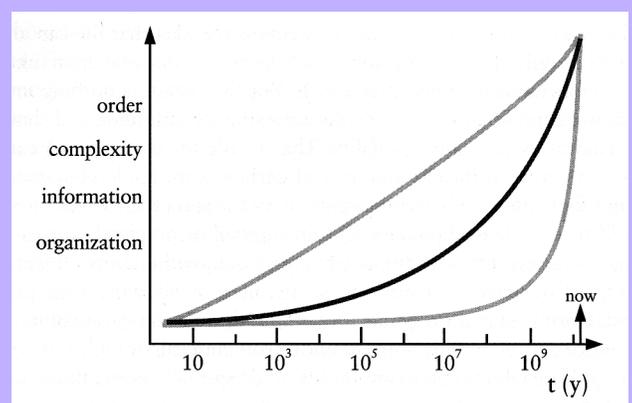
The three figures on the next page and their long captions encapsulate the essence of this web site—namely, set the stage for a research agenda suggesting how, over the course of billions of years, complexity has gradually arisen from big bang to humankind—including, in turn, galaxies, stars, planets, life, and society—at least on one planet in the known Universe.



An arrow of time usefully highlights salient features of cosmic history, from the beginning of the Universe to the present, ~14 Gy. Sketched diagonally along the top are major evolutionary phases that have produced, in turn, increasing amounts of order and complexity among all material things. Cosmic evolution encompasses all of these 7 epochs. Time is assumed to flow linearly and irreversibly unfolding at a steady pace, much as other central tenets are presumed, such as the fixed character of physical law or the notion that $2 + 2 = 4$ everywhere. Despite its implication of "time marching on," the arrow is neither deterministic nor progressive. Much as for its most celebrated component—neo-Darwinism—the twin agents of chance and necessity meander throughout all aspects of the cosmic-evolutionary scenario, whose temporal "arrow" hereby represents a convenient symbolic guide to natural history's many varied changes. While we cannot predict where the arrow of time might be headed in the future, we can attempt to describe how it came to be in the past.



Time's arrow is not anthropocentric; it points not at us. We humans are neither likely the pinnacle, nor surely the end product, of the cosmic-evolutionary scenario. The shape of this figure—a more artistic, less diagrammatic "arrow" than the previous one—suggests that the number and diversity of structures have increased with time, yet without any resemblance to classical evolutionary trees having main trunks and offshoot branches. Whatever measure of complexity is used, it is hard to avoid the notion that systems—whether galactic clouds, slimy invertebrates, luxury automobiles, or the whole Universe itself—have generally become more intrinsically intricate and more energy-rich throughout the course of history.



Sketched here is the rise of order, form, structure, complexity, organization, information, inhomogeneity, clumpiness—or whatever broadly synonymous term one wants to use qualitatively to describe the development and evolution of localized material assemblages—"systems" throughout the history of the Universe.

(Note that the horizontal, temporal scale is logarithmic, in contrast to the linear scales of the above two figures, a change better able to illustrate certain details as this web site unfolds; time is still assumed to flow linearly.) That the complexity of ordered structures has generally increased over the course of time is well-recognized, albeit difficult to understand and even harder to measure. The bold curve drawn here represents an innate feeling for steeply rising complexity within and among systems in relatively recent times, although that rise might have been more gradual (even linear) or more exponential (even hyperbolic), as also drawn in lighter gray. Our main task in this web site is to justify the general trend of rising complexity in Nature, to specify this rising curve more quantitatively, and to do so empirically with modern scientific principles. We are especially keen to explain how "islands" of complexity have so dramatically emerged over the course of the past ~500 My since the Cambrian "explosion," which represents only the past few percent of the total, ~14-Gy age of the Universe.

Equilibrium Thermodynamics

Four laws of thermodynamics were developed during the 19th and early 20th century, although many researchers consider that the zeroth and third laws follow directly from the first and second laws, thus that there are really only two fundamental laws of thermodynamics.

Zeroth law: No heat flows between any two bodies at the same temperature, T.

First law: Energy, E, is conserved—the sum of all energy is constant for all time, and can be neither created nor destroyed. Energy can change its type (*ie*, quality), but not its total magnitude (quantity).

Second law: Entropy, S, rises steadfastly, and many different ways can express it (among >two dozen ways of stating it over the past ~150 y):

- energy flows spontaneously from hot to cold, and not the reverse; real systems in Nature are irreversible
- it is impossible to transfer heat, Q, from a colder to a hotter object without any other net change in the Universe
- it is impossible to convert heat in a single heat reservoir into work without any other net change in the Universe
- a device operating in a cycle between two heat reservoirs at T_1 and T_2 (where $T_1 > T_2$) can convert heat from the hot reservoir into work with efficiency $\eta \leq 1 - T_2/T_1$

- any system, when left to itself, proceeds toward a state of higher thermodynamic probability (disorder)
- isolated systems in particular, as well as the Universe generally, proceed toward a state of higher thermodynamic disorder
- energy naturally disperses from locally concentrated states to more widely diffused states if nothing prevents it; thus, change in S is a measure of E dispersal.

Third law: At $T = 0$ K, all thermal motion ceases (though quantum-mechanical vibrations continue).

Numerically, the change in entropy, dS, varies directly as the heat exchanged (or energy dispersed), dQ, between two systems, and indirectly as temperature, T, at which the change occurs:

$$dS = dQ / T,$$

or, stated another way, entropy is the amount of heat exchanged from one part of the Universe to another divided by the temperature at which that change occurs—that is, usually, energy dispersed from a system to its surroundings, divided by T.

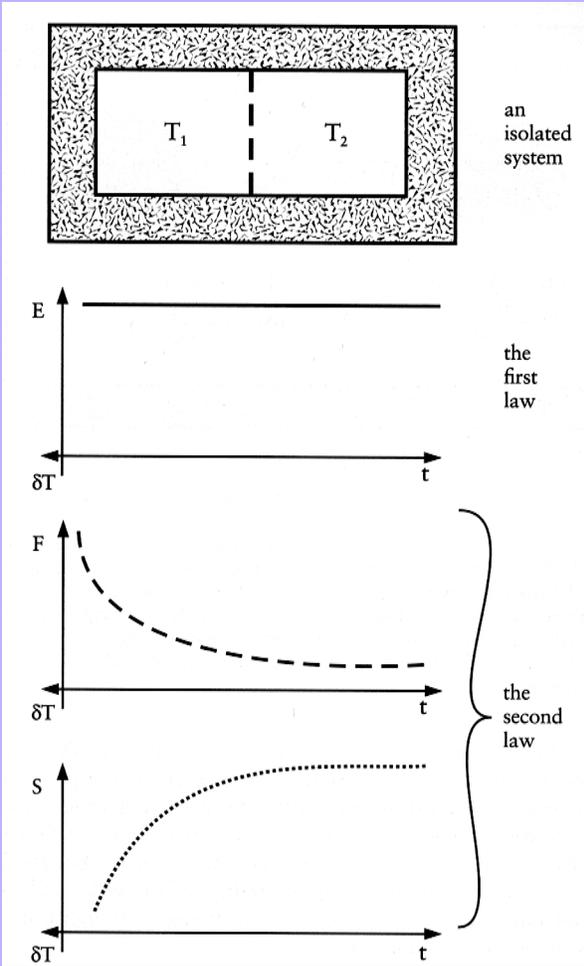
Yet another way to express the 2nd law is this: For realistic (*ie*, irreversible) events, total entropy increases, since with each such process less energy is available to do something useful. In symbolic form,

$$E = F + TS,$$

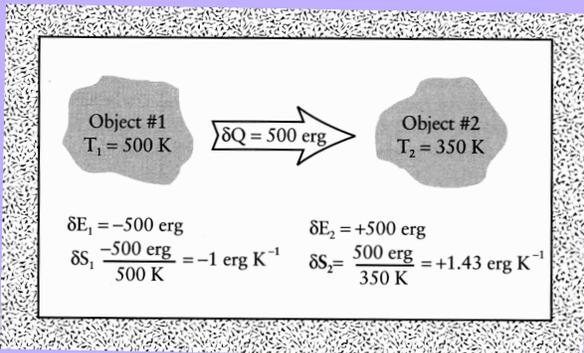
and stressing differences (hence the d) since the key to any process is the change in a system's state,

$$dE = dF + TdS + SdT,$$

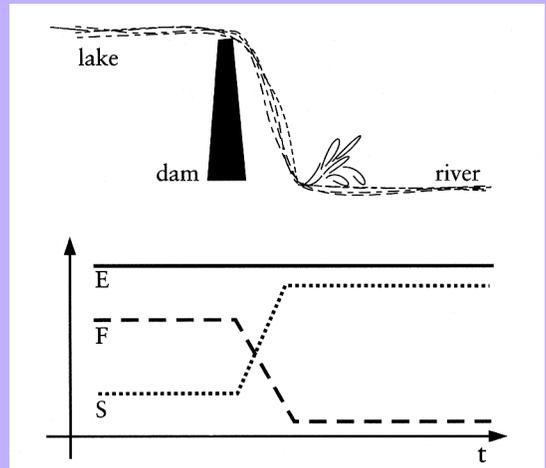
where E is the total internal energy of the system and F is its free energy available to do work. Hence for a fixed E and a given T (*ie*, $dT = 0$), if F decreases then S must increase. The three figures below depict these ideas graphically and give a numerical example.



The essence of classical, irreversible thermodynamics is graphed in the above figure: In a system isolated from the outside world, heat within a gas of temperature, T_2 , will flow in time, t , toward a gas of temperature, T_1 , where $T_2 > T_1$ and $dT = T_2 - T_1$, thus conserving the system's total energy, E (via the 1st law of thermodynamics), all the while its free energy, F , decreases and its entropy, S , rises (via the 2nd law).



Energy and entropy changes computed for the case of an isolated system wherein 500 ergs of thermal energy (dQ) flow from a 500 K object to a 350 K object. This amount of heat transferred is so small that it hardly affects the temperature of either object. Net energy is conserved, $dE_{total} = 0 \text{ erg}$, in accord with the 1st law of thermodynamics; net entropy increases, $dS_{total} = +0.43 \text{ erg/K}$, in accord with the 2nd law. In sum, the entropy increase of the cooler object exceeds the entropy decrease of the warmer object.



Another familiar example of irreversible energy change is the case of water falling over a dam into a basin below. As water flows over the dam, gravitational potential energy (or free energy, F , dashed line) can be converted into other types of energy, such as electrical or mechanical. In the process, as time, t , advances, F decreases (mimicking the water's drop), the system's total energy, E , (solid line), remains the same, and the entropy, S (dotted line), increases.

Isolated systems are cut off from their surrounding environments and thus no new energy or matter flows in or out. In such systems, E states always tend to even out, that is, achieve equilibrium. In the examples noted above—gas diffusing within a bounded container, water flowing into a river basin, as well as others such as heat spreading along a metal bar—equilibrium is the end product. That's the central meaning of the celebrated 2nd law: Nature abhors differences while striving to eliminate inequalities, eventually attaining uniformities in the distribution of matter and energy, and thus achieving a maximum- S configuration, S_{max} , for any unconstrained system.

The equilibrium state characterizing any isolated system is therefore a condition of S_{max} —a stable state

where E can no longer perform useful work. In short, equilibrium is best described by an absolute minimum of free E and a consequent maximization of S. Interestingly enough, only in equilibrium can we not distinguish past from future, for in such a uniform state change has no direction, no meaning; the concept of irreversibility itself ceases at equilibrium.

Early Universe Equilibrium in the Particle Epoch

That the early Universe was in thermal equilibrium can be shown by comparing the expansion time of the cosmic matter with the typical time for interaction among particles comprising that matter.

Assuming that gravity is the controlling force early on, Newton's laws prevail. Thus, the acceleration, a , of a particle of mass, m , in response to a force, F , acting over a distance, r , is:

$$a = F/m = GM/r^2 \approx G\rho r.$$

Also, from Newtonian physics, $r \sim at^2$, so that

$$a = G\rho at^2,$$

or therefore,

$$t_{\text{exp}} = (G\rho)^{-0.5} \propto n^{-0.5},$$

where n is the number density of particles in the expanding fireball.

Contrast this with the timescale for interaction of the particles among one another and with radiation, where ℓ is the mean free path and s the collision cross section:

$$\ell = (n\sigma)^{-1} \propto n^{-1}.$$

Therefore, $\ell/t_{\text{exp}} \sim n^{-0.5}$, which $\rightarrow 0$ for large number densities in the early Universe. And if $t_{\text{exp}} > \ell$, then surely $ct_{\text{exp}} \gg \ell$, thus the mean free path for interactions \ll radius of the Universe at the time.

All of this is a mathematical way of stating that the particle epoch was uniform, equilibrated, and boring—which is why we shall see below that then the energy rate density, $\Phi_m \approx 0$ erg/s/g. The early Universe was characterized by no ordered structures, organized systems, or any appreciable complexity.

Even so, there is plenty more to say here, especially as an introduction to non-equilibrium thermodynamics of systems that are open to their environments and thus occasionally receptive to energy flowing in from the outside. It is such energy flows that apparently create, or help to create, complexity in the Universe, indeed increasingly so with the march of time.

Statistical Principles and Entropy

Given that the element of chance has *some* role to play in all natural events, only when vast numbers are involved do events begin to show average patterns

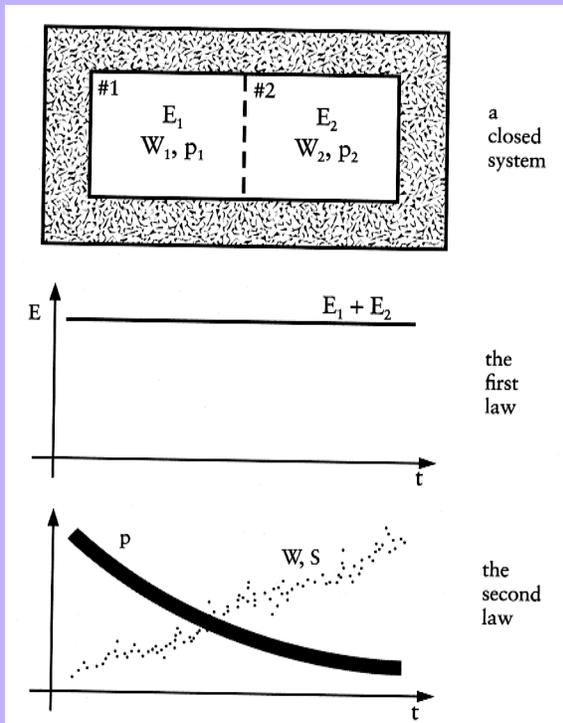
consistent with terrestrially familiar behavior of matter in the macrocosm. In this way, we can understand how random processes yield unpredictable order, though only when working with large numbers and repeated trials—much as probability theory can elaborately predict the results of tossing numerous pairs of dice. Even so, a price is paid: Whenever a system is represented by an average, some information is inevitably lost about the details of the system. As a measure of the information lost when working with averages, it is customary to specify the number of individual cases used to determine a particular average.

These statements can be clarified by invoking the modern, probabilistic subject of *statistical* mechanics, which supplements classical, mechanistic physics of old. Introduced in the late 19th century by Boltzmann and Gibbs, statistical mechanics employs large aggregates of particles to represent thermodynamic concepts. Of paramount import, in 1877, Boltzmann proposed his famous entropy formula (a version of which is engraved on his gravestone in Vienna),

$$S = k_B \ell n W.$$

Here, k_B is Boltzmann's constant, ℓn the natural logarithm to base e , and W the number of different arrangements of microscopic states, or "complexions"—positions, velocities, compositions, in addition to various quantum properties—of the individual parts comprising a given macroscopic system.

As an illustrative example, imagine two bodies (1 and 2) in contact, as shown in the figure below. Assume further that both bodies are immersed in a perfectly insulating container, so they can exchange heat—but only heat, no matter. At any instant, each body will have some energy, E_1 and E_2 , and the first law of thermodynamics demands that the sum of these two energies, $E_1 + E_2$, is constant at all times. Still, at any one time, there will be W_1 states of the microscopic entities comprising Body 1 and likewise W_2 microscopic states for Body 2; here W_1 is a function of E_1 , and W_2 a function of E_2 . The total number of states for the *whole* system is then $W = W_1 \times W_2$, a multiplicative result since *each* state in Body 1 can be associated with *each* state in Body 2. The multiplicative nature of W , in contrast with the additive nature of E (or S), accounts for the logarithmic function in the above Boltzmann formula. It's not unlike the way betting odds are established at the racetrack; we know that our chance (probability) of picking a given horse to win *or* place is the sum of the individual odds, whereas our chance of picking two horses to win *and* place is their product.



A body of energy, E_1 , having W_1 microscopic states and a probability, p_1 , of the occurrence of an individual state, in contact with another body characterized by E_2 , W_2 , and p_2 , has a total system energy equal to the sum of the two energies, $E_1 + E_2$, but a total number of microscopic states equal to the product, $W_1 \times W_2$. Thus, the system's entropy, $S = k_B \ln W = -k_B \ln p$, can increase dramatically with microscopic disorder among those states. All this statistical reasoning accords well with the essence of the classical ideas noted elsewhere in this Advanced Track for the PARTICLE EPOCH, but here it is statistical reasoning, not strict determinism.

The role played by statistics can be further appreciated by recognizing that in any macroscopic system the number of microscopic states, W , essentially measures the inverse probability, p , of the occurrence of those states. That is, $p = W^{-1} = 1$ for a 100%, completely certain state. This is true because the most likely configuration of the particles in a system is the high-entropy state for which they are evenly mixed up or "disordered"; hence the probability is low for any particle to be in a specific microstate. Likewise, during a poker game, the likelihood of certain cards being involved in a desirable hand is high since the entropy of such a preferred or "ordered" set of cards is considered low. Regarding the two-body system described above, the most likely energy distribution is

that for which W is maximized, a condition realized when the temperatures of the two bodies are equal. Thus, we can rewrite the 2nd law of thermodynamics as

$$S = k_B \ln(1/p) = -k_B \ln p,$$

and interpret it in the following way: Any isolated system naturally tends toward an equilibrium state of minimum microscopic probability—namely, a uniformity of temperature, pressure, chemical composition, and so on. And since ordered molecular states (for example, where molecules in one part of the system have one property value, but those in the remaining part have another) are less probable than those of random or disordered states, Boltzmann's law then signifies that ordered states tend to degenerate into disordered ones. This law also explains why any material system's available (free) energy tends to diminish with time; useful energy is orderly (or high-grade) energy, whereas heat, associated with the random motions of large numbers of molecules, is usually disorderly energy. Therefore, the energy of an isolated system indeed remains constant but tends to become asymptotically less free to perform useful work as more of it changes into low-grade heat, thereby increasing the disorderliness of its component parts.

This is how the principle of increasing entropy has come to be regarded as a measure of the disorder of a system. The idea of increasing entropy has ceased to be an inviolable law of Nature; rather, it is a statistical law. Even in equilibrium thermodynamics, a reversal of the usual trend—toward a state of lower entropy—is no longer impossible but only highly improbable. For example, a portion of the water in a kettle atop a fire could (theoretically) freeze while the remainder boils, although this is so unlikely as to be considered impossible in our practical experience.

Thus, the static Newtonian view that treats (idealistically) all substances as stable, fixed, isolated components of matter has given way to the conception that all (realistic) phenomena are intrinsically unstable and share part of a dynamic flow. Much like Heraclitus of Greek antiquity, we no longer regard things as "fixed" or "being," or even that they "exist." Instead, everything in the Universe is "flowing," always in the act of "becoming." All entities—living and non-living alike—are permanently changing.

Now, since all things are made of matter and energy, both of which regularly change, we can conclude that the process of becoming is governed by the laws of thermodynamics. The 2nd law determines the *direction* in which matter and energy change (or flow), but it cannot determine the rate of that change.

In Nature such rates fluctuate, according to the way systems interact with their environments; even close to home, for this too is part of Nature, earthly events have accelerated in recent times owing to the cultural impact of human beings (*cf.* Advanced Track for CULTURAL EPOCH). There is nothing smooth about the ebb and flow of the becoming process. Change proceeds in jumps and spurts or, to use a fashionable term, borrowed from biological evolution, in an irregular, "punctuated" manner. Accordingly, the process of change is better characterized by non-equilibrium thermodynamics, and we use this relatively new discipline to simulate what *might* happen during any given event, what *might* result from any given change.

Technical Note on $S = k \ln W$: More generally, assuming that n microstates are not equally probable but have individual probabilities p_i , the entropy $S = -k \sum_{i=1}^n p_i \ln p_i$, where the p_i are positive numbers that sum to 1. Note also that when equal expectations exist, $p_i = 1/W$, and since the unconstrained sum over all configurations yields W total microstates, the general equation above reduces to the simplified form used elsewhere,

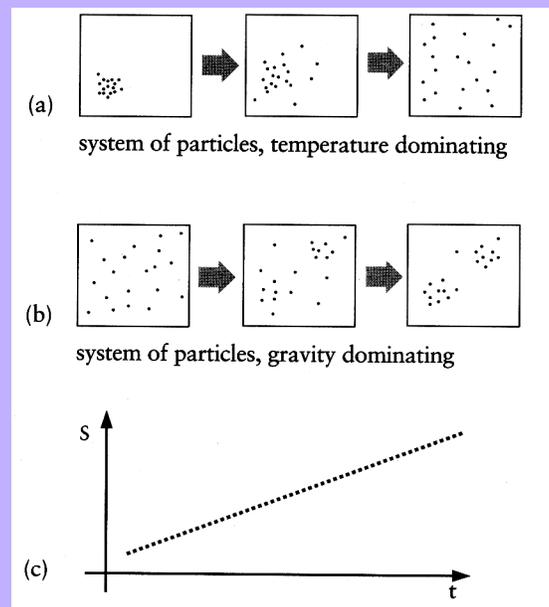
$$S = -k \sum W^{-1} \ln W^{-1} = -k \sum W^{-1} (\ln 1 - \ln W) = -k W W^{-1} (-\ln W) = k \ln W.$$

Gravitational Entropy

Most entropy considerations, as those above, are thermal or chemical in nature—*ie.*, the 2nd law's general trend toward temperature uniformity and chemical homogeneity. But there is entropy of gravity as well, especially for those massive systems dominated by gravitational interactions. At first notice, gravitational entropy behaves a little oddly, for gravity displays counter-thermodynamic tendencies. For example, as gravitating systems lose energy, they grow *hotter* owing to core contraction. The figure below provides some perspective (*cf.* Penrose, *The Emperor's New Mind*, Oxford Univ Pr, 1989; Saslaw & Hamilton, *Astrophys. J.*, v276, p13, 1984.)

Gravitational entropy is especially important in understanding how, in the early Universe, the primordial cosmic fireball began in a low-entropy state, despite its then-prevailing thermal and chemical equilibrium. Suffice it to say that, for an ordinary gas in a box, wherein gravitational effects are negligible, entropy increases impel the gas toward greater uniformity, namely less structure and more disorder. But for a system of gravitating bodies, the reverse is true, largely because of the unshielded, long-range, and

attractive nature of the gravitational force. In other words, a large ensemble of particles in the absence of gravity will tend to disperse, yet in the presence of gravity will tend to clump; either way, the net entropy increases. As implied by the figure below, entropy gains can be considerable when a massive cloud fragments and contracts into a planet, star, galaxy, or larger structure. Actually, the entropy increase occurs outside such ordered systems; the systems themselves lower their entropy by radiating it away into the surrounding space.



(a) Entropy, S , increases as ordinary gas disperses in a box having dimensions small enough for gravitational interactions to be neglected. (b) Among gravitating bodies on larger scales, entropy increases when the opposite occurs, namely, when diffuse gas clumps to form ordered structures. (c) For either case, the net entropy rises, but the details and resulting phenomena depend on scale.

The case of star formation will serve as a numerical example (*cf.* Advanced Track on STELLAR EPOCH). Like many ordered systems and processes among myriad complex structures in Nature, newly formed stars can be shown quantitatively to have lowered their S at the expense of their surrounding environment. Stars, too, are open systems, yet we can employ some of the same thermodynamic principles that chemists use to analyze gas dynamics or that engineers use for heat engines.

Consider, initially, a huge interstellar cloud of perhaps light-year dimensions, for all practical purposes structurally, chemically, and thermally homogeneous throughout. Such a system is virtually in steady-state equilibrium, its temperature, T , nearly uniform everywhere (~ 15 K), and its composition (mostly H) well mixed. With R_g (the ideal gas constant) = 8.3×10^7 erg/K/mole, C (the heat capacity/mole) = $3/2 R_g$ for a monatomic gas, and V , the volume of the cloud, the entropy/mass of such a tenuous cloud is adequately given by the ideal gas formula,

$$S = C \ln T + R_g \ln V .$$

Now suppose a gravitational instability occurs. This change might be triggered by the passage of a parent galaxy's spiral-density wave, by the concussion induced by a supernova explosion of a nearby star, or by any number of other events (even solely chance perturbations in density could do it) that cause the interstellar cloud to begin infalling. The cloud's gravitational PE is thereby converted to KE, half of which is radiated away and the other half retained as heat (as stipulated by the Virial Theorem of gravitational physics). That such a condensation results in a decrease in system entropy can be proved by calculating the entropy change per unit mass between the initial interstellar cloud and the finally formed star. This is δS_{sys} in our standard notation, the entropy change produced by irreversible processes within the stellar open system:

$$\delta S_{\text{star}} = \delta S_{\text{sys}} = \frac{3R}{2m} \ln(T_f/T_i) + \frac{R}{m} \ln(\rho_i/\rho_f) .$$

Here, m is molar mass of atomic H and we have used the fact that $V_f/V_i = \rho_i/\rho_f$, where the densities $\rho_i = 10^{-22}$ g/cm³ and $\rho_f = 1.5$ g/cm³. Substituting also for $T_i = 15$ K and $T_f = 10^7$ K, the minimum temperature needed for H fusion, we find a net reduction in S for the newly formed star:

$$\delta S_{\text{star}} = \delta S_{\text{sys}} \approx -2.5 \times 10^9 \text{ erg/g/K} .$$

According to the 2nd law, such an entropic decrease can occur only if there were an equivalent or larger increase in entropy elsewhere in the Universe. Computing the amount of entropy radiated away electromagnetically by the embryonic star, the increase in entropy of the surrounding interstellar environment per unit mass of material condensed is

$$\delta S_{\text{env}} = \delta Q/T = \delta U/M \langle T \rangle ,$$

where δU is the change in gravitational PE during the star-forming process, M is the total mass of the star, and $\langle T \rangle$ is the mean temperature at which radiation is released during the formative stage (namely, at which

the original gravitational PE is dissipated). With spherical symmetry assumed for the original galactic cloud and a radius, r , for the final star, the gravitational PE,

$$U = -G \int_0^M m/r \, dm \\ = -3GM^2/5r ,$$

half of which is lost (*ie*, $-1/2$) via radiative dissipation during the star-forming process. Finally, using typical solar values of $M = 2 \times 10^{33}$ g, $r = 7 \times 10^{10}$ cm, and $\langle T \rangle = 1000$ K as the mean effective radiating temperature during formation, we have

$$\delta S_{\text{env}} \approx +4 \times 10^{11} \text{ erg/g/K} .$$

Thus, the increase in entropy of the surrounding interstellar environment is more than a hundred times greater than the computed decrease in entropy of the newly structured star (and plenty to overcome any unreasonable estimates in the above calculations). Clearly, the star has become an ordered clump of matter at the considerable expense of the rest of the Universe. The order is generated by the long-range, attractive gravitational force; the disorder is generated by the conversion of gravitational to heat energy, much of which the protostar ejects into its surroundings. The net effect of the *entire transaction*—the star's open system plus the surrounding environment—is a demonstrable increase in entropy, in complete accord with the 2nd law of thermodynamics.

Entropy or energy; which is more basic?: A common mistake in interpreting entropy is to claim that disordered objects have more of it, or ordered systems less of it (Lambert, *J Chem Ed*, v79, p1241, 2002). Theoretically it's wrong to regard ordered or disordered systems as physically containing more of the quantity S ; and experimentally, it's impossible to measure S —have you ever seen an "entropymeter"? To many chemists especially, it's more correct to think of order and disorder in terms of energy, which does seem more basic than entropy—or at least more measurable. Highly entropic systems are ones that have highly, not matter that has become disorderly, as much as one that displays dispersed energy among its changing parts; it is energy that is actively altering things around within ordered and disordered states. Entropy change, dS , is really a measure of the extent of a system's energy dispersal. As we shall see below and throughout this research agenda, it is energy flow, not entropy decrease, that actively causes complexity to grow in Nature.

Non-equilibrium Thermodynamics

First, a few definitions that will help distinguish different kinds of systems:

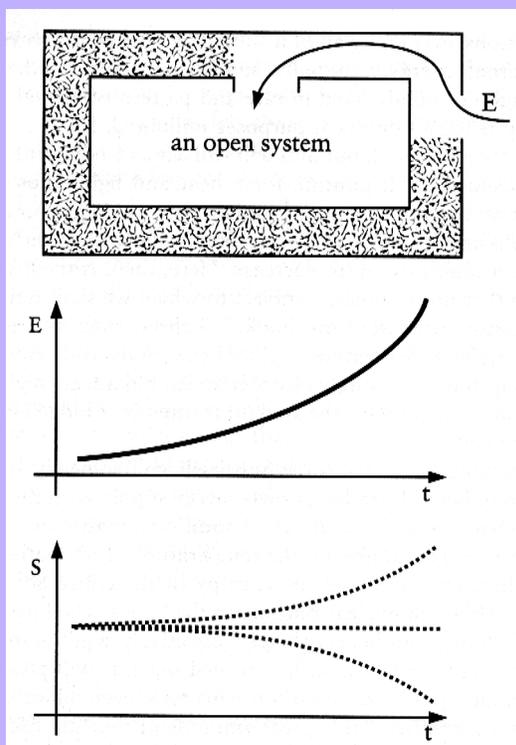
Isolated system: one totally divorced from its environment; no exchange of either matter or E.

Closed system: one able to exchange E, but not matter, with its environment.

Open system: one able to exchange both E and matter with its environment.

Earth is an open system, not in thermodynamic equilibrium. Matter and energy, especially sunlight, reach Earth's surface daily. As diagrammed in the figure below, the thermodynamics of open systems allow a system's entropy to remain constant or even to decrease. This is the gist of non-equilibrium thermodynamics: Localized, open systems can be sites of emergent order within a global (*ie*, universal) environment that is largely and increasingly disordered.

The 2nd law has universal applicability; there is no reason to suspect otherwise. Not merely dictating the evolution of Earth and Sun, the 2nd law is presumed to apply also to stars, galaxies, life, and everything, indeed to the Universe as a whole.



In an open system, energy (in the form of radiation or matter) can enter the system from the outside

environment, thereby increasing the system's total energy, E (and often its energy density), over the course of time, t. Such energy flow can lead to an increase, a decrease, or no net change in the entropy, S, of the system. Even so, the net entropy of the system and its environment still increases.

For open systems, then, the 2nd law must be reformulated. Specifically, we know recognize two contributions to the total entropy change of any event in Nature: One is the (normally positive) entropy production inside the system per se caused by irreversible events, such as lossy friction, chemical reactions, or heat conduction; the other is the (always positive) entropy production in the environment caused by exchanges between the system and the outside world. Symbolically, the total entropy change,

$$dS = dS_{\text{sys}} + dS_{\text{env}} \geq 0,$$

where dS_{sys} and dS_{env} are the entropy changes of the system itself and of its surrounding environment, respectively. Although no formal proof of this inequality exists (or is perhaps even possible), the absence of any experimental exceptions provides confidence of its widescale validity.

For a totally isolated system in which neither matter nor energy is exchanged with the external environment, $dS_{\text{env}} = 0$ and $dS > 0$ (save for the case of an ideal, reversible, and unrealistic process for which it is zero); the total entropy change is then uniquely determined by dS_{sys} , which necessarily grows as a realistic system performs work. By contrast, for an open system, the entropic change caused by environmental interaction is always positive ($dS_{\text{env}} > 0$), whereas the internal entropy change (dS_{sys}) can be either positive or negative (as graphed in the figure above). The sign of the internal contribution to the total entropy change is generally undetermined and depends on the quality and rate of the flow of energy across an open system's boundary. Provided that dS_{env} increases more than dS_{sys} decreases, the 2nd law is still obeyed because the total entropy change $dS > 0$, meaning that a system can become locally ordered at the expense of a global increase in entropy in the Universe beyond.

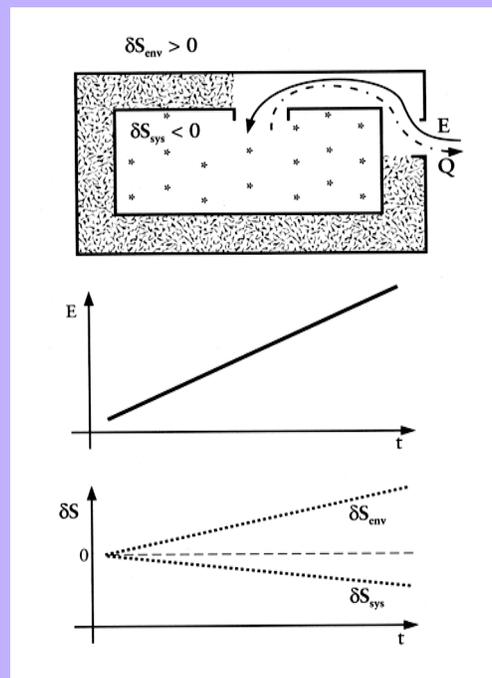
Accordingly, in principle at least, an open system can establish and sustain a negative entropy (or "negentropy") change in relation to its environment, and during the course of evolution may reach a state wherein its entropy has physically decreased to a smaller value than at the start. Note that this does not mean that the rate of entropy growth merely

becomes lessened or even reduced to zero. Under appropriate conditions, most notably an optimal energy flow, the entropy itself within open systems can actually be reduced, *ie*, $dS_{\text{sys}} < 0$. For such a non-equilibrium state, order can be achieved within a system by means of the spontaneous emergence of organization. However, such a rise in complexity is not, as is often stated, a kind of "self-organization," or "self-assembly." Rather, energy is always involved.

Furthermore, open systems can be prevented from reaching equilibrium by the regular introduction of fresh reactants and by the regular removal of waste products. Some such systems can be regulated to achieve a constant ratio of incoming reactants to outgoing products. The system then *appears* to be in equilibrium because this ratio does not change over time. But in contrast with true equilibrium (where entropy is maximized), this kind of process continually produces entropy and dissipates it into its surrounding environment. In this way, both order and entropy can actually increase together—the former locally and the latter globally (*cf*, Landsberg, *Phys Lett*, v102A, p171, 1984).

The phenomenon of refrigeration exemplifies the creation and maintenance of non-equilibrium order within an open system at the expense of increasing disorder outside that system. Imagine, as illustrated below, a container of water saturated with sugar. Normally, such a solution comprises a relatively random state, the water and sugar molecules freely able to move about, thus occupying a great many positions relative to one another. As the system cools, sugar crystals begin forming spontaneously, in the process becoming highly organized as individual molecules occupy rather exact positions in the emerging matrix comprising the crystal. Now displaying order, the newly formed crystals themselves necessarily possess lower entropy than the surrounding solution; the act of crystal formation actually decreases the entropy in certain localized parts of the system. To compensate, we should expect to find an increase in entropy somewhere else, but the solution itself is unlikely to have appreciably increased entropy since its temperature has also been lowered. We need to enlarge our view beyond the confines of the vessel housing the solution, for as the solution cools, heat flows to the surroundings beyond the container. Therefore, it is the air outside the system that must suffer an increase in entropy—which is exactly why an open refrigerator cannot be used to "air-condition" a kitchen in

midsummer; a refrigerator, while cooling its contents, in fact tends to warm the kitchen.



A refrigerated solution of sugar and water exemplifies how energy, E , entering the solution (for example, from an electrical outlet) can drive parts of the open system far from equilibrium, thus forming islands of ordered structures known as sugar crystals. The resulting expulsion of heat, Q , to the surrounding environment can cause a lowering of the system's entropy, dS_{sys} , all the while the entropy beyond the open system, dS_{env} , is increased; in fact, dS_{env} increases more than dS_{sys} decreases, keeping the total $dS > 0$, in accord with the 2nd law of thermodynamics.

Diverging Temperatures

Prior to decoupling at $t \approx 4 \times 10^5$ y after the big bang, when matter and radiation were still well mixed in the Radiation Era, $T \sim t^{-0.5}$. A single T at any time is sufficient to describe the early thermal history of the Universe, for the overgreat densities then produced so many collisions as to guarantee equilibrium. During this early cosmological era, disorder reigned supreme and the traditional form of S was maximized, but this is thermal and chemical S ; gravitational S (as noted in the previous section) was not at all high in the Radiation Era. The absence of any T gradients between radiation and matter dictated virtually nil macroscopic order, in the early Universe. As regards complexity, it apparently really was a boring time.

Once the Matter Era began, however, matter became atomic, the gas-energy equilibrium was destroyed, and a single T is no longer enough to specify the bulk evolution of the cosmos. Two temperatures are needed; one to describe radiation and another to describe matter. It so happens that the expression in the above paragraph for the variation of T with t is valid throughout all time for radiation, which is effectively an expanding relativistic gas consisting of pure photons. Recalling that the observed T is red shifted in precisely the same manner as is the frequency of an individual photon, and since $u \propto T^4$ and also $u \propto R^{-4}$ (where R is the cosmological scale factor), we can now rewrite

$$T_r \propto R^{-1},$$

or

$$T_r \approx 10^{10} t^{-0.5},$$

with T_r being the average "radiation T " at any time t , expressed in seconds.

By contrast, once (re)combined in the neutral state, matter cooled much faster and (at least for neutral H and He at $T < 4000$ K) obeyed the relation for a perfect, non-relativistic gas. For such an ideal gas, the equation of state, $PV = R_g T_m$; also for adiabatic ($dQ = 0$) expansion, $PV^{5/3} = \text{constant}$. Therefore, $T_m \propto V^{-2/3} \propto (R^3)^{-2/3}$, so that for $t > 4 \times 10^5$ y after the big bang,

$$T_m \propto R^{-2},$$

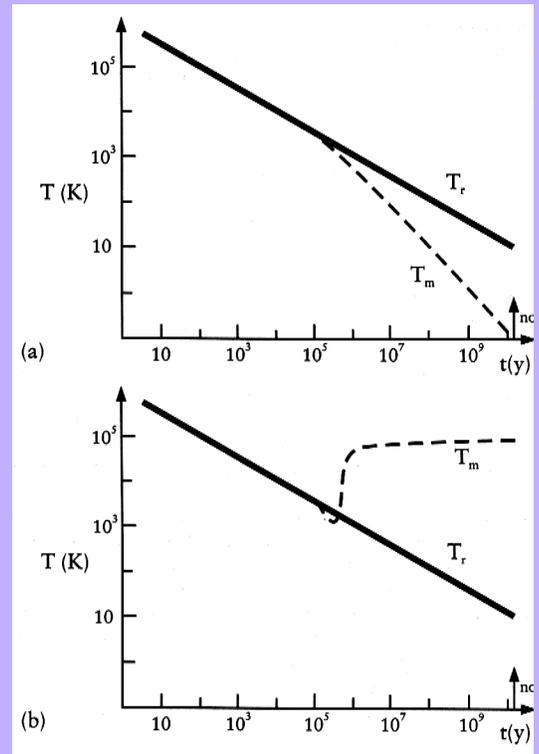
or,

$$T_m \approx 6 \times 10^{16} / t.$$

This does not imply a universal thermal distribution for neutral intergalactic matter akin to the detected cosmic microwave background (CMB); astronomers remain uncertain about the state of this loose dark matter. While T_r would have fallen by a factor of ~ 1500 between decoupling and the present epoch—from 4000 K to 2.7 K (as measured from the CMB)— T_m would have theoretically fallen far more, in fact by as much as a factor of a million. If so, T_m for intergalactic matter would now be only ~ 0.001 K, again an average T of all matter in bulk.

The figure below illustrates these diverging thermal histories as the Matter Era evolves. Much as for the steady decrease of T and matter density ρ_m , these temperature profiles refer to nothing in particular, rather everything in general—in this case, the widespread environmental conditions in the Universe after decoupling. The reason for matter's rapid cooling is that the exchange of energy between the radiation field (photons) and the gas particles (mainly H and He atoms) failed to keep pace with the rate of general expansion of the particles away from one another. The

equilibrating reaction rates ($\propto \rho_m$) fell below the cosmic expansion rate ($\propto \rho_m^{0.5}$) and non-equilibrium states emerged. Thus, once the grand symmetry between matter and radiation was broken, the thermal decline of matter exceeded, all the while its energy density decline lagged, the corresponding values of the radiation field—a curious result, yet one that enabled matter, in the main, to "build things."



The temperatures of matter and radiation went their separate ways once these quantities became fully decoupled at $t \approx 4 \times 10^5$ y. Since that time, the Universe has been in a non-equilibrium state. Frame (a) is the case of T_m decreasing monotonically since then, whereas frame (b) shows the possible dramatic reheating of loose intergalactic gas within a billion years after decoupling. Either way, whether the loose gas steadily cooled or rapidly heated, a definite T gradient developed between radiation and matter in the expanding Universe, a clear manifestation of non-equilibrium conditions prevailing throughout.

As implied by part (a) of the figure above, if other processes had not intervened, the present value of T_m would be very low, roughly 0.003 K. However, other events did occur, including the formation of galaxies, the release of cosmic rays, the emission of UV by stars, and the production of non-thermal radiation.

Unclustered intergalactic matter, in particular, likely suffered an alternative fate. Some theoretical studies imply that, within 10^9 y after decoupling, neutral intergalactic matter might have been reheated, and perhaps even reionized to the plasma state, by intense energy sources such as the primeval quasars (QSOs) blazing forth in their youth as well as UV radiation from the first generation of massive star clusters now mostly gone (*cf.* Advanced Track for STELLAR EPOCH). Circumstantial evidence favoring such a grand reheating derives mainly from the observation that highly red-shifted absorption lines toward distant QSOs are relatively metal-rich (though only $\sim 1\%$ that in the Sun today), and these heavy elements were likely produced inside an early population ("Pop-III") of massive stars. (Population-I stars are observed young stars that have formed in recent times, Pop-II those still observed but very old, and Pop-III a theorized class of stars that formed in the relatively early Universe and have already likely exploded as supernovae thus destroying any evidence of their own existence—in fact, no stars with zero heavy elements have ever been found—see Advanced Track for STELLAR EPOCH.)

The figure above shows how the run of T_m might have played out over time if this reheating did occur, as the overall average T_m rose again to some 10^4 - 10^5 K, comparable to nebular gas engulfing today's star-forming regions. Despite its great T, this loose intergalactic gas that never managed to accumulate into well-formed structures would now be invisible, owing to its extremely low density well beyond the galaxies and galaxy clusters— ρ on the order of at least 10^6 times thinner than the already near-vacuum gas of interstellar space within the galaxies, and less than that needed (in the form of dark matter) to close the Universe.

Even if loose neutral H did reionize at $z \approx 50$, T_m and T_r would never again be equalized (unless the Universe does someday collapse), ensuring the disequilibrium conditions presumably needed for the onset of order, flow, and complexity in the Universe. This intergalactic matter must have had an integral role regarding the origin of the galaxies early on, and even now might persist in the form of significant amounts of dark matter. In fact, however, only small amounts of true (beyond-galaxy-clusters) intergalactic matter have been observationally found to date, either directly as diffuse gas radiating in the $\lambda 21$ -cm radio band or indirectly as foreground-absorbing clouds (the "Lyman- α forest") in the optical spectra of highly red-shifted QSOs. The status, alas even the existence, of true intergalactic matter, now and throughout the history of the

Universe, remains unclear. At any rate, for the purposes of this work, its thermal behavior differs from that of photons, once decoupled at $z \approx 1500$; except for the first $\sim 4 \times 10^5$ y, matter and radiation have differed enough in average T to consider the entire Universe as a vast heat engine. It is the *existence* of a thermal gradient that counts most, whatever it cause.

Equally important is the idea that the difference between these 2 temperature fields would have grown as the cosmos, on average, departed gradually from its original equilibrium state. The establishment of a cosmic T gradient is the essential point. Such a thermal gradient is the patent signature of a heat engine, and it is this ever-widening gradient that has rendered environmental conditions suitable for the growth of complexity. The result is a grand flow of energy between the 2 diverging fields, and with it a concomitant availability of energy (for use in work) over and above that extant in the early, equilibrated Universe. Hence, the Matter Era has become increasingly unequilibrated over the course of time; the expansion of the Universe guarantees it. Such non-equilibrium states are suitable, indeed apparently necessary, for the emergence of structure, form, and organization—of order! Thus we reason that *cosmic expansion itself is the prime mover for the construction of a hierarchy of complex entities throughout the Universe.*

Information and Negentropy

The extent to which a system is ordered can be estimated by appealing to information theory; the more ordered a system, the greater the information content (or negentropy) it possesses. To be more specific, imagine a system that has a large number, B_i , of possible initial structural arrangements. Suppose, further, that after some information is finally received, the number of possible states of the system is reduced to B_f , so that $1 \leq B_f \leq B_i$; this is true because additional information about the state of the system is at hand, in particular information about its structure. Quantitatively, these statements can be expressed in terms of the net information transmitted, dI , which equals the difference between the initial and final informational states of the system:

$$dI = I_f - I_i = K \log (B_i/B_f).$$

Here, we apply the Shannon-Weaver formula stipulating that information depends inversely on the log of the probability distribution of states within a system; when B_f is small (after some information has

been received), dI is large, and conversely. Note that this equation increases as B_i increases and B_f decreases, that it maximizes for a given B_i when $B_f = 1$ and vanishes when $B_i = B_f$, and that it makes information received in independent cases additive. This agrees with human intuition and empirical findings.

The above relation for information exchange has an uncanny resemblance to that describing a change in S for a system having different numbers of microscopic states W before (i) and after (f) the change, to wit,

$$dS = S_f - S_i = k_B \ln(W_f/W_i).$$

Manipulating these 2 equations, we find an explicit connection between entropy and the net information exchanged,

$$dI = Kk_B^{-1}(S_i - S_f).$$

And since $S_i = S_{\max}$, because the initially large number of receivers (microstates) relates to the maximum entropy, the information gain of a system can be expressed as the difference between the system's maximum possible S and its actual S at any give time—namely,

$$I = Kk_B^{-1}(S_{\max} - S).$$

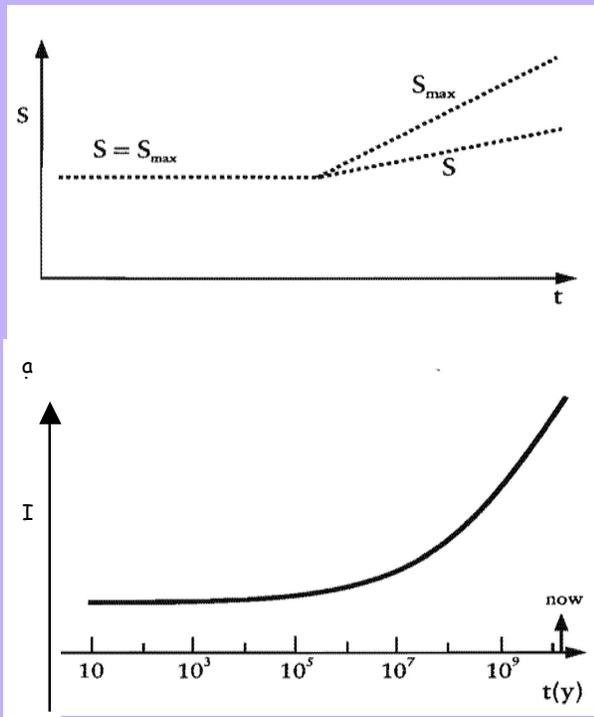
This is the origin of the well-known argument that order, information gain (+ dI), and negentropy (- dS) are intimately related. This is also consistent with the definition of order as an "absence of disorder," for the amount of order present in any system equals the size of the gap by which the actual randomness differs from the maximum possible randomness (Frautschi, *Science*, v217, p593, 1982; Brooks and Wiley, *Evolution as Entropy*, UChicago Pr, 1988; Layzer, in *Entropy, Information and Evolution*, Weber, et al (eds), MIT Pr, 1988).

Now we can apply these ideas to the central query of this research work: What is the source of order, form, and structure characterizing all material things? Recall the 2nd law, $dS = dQ/T$, meaning that for a given amount of heat transferred between two systems, S_{\max} will occur for minimum T ; for an evolving Universe, this is the system of matter characterized by T_m , just to take as an example the case in which the young Universe did not reheat during the early galaxy period. By contrast, a smaller, actual S will pertain to the system of radiation defined by T_r , which after the decoupling (or recombination) phase at $\sim 4 \times 10^5$ y, always exceeds T_m . Thus, by virtue of this finite T difference between matter and radiation, as well as the associated irreversible flow of energy from the radiation field to material objects, we obtain a quantitative estimate of the potential for information growth throughout cosmic history:

$$I = Kk_B^{-1}(T_m^{-1} - T_r^{-1}).$$

As asserted earlier, the necessary (though not necessarily sufficient) condition for the growth of I is guaranteed by the very expansion of the Universe. The Universe self-generates a thermal gradient, and increasingly so with time, suggestive of an ever-powerful heat engine were it not for its unfortunate mechanistic (or entirely deterministic) inference. To be sure, we emphasize the statistical nature of all these processes, meaning that the growth of order is not a foregone conclusion, nor is the Universe a machine. Thermodynamics tells us if events can occur, not whether they actually will occur. Likewise, this is *potential* information, realized only should Nature take advantage of the newly established conditions for the development of systems.

With the temporal functions for T_m and T_r known, the evolution of I can be tracked throughout cosmic history. The figure below sketches such an I - t diagram, as well as the evolution of negentropy from which it derives. Notice how I was essentially zero in the early Universe when matter and radiation were equilibrated; dS then was also zero, even as the Universe continued expanding. This is as it should be, for the early Universe would have experienced adiabatic expansion in the absence of any significant radiation sources; with $dQ = 0$, then $dS = 0$. After decoupling, however, the potential for the growth of I rose steadily as T_m and T_r diverged when the matter and radiation steadily departed from equilibrium; I has become substantial in recent times. Thus we confirm the seemingly paradoxical yet wholly significant result for the scenario of cosmic evolution: In an expanding Universe, both the disorder, S (globally]) and the order, I (locally), can increase simultaneously—a fundamental duality, strange but true.



In an expanding Universe, the actual S increases less rapidly than the maximum possible S_{max} , once the symmetry of equilibrium was broken at $t \approx 4 \times 10^5$ y. By contrast, in the early, equilibrated Universe, $S = S_{max}$ for the prevailing conditions at the time. (b) The potential for the growth of I —related to the difference between the two values of entropy—has increased ever since decoupling. Accordingly, the expansion of the Universe can be judged as the ultimate source of order, form and structure, promoting the evolution of everything in the cosmos.

Early on, when primordial nuclei began departing from equilibrium, their reactions still generated S increases (mainly by creating new photons and neutrinos, as would later occur in the cores of stars), but these increases were insufficient to reestablish equilibrium. Accordingly, the gap between the actual S and the maximum possible S that would have been achieved had equilibrium been restored increased even more, thereby building up free energy, to be released much later when stars formed. Here, then, we gain insight into the origin of free energy; it is not new energy as such, rather newly rearranged energy thereafter available for use in the course of evolution.

The very expansion of the Universe, then, provides the environmental conditions needed to drive order from chaos; the process of cosmic evolution itself generates information. How that order became

manifest specifically in the form of galaxies, stars, planets, and life-forms has not yet been deciphered in detail; that is the subject of this broad research work and that of many other specialized areas of current scientific investigation. We can nonetheless identify the essence of the development of natural macroscopic systems—ordered physical, biological, and cultural structures able to assimilate and maintain I by means of local reductions in S —in a Universe that was previously completely unstructured.

Furthermore, because the two T characterizing the Matter Era diverge, the growing departure from thermodynamic equilibrium allows the cosmos to produce *increasing* amounts of net S and macroscopic I . We thereby have a means to appreciate in the main, if perhaps not yet understand the particulars, the observed rise in complexity throughout the eons of cosmic evolution. To be sure, we have not overlooked the similarity of the culminating graph in the figure immediately above with that of our initial impression in the third figure (on rising complexity) at the start of this Advanced Track on the PARTICLE EPOCH—a pair of curves that address this book's core objective: To explain the growth of order, form, and structure among all material things, yet to do so by identifying specific, quantitative ways of generating substantial amounts of organization, negentropy, and information characterizing an immense number of complexities as intricate as the rings of Saturn or the insects of a tropical forest, let alone the labyrinthine architecture of the human brain.

Emergence

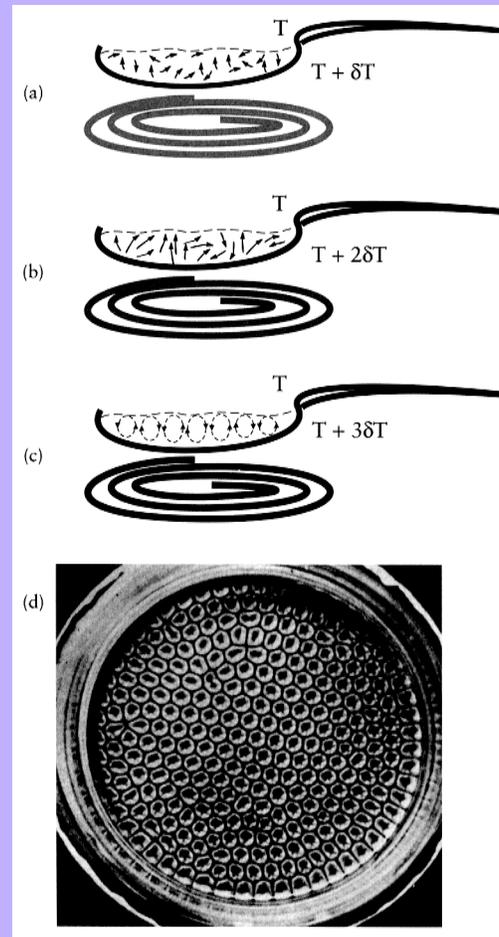
A suggested definition: Emergence is the appearance of entirely new system properties at higher levels of complexity not pre-existing among, nor predictable from knowledge of, lower-level components; the whole is greater than the sum of its parts; the process of a system "becoming" from its environment at certain critical stages in its development or evolution.

Although the *destruction* of order always prevails in a system in or near thermodynamic equilibrium, the *construction* of order may occur in a system far from equilibrium. Whereas classical thermodynamics deals with the first type of physical behavior, novel aspects of non-equilibrium thermodynamics only now being developed are needed to decipher the second type of behavior.

Heating of a thin layer of fluid from below provides a good illustration of such dual behavior (*cf.*, Chandrasekhar, *Hydrodynamic and Hydromagnetic*

Stability, 1961, Clarendon Press, Oxford), a case technically termed a "hydrodynamics instability" or simply a Benard cell, after the French physicist Henri Benard, who conducted a series of ingenious experiments in thermal transfer about a century ago. As shown in the figure below, externally applied energy generates a vertical thermal gradient in a fluid capable of enhancing any random molecular fluctuations; small pockets of molecular aggregates spontaneously form and disperse. When the heating is slight (*ie*, below some critical T or instability threshold), the energy of the system is distributed by conduction among the thermal motions of the fluid's molecules and the fluid continues to appear homogeneous; the natural, random fluctuations are successfully damped by viscosity, which prevents pockets of warm water from rising more rapidly than the time required for them to attain the same T as their neighbors, and the state of the system remains stable and incoherent, or effectively equilibrated. But beyond this threshold (*ie*, when the fluid is heated extensively), instabilities naturally amplify as large thermal gradients develop, thereby spontaneously breaking the initial symmetry (or homogeneity) of the system; this causes the onset of macroscopic inhomogeneities, or bulk mass movements, in the fluid—namely, small but distinctly and coherently organized eddies that upwell and descend via convection, not conduction.

Anyone can verify this well-known convective phenomenon by slowly heating a pot of shallow water on a stove (deep layers of water obscure the effect); as the water is brought to near boiling, cells housing millions of H_2O molecules become buoyant enough to overcome viscosity and to move systematically, thereby forming a stable, circulating pattern of characteristic size. In this way, order can naturally emerge (*ie*, spontaneously organize) when the system is driven far beyond its equilibrium state. That's what is meant by the principle of "order through fluctuations," or "energy flow ordering." The phenomenon is also often called "self-organization," although as noted above that term and others like it (any with the prefix "self-") are deceptive in that such ordering is actually occurring not by itself, as though by magic, but only with the introduction of energy.



The emergence of ordered convection (Benard) cells is illustrated here as a shallow pan of water is progressively heated from below. The temperature T of the fluid layer at the bottom exceeds that at the top by an amount δT ; actually, δT determines the temperature gradient, technically related in turbulence theory to the so-called Reynolds number (cf, Feynman et al, Feynman Lectures on Physics, v 2, 1964, Addison-Wesley). In frame (a), random instabilities arise upon slight heating (small δT), but the water molecules move around aimlessly without any order or pattern; heat flows evenly through the system from molecule to molecule and the system is close to equilibrium. In (b), with greater heating (moderate δT), the molecules have higher velocities but their motions are still mostly random; the liquid remains largely disorganized and approximately equilibrated all the while beginning to develop increased thermal and density gradients. In (c), as the T gradient in the water exceeds some critical value (large δT), the fluid's molecules depart from equilibrium and partake of an organized convection pattern; a T inversion is now sufficient to set the medium into a series of rolls or hexagons, with

the warmer, low-density fluid rising and the cooler, high-density fluid falling in an orderly fashion that is stable in time. Part (d) shows an actual photograph, looking down onto the field of hexagons comprising the convection cells of such an ordered system; once the heat source is removed, the cooperatively ordered movements soon cease.

How does such structuring occur? How can such ordering emerge from a condition where there was otherwise and previously no such thing? We know well that fluctuations—random deviations from some average, equilibrium value of ρ , T , P , etc, also called “instabilities” or “inhomogeneities”—are common phenomena in Nature. They inevitably yet stochastically appear in any system having many degrees of freedom. Normally, as in equilibrium thermodynamics, such instabilities regress in time and disappear; they just come and go by chance, the statistical fluctuations diffusing as quickly as they initially emerged. Even in isolated systems, such internal fluctuations can generate local, microscopic reductions in entropy, but the 2nd law ensures that they will always balance themselves out. Microscopic fluctuations in T , for example, are said to be thermally relaxed. Nor can an open system *near equilibrium* evolve spontaneously to new and interesting structures. But should those fluctuations become too great for the open system to damp, the system will then depart far from equilibrium and be forced to reorganize. Such reorganization generates a kind of “dynamic steady state,” provided the amplified fluctuations are continuously driven and stabilized by the flow of energy from the surroundings—namely, provided:

energy flow rate $>$ thermal relaxation rate.

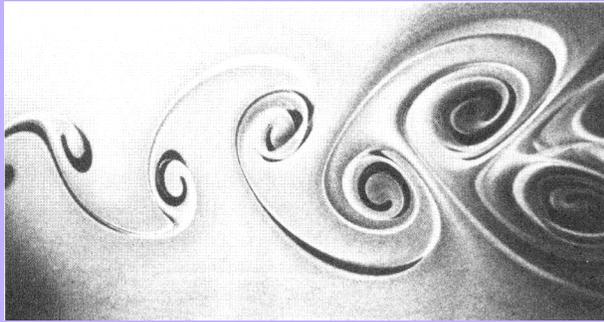
Global coherent cycling, is often the result, since under these conditions the spontaneous creation of macroscopic structures dissipates energy more rapidly than the ensuing, and damaging, heat can smooth out those structures. Furthermore, since each successive reordering causes more complexity than the preceding one, such systems become even more susceptible to fluctuations. Complexity itself consequently creates the condition for greater instability, which in turn provides an opportunity for greater reordering. The resulting phenomenon—which is again termed “order through fluctuations”—is a distinctly evolutionary one, complete with feedback loops that drive the system farther from equilibrium. And as the energy consumption and resulting complexity accelerate, so

does the evolutionary process (*cf*, Haken, *Rev Mod Phys*, v47, p67, 1975; Prigogine, *From Being to Becoming*, 1980, WHFreeman; Matsuno, *Protobiology: Physical Basis of Biology*, 1989, CRC Pr.). We are now into the realm of true thermodynamics, the older, traditional thermodynamics relegated to the status of “thermostatics.”

How, specifically, do the coherent structures come about in the above pot of H₂O, and what is the origin of the sudden disorder-to-order transition? Here is a way of physically intuiting it. The energy flowing into the system first creates a T gradient from top to bottom in the fluid. Eventually, as the T difference exceeds some threshold (depending on the nature of the fluid and the environmental circumstances), a structure emerges, in this case the hexagonally shaped Benard cells that enhance the movement of heat. Such structures actually attempt to break down, or neutralize, the gradient by increasing the rate of heat transfer. The newly formed structures themselves, then, are Nature’s way of trying to return the system to equilibrium. Provided energy continues to enter the system from outside, the individual structures remain more or less intact. In a crude sort of way, they are selected to endure. In even cruder terms, the regular energy flow resembles a primitive metabolism, somewhat akin to a more highly organized version operating in life forms (*cf*, Advanced Track for BIOLOGICAL EPOCH). For Benard cells, the greater the flow of energy (per unit mass), the steeper the T gradient, and the more complex the resulting structure—at least up to some limit beyond which the energy becomes so great that the structure, and perhaps the entire system, are destroyed.

Likewise, coherent, whirling eddies can be generated by slowly passing our hand through a tub of water or a teaspoon through coffee. Rapid and irregular passage only produces splashing (a kind of turbulent chaos), but moderate, steady movement yields organized whirlpools, or vortices, of swirling water in its wake. Here the tub of water or coffee cup can be considered an open system, with our hand providing some energy from outside. Without this (free) energy the water would remain idle and quiescent, the epitome of a closed system in perfect equilibrium. But the application of external energy enables the liquid system to generate a ρ gradient, depart from equilibrium, enhance statistical fluctuations—and, so long as energy is provided, establish somewhat ordered structures such as that in the figure below. By contrast, too much energy would

cause the water to spill out or boil away, the medium itself to disperse.



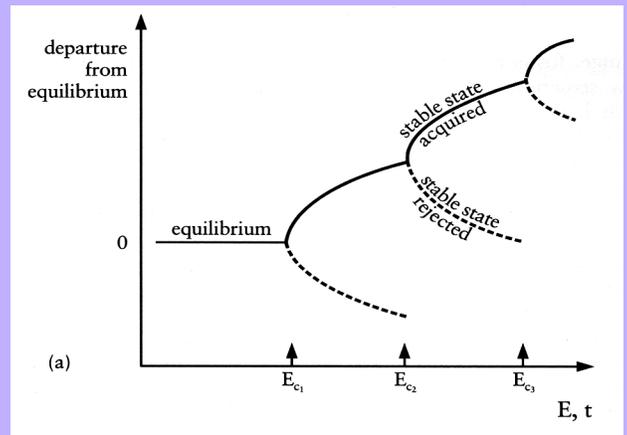
Temporarily ordered vortices naturally occur in the wake of a rock in a stream, a moving canoe paddle in a lake, a spoon while stirring coffee—or as energy flows near material inhomogeneities in the Universe.

Bifurcation

Many physical systems are stable against small perturbations, but become unstable if they undergo a disturbance of more than a certain amplitude. Systems of this type, which are subject to nonlinear effects, are termed *metastable*.

A common solution to the dynamical-system equations governing non-equilibrium states is that of a "bifurcation" (Poincare, *Science et Methode*, 1914, Flammarian; Turing, *Phil Trans Roy Soc London, Ser B*, v237, p37, 1952). The fork diagram of the following figure illustrates such a twofold solution, showing how a steady state can spontaneously break its symmetry upon entering a non-linear mode beyond some energy threshold. The result is 2 new, possible, dynamical steady states, only 1 of which a given system actually selects, depending partly on the system's history and partly on environmental fluctuations at the time of bifurcation. In non-equilibrium thermodynamics, the new states can result in whole new spatial structures at each bifurcation, much as in equilibrium thermodynamics when changing temperatures cause phase changes in various states of matter. As before, it is the (free) energy entering the system from the outside that helps create the conditions and engenders the changes needed to enhance the potential growth of complexity with time. The interplay between random factors (at the bifurcation point) and deterministic factors (between bifurcations)—chance and necessity, as always operating in tandem—not only guides the systems from their old states toward new ones, but also specifies which new configurations are realized. However, with statistical fluctuations triggering such

events and the role of chance once more evident, the evolutionary trajectories are indeterminate, the new complex states unpredictable. *Evolution is not predictable*; evolution merely attempts to explain the rich ensemble of past events that produced what we observe in Nature, whatever their convoluted, historical paths might have been.



Sketched here is an arbitrary equilibrium coordinate of an open system as a function of both time and energy, either of which serves diagrammatically to illustrate the extent of departure of that system from equilibrium. The time axis makes clear that this is an historical, evolutionary process, whereas the parallel energy axis denotes the free energy flowing through the open system as a vital part of that process. At a certain critical energy, labeled here E_{c1} , a system can spontaneously change, or bifurcate, into new, non-equilibrium, dynamic steady states. Statistical fluctuations affect which fork the system selects upon bifurcation (arrows), namely which spatial structure is achieved, therefore the end result is inherently unpredictable. At right, a 2nd and 3rd bifurcation occur further on in time, with the application of additional energy, E_{c2} , and then E_{c3} . (Cf, *Advanced Track for BIOLOGICAL EPOCH*.)

Nature's many ordered systems can now be regarded as intricately complex structures evolving through a series of instabilities. In the neighborhood of a stable (equilibrium) regime, evolution is sluggish or nonexistent because small fluctuations are continually damped; *destruction* of structure is the typical behavior wherein disorder rules. By contrast, near a transition (energy) threshold, evolution accelerates and the final state depends on the probability of creating a fluctuation of a given type. Once this probability becomes appreciable, the system eventually reaches a

unique though dynamic steady state, in which *construction* of structure wherein order rules is distinctly possible. Such states are thereafter starting points for further evolution to other states sometimes characterized by even greater complexity.

Information and Negentropy Reconsidered

How can order and complexity be best characterized, in some practical, quantitative sense? Is there a single common term capable of quantifying order on all spatial and temporal scales?

While appealing to the real world surrounding us, it is perhaps best to avoid use of the term **information**. When examined on a system-by-system basis, information content can be a slippery concept full of dubious semantics, ambivalent connotations, and subjective interpretations (Wicken, *Evolution, Thermodynamics, and Information*, Oxford U Pr, 1987; Brooks and Wiley, *Evolution as Entropy*, U Chicago Pr, 1988; Marijuan, Conrad, *et al*, *BioSystems*, v38, pp87, 1996). Especially tricky and controversial is *meaningful* information, the value of information. What is a meaningful message or a meaningfully ordered structure, as opposed to information in a system that is of no particular use to that system, or one that is unrelated to the behavior of the system? For example, an entire DNA strand made of only one type of nucleotide base does contain raw information, but hardly any programmatic information of the type needed to manufacture proteins. Furthermore, as some researchers argue, perhaps information does need to be interpreted for it to exist, in which case it would presumably be associated only with biological and social systems; yet the telephone company doesn't care about the content of its transmitted messages, charging only by the length of the information string—a wise and appropriate way to bill its customers if it wishes to stay in business. The conceptual idea of information has been useful, qualitatively and heuristically as noted above, as an aid to appreciate the growth of order and structure in the Universe, but this term is too vague and subjective to use in quantifying a specific, empirical metric describing a whole range of real-world systems. Nor is there any compelling need to treat information as a third, fundamental ingredient of the Universe—after matter and energy—for, after all, information might basically be a form of energy, whether acquired, stored, or expressed.

Likewise, the term **negentropy** (or negative *S*) is virtually impossible to measure, alas even to define adequately regarding non-equilibrium states. Even

Schroedinger, who initially championed negentropy, noted his uneasiness with the term in the reprinting of his classic essay, *What is Life?* (Cambridge U Pr, 1944). Entropy, whether positive or negative, holds true only for static, equilibrium conditions. Approximations are possible for changing states, but only in local regions, where *T*, *P*, and other such quantities change so slowly as to be measurable in small space-wise (and time-wise) neighborhoods. These are so-called LTE, or "Local Thermodynamic Equilibrium," mini-states wherein a system's macroscopic changes are assumed to occur much more slowly than any of its microscopic changes. Hence, *S* estimates (even if they could be measured) involve a technicality based on an assumption, in fact one that might not always prevail for rapidly changing evolutionary events. (*Cf*, Corning and Kline, *Systems Research*, v15, p273, 1998, for a strong critique of any kind of *S* metric.) Entropy can be as "slippery" as information, given the many varieties of thermodynamic *S* used by specialists, including configurational *S*, conformational *S*, positional *S*, residual *S*, and even informational *S* [sic], which in turn distinctly differ from other kinds of *S*, such as chemical or thermal *S* and gravitational *S*. Furthermore, even if we did have a way to estimate *S* quantitatively, the whole concept of *S* as a measure of disorder, and therefore negentropy as a measure of order, remains controversial; this is not to say that the time-honored case of a cluttered room is not a good *analogy* of disorder in everyday life, but it is not an example of thermodynamic *S*.

Energy Flow

All things considered, it's perhaps best to attempt to quantify the scenario of cosmic evolution and the attendant rise of its complex structures in Nature in the a straightforward way by returning to a steadfast concept of fundamental thermodynamics—in short, by embracing the most common currency in all of natural science: **energy**.

Energy and energy flow are more accessible, explicit, and primary quantities than information or negentropy. Energy is well-defined, measureable, and unambiguously understood. What's more, the concept of energy remains meaningful for any macroscopic state, obviating the difficulties noted above for *S* or *I*. As we shall see for each of the Advanced Tracks of the 7 epochs of this web site, energy, more than any other quantity, plays a central role throughout the physical, biological, and cultural evolutionary parts of cosmic evolution. In short, energy is a common, underlying factor like no other—a "DC baseline," in

physicists' lingo, that cuts across undergirds all aspects of the research agenda—in our search for unity among all material things.

Recall from basic thermodynamics above that $E = F + TS$. Thus, if for a given T , the S of some system decreases—and this is the essence of order and organization—then F must increase. Yet, open-system, non-equilibrium thermodynamics is not concerned with the absolute value of a structure's total F , as much as with its free energy density. After all, a huge galaxy clearly has more total E than a small cell, but of course galaxies also have greater sizes and masses; it is the energy *density* that enables us to compare and contrast all systems found in Nature, and to do so in an equitable way "on the same page"—much as comparisons of radiation energy density and matter energy density were significant in the early Universe. In fact, what is more important is the *rate* at which F transits an open, complex system of given mass; in this way, all such systems can be compared on a fair and level spectrum.

In other words, a most useful quantity used to specify operationally the order and organization of any system is the **free energy rate density**, alternatively called the specific free energy rate, expressed in units of energy per time per mass and denoted by the symbol Φ_m . (Note that this term differs from the "dissipative function," Φ , a quantity having dimensions of power in conventional non-equilibrium thermodynamics; cf, Caplan and Essig, *Bioenergetics and Linear Nonequilibrium Thermodynamics*, Harvard U Pr, 1985). The term, Φ_m , used here is familiar:

- to astronomers as luminosity-to-mass ratio,
- to physicists as power density,
- to geologists as specific radiant flux,
- to biologists as specific metabolic rate,
- to engineers as power-to-mass ratio.

The more straightforward designation of "free energy rate density" is preferred here partly to emphasize its explicit physical meaning—a rate of energy flow, not a flux per se; and a mass density, not a volume density—and partly to stress its interdisciplinary application among all the natural sciences (Chaisson, *BioSystems*, v46, p13, 1998; Chaisson, *Cosmic Evolution: The Rise of Complexity in Nature*, Harvard Univ Pr, 2001)

Actually, the idea of energy flow is not novel to an understanding of systems, especially ones displaying biological expression. Three-quarters of a century ago Lotka (*Proc Nat Acad Sci*, v8, p147, 1922) identified energy's vital role, with "evolution...proceeding in such a direction as to make the total energy flux through the

system a maximum compatible with the constraints" (see also Odum, *Systems Ecology*, Wiley, 1983). Today, we would suggest that these systems *optimize* their flow, as will often be repeated throughout the Advanced Tracks for each of the 7 epochs of cosmic evolution. Others more recently (eg, Morowitz, *Energy Flow in Biology*, Academic Pr, 1968; Jantsch, *Self-Organizing Universe*, Pergamon, 1980), have embraced the first-order consequences of energy flow, especially in biological systems.

Nor is the idea of energy itself a foreign concept in any natural transaction, least of all universal construction (eg, Dyson, *Sci Am*, v225, p51, 1971; Fox, *Energy and Evolution of Life*, Freeman, 1988; Smil, *Energies*, MIT Pr, 1999). Just about everyone would agree that this most basic of all physical quantities likely plays *some* role at virtually every level of development and evolution among all natural systems. But can the energy argument be made sound, integrated, inclusive, and specifically applicable for all the sciences? Can we go beyond both the sweeping generalities of words yet the limited purview of biology in order to explore specific, quantitative applications of energy to a grander, holistic synthesis of *all* the sciences?

To simplify the analysis, indeed to err (if need be) on the side of the bigger picture and not the devilish details, we consider energy pure and simple, ignoring for now subtle variations proposed by others, such as

- exergy (Eriksson *et al*, *Nature*, v296, p540, 1982)
- emergy (Odum, *Science*, v242, p1132, 1988)
- essergy (Ayres, *Info, Entropy, and Progress*, AIP Pr, 1994)
- endergy (Corning and Kline, *Systems Research*, v15, p453, 1998)

among sundry other utility and efficiency factors affecting the type and quality of energy.

We also reject the occasional criticism that energy, however expressed and harking back to its classical thermodynamic roots, is a 19th-century concept whose usefulness has come and gone. Admittedly an abstract idea invented more than a century ago to quantify the workings of Nature's many varied phenomena, energy nonetheless remains a vibrant, 21st-century term central to the understanding of all material things. One cannot examine a galaxy, a star, a planet, or any life-form without taking energy seriously into account. Energy is indeed the most universal currency in all of science, and we unapologetically employ it liberally throughout this cosmic-evolutionary research agenda.

We begin by computing the energy flowing through a wide variety of structures representing a whole spectrum of perceived order in Nature. Yet, in this initial analysis, we restrict the computations in two ways: First, we consider only a handful of generic structures apparent along the evolutionary track that has historically led to ourselves. This is the big-bang-to-humankind story that is of greatest interest to “big historians” who are foremost interested in who *we* are and whence *we* came (Christian, *Maps of Time*, UC/Berkeley Pr, 2004; Spier, *Big History and Future of Humanity*, Wiley, 2010). Second, as a first approximation, we examine only those structures as they exist now. Later, among each of the Advanced Tracks for the 7 major epochs of cosmic evolution, our analysis broadens and strengthens to include not only relevant structures at earlier times in their evolutionary trajectories, but also a wider range of structures of demonstrable order and increasing complexity not within the specific cosmic-evolutionary line of ascent that specifically led to us.

The CGS metric system is used throughout the analysis, as this is the preferred set of units used by thermodynamicists globally. Thus Φ_m is expressed in erg/s/g; for Scientifique Internationale units (W/kg), simply divide by 10^4 .

Stars: Consider the Sun as we know it today. Later, in the Advanced Track for the STELLAR EPOCH, we compare and contrast other types of stars, as well as compute their Φ_m while they move along their evolutionary tracks. The solar luminosity $L_\odot \approx 4 \times 10^{33}$ erg/s and its mass $M_\odot \approx 2 \times 10^{33}$ g, thus Φ_m for the Sun is ~ 2 erg/s/g. This is the average rate of energy released per unit mass of cosmic baryons that fuse $\sim 10\%$ of their H in 1 Hubble time (~ 10 Gy). This is energy flowing effectively *through* the star, as gravitational PE during the act of star formation is converted into radiation released by the mature star. Such a system, as for any star, utilizes high-grade energy in the form of gravitational and nuclear events to gain for itself greater organization, but only at the expense of its surrounding environment; it emits low-grade light, which, by comparison, is a highly disorganized entity. This is relative statement, however, since such low-grade, disordered sunlight will, when later encountering Earth, become a high-grade ordering form of energy that powers much of biology on our planet; in turn, even lower-grade (IR) energy is then

wastefully re-emitted by Earth (*cf*, Advanced Track for STELLAR and PLANETARY EPOCHS).

Galaxies: Typical, normal galaxies have values of Φ_m comparable (yet usually a little less) to those of normal stars largely because, when examined in bulk, galaxies are hardly more than gargantuan collections of stars plus dark matter. Since the total energy of a galaxy scales roughly as the number of its stars, it has nearly $10^{11} L_\odot$ (most stars are less luminous than the Sun). Yet its value of Φ_m —an effective energy *density*—also scales inversely as the mass of the entire galaxy housing those stars, making Φ_m somewhat smaller than for stars. For example, our Milky Way Galaxy has a net energy flow of $\sim 2 \times 10^{44}$ erg/s (including contributions from interstellar clouds and cosmic rays as well as from stars), and a mass of $\sim 2 \times 10^{45}$ g (including loose interstellar gas and dust in the galactic plane as well as anonymous dark matter thought present in the galactic halo well beyond the plane.) Such a low value of $\Phi_m \approx 0.1$ erg/s/g accords with our preconceived notion that galaxies, despite their majestic splendor, are not terribly complex compared to many other forms of organized matter (*cf*, Advanced Track for GALACTIC EPOCH).

Planets: Planets are more complex than either stars or galaxies, and not surprisingly planetary values of Φ_m are larger—at least for some parts of some planets at some time in their history. Here, not a planet’s whole globe is treated, from interior through surface, since the planets in our Solar System are not evolving much now, some 4.6 Gy after their formation; rather, we are more interested in those parts of planets that are still evolving robustly, still requiring energy to maintain (or regenerate) their structure and organization. Thus, the mass of the entire planet Earth is not relevant in computing Φ_m , not only because the heat generated internally by the Earth is a small fraction of the incident solar radiation (see below) but also because the today’s external solar energy is deposited into the surface layer at the atmosphere-ocean interface. Consider, then, the amount of energy needed to drive Earth’s climasphere, the most impressively ordered inanimate system at the surface of our planet today. The climasphere includes the lower atmosphere and upper ocean, which most affect meteorological phenomena capable of evaporating copious amounts of water as well as mechanically circulating air, water, wind, and waves. The total solar radiance intercepted by Earth is 1.8×10^{24} erg/s, of which only $\sim 70\%$

penetrates the atmosphere (since Earth's albedo ≈ 0.3). This is several thousand times the power that Earth's surface now receives from its warm interior, which can thus be neglected, but later in the Advanced Track for the PLANETARY EPOCH, we return to examine Earth's radiogenic and accretional energies during its formative stage. Since our planet's air totals 5×10^{21} g, and the upper 30 m of the ocean engaged in weather comprises approximately double that, the value of Φ_m for planet Earth is ~ 75 erg/s/g. The re-emitted IR photons (equal in total energy to the captured sunlight) are both greater in number and lower in energy (~ 20 times difference per photon) than the incoming sunlight of yellow-green photons, thus again continually contributing to the rise of S beyond Earth (*cf*, Advanced Track for PLANETARY EPOCH).

Plants: Living systems require substantially larger values of Φ_m to maintain their order, including growth and reproduction. Photosynthesis is the most widespread biological process occurring on Earth, dating back ~ 3.3 Gy when rocks of that age first trapped the chlorophyll porphyrins that activate this process in green plants, bacteria, and algae. These lower life-forms need 17 kJ for each gram of photosynthesizing biomass, and they get it directly from the Sun. Since the annual conversion of CO_2 to biomass is 1.7×10^{17} g (or $\sim 10^9$ tons of carbohydrates), the entire biosphere must use energy at the rate of nearly 10^{21} erg/s (or $\sim 0.1\%$ of the total radiant energy reaching Earth's surface). And given that the total mass of the terrestrial biosphere (living component only) is $\sim 10^{18}$ g, then Φ_m for the physico-chemical process of photosynthesis is ~ 900 erg/s/g (*cf*, Advanced Track for BIOLOGICAL EPOCH).

Animals: Humans, by contrast, consume ~ 2800 kcal/day to drive our metabolism (or ~ 130 W in the form of food; note that 1 physicist's kcal = 1000 calories = 1 dietician's Calorie = 4184 joules). This energy, gained indirectly from that stored in other (plant and animal) organisms and only indirectly from the Sun, is sufficient to maintain our body T and other physiological functions as well as to fuel movement during our daily tasks. Metabolism is a genuinely dissipative mechanism, thus making a connection with previous thermodynamic arguments that some might have (wrongly) thought pertinent only to inanimate systems. Having an average adult body mass of 50 kg, we therefore maintain $\Phi_m \approx 3 \times 10^4$ erg/s/g while in good health. This is how humankind contributes to the rise of S in the Universe: We consume organized energy in the form of structured

foodstuffs and we radiate away as body heat an equivalent energy in the form of highly disorganized IR photons. We, too, are dissipative structures—highly evolved dissipators (*cf*, Advanced Track for BIOLOGICAL EPOCH).

Brains: The adult human brain—the most exquisite clump of natural matter in the known Universe—has a cranial capacity of typically 1300 g and requires ~ 400 kcal/day (or ~ 20 W) to remain structured and functioning properly. Our brains therefore have $\Phi_m \approx 1.5 \times 10^5$ erg/s/g. This large energy density flowing through our heads, mostly to maintain the electrical actions of countless neurons, testifies to the disproportionate amount of worth Nature has invested in brains; occupying $\sim 2\%$ of our body's mass yet using nearly 20% of its energy intake, our cranium is striking evidence of the superiority, in evolutionary terms, of brain over brawn. Thus, to keep thinking, our heads glow (in the far-IR) with as much energy as a small lightbulb; when the "bulb" stops shining, we die (*cf*, Advanced Track for BIOLOGICAL EPOCH).

Society: Finally, consider civilization, which is an open system of all humanity, taken together as an aggregated human social network, comprising modern society going about its daily, energy-driven business. Today's ~ 7 billion inhabitants utilize ~ 18 TW to keep our technological culture fueled and operating, admittedly unevenly distributed in localized pockets across the globe. The cultural ensemble equaling the whole of humankind then has an average, global Φ_m value of $\sim 5 \times 10^5$ erg/s/g. Not surprisingly, a group of brainy organisms working collectively is more complex than the totality of its individual components, at least as regards our complexity metric of energy rate density—a good example of "the whole being greater than the sum of its parts," without resorting to anything other than the flow of energy through an organized, and in this case social, system (*cf*, Advanced Track for CULTURAL EPOCH).

Table and graphs of cosmic evolution: The table below summarizes the values of Φ_m for the above 7 representative systems spanning a wide spectrum of complexity, along with their specific structures computed in parentheses. These systems are those most pertinent to the eventual emergence of life on Earth, and as such they are specific to us, and thus of most interest to "big historians" interested in the evolutionary events that led to humankind. In the

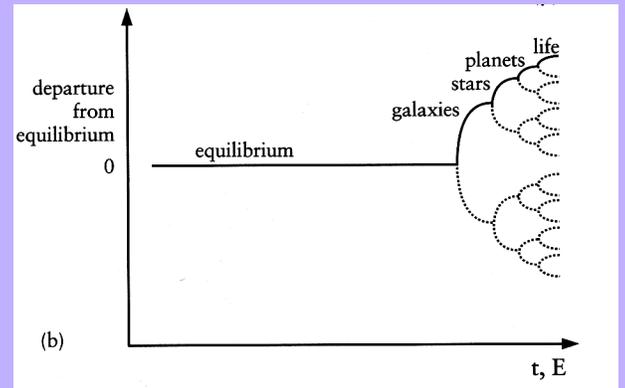
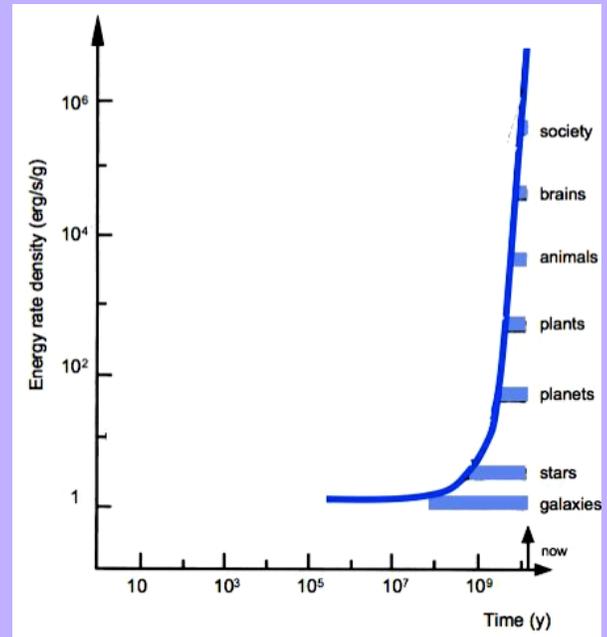
summary section below, and especially in depth for each of the remaining Advanced Tracks of the 7 epochs of this research agenda and web site, we shall explore more generally how these specific findings might also apply to all such complex structures in the Universe writ large, and thus interest "cosmic evolutionists" studying all physical, biological, and cultural systems across the wider Universe. Also listed in the table are the approximate dates of origin for each type of structure, extending back to when each first appeared in the observational record.

The values of Φ_m tabulated here are typical for the general categories to which each system belongs, yet as with any simple, unifying theme—especially one like cosmic evolution that aspires to address all of Nature—there are variations and outliers. As we shall see, it is likely that from those variations arose the great diversity among complex, evolving systems everywhere.

Some Estimated Energy Rate Densities

System	Age (10^9 y)	Φ_m (erg/s/g)
society (modern culture)	0	500,000
brains (human cranium)	0.005	150,000
animals (human body)	0.07	30,000
plants (biosphere)	3.3	900
planets (Earth)	4.5	75
stars (Sun)	5	2
galaxies (Milky Way)	12	0.1

The figure below graphs the evident temporal gain in Φ_m among these tabulated open systems, illustrating the rapid rise of this quantity in recent times. Part (a) plots these data on a logarithmic temporal scale that matches other plots presented elsewhere in this Advanced Track for the PARTICLE EPOCH; such a plot necessarily compresses events associated with the evolution of complex structures into the right-hand part of the graph, since this is where almost all of the events of the past ~12 Gy are graphed. Part (b) illustrates one way to view these data, making a connection with the bifurcation arguments presented at the end of the previous section above.



(a) The rise in energy rate density has been slow yet steady in the first few Gy and more rapid in the last few Gy, much as expected from intuitive ideas hypothesized near the start of this Advanced Track for the PARTICLE EPOCH. The solid blue line of Φ_m values taken from the above table approximates the upturn in negentropy or information content, as noted and graphed a few figures prior. This log-log graph is specific to those structures listed in the previous table, thus relevant to the rise of complex, sentient life on Earth, such as specifically the origin of the Milky Way and our Solar System during physical evolution ~12 and 5 Gya, respectively, followed by biological evolution of life and intelligence and cultural evolution of society more recently.

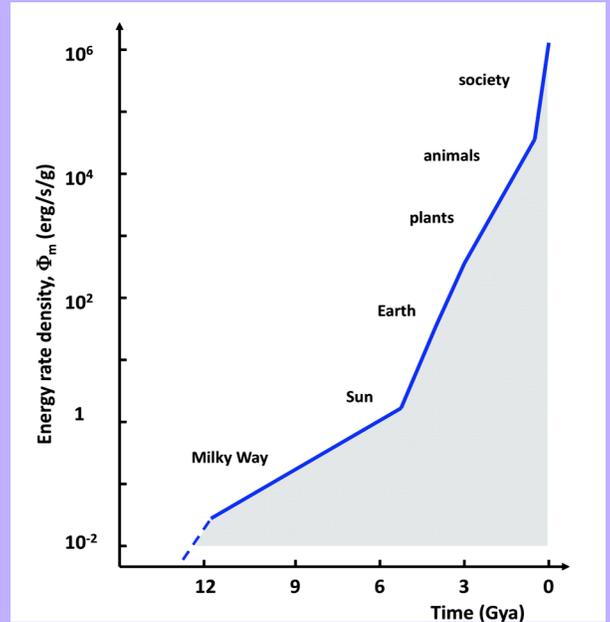
(b) This qualitative analog of the quantitative plot in (a) makes a connection with the earlier discussion (and bifurcating chart in the previous section) of systems' chancy fluctuations responding deterministically to environmental conditions, which in turn gave rise to a

hierarchy of complex states via bifurcating changes. The solid lines represent the paths taken historically, the dotted lines options never realized.

Here, values of Φ_m are plotted as horizontal histograms, starting at those times (estimated in the previous table) when each of these different systems first appeared in Nature and extending to the present; not only has each type of system originated long ago but each has also endured since then. Thus, the histograms are not meant to span ages of individual structures, rather the total duration of each type of system in the observational record. As such, the histogram for stars does not mean to imply, for example, that all stars are 10 Gy old; rather, stars generally have existed over the course of the past 10 Gy. Likewise, no given life-form has an age of 3 Gy, but Earth's photosynthesizing biosphere has existed for at least that long.

None of this implies, by any means, that galaxies per se evolved into stars, or stars into planets, or planets into life. Rather, this analysis suggests, and not just qualitatively in words but with quantitative reasoning throughout, that galaxies gave rise to environments suited for the birth of stars, that some stars spawned environments conducive to the formation of planets, and that an untold number of planets fostered environments ripe for the emergence of life. In short, new and more complex systems likely emerged as energy flows became more prevalent yet more localized—and that some systems capable of utilizing optimum energy were selected to survive and perhaps further complexify, all the while others could not, did not, and became extinct.

Logarithmic plots like this one above are useful for examining the full range of events cosmologically, especially those in the earlier Universe. They are not, however, as instructive as linear temporal plots that better examine the details of events that have happened more recently. The next figure plots the same data from the above table, yet in a semi-logarithmic manner; in this way, the abscissa is linear and the full run of time is stretched horizontally, thereby allowing us to discern more clearly some of the major events and emergence of systems with the rise of Φ_m over the past ~12 Gy.



The same data as plotted in the previous figure fully logarithmically are here plotted semi-logarithmically, namely with the time axis now presented linearly. That is, the solid blue, rising curves in both figures represent the same data plotted differently. In this figure, some of the details of the rise in Φ_m can be better discerned over the course of the past ~12 Gy. The shaded area beneath the blue curve represents the domain in time when myriad systems evolved and complexified, not merely the half-dozen systems represented in this plot. This iconic graph, to which we shall return many times in these Advanced Tracks (especially while exploring in greater detail the range and change of Φ_m within that shaded area), suggests that it is energy flow that well characterizes the rise of order, form, and structure in the evolving Universe.

The significance of plotting on a single page the same quantity for such a wide range of systems observed in Nature should not be overlooked. It is unclear if any other single quantity exists that can characterize so extensively a principal system dynamic over >20 orders of magnitude in spatial dimension and nearly as many in time. Intellectual analysis and detailed exploration of this graph forms the essence of all that remains in this web site's research agenda.

Whichever plot is preferred, Φ_m has clearly increased as more intricately ordered structures have emerged, in turn, throughout cosmic history, indeed dramatically so in relatively recent times. Although the total energy flowing through a star or planet is hugely larger than that through our human body or brain, the *specific rate*—in effect, the *rate density*—is much larger for the latter. Thus, organized systems

observed in the Universe do in fact temporarily increase their complexity, or information content, in actuality Φ_m faster than I , no doubt because factors such as functional traits in biological evolution grant distinct advantages to those systems able to process additional energy over and above that provided by thermal gradients engendered by the expanding Universe.

That the temporal dependence of Φ_m mimics the suspected rise of complexity discussed at the start of this Advanced Track should not be overlooked. In particular, compare 3 curves:

- the heuristic graph of our innate feeling that complexity likely grows as a function of time, sketched earlier as the 3rd figure of this Advanced Track, and speculating there whether complexity has risen linearly, exponentially, or in some other way
- the theoretical graph of rising I midway through this Advanced Track, implying how cosmic conditions in an expanding Universe can potentially generate complexity
- the two graphs just above, displaying actual data for Φ_m and proposing this quantity as a complexity metric of some note and worth.

The last of these curves—namely, the one containing real, empirical data—rises more sharply than any of the other, theoretical curves suggest, though this should not surprise us. The rising curve for Φ_m may well be faster than exponential, but only more and better data will tell for sure. As noted later in the Advanced Tracks for the BIOLOGICAL and CULTURAL EPOCH, Darwinian biological evolution and Lamarckian cultural evolution, among other catalytic effects during physical evolution, might well have fostered additional complexity on local scales beyond that possible by universal expansion alone. That's probably why, in a relative sense, physical evolution is sluggish, biological evolution moderate, and cultural evolution rapid. Φ_m encapsulates a kind of motor of evolution (or at least its fuel), accelerating some systems' abilities to assimilate increased power densities—at least for the ones that survive.

Nor should we be surprised by the shape of the Φ_m curves immediately above; there is nothing peculiar about the extraordinary rise in Φ_m during the most recent ~ 0.5 Gy. The mathematical nature of any exponential curve—much like that for human population on Earth—causes it to increase initially only very slightly and slowly over long time intervals (increasing, for example, from 1 to 2% in one doubling period), after which it surges upward nearly explosively during short

durations (rising from 50 to 100% also in a single doubling period).

No designer agents or mystical acts, yet unidentified, need be responsible for the dramatic increase in Φ_m values throughout cosmic history; the natural phenomena described as part of this cosmic-evolutionary research agenda seem quite capable of accounting for it, and no new science is required to explain the rich panoply of systems observed in Nature.

Caution in Interpreting and Calculating Φ_m

Two caveats are worthy of underscore—one philosophical, the other technical. Foremost, in no way whatever is the rising curve of Φ_m meant to imply anthropocentrism. That contemporary humankind and its social inventions comprise the greatest complexities known in Nature seem indisputable; that we harbor in our heads the most intricate bundle of matter observed anywhere is presently impossible to deny. Yet no inference is construed about humanity epitomizing any pinnacle or culmination of the evolutionary process. No hidden, anthropocentric agenda lurks here. We are neither the centerpiece nor the final product of this remarkable cosmic-evolutionary narrative, even though we *are* the only known systems consciously telling that story. To be sure, it does not follow that some straight and narrow evolutionary path led directly from big bang to humankind (as is sometimes claimed by critics who do have a personal agenda); rather, that path, extending over ~ 14 Gy, was at best a meandering one, with many failures, extinctions, and sidetracks amid a smaller number of natural successes along the way.

The empirically derived plot of Φ_m , matching pretty well our gut feelings about rising complexity, captures the highlights of the salient events that did eventually produce a hierarchical distribution of many evolved systems, in effect representatives of the "winners," without showing the countless "losers." In fact, disorder is generally more probable than order largely because so many more paths to disorder prevail, much as there are always more ways to make mistakes than to get something right (or more nonsense prevalent in today's society than sense). The above table and plot of rising Φ_m together comprise one way of displaying examples of complex systems on a common technical ledger—"on the same page," so to speak—which was one of our unifying objectives from the outset of this cosmic-evolutionary research program. To be sure, complexity is still rising in Nature today, but to what end—if there is an end—contingent science cannot say.

Nor, despite much development and evolutionary advancement evident throughout natural history, is any evidence for supernatural design or overt purpose.

A second caveat concerns the level of detail in the above computations; to be honest, much of the analysis skirted some of the hardest details in this preliminary, broad diagnosis in this Advanced Track for the PARTICLE EPOCH. In particular, the values for Φ_m employ only bulk energy flow, that is, total energy available to a handful of representative open systems. Accordingly, quantity, or intensity, of energy has been favored while largely neglecting measures of quality, or effectiveness, of that energy. A more thorough analysis needs to incorporate such factors as temperature, type, and variability of an emitting energy source, as well as the efficiency of a receiving system to use that energy flowing through it. Input energy of certain spectral wavelengths can be more useful or damaging than others, depending upon a system's status, its receptors, and its relation to the environment. Likewise, the efficiency of energy use can vary among systems and even within different parts of a given system; under biological conditions, for example, only some of the incoming energy is available for work, and technically only this fraction is the true free energy (even so, as we shall see in the Advanced Track for the BIOLOGICAL EPOCH, the product TS for life forms is usually small, thus $E \approx F$, and the total energy acquired by living systems is a good approximation of the actual free energy capable of building structure and function).

Energy's capacity to benefit some parts of a system more than others is a necessary refinement of the more detailed analyses within each of the Advanced Tracks for all subsequent epochs of this Web site. For this general abridgment in this, the first Advanced Track for the PARTICLE EPOCH, our above estimates of Φ_m suffice as our objective here has been to display general trends among a broad sweep of complex systems observed throughout Nature.

Even the absolute quantity of energy flowing through open systems needs to be more carefully considered in the detailed analysis to come in each of the subsequent Advanced Tracks. Not just any energy flow will do, as it might be too low or too high to help complexify a system. Very low energy flows often mean systems will likely remain at or near equilibrium with their external thermal sinks, whereas very high flows will usually cause systems to approach equilibrium with what must effectively be a hot source—that is, damage the system to the point of destruction. That much was clear for the classically dissipative Benard cells encountered in

the above section on "emergence." Sustained order is a property of systems enjoying moderate, or "optimum," flow rates; it's a little like the difference between watering a plant and drowning it, or the "goldilocks" criterion for what's right—not too little and not too much.

Previous researchers, while studying flow rates in complex systems, have sought to identify maximum and minimum principles guiding the growth and evolution of those systems. For example, Lotka (*Elements of Math'l Biology*, Dover, 1924) claimed that ecosystems evolve so as to maximize the total system throughput—a "principle of maximum power production"—whereas Prigogine (*From Being to Becoming*, WHFreeman, 1980) argued that certain non-equilibrium systems have the lowest possible S generation for a given set of conditions—a "principle of minimum S production." By contrast, the current work embraces neither maximum nor minimum principles that have often been a hallmark of reductionistic science; the empirical data simply don't support such max/min principles. Instead, this analysis embraces optimization strategies suggestive of less reductionistic, that is more holistic, interpretations of systems interacting with their environments—criteria that best suit organized systems employing moderate flows of energy, large enough to sustain them yet small enough not to destroy them. No unambiguous extremum principles have been found in this study, nor are any likely to hold over such a wide range of ordered structures, from primordial atoms to sentient brains. *Optimality* seems key regarding energy flows fostering the further development and evolution of complex systems.

In sum

The sources and sinks of energy flows through complex, yet connatural, systems such as stars, life, and society all relate back to the time of thermal symmetry-breaking in the early Universe. This is history's preeminent change from the Radiation Era to the Matter Era, a long-ago period when the cosmic conditions naturally evolved to foster the emergence of order and organization, and increasingly so with the expansion of the Universe ever since. More than any other single factor, energy flow is the principal means whereby all of Nature's diverse systems naturally generate complexity, some of them evolving impressive degrees of order characteristic of an intricately structured and functioning civilization.

For all structured systems—whether physical, biological, or cultural— S increases in their larger

surrounding environments can be mathematically shown to exceed the S decreases within localized systems per se, guaranteeing good agreement with the 2nd law. Furthermore, as S increases globally, our empirical complexity metric Φ_m often increases locally. We thus arrive at a clean, clear reconciliation of the theoretical destructiveness of thermodynamics and the observed constructiveness of cosmic evolution.

If any fundamental phenomenon underlies the evolution of order, form, and complexity within systems all around us, it would seem to be nothing more, yet nothing less, than the expansion of the Universe. The organized dynamics of the Universe itself are a necessary, if not sufficient, condition for the emergence of increasingly complex systems. Those dynamics established the temperature gradients, began the free energy flowing, and fostered environmental changes literally everywhere.

Yet cosmic expansion is not likely the only source of order and complexity in the Universe. Superposed on the primal, gradual changes in the early Universe that set the stage for the rich hierarchy of many varied events to come, other, more sophisticated mechanisms of change have been, and are, at work. Gravitational force in physics, natural selection in biology, and technological innovation in culture are all examples of diversified actions that can give rise to accelerated rates of change within locales much, much smaller than the Universe per se—such as the islands of order called stars, life, and society. All these systems, processes, and events, indeed much more, comprise the remainder of this research agenda to better understand cosmic evolution—and how we as sentient beings are able to reflect back upon this grand worldview for the new millennium.