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THE INITIAL LOW GRAVITATIONAL ENTROPY OF THE UNIVERSE AS THE ORIGIN OF DESIGN IN NATURE

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Great fleas have little fleas upon their backs to bite 'em,
And little fleas have lesser fleas, and so ad infinitum.

—Augustus De Morgan

Big whirls have little whirls that feed on their velocity,
and little whirls have lesser whirls and so on to viscosity.

—Lewis Fry Richardson

1. The Second Law of Thermodynamics: Entropy Increases

Life and other far-from-equilibrium dissipative structures such as galaxies, stars, planets, convecting mantles and hurricanes, increase the entropy of the universe (Lineweaver and Egan, 2008). They need gradients of density, temperature, chemical potential, pressure, humidity or luminosity to form and survive (e.g. Schroedinger, 1944; Schneider and Kay, 1994; Schneider and Sagan, 2005; Kleidon, 2010). Each one of these gradients can be traced back to other larger-scale gradients which are the sources of free energy.

For example, the Sun is hot (~6,000 K) while the Earth is cool (~290 K). Since the Earth is a sphere, the equator receives more sunlight. Equatorial sunshine evaporates the oceans and warms the tropics. Large-scale hemispheric temperature and humidity gradients are set up and maintained by sunlight. These gradients drive winds, thunderheads and hurricanes. Water evaporates, goes up into clouds, gets blown over land and rains down on mountains. We convert the resulting difference in gravitational potential (gravitational gradient) into a voltage gradient using a turbine in a hydroelectric power station. With a windmill, we convert the momentum gradient of the wind into a voltage gradient. Then with heaters, refrigerators and air conditioners, we convert the voltage gradient into conveniently placed small-scale thermal gradients – which then dissipate into waste heat. Each conversion is irreversible in that it is dissipative and produces waste heat. Physicists call the non-existent exceptions to this rule dissipationless, reversible processes.

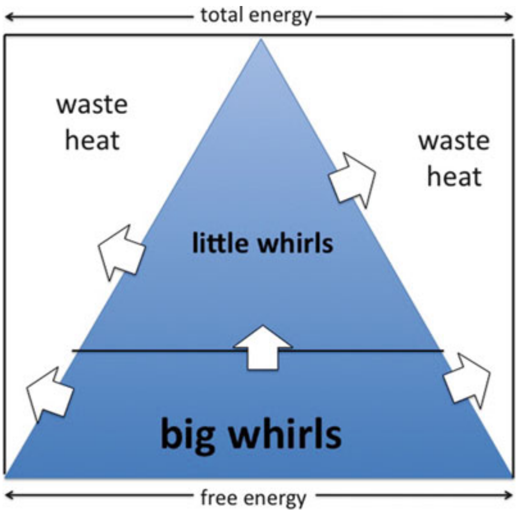

Figure 1. The dissipation of free energy. Starting at the bottom, the free energy of a few big whirls gets converted into many more little whirls and dissipated into waste heat. The total energy (= width of figure) is conserved. Big whirls turning into little whirls which turn into waste heat is a simple way to understand the more complicated picture of Fig. 2.

The conversion of free energy into waste heat can be similarly described for all processes (Kleidon, 2010). While Earth-bound climate scientists take the free energy from the Sun as a given, astrophysicists can dig deeper into the origin of free energy. Figure 2 is a more explicit version of Fig. 1 that tries to do that.

Just as big atmospheric whirls on Earth dissipate into little whirls and soon become microscopic waste heat, on a cosmic scale, the energy of the universe – initially stored in a small number of degrees of freedom – dissipates as it spreads out over a larger number of degrees of freedom (Fig. 3). In this way, free energy is converted into waste heat by dissipative structures, and the overall ability to do useful work diminishes. Energy is conserved, but distributing it over a larger number of degrees of freedom makes it less extractable to do work. This is how entropy increases (Jaynes, 1984).

Since there are no net flows of energy between large (>100 Mpc^3) comoving volumes of the universe, energy is conserved (first law of thermodynamics). This constant energy is represented by the constant width of (Figs. 1, 2, and 4). The second law of thermodynamics (entropy increase) is represented by the diagonal lines of the pyramid – the boundary between useful free energy and waste heat. The relationship between the Helmholtz free energy F, total energy U and waste heat TS (T: temperature, S: entropy) can be written as

$$F = U - TS, \tag{1}$$

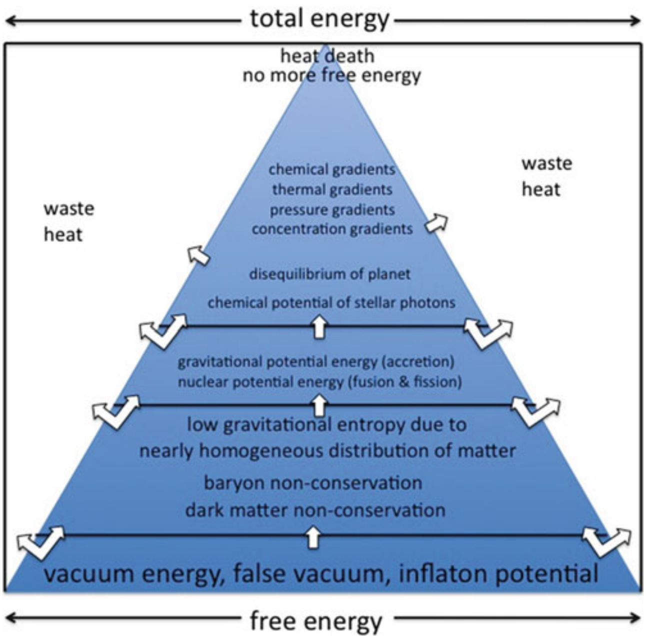

Figure 2. Trophic pyramid of free energy production – a more explicit and comprehensive version of Fig. 1. The free energy available at one level comes from the level below it. The width of the pyramid is the amount of free energy available. As free energy spreads into more and more processes at smaller and smaller levels, waste heat is produced as dissipative structures (*white arrows*) feed off the steady state disequilibrium. Dissipative structures can also transfer free energy to other structures. For example, stars provide high-energy photons that power the thermal gradients that make winds blow and evaporate oceans, driving the hydrological cycle, and energy for plants, which produce waste heat but also oxygen and apples (the free energy of chemical redox gradients) for heterotrophs. The lower levels are prerequisites for the life above it. Far-from-equilibrium dissipative structures traditionally classified as life forms (FFEDSTCALFs) are restricted to the top level. The narrowing at the top of the pyramid represents the decreasing amount of free energy available at higher trophic levels (Figure modified from Lineweaver and Egan, 2008).

or in words,

$$\text{Available work} = \text{Internal energy} - \text{Waste heat}.$$

Figure 4 is just a version of Fig. 2 annotated with Eq. 1. Taking the differentials of Eq. 1 for a system in which total energy is conserved and temperatures are not changing (i.e. T_{Sun} = constant ~ 6,000 K and T_{Earth} = constant ~ 290 K) yields

$$dF = -T\,dS, \tag{2}$$

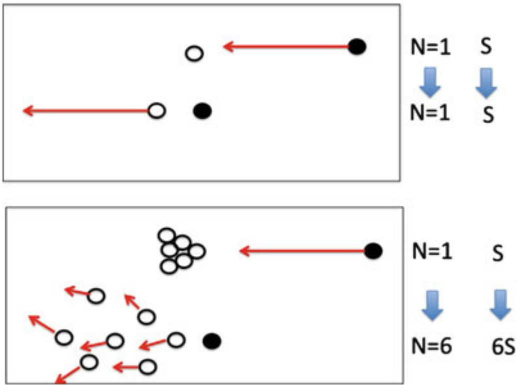

Figure 3. Entropy, S, increases when the number of degrees of freedom over which the energy is spread increases. In the *top panel*, the kinetic energy of one *black ball* is transferred to the kinetic energy of one *white ball*. The number of degrees of freedom over which the energy is spread (and thus the entropy) is constant. In the *bottom panel*, the kinetic energy of the *black ball* is transferred to six *white balls*. The number of degrees of freedom increases from 1 to 6, and the entropy increases from S to $6S$.

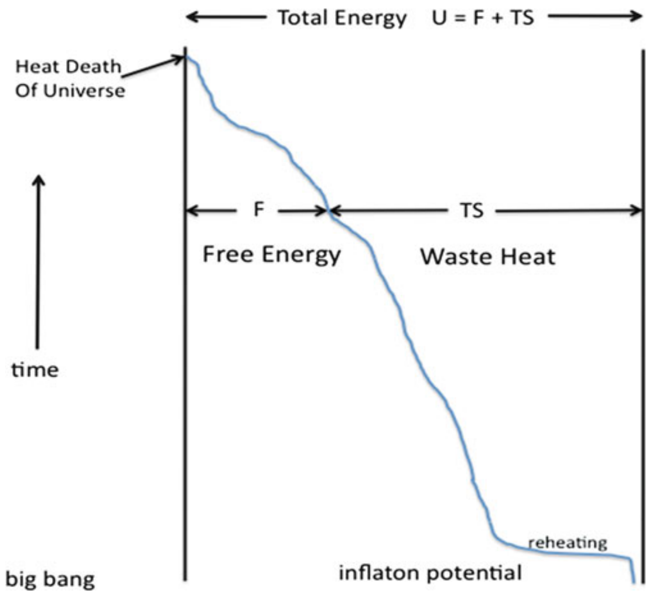

Figure 4. We can separate the total energy U into useful free energy F and waste heat TS (since $U = F + TS$). With a constant U, starting at the big bang at the bottom of the figure, entropy increases and F decreases. As time goes by, more and more of the initial free energy is converted into waste heat.

which means that in such a system, all extracted free energy dF is eventually converted into waste heat TdS.

The various forms of free energy are usually written as (Bejan, 2006; Kleidon, 2010)

$$(dF = pdV + \phi dm + \boldsymbol{v} * \boldsymbol{dp} + \Sigma_i \mu_i \, dN_i) \tag{3}$$

where p is pressure, V volume, ϕ gravitational or electric potential, m mass or charge, **v** velocity vector, **p** momentum vector, μ_i chemical or nuclear potential of species i, and N_i number of particles of species i. For each pair of variables, the first is an intensive quantity, while the differential is of an extensive quantity. The extractable work comes from the gradients of the intensive variables (gradients in pressure, gravity, momentum and chemical potential). Work can be extracted from macroscopic gradients, i.e. gradients of a scale larger than the microscopic particles (atoms, molecules, charges) which get pushed around or fall through the gradients and importantly provide the large number of degrees of freedom for waste heat. A pressure gradient (think pistons of a steam locomotive or internal combustion engine) does "pdV" work. A gravitational potential gradient can do work when a mass, dm, falls (hydroelectric power plant). If the potential is from an electric field, work is done when a charged dm falls from high potential to low potential (inside a kitchen appliance for example). In the presence of a velocity gradient, momentum exchange does work (windmill). Work can be extracted from a chemical potential gradient (concentration gradient) when a particle species does work by going from high concentration to low concentration (lithium batteries, osmotic pressure engines, metazoan digestive tracts). Jaynes (1984) describes the relationship between the Carnot efficiency of a heat engine and the efficiency of muscles and insightfully relates both to work and the number of degrees of freedom.

2. Spiegelman's Monster

A differentiated and information-rich terrestrial environment applies selection pressure on whatever is existing or evolving in that environment. If the environment is hot, then molecules and membranes that can withstand the heat survive. On Earth-like planets, temperature, humidity, pH and surface chemistry vary both spatially and temporally. Any life form in these environments has to be able to survive the conditions and maintain enough variability in the population to be able to adapt to the changing condition. Thus, both the phenotypes and the dispersion of the genotypes are selected by the environment. The evolution of the dispersion is known as the evolution of evolvability (Kirschner and Gerhart, 1998).

As an example of how the information in the environment enters the genotype, and to quantify the minimal set of genes necessary to keep something alive, Spiegelman conducted some experiments (Kacian et al., 1972). He created environments that were ideal for a Qb virus. Everything the virus needed to survive and replicate was provided (RNA replicase, some free nucleotides and some salts). After 74 generations, the original viral strand of 4,500 nucleotide bases had evolved into a streamlined 218 nucleotide bases. All the extraneous bases normally used as molecular locks or keys to help the virus obtain what it needed atrophied away. The simplest explanation of these results is that in an information-poor environment where there are no challenges, no selection pressure, and no tricks are needed, the information in the bases of the virus is not selected for and diffuses away. Thus, the amount of information in the genotype reflects the amount of information in the environment. This lazy, streamlined, couch potato of a virus became known as Spiegelman's Monster. Thirty years later, Oehlenschlager and Eigen (1997) showed that Spiegelman's Monster could become even shorter, containing only ~50 nucleotides, which provide the binding sites for the RNA replicase (Mareno and Ruiz-Mirazo, 2009). This relationship between environment and genes is generic. If extraterrestrial life exists, then the information in its inheritable molecules will also reflect the information of its environment.

3. The Entropic Paradox: A Low Initial Entropy Seems to Conflict with Observations

There is general agreement that life on Earth (and elsewhere) depends on the non-equilibrium of the universe (Anderson and Stein, 1987; Schneider and Kay, 1994). If stars are shining, if there is any friction, if life of any kind exists in the universe, then the second law of thermodynamics tells us that the entropy of the universe is monotonically increasing. Since the big bang, ~13.7 billion years ago, irreversible dissipative processes have been increasing the entropy of the universe. Thus, the initial entropy had to be much lower than it is today, and in the future, it will be much higher than it is today (Figs. 5 and 6).

The cosmic microwave background (CMB) radiation is almost isotropic. The temperature of this radiation is ~2.7 K in all directions. There is, however, a very low level of anisotropy. The amplitude of the temperature anisotropies are $\Delta T/T \sim 10^{-5}$ (Smoot et al., 1992). This low level of temperature anisotropy after the big bang means that the universe was close to chemical and thermal equilibrium 400,000 years after the big bang. There were no stars or planets, no hurricanes and no luminosity gradients. Density inhomogeneities were comparable to the temperature anisotropies ($\Delta\rho/\rho \sim 10^{-5}$). Thus, according to the standard accounting of entropy (which importantly does not include any term for gravitational entropy), the universe was near equilibrium and therefore near maximum entropy, not minimum entropy. All the entropy terms that we know how to compute were already close to their maximum values. With S at an apparent maximum, in Eq. 1, we would have $F = 0$. That is why in Fig. 5, the point labelled "observed in CMB" is in the upper left. If this were the whole story, the universe would have started near maximum entropy and nothing would have happened: no

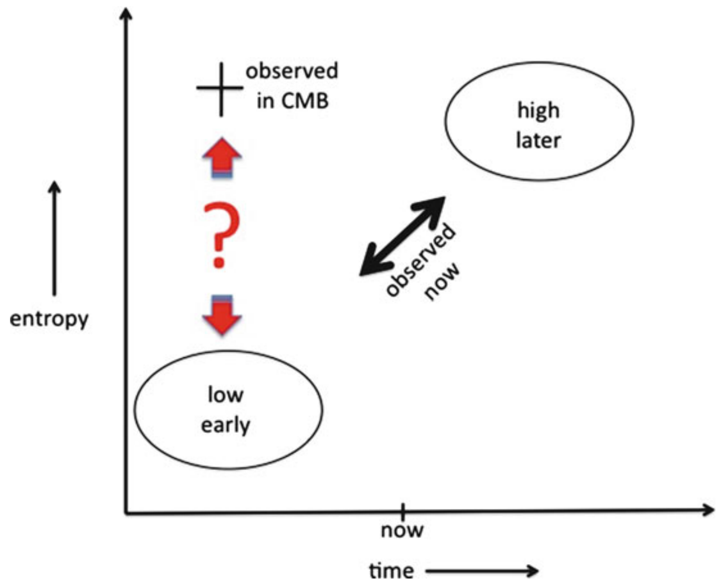

Figure 5. The entropic paradox. The entropy of the universe is increasing. Therefore, in the future it will be higher, and in the past it was lower. A telescope is a time machine; as we look further away, we look into the past. When we look as far away as we can, we see the cosmic microwave background (*CMB*) radiation – the afterglow of the big bang (Smoot et al., 1992). By analysing this radiation, we can see that the early universe was close to thermal, chemical and density equilibrium. That is, the entropy of the universe appears high ~400,000 years after the big bang when the CMB was emitted. Thus, a low initial entropy seems to conflict with CMB observations. There must be some component of the early universe that was at low entropy – so low that it dominated the other entropic terms.

stars, no life, no observers. An observable universe has to start in a low entropic state in order to produce structures like observers.

How can a big bang universe, apparently near equilibrium, have a low entropy? There has to be another entropy term responsible for the low initial entropy, and this term has to dominate the entropy budget of the universe because the other terms were already close to their maximum values. This is an important point. It means that all the chemical, thermal and luminosity gradients that now exist in the universe and support life are ultimately due to a poorly understood and unquantified entropic term that was initially low but which still dominated all the other terms that were close to their maximum values. The missing term is the entropy associated with gravity (cf. next section).

Figure 6 illustrates how entropy, starting at some minimal initial value S_{ini}, has increased over time and is approaching a maximum S_{max}. If $S(t)$ were now at its maximum possible value S_{max}, then the universe would be in equilibrium. Thomson (1852) understood this as a heat death since no heat could be exchanged – everything would be at the same temperature. The universe would be isothermal,

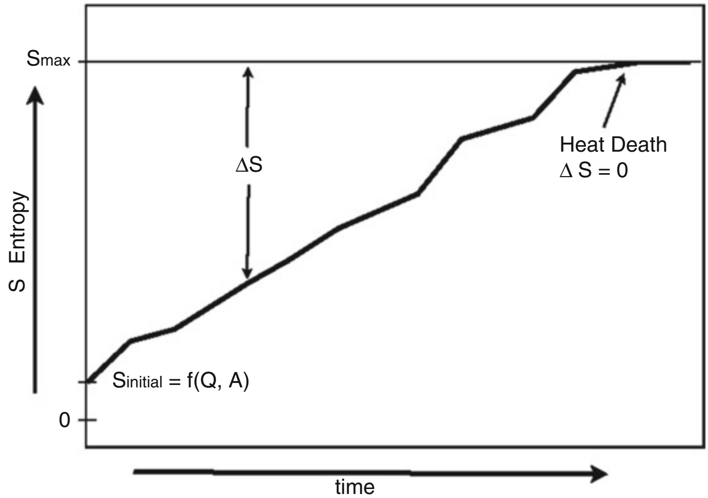

Figure 6. Same as Fig. 5, but constructed to show the entropy gap ΔS (Eq. 4). The second law of thermodynamics tells us that as long as life or any other irreversible dissipative process exists in the universe, the entropy of the universe S will increase. Thus, the entropy of the very early universe had to have some initially low value $S_{initial}$ where "low" means low enough compared to the maximum possible entropy S_{max} so that ΔS is large and can produce and support irreversible processes (including life forms) in the universe. As indicated in the lower left of the figure, the initial entropy is some function of the parameters Q and A which are used to quantify the level of inhomogeneity of the cosmic density distribution (Figure from Lineweaver and Egan, 2008).

isobaric, isodensity – iso-everything. There would be no gradients, no structure, no design and no observers to see all this featurelessness. Equilibrium is a structureless, designless heat death. Since this is not yet the case, there is an entropy gap ΔS between the maximum possible entropy and the actual entropy of the universe,

$$\Delta S(t) = S_{max} - S(t). \tag{4}$$

In Lineweaver and Egan (2008), we showed how the entropy gap is the driver of all irreversible processes.

Since $\Delta F = -T\Delta S$ (Eq. 2), solving Eq. 4 for $\Delta{\sim}S$ would yield an estimate of how much free energy is available in the universe to support life or maintain any far-from-equilibrium dissipative structure. To solve Eq. 4, we need to know $S(t)$ and S_{max}. In Egan and Lineweaver (2010), we reviewed previous estimates of $S(t)$. Based on the latest observations of the mass function of supermassive black holes, we found $S(t)$ to be at least 30 times larger than previous estimates. With this new estimate of $S(t)$, S_{max} is the only important remaining unknown which we address in a paper in preparation (Egan and Lineweaver, 2012). Thus to understand the origin of design in nature, we need to understand the low initial value of the entropy of the universe and the corresponding high initial value of ΔS.

4. Gravitational Entropy

The relationship between entropy and gravity is fundamental and poorly understood. Penrose (1979, 1987, 1989, 2004) has been concerned with the relationship between entropy and gravity for more than three decades (see also Barrow and Tipler, 1986, their section 6.15). Penrose (1979) suggested that a low gravitational entropy was responsible for the initially low value for the entropy of the universe. The low gravitational entropy of the nearly homogeneously distributed matter has, through gravitational collapse, evolved gradients in density, temperature, pressure and chemistry that provide the free energy required by life. As seen in the top panel of Fig. 7, when thermal energy dominates the gravitational binding energy, maximum entropy corresponds to an even distribution of matter. In contrast, when gravitational binding energy dominates, maximum entropy corresponds to collapse into black holes and evaporation, through Hawking radiation into photons. In other words, the low initial entropy of the early universe is explained by the even distribution of matter subject to gravitational force, which

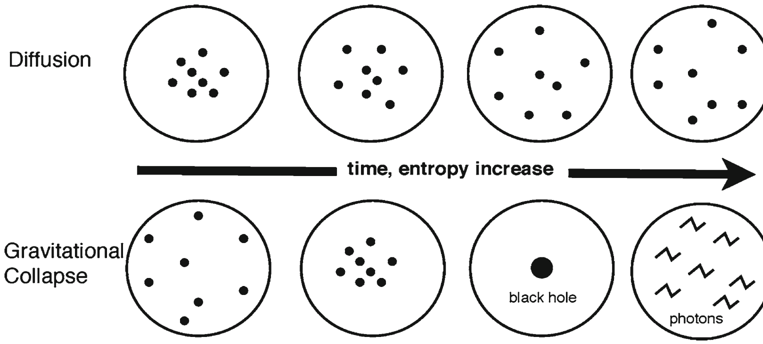

Figure 7. Entropy increases during both diffusion (*top*) and gravitational collapse (*bottom*). It is widely appreciated that non-gravitating systems of particles evolve towards homogeneous temperature and density distributions. The corresponding increase in the volume of momentum-position phase space occupied by the particles represents an increase in entropy. If thermal energy dominates the gravitational binding energy (*top*), then entropy will increase as material diffuses and spreads out over the entire volume (think perfume diffusing in a room). We know how to compute this phase-space entropy (e.g. Binney and Tremaine, 2008). If gravitational binding energy dominates thermal energy (*bottom*), then entropy will increase as some material and angular momentum is expelled to allow other matter to have lower angular momentum and gravitationally collapse into galaxies and stars. We do not know how to compute the entropy associated with gravitational collapse. Stars eventually collapse and/or accrete into black holes, whose entropies we do know how to compute (Bekenstein, 1973; Hawking, 1974). If the temperature of the background photons is lower than the temperature of the black hole, the black hole will evaporate to produce the maximum entropy state – a bath of photons spread out over the entire volume (*last circle in lower panel*). We know how to compute the entropy of a photon bath (e.g. Kolb and Turner, 1990). Thus, the only entropy that cannot be computed is the entropy associated with the gravitational collapse in the *left side* of the *lower panel* (which corresponds to the initial state of matter in the universe) (Figure modified from Lineweaver and Egan, 2008 and Fig. 27.10 of Penrose, 2004).

over time resulted in gravitational collapse that created the energy gradients on which life depends.

Gravitational entropy is fundamental to the evolution of the universe. It is responsible for both the low initial entropy of the universe, and it is the dominant contributor today in the form of the entropy of supermassive black holes. Previous authors have looked at the future of life (Dyson, 1979; Barrow and Tipler, 1986) and the future of astrophysical objects (Adams and Laughlin, 1997). But this fundamental concept is only poorly understood. No consensus about the ultimate future of life and dissipative processes has emerged because the relationship between gravity and entropy has remained confused and unquantified.

How can we quantify the entropy associated with density fluctuations and gravitational collapse? There is no accepted mathematical equation that relates entropy with any of the observable parameters of the initial density perturbations. Initial density perturbations in the universe have been measured (Smoot et al., 1992) as the power spectrum of cosmic microwave temperature fluctuations and as galaxy density fluctuations (e.g. Peacock, 2000). $Q \sim 10^{-5}$ is the observed normalization of the initial fluctuations. We have no mathematical formulation of the relation between the initial entropy of the universe and these measures of deviation from a homogeneous distribution of matter. We have no formula of the form

$$S_{\text{initial, grav}} = f(Q). \tag{5}$$

In addition, observational cosmologists measure and model the growth of large-scale cosmic structure as a power spectrum,

$$P(k,t) = g^2(t) A k^n, \tag{6}$$

where k is inverse wavelength, n is the spectral index, $g^2(t)$ is the growth factor, and A is the initial normalization shown in the lower left of Fig. 6. Yet we have no formula relating A to the initial entropy or the growth factor to the growth of entropy.

Much has been made of our current inability to unify general relativity and quantum mechanics to arrive at a theory of everything. Although the murky relationship between gravity and entropy may provide key insights into the theory of everything, it has received much less attention. Gravity is almost universally ignored in thermodynamics textbooks. What is known about the relationship between entropy and gravity is similar to what was known about the relationship between energy and heat 200 years ago when the concept of energy conservation in thermodynamics was being developed. It took many decades for the different forms of energy (e.g. potential, kinetic, heat) to be recognized. It seems to be taking even longer to recognize and define the different forms of entropy. The relationship between information entropy (Shannon, 1950) and thermodynamic entropy has been partially clarified (Dewar, 2003; Brissard, 2005). But we still need to clarify and quantify the relationship between gravitational entropy and the other forms of entropy.

5. Inflation, Baryon Non-conservation, and the Homogeneous Distribution of Matter After Reheating, as the Sources of Free Energy

In the last 30 years, to extend the big bang models to earlier times and solve several problems, quantum cosmologists have constructed inflationary scenarios. In these models, the low amplitude initial density fluctuations that have been observed at large scale in the cosmic microwave background radiation, have their origin in irreducible vacuum fluctuations of a false vacuum also known as the inflaton potential (Lineweaver, 2005). Inflation can occur either at the Planck time (10^{-43} s after the big bang) or at the GUT scale (10^{-35} s after the big bang). At the end of inflation is a period called reheating, in which all the energy of the false vacuum is dumped into the universe (Kofman et al., 1994). Matter and anti-matter particles annihilate. However, because of baryon non-conservation and non-equilibrium conditions described by Sakharov (1967), there was a slight excess of baryons over anti-baryons (Dolgov, 1997; Quinn and Nir, 2008). If there were not, all of the matter and anti-matter dumped into the universe at reheating would have annihilated and turned into radiation. Thus, the universe would have started off in a maximum entropy state and stayed that way (Lineweaver and Egan, 2008) – and we would not be here to think about it. However, there was a slight excess of matter over anti-matter, and so the result of reheating in combination with baryon non-conservation was to spread matter more or less homogeneously throughout the universe. Since this corresponds to low gravitational entropy, the universe starts off with a large entropy gap ΔS and lots of free energy, which, on its way to waste heat, can produce and maintain (for a while) all the complex, differentiated structures in the universe.

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