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Life, Information, Entropy, and Time:

Vehicles for Semantic Inheritance



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Abstract

Attempts to understand how information content can be included in an accounting of the energy flux of the biosphere have led to the conclusion that, in information transmission, one component, the semantic content, or “the meaning of the message,” adds no thermodynamic burden over and above costs arising from coding, transmission and translation. In biology, semantic content has two major roles. For all life forms, the message of the genotype encoded in DNA specifies the phenotype, and hence the organism that is tested against the real world through the mechanisms of Darwinian evolution. For human beings, communication through language and similar abstractions provides an additional supra-phenotypic vehicle for semantic inheritance, which supports the cultural heritages around which civilizations revolve. The following three postulates provide the basis for discussion of a number of themes that demonstrate some important consequences. (i) Information transmission through either pathway has thermodynamic components associated with data storage and transmission. (ii) The semantic content adds no additional thermodynamic cost. (iii) For all semantic exchange, meaning is accessible only through translation and interpretation, and has a value only in context. (1) For both pathways of semantic inheritance, translational and copying machineries are imperfect. As a consequence both pathways are subject to mutation and to evolutionary pressure by selection. Recognition of semantic content as a common component allows an understanding of the

Supplementary Sources

For many of the topics covered here I can claim no expertise. The resources of the WWW have proved invaluable in providing some of the background material. In particular, the following have all proved to be valuable sources for both history and philosophy.

The MacTutor History of Mathematics archive (<http://www-gap.dcs.st-and.ac.uk/~history/index.html>): created and maintained by John J. O'Connor and Edmund F. Robertson of St. Andrews University, Scotland, has provided delightful reading on the development of ideas in arithmetic, mathematics, and philosophy.

The History Guide (<http://www.historyguide.org/index.html>): edited and maintained by Steven Kreis, has supplemented by inadequate knowledge of history.

The *Stanford Encyclopedia of Philosophy* (<http://plato.stanford.edu/>): edited by Edward N. Zalta.

The History of Philosophy pages (<http://www.friesian.com/history.htm>).

The Internet History Sourcebooks Project, maintained by Paul Halsall (<http://www.fordham.edu/halsall/>).

The Hanover Historical Text project, from which the quotation of Parmenides was taken

(<http://history.hanover.edu/texts/presoc/parmens.html>).

During the time over which this essay has been developed, Wikipedia has emerged as a useful and reliable reference tool

(http://en.wikipedia.org/wiki/Main_Page).

The quotations from Gibbon's *Decline and Fall of the Roman Empire*, another good read, are taken from the Web version provided by Philip Atkinson and maintained by the Christian Classics Ethereal Library at Calvin College

(<http://www.ccel.org/g/gibbon/decline/home.html>).

The web sites for NASA (<http://www.nasa.gov/home/index.html>; see particularly the environmental monitoring of ocean and land at

<http://modis-ocean.gsfc.nasa.gov/>, and <http://modis-land.gsfc.nasa.gov/>, respectively), the European Space Agency

(<http://www.esa.int/esaCP/index.html>), and the National Oceanic and Atmospheric Administration (<http://www.noaa.gov/>), provide links

to much recent work on monitoring of energy fluxes, net photosynthetic productivity (NPP), weather, etc.

A compelling overview of the seasonal flux of NPP can be obtained from movies available at the Earth Observatory site

(<http://earthobservatory.nasa.gov/Newsroom/NPP/npp.html>).

The Richard Dawkins essay “Viruses of the Mind” is available on the web

(<http://cscs.umich.edu/~crshalizi/Dawkins/viruses-of-the-mind.html>), and the last chapter of *The Selfish Gene*, in which the idea of

memes was introduced, is available at <http://www.rubinghscience.org/memetics/dawkinsmemes.html>.

relationship between genes and memes, and a reformulation of Universal Darwinism. (2) The emergent properties of life are dependent on a processing of semantic content. The translational steps allow amplification in complexity through combinatorial possibilities in space and time. Amplification depends on the increased potential for complexity opened by 3D interaction specificity of proteins, and on the selection of useful variants by evolution. The initial interpretational steps include protein synthesis, molecular recognition, and catalytic potential that facilitate structural and functional roles. Combinatorial possibilities are extended through interactions of increasing complexity in the temporal dimension. (3) All living things show a behavior that indicates awareness of time, or chronognosis. The ~4 billion years of biological evolution have given rise to forms with increasing sophistication in sensory adaptation. This has been linked to the development of an increasing chronognostic range, and an associated increase in combinatorial complexity. (4) Development of a modern human phenotype and the ability to communicate through language, led to the development of archival storage, and invention of the basic skills, institutions and mechanisms that allowed the evolution of modern civilizations. Combinatorial amplification at the supra-phenotypical level arose from the invention of syntax, grammar, numbers, and the subsequent developments of abstraction in writing, algorithms, etc. The translational machineries of the human mind, the “mutation” of ideas therein, and the “conversations” of our social intercourse, have allowed a limited set of symbolic descriptors to evolve into an exponentially expanding semantic heritage. (5) The three postulates above open interesting epistemological questions. An understanding of topics such dualism, the élan vital, the status of hypothesis in science, memetics, the nature of consciousness, the role of semantic processing in the survival of societies, and Popper's three worlds, require recognition of an insubstantial component. By recognizing a necessary linkage between semantic content and a physical machinery, we can bring these perennial problems into the framework of a realistic philosophy. It is suggested, following Popper, that the ~4 billion years of evolution of the biosphere represents an exploration of the nature of reality at the physicochemical level, which, together with the conscious extension of this exploration through science and culture, provides a firm epistemological underpinning for such a philosophy.

Keywords

DNA; genotype; evolution; chronognosis; semantic content; Popper; evolutionary epistemology; memes

Introduction

The arguments of this essay arise from two apparently unrelated themes. The first of these is an attempt to address the question of how to integrate the information content of the biosphere into quantification of global energy flux. The second is the evolution of temporal perception and its extension into consciousness. Somewhat surprisingly, these areas coalesce because of a previously unrecognized property of one component of information content. As Shannon recognized, communication requires two components—a thermodynamic framework for coding and transmission, and the semantic content—the “meaning in the message.” I will argue that this latter component adds no additional thermodynamic burden. This thermodynamic inconsequence raises questions about how we know about the world, echoing the epistemological concerns of philosophers down the ages. My first task therefore is to explain why there is a problem in incorporating information content into the framework through which we perform our energy accounting. The second line of enquiry introduces recognition of the importance of temporal perception in defining behavior and the linkage between sophistication in sensory perception, and awareness of time—a theme that leads into the perennial philosophical enquiry about the nature of the mind. The two come together in our understanding of the role of information transmission in evolution and in civilization, of the emergence of life and of consciousness, and of how our present view of the world has evolved over the past

few millennia. What comes out of this enquiry is a fresh perspective on topics such as the emergence of biological complexity, the duality of mind and body, consciousness, and the “vital force.” For each of these, some aspects have been rejected from consideration by conventional science, but they continue to interest philosophers. They can be brought into a scientific context by recognition of a necessary coupling between the two components of communication recognized by Shannon: the “engineering problem” and semantic content.

Interception of Solar Energy by the Biosphere

Earth intercepts a small fraction of solar radiation, determined by simple geometric parameters. Since, in the aggregate, earth remains in steady state, the energy loss must balance the energy input. The universe pays its second-law dues by releasing a larger number of quanta, mainly in the IR, each at a lower energy appropriate to the differences in temperature between sun and earth. The different fluxes contributing to this overall process are quite complex. Major fractions include reflection and scattering by clouds, polar ice, bare land, and water; absorption by the atmosphere with energy loss through thermal (infrared emission) and chemical pathways; passive absorption and re-emission of IR by bare land; absorption by water, with direct re-emission as IR, or after a delay through the hydrologic cycle; and absorption by plants. The overall energy balance also includes the thermal emission from earth's endogenous heat sources.

Where does life come into the equation? As recognized by Boltzmann as early as 1886

The general struggle for existence of living beings is therefore not a fight ... for energy, which is plentiful in the form of heat, unfortunately untransformably, in every body. Rather, it is a struggle for entropy ... that becomes available through the flow of energy from the hot Sun to the cold Earth. To make the fullest use of this energy, the plants spread out the immeasurable areas of their leaves and harness the Sun's energy by a process as yet unexplored, before it sinks down to the temperature level of our Earth, to drive chemical syntheses of which one has no inkling as yet in our laboratories. Broda [1]

Although the mechanism of photosynthesis is now well explored, and we have more than an “inkling” of the chemical processes, Boltzmann's insight and general heat-engine treatment are still appropriate [2,3]. If we assume that the biosphere is, over an appropriate time interval, in steady state, any energy intercepted by the thin layer of life at the surface of earth must also eventually be converted to heat at terrestrial temperatures. As a consequence, since the cross-sectional area for solar interception is the same, the overall energy equation would be unaltered. Factors influencing albedo and emission, such as changes in the greenhouse effect, will complicate this simple picture, but we will ignore these for the moment. A substantial fraction of the incoming light energy is intercepted by the biosphere, predominantly by green plants, algae, and cyanobacteria. The intercepted fraction provides the input for photosynthesis, and hence the main driving force that sustains life on earth. Estimations of the fraction diverted to the biosphere vary somewhat, but the fraction is significant. Of the solar flux intercepted by the planet (the solar constant of $\sim 1379 \text{ W m}^{-2}$ of projected area) about 50% reaches the surface (Figure 1). On land about 33% arrives during a growing season, and about 20% of that is intercepted by leaves. Additional losses due to reflection (20%) and a poor color match (50%) mean that only about 0.8% of the light intercepted is saved as photosynthetic product. Of that, about 40% is used for maintenance, so $\sim 0.5\%$ of the solar flux at the land surface is available to fuel the other side of the biosphere: animal consumption, bacterial and fungal recycling. The productivity in the oceans is buffered seasonally, so that, although the instantaneous flux doesn't match that of the land, the gross annual ocean productivity is about the same as that of the land. It is estimated that about 100 billion metric tons of carbon dioxide are assimilated annually through photosynthesis, corresponding to $3 \times 10^{18} \text{ kJ}$ (compared with $4.35 \times 10^{17} \text{ kJ}$

world energy consumption by man in 2002) [4,5]. This ratio is usually used to illustrate the scale of the photosynthetic energy system, but it is salutary to realize that already the

anthropogenic contribution is $\frac{1}{7}$ that of the rest of the biosphere.

Harvesting the Entropic Yield: The Other Great Revolution in Biology

Our knowledge of the energy fluxes through the biosphere is still far from complete. However, the broad outlines are well understood, suggesting that in principle we could quantify terms necessary for a more complete thermodynamic description. Much recent attention has been given to this area in the context of attempts to predict the effects of increased CO₂ and global warming on biomass yield, crop productivity, etc. [4,5], but major advances in our understanding of the molecular mechanisms involved provide the bedrock on which these efforts are based.

When photons are absorbed, they excite transitions in absorber bands matched in energy, which decay through photochemistry, or through emission of fluorescence, phosphorescence, and/or of IR photons. For most materials, the IR emission dominates. Some of the photons are emitted more or less instantaneously; others are retained by absorption in lower vibronic bands, leading to a temperature change and exchange of heat with the environment, and are re-emitted in the IR after a delay, the so-called latent heat. For absorption of radiation incident on the earth, the timescales for these processes range from “instantaneous” scattering with minimal loss of energy, to picoseconds for internal conversion, up to the diurnal and annual (or longer) cycles involving latent heat, the latter reflecting, for example, redistribution of thermal energy through winds and current, and the cyclic loss and accumulation of ice at the poles. Without biological intervention, these decay processes are uncoupled from any complementary process through which the potential work content can be conserved; they are completely dissipative. Some absorption by water leads to evaporation and a different sort of delay through the hydrologic cycle, with a range of time scales that can be much longer. This delay is due in part to a coupling of the energy absorbed to evaporative work against gravity, and against the osmotic potential of salt waters. However, this conserved energy is eventually also dissipated without further coupling.

In contrast to the dissipative processes above, absorption of photons by photosynthetic systems introduces pathways for energy conversion that are directly coupled to photochemical, chemical and electrochemical reactions through which some of the work content is conserved [2,3]. These initiate the chain of reactions through which the biosphere is sustained. Our understanding of these reactions has developed remarkably over the last few decades, but is only part of a larger revolution in biology. One of the triumphs of the biological sciences over the last 70 years has been the elucidation of the metabolic web of *coupled reactions* through which the energy content of light or food is conserved and used to drive the synthetic processes through which life is maintained. After the introduction of Mitchell's chemiosmotic hypothesis [6–10] in 1961, elucidation of the mechanisms of the main energy transduction processes of the biosphere, photosynthesis and respiration, has revealed a whole set of electrochemical mechanisms coupling photochemical and electron transfer reactions to transport of protons (or in a few cases Na⁺) across membranes. From a combination of biophysical, biochemical, structural, and molecular engineering studies, these reactions are in many cases now understood at the molecular level [11]. The electrochemical proton gradient is used to drive phosphorylation of adenosine diphosphate (ADP) to adenosine triphosphate (ATP) through a molecular turbine linked to a rotating catalytic machine. This stored work potential is then used to drive anabolic (building up) processes in the synthetic direction by coupled reactions in which ATP is hydrolyzed to ADP and phosphate. At the metabolic level, some of the work available from spontaneous catabolic (breaking down) reactions is also used to drive ATP

synthesis. The ATP is the “energy currency” of the cell. The overall reactions of metabolism, and of photosynthesis and respiration, can be broken down into partial processes that match the energy scale of the ATP/(ADP + phosphate) inter-conversion and thus facilitate the coupling between these reactions through which some of the energy is conserved for synthesis. By breaking down the overall reactions to many partial processes, and coupling these through the ATP/ADP system, metabolism introduces a delay in entropic decay of the intercepted energy, during which the available work can be used to drive the biosphere.

The coupled reactions through which photosynthetic and respiratory electron transfer chains drive ATP synthesis carry the major flux of energy in the biosphere. Mitchell's genius was to recognize that, contrary to earlier expectations, they are all transport processes, aspects of vectorial metabolism. The revolution in bioenergetics following from Mitchell's ideas, introduced a spatiotemporal dimension into biochemistry that has brought into focus the importance of membranes, transport, compartmentalization, etc. and that has colored the whole of biology [9].

Incorporating Information Content into the Energy Accounting

While in principle we can treat the biosphere as a physicochemical system operating under the standard laws, one aspect of the energy balance presents difficulties. The problem is how to deal with the informational content of the biosphere. Information content comes into the picture at two levels: that associated with the biochemistry of the biosphere and that associated with human communication. For the period of evolution before the invention of abstract representations (about 30,000 years ago), the energetic components could be subsumed under the chemical free-energy changes associated with synthesis of DNA. However, *Homo sapiens* as a species has learned how to communicate through language, to archive experience, and to transmit information between generations. This has led to a significant change in the informational content of the biosphere, or at least in its distribution. Apart from shifts in distribution among life forms, no obvious corresponding increase in the chemical potential attributable to the biosphere has been documented. There are dramatic changes in the artifacts of civilization (cities, roads, ports, the Internet, etc.), and anthropogenic effects on the biosphere itself, which might be taken as consequences of the increased sophistication in exploitation of information, and these can in principle be quantified through econometric methods. But these are separate from the information content itself. How do we account in our energy balance for the interventions of human society that have led to such massive changes in the environment?

Biological Information

It is common parlance when discussing the ordered state of a system to refer to its “information content.” When used in this context, an explicit connection between information content and entropy is clearly established through the organization of the system. Information content is encoded in a physical system through an ordering that requires input of work, and the term is then used as a synonym for the increase in order (negentropy) in its standard physical sense. The physicochemical changes in state can be described through standard thermodynamics. Information is encoded in the local gradients, physical or chemical, that define the state of each coding element, and the effectiveness of storage is directly related to the stability of the gradients formed. Attempts to record the data in a fluid medium would lead to its disappearance by diffusion. This physicochemical usage relates to the physical state of the system, but tells us nothing about the semantic content of the information stored (the message encoded). The term information content has alternatively been used to cover this semantic aspect, although the distinction between usages is often obscured. It is just this distinction between the thermodynamic and semantic usages of the term that I wish to discuss further here.

Semantic Content Cannot be Evaluated by Physical Measurement

It is useful to recognize some interesting features of information content, and use of this term in chemistry, physics, communication engineering, and biology. The first of these is quite general and stems from the problem of relating information content of a system to classical thermodynamics. The classical definition of entropy through probability, arising from the work of Carnot, Clausius, Boltzmann, and Gibbs, is related to our general thermodynamic framework through its use in relation to physical states and their temperature. The Boltzmann constant and the gas constant are proportionality factors, the values of which can be determined experimentally. They relate degrees of freedom in the system and its temperature to energy and determine the units. Such constants allow information content to be related to classical thermodynamics, but only when specifically related to physical states. However, it seems to me that a problem arises when we come to consider the semantic component. Although encoding and transmission of a message require changes in physical states, the “meaning of the message” itself is not related to these physical states in any thermodynamic sense. Of course, we need a “thermodynamic” framework (data storage, coding, carrier, etc.), but we cannot tell by examination of its *physical* properties whether a CD-ROM contains the complete works of Shakespeare or gibberish. The “meaning” is intangible; it occupies no volume, has no mass, no electromagnetic property, and is not dependent on temperature. We can transfer the *Encyclopedia Britannica* to a hard disk in our car, but we have not identified any mechanism through which we could drive off using the “energy” released as the meaning is unraveled. We can transmit the informational content of the human genome at the speed of light without altering the wavelength of the light. By use of appropriately tuned devices, we can activate Voyager to transmit pictures by radio of the far planets and receive the data, regardless of the low temperature and near vacuum of the intervening space. In these last two examples, the energy cost of transmitting a meaningful message or equivalent amounts of encoded random data would be the same; the data can only be determined as meaningful after translation. The importance of translation can be highlighted by introduction of the notion that each of these messages would have been appropriately formatted and might have been deeply encrypted. In each of these examples, it is apparent that a message on which we place a high value behaves as if it had no energy content; it confers no *additional* thermodynamic burden. Of course, the information content at some point has to be recorded in physical format, and the archival medium is interrogated and the transmission medium altered in the process with an energy cost, and transmission of data requires a carrier, encoding and decoding functions, also with an energy cost; but the *value* of the message itself, its meaning, is not a thermodynamic term. It depends on a translational context.

Shannon's Recognition of the Distinction Between Engineering and Semantic Aspects

The fidelity of transmission of information is the subject of a vast canon of literature on communication engineering following from Shannon's elegant development of Information Theory [12]. There has been a longstanding controversy¹ over the relation between “informational entropy” and thermodynamic entropy, and much confusion arising from the loose usage of the term information. As noted above, it can be used in a context in which informational entropy is equivalent to thermodynamic entropy, but only if related explicitly to physical states. Alternatively, in the communications usage, it is appropriate when used comparatively, with reference to general problems of maintaining the integrity of the information, for example, when the informational entropy, a probability function, is being compared between two states such as a transmitted and a received message. The utility of informational entropy lies in the fact that two encoded messages, before and after transmission, for example, can be compared in the context of the coding elements, even when the encoding is different. If coding is implicitly binary, and physical states are treated as explicit binary

elements, informational entropy is again synonymous with thermodynamic entropy. However, as Shannon pointed out in his seminal paper [12], the semantic aspects of information (the meaning of the message) are irrelevant to such engineering problems. Without examining the message itself, we have no way of knowing its semantic content, or its value. Implicit in Shannon's distinction is the question of the thermodynamic status of semantic content pointed out explicitly above.

We therefore appear to have three different aspects of the information content:

- i. the thermodynamic side, in which the information content is related to the ordering of systems in which the data are stored, encoded, transmitted and restored,
- ii. other engineering aspects associated with the integrity of information coding, in which probabilistic methods can be applied, and
- iii. the semantic component of information transmission, where we lack a philosophical apparatus for relating the information content to the thermodynamic world.

Clearly, the semantic content is of importance, but if, as Shannon seems to imply, we cannot measure an energy content through its interaction with the physical world, how can we bring

¹Shannon discussed the problem with Von Neumann [70], who advised him to call his probability function "entropy": "You should call it entropy, for two reasons. In the first place your uncertainty function has been used in statistical mechanics under that name, so it already has a name. In the second place, and more important, nobody knows what entropy really is, so in a debate you will always have the advantage." Several physical chemists have expressed the view that Shannon should never have taken this joke seriously; as noted in the text, the expressions are the same only when they refer to the same physical states. The modern usage of "information" in physics seems more general; there is an implicit relation to entropy through linkage to physical states, but the constant is omitted, and the treatment is assumed to relate to binary states which can in principle be at any scale, down to sub-atomic spin states (the entropy is determined by

the total degrees of freedom of matter/energy). Shannon's equation for uncertainty ($H = -K \sum_{i=1}^n p_i \log p_i$) and Boltzmann's H-equation have the same form, a probabilistic form first developed by DeMoivre in a treatise on games of chance from the early 18th century (*The Doctrine of Chances*, first published in 1718). In Shannon's words in relation to informational entropy, "the constant K merely amounts to a choice of a unit of measure." If the unit of measure is directly related to a physical system, k_B , or its molar equivalent, R, is appropriate. If two messages are stored in an equivalent medium, use of the equation in a comparative context becomes quantitative, but not equivalent to a thermodynamic usage. If K refers to an arbitrary coding element, comparisons can be made quantitative if any difference in coding elements is explicitly recognized (by use of two different Ks, by choice of an arbitrary (usually binary) coding element, or by omission of K). If a binary coding element is identified with a binary physical state, informational entropy has the thermodynamic meaning commonly used in physics. However, this usage introduces a problem of nomenclature; does "information" carry an implicit semantic component? If so, then use of information as synonymous with negentropy is misleading. If information is taken to include the semantic component, then it necessarily has to involve, at the least, an implicit receiver, with interpretational and translational components of a physical or biological apparatus.

In Weaver's introduction to a later summary of Shannon's work [12,71] he pointed out that the problem of information transfer can be partitioned into three separate levels. Only the first of these is addressed explicitly by "classical" information theory: 1. How accurately can the symbols that encode the message be transmitted ('the technical problem')? 2. How precisely do the transmitted symbols convey the desired meaning ('the semantics problem')? 3. How effective is the received message in changing conduct ('the effectiveness problem')? Weaver has interesting ideas on each of these areas and recognizes the difficulties in formalizing any treatment of the last two. Weinberger [72] has recently developed a treatment of the third theme by applying the Shannon equation to an analysis of the consequences of action. He defines "pragmatic information" as the information gain in the probability distributions of the receiver's actions, both before and after receipt of a message in some predefined ensemble. The treatment involves finding the mutual information between the ensemble of messages that could have been sent and the ensemble of outcomes resulting from these messages. This allows for some interesting conclusions, but omission of the constant K in the Shannon entropy of message and outcome ensembles leads one to wonder what states are scored in the probability functions and how they can be treated in real terms, as apposed to the abstract. In any evolving system, the pragmatic solution is of course simpler and more savage: survival of the fittest.

Weinberger's treatment does not address the status of semantic content—the component of Weaver's partitioning previously recognized by Shannon—though he does refer to attempts to deal with it in the context of complexity (see references below). However, he offers the opinion that none of these treatments have been very successful, and it seems unlikely to me that any treatment that fails to recognize that semantic content has value only in context, and only after translation will be successful. An unabashed recognition that semantic content contributes no additional thermodynamic burden does seem to lead to a productive line of thought. However, I am aware that recognition of the importance of a component of biology that is not accessible to physical measurement will be anathema to many of my scientific colleagues. I should therefore make it clear (again) that I am not proposing anything unnatural here. As long as the message is tied to thermodynamic representation, we can deal with it in a secure framework of realistic philosophy, and pursue the interesting implications.

For a discussion of different perspectives on the relation between classical thermodynamics and information theory; see [73–76]. For other references see Brian Harper at (<http://www.asa3.org/archive/evolution/199707/0124.html>). Further discussion of complexity in the semantic context can be found in [77–80].

it into the context of measurement through which we evaluate the energy balance of the biosphere? There is an obverse of this question; can there be any message without an encoding in some physical form?

Statement of Purpose

The main thrust of this essay is to explore these questions and their ramifications in biology and philosophy. I will take the view, first, that the semantic content of a message cannot be evaluated in a conventional thermodynamic framework. The “meaning of the message” is not something which we can measure using the tools of science. Semantic content has a value that depends on a context and becomes apparent after processing through a translational machinery. Second, I will take it that use of the term “information” in a context that implies that semantic transmission can occur without a thermodynamic vehicle, takes us outside the scientific realm. By adhering to these two principles, I will show that some interesting aspects of biology and philosophy that have proved puzzling, and even intractable, can be opened up to examination, despite the limitations implicit in my first principle.

The Engineering Problems: The Thermodynamic Component

The engineering problem of data storage is straightforward; in order to store information we have to modify a medium by “ordering” it locally, either through physical or chemical change. This necessarily involves an input of work. A particular message is stored through an ordered set of codons, or through some equivalent change in the medium.² Does this necessarily mean that the gradients are exploited in transmission of information? In principle, the work involved in defining a codon could be returned by coupling to an appropriate system in the surroundings. This would require a device in which work-terms, scale, and pattern were appropriately matched. But transmission of information using the stored work would necessarily lead to some loss of the stored information; it might be useful for a one-shot transmission, but not for archival purposes. Any reading would deplete the stored information; eventually all information would be lost from the original medium, essentially by diffusion. In practice, in all systems that depend on fidelity and long-term storage, information is read from a medium by interrogation of the state with an *input* of work, rather than through output by exploitation of the work potential stored.

The same general engineering problems are dealt with in biological systems. Storage of genetic information in a stable form requires work through synthesis of DNA polymers, and the semantic content is abstracted by specific chemical interrogation, again with input of work. The data are stored in linear format, information is encoded in the sequence, and translation leads either to replication or to synthesis of linear molecules in which the code is directly reflected. Biological diversity results from exploitation of the combinatorial possibilities of the code. “Coding elements” are recognizable by sequence characteristics encoding protein sequences. The triplet code of different combinations in sequence of the 4 bases, allows coding for 20 amino acids, with excess informational capacity for redundancy, punctuation, and control. The combinatorial possibilities provided by 20 amino acids with different physicochemical properties, each with several conformers, allow for a much larger range of proteins with different catalytic, control, and structural functions. Many of the so-called “noncoding” elements encode sequence expressed as RNA polymers that have roles in the translational machinery, control and timing. All these translational products in turn provide a

²Writing is an interesting case: a blank medium is modified by a local covering of opaque dye, using symbols that originated as pictograms, but have developed more abstract forms. The data encoded can be read through use of light reflected from the surface and focused onto an appropriate decoding device that deciphers the symbols, most commonly the eye/brain interface.

basis for the higher orders of combinatorial complexity that lead to the full range of diversity of the biosphere.

Semantic Content has Value Only in an Appropriate Context

In order to bring out the distinction between the engineering and semantic uses of the term “information content,” I will introduce the next part of my discussion through Olsen's “miracle.” My colleague Gary Olsen told me how in high school he had undertaken a physics exercise in which he and his fellow students were asked to toss a coin and record the statistics. Being a conscientious student, Gary recorded not only the net yield of heads and tails, but also the sequence, for a thousand or so trials. Not surprisingly, he found that the two options occurred with about equal probability. However, Gary noted that the probability of obtaining the *same sequence* of heads and tails in any subsequent trial was exceedingly low, hence the miracle. The important lesson from this example is that the semantic content of the sequence had a special significance, but *only* in relation to its peculiar context. There was no less informational entropy in this particular sequence than in any of the other equally improbable sequences explored by the class, but it became significant because Gary noticed its interesting semantic properties.

We will return to this distinction between a statistical and a sequential view later. For the moment, I want to emphasize that the value of this particular message depended on context. This brings up the interesting possibility that the semantic content of all biological information must fall into this same general contextual framework; it has value only in relation to a biological context. The idea that semantic content does not contribute to the thermodynamic cost of communication might seem to take consideration of this topic outside the domain of science. However, if semantic content is tied to a thermodynamic representation, then the latter can provide constraints that justify further consideration. In the following, I will explore the consequences of accepting this proposition.

The Distinction Between Thermodynamic and Semantic Components of Genetic Inheritance

As noted above, the engineering side of biological semantic transmission is handled at the level of coding and information storage in DNA (or RNA). However, the semantic content of a particular encoding in the DNA sequence of a genome, the genotype, has significance only after translation, and expression in some *functional* context, such as a particular protein, control mechanism, behavior, organism, etc., features lumped together as the phenotype. Notwithstanding the dominant role of the gene [13], it is the phenotype that is tested by evolution. Dawkins [14] suggests that we “... think of phenotypes as the levers of power by which the successful replicators manipulate their way into the next generation ...”. The distinction between the gene as a physical entity, and the message carried by the gene, is subtle. Although the metabolic cost of synthesis of DNA can be quantified, the cost is sequence-independent. The informational entropy of a DNA sequence could be scored through a probability function, and probability approaches are of importance in comparison of sequences and in determination of the history and fidelity (or otherwise) of information transmission within and between families, but the probability score for a particular sequence has no greater significance than that for many other of the similarly improbable instances derived from the same set of codons. Of course, in a comparative context, the informational entropy would have value in scoring the similarity of two sequences. It is the message, however, that is unique. The particular sequence of a particular genome defines a particular semantic content, the message that is passed on, and hence the particular organism, and, with small local variations, the species. It is the message that has a value, but only in the context of Darwinian evolution (with all the necessary complexities in terms of mechanism).

Interestingly, the distinction between semantic and mechanistic aspect of information transmission was already noted by Gamow in the days of the RNA tie club, shortly after the first introduction of the Watson-Crick model [15]. He pointed out that the problem of semantic transmission in inheritance is separate from the precise mechanism, a distinction implicit in Shannon's earlier treatment of information theory. The mechanism that has emerged from much subsequent research, although at first sight much less elegant than several of those proposed, is optimal and almost universal, but not accidental [16]. However, the mechanism is part of the engineering side. A reading of the stored information does not change the physical state of the storage medium or the information stored. In contrast, the meaning (the semantic content) is apparent only after translation, and its thermodynamic status is tenuous. The value of the message is tested by evolution. The organism is fitted through its inheritance of information for a particular ecological niche in which it has the best chance of survival. The niche is itself a complex matrix of geological, biological, and spatiotemporal interactions in which a dominant term is competition or collaboration within and between species in the quest for limited resources. But each of the species interacting in any particular ecological context is itself defined by its own inherited information, which determines the behavioral repertoire, and hence the parameters of interaction. The informational context, the multiple feedback loops between different species, is therefore extremely complex. Some flavor of this is given by Darwin's elegant closing remarks in *The Origin of Species*

It is interesting to contemplate an entangled bank, clothed with many plants of many kinds, with birds singing on the bushes, with various insects flitting about, and with worms crawling through the damp earth, and to reflect that these elaborately constructed forms, so different from each other, and dependent on each other in so complex a manner, have all been produced by laws acting around us There is grandeur in this view of life ... from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved.

It might be argued that, with the revolution in biology following the Watson-Crick model, we know a great deal about the genetic message; after all, we can read the code for Craig Venter, warts and all, and there's nothing insubstantial about it! However, our recent acquisition of an ability to decode the genetic message is a reflection of our understanding of the first level of decoding, leading to translation into protein. In the protocols for analysis of genes, which are mainly aimed to the "coding elements," we have developed an abstract analogue of the natural translational processing at this level, roughly equivalent to optical character recognition compared to an appreciation of Shakespeare. We are far from being able to determine from Venter's DNA what makes him a successful human being. If this higher level of sophistication is ever realized, it will be found still to be an analogue of translational processing. However, it will require a deeper knowledge of biology than is currently available; details of the developmental environment from conception to the time of his maturation. This would have to include a complete assessment of metabolic and cellular "fitness" from the molecular level on up, and a complete analysis of his personal "ecology," including not only the physical, but also mental, psychological, and social development, culminating in the niche to which he is fitted. A successful analysis might conceivably, in the future, be realized in retrospective, but, as the discussion on emergence below will show, not in predictive mode.

A point needs to be emphasized in relation to the distinction above, which refers to information transmission between generations. The synthesis of DNA leading to the germ cell line, or any other reproducing state, is clearly a copying function. The metabolic cost is part of the engineering side and is a relatively small fraction of the synthetic and maintenance costs of the cell. In contrast, the semantic content is defined by the message transmitted between generations. This depends on transfer of the message carrier into a translationally competent environment. In bacteria, and in asexual reproduction in the protista, simple cell division transfers a replica of the genome at the same time as it splits off a chunk of the cellular

machinery to provide the translational function. In sexual reproduction in higher organisms, the haploid gametes are highly specialized cells, with motile (male) and more sessile (female) forms. The female gamete carries the somatic machinery that provides the translational apparatus. The major bulk of the mature phenotype, generated by asexual (mitotic) reproduction and tissue specialization, plays only a mechanical role. In all cases, the semantic content changes slowly by essentially stochastic processes—mutation and selection—over evolutionary time. If this had any energy cost over and above that of copying, it would have been amortized over the evolutionary span. Assuming a common origin, this timescale, about 4 billion years, is the same for all extant organisms.

The Interplay Between the Biosphere and the Physical Environment

As a comparison of a global map of population density with one showing the environmental determinants of photosynthetic productivity will demonstrate, the biosphere is highly dependent on the physical environment. In addition to temperature, water availability, nutrients, and insolation, the distribution of life depends on such factors as the latent heat effects mentioned earlier. The winds, currents, and tides distribute thermal energy around the globe, ameliorating the seasonal change in insolation, and life on land depends on the fresh water delivered by the hydrological cycle. We should also note that the biosphere has, in turn, affected the environment. Among other things, life has changed the energy distribution of the light absorbed. The most obvious effect has been through the color of plants. The earth looks green from space; it is this that allows the seasonal sweep of spring from hemisphere to hemisphere to be monitored by satellite [5]. Another major effect has been on the atmosphere, which is in a very different state from that which would be found without life. In particular, the abundance of oxygen and ozone and the rather low concentration of CO₂ are a direct consequence of the invention of oxygenic photosynthesis and the change from an anaerobic to mainly aerobic environment some 2.2 billion years ago. Other less obvious effects have followed; the whole redox poise of the atmosphere, oceans, and surface chemistry has been shifted with the evolution of an aerobic atmosphere. Again, the web of interactions has been quite complex. The modern biosphere is, of course, adapted to the present environment, and most of its characteristic features are dependent on it. Although the biosphere is relatively robust to local disasters, and adapts well to long-term changes, the limited information we have about response to global changes occurring over short periods points to a more fragile balance. The evolutionary record shows numerous “extinction events,” only a few of which have been satisfactorily explained. This might give us pause in contemplating the more dramatic anthropogenic changes we have imposed on the environment in recent years.

It takes no great stretch of imagination to see from the above arguments that the biosphere has evolved as a whole, and in a dynamic exchange with the physical environment. Interactions between organisms feed back on the genotype of each contributing species through survival of the fittest. The semantic content of the biosphere, as reflected in the sum of the semantic contents of all genotypes, has been changing so as to adapt it to the opportunities available. Recently, those adaptations have included the peculiar abilities of our own species to expand the informational context on the semantic side. However, the starting point for each new generation is the information content that has survived from previous changes.

Semantic Transmission in Human Communication and the “Insubstantial” in Literature and Philosophy

The general conclusion that the semantic significance of information is determined by the context seems to apply equally well to the sophisticated end of the informational spectrum and might be more easily appreciated there. The works of Shakespeare (or Einstein's views on relativity) are of significance only in the context of an informed audience, equipped to translate

both the code (language) and the semantic content (meaning). The improbability of such works is of course remarkable. It might take a zillion monkeys the lifetime of the universe to generate the works of Shakespeare by typing at random. But so what? Any combination of the same alphanumeric and formatting symbols could have similar informational entropy. Each one would likely be unique. We value only the one, and that evaluation is specific to our particular cultural, linguistic, and temporal context.

An instructive experiment you can try is to ask a friend to close her eyes, and then say some phrase like “We are such stuff as dreams are made on, and our little life is rounded with a sleep.” You can then ask what came into her head when she heard these words. You could ask yourself the same question now, after reading the phrase. You will get a wide range of answers — “What’s this guy up to here?,” “Isn’t that a quote from somewhere?,” “That’s an interesting proposition,” or maybe even “Why, that’s Prospero’s speech from Act IV of the *Tempest*”! All these are wrong. In fact, nothing enters the head under such circumstance. No matter what channel is used (sound or sight here), the medium for transmission is physical or chemical and is intercepted before it enters the head (Figure 2). What is perceived as “coming into your head” involves a hierarchical set of translational and interpretational processing functions, triggering associative memories already resident in the mind. The phrase has meaning only because we have a mind and an education and the necessary translational machinery.

The insubstantial nature of mental processes has been a recurring theme in poetry and literature, as the quotation above will illustrate. The same theme recurs in philosophy, going back at least to Parmenides, Platonic Forms, and Aristotle’s phantasma, popping up in mediaeval theology in debates about universals and surfacing again more recently, for example, in Descartes’ distinction between mind and body, in Bishop Berkeley’s “ingenious sophistry,” in the Kantian distinction between noumena and phenomena, and in Putnam’s brain-in-a-vat scenarios (borrowed in the Matrix movies), and is discussed more extensively below. The recognition of two contributions to information content and my discussion of the thermodynamic inconsequence of semantic content both speak to this recurring theme. If the value of semantic content depends on context, then it also depends on the translational machinery through which that content is appreciated. For that component transmitted through DNA, the translational machinery is the common biochemistry of the biosphere. For the semantic content of our civilization, however, the machinery is that of the individual mind. Further pursuit of this theme in the context of the mind requires that we address the question of the origin of this remarkable contraption.

Biological Complexity, Behavior, and the Perception of Time

The evolutionary context in which the above discussion is framed introduces a temporal element, the ~4 billion years of development of the present biosphere, and the recent evolution of humankind (Richard Dawkins has a nice “reverse” account in *The Ancestor’s Tale* [17]). Our discussion of the semantic content of the genome requires consideration of time, the perception of time, and the evolutionary perspective, because the content has value only in a dynamic context that includes behavior among other temporal aspects. It is interesting to enquire when time became significant for the inhabitants of the biosphere.

All living things show behavior; they respond to stimuli from the environment. The environment is dynamic, and the behavior is adaptive. Because of this, the behavior has a temporal component; the organism anticipates its future in relation to the present. The success of this behavioral anticipation is essential to survival. In this sense, all living organisms are aware of time. To sidestep the accusation of an anthropocentric view, I will introduce as a term for this perception of time, the word *chronognosis*,³ with the adjectival form *chronognostic*.

This avoids the use of words like awareness and perception, which carry implications of a higher order of mental activity.

Bacteria have relatively simple patterns of behavior; the organism responds to gradients, either physical or of chemical effectors, by modifying the direction of rotation of a bundle of flagella. This determines whether they either swim in a straight line (clockwise rotation: the flagella are all in phase), or tumble (counter clockwise rotation: the flagella fly apart), in order to muddle their way to (or from) the source of attractants (or repellants).⁴ A change in behavior is triggered by a simple “perception machine.” For many bacteria, the behavior indicates a relatively short range of temporal perception (the chronognostic range) determined by a well-characterized set of mechanisms. These include detection of attractant or repellent molecules by binding to chemo- (or photo-) receptor proteins that span the cell membrane, followed by signal transmission through a conformational change that transmits a message from outside to inside. This activates a “cascade” involving various pathways, typically a two-component histidine kinase/response regulator system that leads to modulation of flagella response. An essential component of the mechanism is *adaptation*, a biochemical process with variable time constants that play off against each other to allow detection of a change in gradient (Figure 3). The precise role varies between organisms, but the system can be regarded as involving competing decay and refresh pathways, in which the time constants for some functions are under control by the state of activation of the receptor. This allows recognition of changes in gradients, with a time scale on the seconds-to-minutes range. We might take this range of time constant as defining their chronognostic range. However, for a worm, an ant, a fish, or a dog, the range is obviously longer. With the increasing complexity of metazoans, development of a nervous system, differentiation of organs of sense and development of the head-tail polarity, and a brain and memory in higher animals, the scope for behavioral complexity also increases, and along with this, the complexity of mechanisms for perception and the chronognostic range.

The temporal context of behavior is not restricted to animals. Mobility is the main feature distinguishing animals from plants and introduces a spatial element. I will call this the chronognostic scope, given by the product of spatial range and temporal perception. We can recognize that plants have a much more limited scope than animals. However, although the time scale of response and their mobility make behavior more obvious in animals, the need for regulation of the photosynthetic apparatus in response to the diurnal cycle requires anticipatory behavior in even the simplest photosynthetic organisms. At the lowest level, the cyanobacteria use a circadian biochemical clock, whose proteins are encoded by the *kai* genes,⁵ which extends their chronognostic range to several days. In higher plants, the daily and seasonal responses in anticipation of sunlight, temperature, water, etc. demonstrate a range at least of years and are regulated by more complex clocks, allowing quite sophisticated responses sometimes referred to as plant intelligence [18].

The circadian clocks were reinvented in the animal world,⁶ and have given all complex animals built-in, biochemical, temporal reference systems that regulate their time-dependent metabolism and physiology [19,20]. It seems likely that all living things have built-in biochemical timers, directly linked thereby to the semantic inheritance through DNA and that these are also important as determinants in behavior. The primitive timers might be thought of as the first steps towards perception.

³From Greek *κρόνος* (*chronos*, time) + *γνώσις* (*gnosis*, investigation, knowledge gained from experience). An alternative word, originally introduced in the context of bee behavior but now used more extensively, might be *zeitgedächtnis*, German for time-memory [81], but this also implies a higher-order memory function.

⁴See the References [82–85] for articles on biophysical, biochemical, and physiological aspects of the flagella motor and bacterial motility.

⁵While some elements of the *kai* system seem to be restricted to the cyanobacteria, other *kai* genes are more widely spread. Homologs of the *kaiC* gene, encoding the RecA-superfamily of ATPases implicated in signal transduction, are found throughout the bacteria and archaea and are involved in circadian functions in some of these [86].

The Emergence of Biological Complexity

The increasing complexity of living things has depended on the evolution of different ways of exploiting the combinatorial possibilities inherited in the information encoded in the genotype. From the above discussion it will be obvious that semantic inheritance is a necessary corollary of life. Any self-replicating system requires a “genetic” message—the instructions for replication and for the phenotype—with its necessary engineering and semantic components. While recognizing that both are essential, it is of interest to note that the semantic content has many of the properties of the *élan vital* [21], except that, although it may be vital, it is not a force. The concept of a “vital force” has invited the scorn of the scientific community [22], so, in drawing this analogy, it would be as well to re-emphasize that the thermodynamic component ties semantic transmission to the physical world. Nevertheless, it is the message that is transmitted between generations, and this nonthermodynamic component is essential to all life. For all extant forms, the semantic content has been honed through evolution; any current message represents the result of an investigation of the nature of reality through the ultimate test of survival.

As noted many years ago by Eigen [23–25], evolution is a continuing exploration of the possibilities opened up by combinatorial complexity. In this section, I want to show that it is only in evolving systems, based on transmission, translation, and mutation of a semantic heritage and that this potential for higher complexity can be practically realized. Paul Davies has suggested that “Physical systems are causally open when they exceed a certain level of complexity—determined by the information-processing capacity of the universe,” which is taken to be in the range 10^{120} – 10^{122} bits (see Davies [26] and references therein). There are enough bits to specify the configurational possibilities for a protein of only 60–90 amino acids, or the coding potential in ~200 nucleotides, hardly enough for a Laplacian intelligence (or any other designer; Figure 4) to use as a deterministic basis for the complexity of the biosphere. Davies therefore concludes that life is an emergent phenomenon. A similar theme was introduced much earlier by Levinthal in discussion of protein folding pathways [27]. The informational complexity of the genome is determined by the 4^n possibilities inherent in a genetic code of four bases in an n -length sequence. For translation to protein, the triplet code allows specification of the sequences made up from the 20 amino acids (each protein of defined length), with redundant coding, punctuation, and control built into the excess capacity. The combinatorial possibilities arising from 20 amino acids with different physicochemical properties, each of which can be deployed in several different conformers, provide a wide range of opportunities for protein configuration [assuming 5 conformers we have $(20 \times 5)^{60}$ for a protein of 60 amino acids, to match Davies' 10^{120} information bits], exploited in the many structural, enzymatic, and control roles found in living organisms.

It should be noted in the context of protein synthesis that the translation from a linear DNA code [essentially a one- or two-dimensional (2D) informational system] to proteins does not involve any increase in information content, rather the reverse. Apart from the maternally inherited mitochondrial DNA in eukaryotes, and the initial somatic machinery [8,9] (not an unimportant component, since it provides the essential translational apparatus), the genome necessarily contains all the information for specification of the phenotype. For any particular

⁶The *cryptochrome* photoreceptors that provide synchronization of circadian clocks through photoactivation by daylight are found throughout the three domains of life. The period, cycle, and timeless proteins of *Drosophila* and the clock proteins of vertebrates, each suggested as having a circadian function, seem to be fairly widespread. Most work reported has been on insects and vertebrates. Period 1 homologs are found in mollusks and nematodes, as well as in the higher animal families. Period 2 homologs are found in bacteria and many metazoans, but not necessary in a circadian context. Timeless homologs are found throughout the Eukarya, mostly identified in Metazoa, including plants and fungi, but are rare in bacteria. Clock protein homologs with timing function are in all vertebrates, and also in insects. Clock homologs of unknown function are more widely spread, from *Dictyostelium* onward, in animal, plant and fungal branches of the *Eukaryota*. Of interest to anyone working in bioenergetics, *clk1* encodes a di-iron hydroxylase in the ubiquinone synthesis pathway [87,88].

span, the information content is related to the length of the coding sequence and the number of coding states. The 3-to-1 length ratio implicit in the use of 3 DNA codons to specify each amino acid, and the ratio of 4 to 20 in coding elements play off against each other. The information content in DNA is richer than that of the expressed protein, because it also includes redundancy, syntax, control, and other functions associated with the so-called noncoding elements. The translational processing involves a degradation of information content, but an increase in complexity. How is this achieved? The trick is to increase the combinatorial possibilities, and the mechanism works through the translation to different levels of complexity expressed in the third and fourth dimensions (Figure 5). The topology of proteins involves local specificities that arise from the different properties of amino acid side chains, and the combination of forces in three dimensions to provide spatially unique physicochemical surfaces. These are available, for example, as external recognition templates, as cavities tailored for specific binding of substrates associated with catalysis or control, or as surfaces for partitioning between lipidic and aqueous phases, essential to the functionality of cell membranes and their vectorial metabolism. Genomes for humans, and for many other higher animals and plants, encode some 25–30,000 proteins or subunits, most of which have length greater than Davies' "emergence limit." Interactions between these, and with co-opted molecules (lipids, polysaccharides, nucleic acids, metabolites, coenzymes, prosthetic groups, etc.) involved in metabolism, construction, recognition, and function of cells and tissues, extend the combinatorial possibilities to a wider range of phenotypical complexity. The emergent property of life is therefore clearly dependent on the semantic processing. Essential prerequisites for the *amplification* in complexity are the translational steps through which the genetic message is interpreted, initially in protein. These provide an increase in combinatorial opportunities through the interaction specificities and catalytic potential built into the protein structures. The variation in the properties of the specific surfaces through mutation and the selection of useful variants by evolution allow, over time, for an exploration of many different structures.

That selection is an essential component, even at the initial level, becomes obvious if we invert the problem. In principle (and in practice for small proteins) we could synthesize DNA to encode a designer protein, and generate it using the cellular machinery abstracted in vitro, or by borrowing an in vivo machinery. If we wanted to fully realize the design potential, we would come up against the same problem as Levinthal's paradox or Davies' Laplacian intelligence: we would not have the computational resources to do a comprehensive job. Evolution does the job without design. A large number of configurations are explored over time simply by making mistakes. The evolutionary process discards the duds.

The interaction specificities arising from translation to structures with 3D surfaces represent only one level of potential combinatorial possibility. The fourth dimension comes in at several levels. The stochastic diffusional processes through which molecules bump into each other are tied simply to time, but reaction mechanisms and catalysis are related to time through more complex functions. Enzymatic catalysis allows more turnovers per unit time (typically by factors in the range 10^{12}), but also allows for specificity in reaction steering, and for control, and hence for the evolution of complex metabolic webs. The timing of ontogeny, and of the specification for development of tissues and organs in more complex organisms, is another level, as yet poorly understood. Tissue specificities allow for division of labor and the efficient coordination of complex higher functions. The selective role of evolution requires interactions at the level of ecology and behavior, so that combinatorial complexity is extended even further into the temporal dimension. The combinatorial potential will obvious increases with time, but defining a function to describe quite how presents a challenge; likely, some power law dependence on dimensionality will emerge.

An analogy might be useful here. The digital encoding on a CD of Beethoven's Fifth or a reproduction of the Mona Lisa or the human genome as text would look boringly similar if examined before translation—just a string of zeros and ones. Of course the encoding contains the necessary information and formatting, but it is only after your computer renders the file through a translational processing that something of beauty or wonder is revealed. Not that the computer cares—many additional levels of translation are required before *we* can appreciate these facets.

A Simple RNA World has Limited Potential for Complexity

The hypothesis outlined above to account for the emergent properties of life has implications for early evolution. Information transfer through DNA and translational expression in a proteinaceous phenotype follow a mechanistic pattern that is common to all extant forms. This is interpreted as evidence for a common ancestral condition that evolved some 3.5 billion years ago to allow the development of the modern biosphere [28,29]. Since some translational step is essential for exploration of combinatorial complexity, a critical stage in evolution must have been the introduction of this initial amplification process. A simple “RNA world” would have had the same level of complexity for the genotype and phenotype. The H-bond matching between the bases that make up RNA allows a coding potential, but structural flexibility of RNA allows more degrees of freedom than DNA. In extant forms, these two properties are exploited in recognition during translational processing at *t*-RNA and *m*-RNA levels, in control functions, in specific catalysis by ribozymes, and possibly in timing. An RNA world would therefore have had greater opportunities for complexity than one based on the structurally constrained DNA. In the mechanism now used, DNA serves only for the genotype; the translational steps leading to the phenotype, starting with protein synthesis, provide the pathway to complexity. Whatever possibilities the multiple roles of RNA might have presented for a separate evolutionary mode, they have not survived as the mainstream. The coding potential is exploited in some viruses, but these depend on fooling the translational machinery of the host. In other life forms, the functional possibilities are exploited only in ancillary roles. If an RNA world was precursor to the DNA-protein world, it will be necessary to map out a pathway through which the essential translational step was introduced.

Human Intelligence and the Awareness of Extended Time

The interesting correlation between complexity achieved—the depth of exploitation of the semantic content—and the depth of perception of time has been alluded to above. The increase in chronognostic range allows a power law increase in the combinatorial possibilities through permutations in the temporal dimension. Until ~100,000 years ago, chronognostic range at the species level was linked directly to behavioral complexity and hence to information encoded at the DNA level. The chronognostic range of human kind was likely not greatly in excess of that of other higher mammals; orally transmitted traditions become myths after a few generations. However, all this changed with the evolution of sophisticated language and abstract representation. It is clear that with the invention of archival forms of information and transmission between generations, inherited semantic content was no longer restricted to that encoded in DNA. With the invention of new mechanisms for transfer of information, the chronognostic range has also increased, in both temporal directions. The growth has expanded even more dramatically as civilization has enabled the institutions, both physical and philosophical, through which transmission and storage of information has been formalized. Not least among these have been the social and economic structures that have liberated a small fraction of its more privileged members for the task of exploring and extolling the human condition.

Entropy and the Arrow of Time

Eddington coined the phrase “arrow of time” to describe an implicit directionality in time. This was based on Boltzmann's recognition that for an isolated system the spontaneous direction of any process was toward increased entropy or disorder. Although several other arrows of time have been proposed, this thermodynamic arrow seems the least dependent on prior assumptions [30,31]. However, in the context of our universe, it does depend for directionality on recognition of an initially constrained, dense, high-temperature, high-entropy state, whose evolution was triggered by the Big Bang (Figure 6). With respect to the subsequent expansion into free space and the evolving universe as a whole, this starting condition is considered to have been a low-entropy state. The contrasting state is the equilibrium condition of maximal entropy, in which time has no significance because all processes occur with equal probability in either temporal direction. Under equilibrium conditions, the time symmetry of the physical laws has its full expression, but, ironically, loses all meaning. Any perturbation of the equilibrium state will introduce a Boltzmann asymmetry and restart time. Paradoxically, Boltzmann's equation defining entropy in terms of probability has no temporal term. Its independence from time is its claim to recognition as an independent indicator. However, the development of nonequilibrium thermodynamics [32,33] introduced the dissipation function, which is the rate of production of “irreversible heat,” the entropy production in excess of the heat exchange associated with a reversible process. The temporal state of a system undergoing a reversible process is similar to that of an equilibrium state: the work potentially available in one system is balanced by that in another (formally in the surroundings) through a coupling between them, and neither can budge. Despite gradients that are available for work, the system is metastable, and no significant dissipation occurs because change is infinitely slow. A real change of state can occur only if some of the potential work is dissipated as heat lost to the surroundings. The dissipation function provides a measure of rate for a spontaneous process. When applied to a system undergoing a change in state, the dissipation function gives the rate at which the potential for work is wasted. If no coupling occurs, all the potential work is dissipated as heat. Reversible transitions can occur within a system in flux, between states at similar potential, but these will necessarily all be populated (equally if the work terms are zero, and flux coefficients high), and flux through the system requires a dissipative process at one end or the other.

Returning to the energetics of the biosphere in this context, the major input of work comes from the light absorbed in photosynthesis. Although the energy is eventually dissipated as heat, thereby conserving the balance required by the first law, the strictures of the second law are temporarily smoothed out in the more shallow dissipation function provided by conservation of energy in the web of coupled electrochemical and metabolic reactions. Indeed, the accumulated order and chemical complexity of the biosphere is a direct consequence of this entropic delay. Some of the input energy is borrowed for a while, and invested in life, in maintenance and evolution of the biosphere.

The Argument So Far

It might be tempting to see in the apparent correlation between chronognostic range, and the increased information content of the modern biosphere, some sort of reversal of Eddington's arrow of time. The increase in information content in recent times appears to involve a high degree of organization or negentropy, and, although we can't talk about a reversal of time, our perception of time certainly seems to be extended in a fashion linked to this increase. However, any further development of such speculation comes up against our lack of a philosophical apparatus for relating semantic content to the thermodynamics of the physical world.

At this point, it is worthwhile to summarize the above discussion in the form of the following conjectures:

1. It is necessary to take seriously Shannon's distinction between two contributions to information processing: the semantic content (or meaning) and engineering problems inherent in information storage or signal transmission. Both aspects are essential. Without the physical encoding, there would be no message, without the message there would be no meaning.
2. Information storage involves changes in the physical medium for which the work could in principle be returned by coupling to a suitable external system. These are well described by conventional thermodynamics. The integrity of information transmission can be scored by comparison between two sources using the probabilistic methods of information theory.
3. Semantic content, in contrast, seems to have no consequence that can be measured for the thermodynamic content of the system; it imposes no additional thermodynamic burden over that associated with the terms under 1 and 2 above.
4. The semantic content has a value that is entirely dependent on context. The significance of the information only becomes apparent on translation.

These postulates apply to all forms of biological information from the DNA level to that of human intelligence.

In addition, we have noted the following:

5. Translation of the semantic content of the genotype leads to expression of the phenotype. The emergent properties of living things reflect the possibilities for combinatorial complexity introduced by the translational and interpretational steps. An increase in dimensionality is important in increasing combinatorial potential and hence complexity.
6. One characteristic of the phenotype is a behavior that fits each species to an appropriate ecological niche. The behavior of living things implies a sense of time or chronognosis. Chronognosis seems to be built into all living things through biochemical timers encoded by the genotype, but increasing complexity allows for more sophistication in temporal perception.
7. The ability to modulate behavior in the light of successful prediction of the future has an obvious evolutionary advantage. There is a correlation between behavioral complexity, the complexity of sensory apparatus, and chronognostic range.
8. The evolution of *H. sapiens sapiens* introduced a new development, that of the human mind with the potential for language, writing, etc., and this has provided a pathway for semantic inheritance distinct from that through DNA and opened new possibilities for combinatorial complexity at the behavioral level. These in turn have created opportunities for survival in previously unexplored niches.

In order to appreciate the anthropocentric perspective opened by that last postulate, we now need to review the development of our current views of time, civilization, and the place of man in the scheme of things. From the limitations of space and the author's knowledge of history and philosophy this will be brief and perhaps superficial.

Civilization as an Evolutionary Process: Human Time and Social Order

The origins of language are obscure; it seems likely that transmission of ideas between individuals and generations dates back at least to the earliest tool-making cultures of 3–2

million years ago. Starting with the development of sophisticated languages and the migrations from Africa (Figure 7) around 70,000 years ago,⁷ humans extended their chronognostic range and biological competitiveness by creating new opportunities for combinatorial complexity at the social level. The basic behavioral features involved, social organization in herd, pack, or tribe; communication between individuals through sound, scent, gesture, etc.; and alteration of the physical environment to record status or range, are certainly not unique to humans. However, exploitation of the social opportunities has depended on evolution of several secondary features that, at least locally, are unique to *Homo s. sapiens*. These include the anatomical apparatus for sophisticated speech and a larger brain in which information about the environment can be abstracted and manipulated independently of the external world. Neither vocalization nor the mental functions are unique. Use of sound in communication is common across the animal kingdom, and any dog owner, for example, will recognize that man's best friend has an extensive repertoire of associative memories that provide a good description of aspects of the world of importance to dog. However, in man, some attributes of the brain have clearly been amplified. Records of events from the physical world are stored in an extended memory as coherent "images" that retain some temporal and spatial context. These abstracted images of the outside world can reflect input through any one of the senses and are partitioned in such a way that parts can be compared and their associative properties modulated. Both the capacity and the informational processing aspects have been extended, introducing a far greater potential for manipulation of the stored data in novel combinations. This allows development over time of an internal model of the physical world that can be exploited for predictive purposes.

Some of the earliest evidence for abstract realization of the external world comes from the appearance of figurative carving and cave paintings some 30,000 years ago (Figure 8). The internal world model is cumulative; as recognized by Aristotle [34], the *tabula rasa* of the newborn mind evolves through a learning process. The coherence of our conception of reality starts in the womb and expands as our physical contact with the world makes possible an iterative process of verification and reformulation. In many ways, this learning process at the individual level reflects the development of the human social condition. At the phenotypical level, ontogeny recapitulates phylogeny; at the behavioral level, education recapitulates civilization.⁸ In the development of the individual, as in the advancement of civilization, the acquisition of language is paramount. With language, the advantages of group living are expanded in a multiplicative fashion. Sharing of ideas allows sharing and accumulation of skills, teamwork in the hunt and in defense or attack, and the development of social skills, social cohesion, schooling, and oral history.

The Development of Complex Societies

Although its origins are hotly debated, the development of agriculture—the planting of crops, and animal husbandry—is thought to be more recent, though it was well established 10,000 years ago [35]. Agriculture led to more organized societies, division of labor, property, trade, etc. The development of social order encouraged the extension of counting to accounting and

⁷The migrations from Africa of the populations from which the present distribution of mankind is derived are illustrated by the distributions of mitochondrial DNA types (for the female line), and Y-chromosomal types (for the male line), and the time scale derived from mutation rates (Figure 3). The migrations range over the period from ~70,000 years before present (<http://www.mitomap.org/WorldMigrations.pdf> and <https://www3.nationalgeographic.com/genographic/atlas.html>). Modern language groups date from much more recent times [cf. [89]; and see articles in *Science Vol. 303(5662), Special Issue on Evolution of Language, 2004*].

⁸Ernst Haeckel's famous phrase "ontogeny recapitulates phylogeny" was an important topic of discussion in late 19th century biology, and, although the details of Haeckel's embryology were wrong and the pedants have scoffed at earlier interpretations of this idea, it continues to be fruitful (cf. [64]). The notion that education recapitulates civilization, in the context of development of the mind, was central to Freudian psychology, and has been further developed by other psychologists and in Piaget's writings about childhood development.

development of a number system and records. Number systems in turn allowed dissociation of the concept of numbers from specific association with things, and hence their more abstract use in calculation. Recording led to writing, pictograms to ideograms and phonograms, and a more abstract representation. Parallel developments included recognition of the importance of prediction of seasonal effects to agriculture, which led to astronomy-based calendars. The development of archival records and the invention of predictive devices on a large scale (monumental altars, pyramids, etc.) were associated with a stratified social order with castes, including that of the scholar-priest-scribe. With language, the abstraction of ideas through writing and arithmetic and transmission of ideas between individuals and over generations, the process of learning was extended beyond the individual to the social and beyond the individual lifespan to the duration of society. It led eventually to sophisticated societies.

The point I want to bring out here is that these developments were incremental. Both the phenotypical changes leading to the development of modern man as a species and the behavioral changes leading to modern society were all part of evolution and involved many small changes occurring in parallel to provide a continuity of development, all of which has been in the context of a biosphere also evolving in parallel.

The Supra-Phenotypical

Although the development of civilized societies was an evolutionary process, the developments leading to such societies are different in kind from the biological features generally lumped together as the phenotype. Without intending to imply anything unnatural about these extensions of biological function, it might be useful to recognize the difference as supra-phenotypical (Figure 9), meaning, minimally, that it involves the conscription of the inanimate world to the service of biological behavior. We can recognize that extensions of behavior that make use of inanimate matter, Dawkins' extended phenotype [36], are common in the animal world—use of tools, decoration, nest-building, beaver dams, etc.—and could even be extended to the plant world, where plant form takes every possible advantage of geology or local structure. However, it is in extension of the supra-phenotype that our species has made its mark. In the case of human behavior, this has involved symbolic representation of mental images, abstracted from their biological context in the brain (pictorial images, language, counting, etc.) and recorded in external, inanimate form (art, writing, numbers, etc.). Development of abstract representation and the parallel development of abstraction at the level of mental processing seems to involve a self-amplifying loop, through which the sophistication in processing of a cumulative world model is exponentially increased. Amplification occurs at both the individual and societal levels. Through use of these abstractions, we have extended both the limits of our experience and our chronognostic range. On the more practical side, our manipulation of the inanimate world has given us engineering, architecture, weapons of war, etc. Perhaps the most momentous consequence, as noted briefly above, is that we have introduced new forms of inherited semantic content that are unique (at least locally) to our species. This semantic inheritance at the behavioral level is quite distinct from the semantic content carried by the genotype.

The ordering of society made possible by the inventions briefly outlined above was a necessary part of the development of social structures under which these inventions could be extended and exploited. It is customary to view this process as one of establishing stability. However, organized social structures are necessarily highly ordered and hence inherently *unstable*. Their fragility is all too apparent from history and especially in this age of terrorism. The appearance of stability comes from the development of political, social, economic, technical, and philosophical tools that make possible the continued maintenance, renewal, and evolution of these institutions through the input of work.

Counting Time

The “message” encoded in DNA has value only in the context of life and of behavior. Similarly, our daily conversations have a value only in the context of an evolved intelligence and civilization. A detailed examination of the extensions of behavioral complexity leading to our modern world is beyond the scope of this essay. However, the major part of the process has been in the semantic realm and has been linked to our development of a sophisticated appreciation of time. The evolution of our ideas about man's temporal place in the scheme of things has seen an interesting interplay between social order, religion, and scholarship.⁹ Our recent chronognostic history is linked to the history of numbers. Perhaps the earliest records indicating formal recognition of extended time date back ~20,000 years and are represented by markings on sticks and bones from Europe that are thought to record the days between successive new moons. The earliest Egyptian calendars date back to ~4500 BC, and by 2700 BC they had established a year of 365 days. We owe our daily time scale of 24 hours, divided into 60 minutes of 60 seconds to the Sumerian-Babylonian sexagesimal number system from the same period. Geometry evolved in the context of engineering. The cuneiform tablets from Sumeria and Babylon (1900–1600 BC) are mostly economic records, but some also show a knowledge of Pythagoras' theorem that predated the Greek discovery (~500 BC) by at least several centuries (Figure 10). They also demonstrate the solution of quadratic (and higher-order) equations, and their application to land management. The Ahmes and Moscow papyri from ~1850 BC include examples of calculation of areas of circles and volumes of pyramids. The construction of the pyramids, some of them a thousand years earlier, must have required a fairly accurate knowledge of the properties of triangles. Although less sophisticated, Stonehenge (phase I, ~2950 BC), with its astronomical orientation, dates from about this time. Similar mathematical developments occurred independently in Chinese and Mayan cultures. The earliest Indian written texts, the Vedas, date from 15–5th century BC, and contain the Sulbasutras from ~800 BC as mathematical appendices. These include details of the calculations needed for correctly orienting altars, including Pythagoras' theorem. The Indian decimal number system from this era evolved, with place dependence, zero and all, to give us, via the Arabs, our present decimal number system. These mathematical tools became important in the development of astronomically based calendars, which required records kept over extended periods, and precise geometric measurement. Because of the importance to agriculture, the application of these skills to engineering of irrigation systems and the prediction of seasons brought to those able to make such measurement both power and prestige. The development of religious ideas likely evolved with language and social structure,⁹ but no doubt the expanding temporal perception arising from the development of calendars, and the appreciation of power series, opened deeper speculation about the underlying mysteries. What is of interest here is the emergence of the scholar-priest-scribe caste in which the tools of writing, reading, and arithmetic that facilitate the development of abstract ideas and a perception of time, were applied in both a practical and a religious background. Many of the records that have survived seem also to have served a teaching function, indicating that formal institutions for transmission of knowledge evolved at the same time.

The “Limits of Experience” and the Birth of Modern Science

The development of abstract number systems, and the ability to manipulate scale by power series, led to the idea of infinity and recognition of the philosophical difficulties introduced by this. Parallel developments in different philosophical systems led in different directions. In the

⁹The common roots of religion, philosophy, and science in social behavior was introduced by Durkheim (see <http://durkheim.itgo.com/religion.html>), who is considered by many as the father of sociology. He suggested that these all derive from the need for groups to find a common social identity through shared participation in ritual, creation myths, and exploration of man's connectedness to nature. Robert Alun Jones [90] has a nice critique of Durkheim's *The Elementary Forms of Religious Life* [91].

frame of Western civilization, starting perhaps with Parmenides, the Greeks developed a dialectic approach that separated the philosophical problems from mythology, and effectively partitioned speculation into temporal and eternal domains appropriate, respectively, to man and the Gods. In this divide, man's place was constrained by the limits of experience. The ideas of Plato and Aristotle, as molded by Plotinus, were co-opted by the early Christian church, and the difficulty of placing Jesus in both temporal and eternal realms lead to an evolution from neo-Platonic views to the concept of the Trinity. Despite an extraordinarily liberal pronouncement in the Edict of Milan,¹⁰ the emperor Constantine later proclaimed the Christian faith as the state religion. The hot debate within the Church about the nature of the Trinity, which dominated the theology of this period, was formally settled at the Council of Nicaea¹¹ in 325 AD (Figure 11), and its aftermath,¹² leading to the Council of Constantinople in 381. These led to the triumph of the homoousian view and established orthodox Christianity, but also led to suppression of other beliefs as heresies. Perhaps inevitably, the power brought to the Church by its central politic status eventually placed it in the position of protector of the status quo. A hundred years after the Council of Constantinople, following invasions by Franks, Goths, Saxons, Huns, and Vandals, the Western Empire was in ruins. The Church kept the light of Western scholarship alive through the Dark Ages, but the dual role as state religion and repository of knowledge persisted and led ineluctably to defense of the dogma, which largely froze philosophical development in the Western world for over a thousand years. The development of modern science from Roger Bacon, through Copernicus, Bruno, Galileo, Newton, Spinoza, Darwin, and Einstein, to name but a few,¹³ can be seen as a wresting from

¹⁰Constantine was Emperor of the West. As noted by Gibbon (1737–1794): “The two emperors proclaim to the world that they have granted a free and absolute power to the Christians, and to all others, of following the religion which each individual thinks proper to prefer, to which he has addicted his mind, and which he may deem the best adapted to his own use. They carefully explain every ambiguous word, remove every exception, and exact from the governors of the provinces a strict obedience to the true and simple meaning of an edict which was designed to establish and secure, without any limitation, the claims of religious liberty.”

¹¹Again from Gibbon: “The Greek word which was chosen ... bears so close an affinity to the orthodox symbol, that the profane of every age have derided the furious contests which the difference of a single diphthong excited between the *Homoousians* and the *Homoiousians*.” The former, meaning in this context that the Father, Son, and Holy Ghost were of the same substance (consubstantial, co-eternal), was the essential description of the nature of the Trinity that became the orthodox faith; the latter, meaning of similar substance, was preferred by the Arian faction. Supposedly, the distinction was lost on the majority of Bishops at the Council of Nicaea, hence ‘not an iota of difference’.

¹²The Nicene Creed was meant to settle the issue, but the argument was far from over. Constantius, who followed Constantine as Emperor, supported the homoiousian view. It was hotly contested by Athanasius, Archbishop of Alexander, but with the reign of Julian and the return of paganism, he was exiled (Gore Vidal gives a readable account of this period in his historical novel *Julian*). He was restored to the archbishopric by Jovian, and his views waxed and then waned again under Valens. The orthodox homoousian view, summarized in the Athanasian Creed, eventually prevailed under Theodosius, with the edicts of the Council of Constantinople. The debate has continued, for example, the homoiousian view was revived, under Jefferson's influence, in the Unitarian split from Puritanism in the United States.

¹³Each of the individuals named here encountered resistance from established religion for their temerity in proposing to shift the balance. In all cases, the authorities could have followed a less dogmatic course. The philosophical distinction deriving from the neo-Platonists, which separates the realm of religion from the “limits of experience” of man, was well recognized in the early Church and could have been invoked to ease the transition from dogma. For example, Pope Clement IV rescued Roger Bacon (1214–1292) from obscurity and incarceration, but on Clement's death, Bacon was imprisoned again for much of the rest of his life, charged with suspected novelties in his teaching. (Bacon, and Grosseteste, his mentor, were the fathers of the scientific method; <http://www.fordham.edu/halsall/source/bacon2.html>).

Galileo, in his letter of 1615 to the Grand Duchess Christina of Tuscany (Christine de Lorraine; <http://www.fordham.edu/halsall/mod/galileo-tuscany.html>) articulates a straightforward realist view: “But Nature, on the other hand, is inexorable and immutable; she never transgresses the laws imposed upon her, or cares a whit whether her abstruse reasons and methods of operation are understandable to men. For that reason it appears that nothing physical which sense-experience sets before our eyes, or which necessary demonstrations prove to us, ought to be called in question ...” and invokes with great eloquence the Church Fathers and St. Augustine as recognizing the need to reconcile the teachings of the church with natural experience. It was to be a long time before this view prevailed. The current Catholic perspective is summarized in the address of Pope John Paul II to the *Pontifical Academy of Sciences* on the occasion of their report on the “Galileo case” (1992). This affirms St. Augustine's view: “If it happens that the authority of Sacred Scripture is set in opposition to clear and certain reasoning, this must mean that the person who interprets Scripture does not understand it correctly ...” The address also contains a somewhat belated acknowledgement of the philosophical correctness of Galileo's position: “Paradoxically, Galileo, a sincere believer, showed himself to be more perceptive in this regard than the theologians who opposed him.... We also know of his letter to Christine de Lorraine (1615) which is like a short treatise on biblical hermeneutics.” (An English translation of the address is available at <http://www.its.caltech.edu/~nmcenter/sci-cp/sci-9211.html>).

The distinction between religion and the “limits of experience” has been reformulated in a contemporary setting in Judge Jones' ruling on the Intelligent Design case (Kitzmiller v. Dover School District; http://www.pamd.uscourts.gov/kitzmiller/kitzmiller_342.pdf).

the Church of its claim to the farther reaches of time and space, through extension of the limits of experience of man.

The perception of time as proceeding from the past, through the present to the future, is neatly summarized by the aphorism, “We can know the past but we cannot change it; we can change the future, but we cannot know it.” We may reasonably assume that temporal polarity applies precisely in the physical world, based on time-invariant physical laws, the Big Bang, and Eddington's arrow. But our subjective interpretation of time in the world of experience is obviously conditional; our present view is based on quite recent philosophic developments. The “past” changed dramatically with the introduction of evolutionary time. Starting with Lyell's work on geology and the work on evolution from Darwin and Wallace, our view backward has changed from Archbishop Ussher's creation of the world in 4004 BC, to that of the Big Bang, some 12–14 billion years earlier. As for the future, prediction of cyclic phenomena on an astronomical scale developed quite early; the astronomers of the early Babylonian (Thales likely had some help from this quarter) and Chinese civilizations, and independently, the Maya, were able to predict solar eclipses. Newtonian mechanics extended the range to comets and the orbits of Neptune and Pluto. From Einstein and the revolution in quantum mechanics leading to nuclear chemistry, we can now understand the life and death of stars and galaxies. Everyday life is dominated by more chaotic notions, but these are largely smoothed out by the highly ordered societies in which we participate, so that we can anticipate a trajectory of our lives (‘barring accidents’) with some confidence. As I sit at my desk in the attic, I can watch the last 16 frames of the radar coverage on my computer and reckon with complacency that the tornado cells in the storm front will pass 20 miles to the south.

To return to my main theme, it will be apparent from the above that the relation between information content, time, and energy is quite different from that of our earlier speculation in relation to the arrow of time. The semantic component of information content has no conventional entropic implications and hence no direct relation to thermodynamic energy and the physical world. On the other hand, the depth of our perception of time has everything to do with the extension of behavior into the supra-phenotypical range; the development of language, number systems and abstract thinking that accompanied evolution of the brain's capabilities; and the accumulation of learning, and these are the features that have enabled us to direct energy into the molding of our societies. The present adult mental abilities of our species are predicated on the combined efforts of thousands of prior generations of our kind in establishing the external semantic heritage that provides the base and framework of our knowledge. That cultural development, just as our education, has necessarily been sequential and cumulative. However, the phenotype has probably not changed significantly over this period: the youth who sets off to college today, armed with the rudiments of calculus and modern biology, a smattering of some foreign language, and the beginnings of an appreciation of literature, art and music, is the same youth who knapped flints for his spear or who scraped her skins at the fire while listening to the wisdom of the shaman 30,000 years ago. The mind that shaped the art of Lascaux was not inferior, but educated to a different context.

Some Philosophical Implications

For a neophyte to philosophy, compelled by this question of the thermodynamic status of semantic content to revisit the rudimentary introduction derived from undergraduate days, it has been salutary to find that the themes introduced in the preceding sections run through philosophical thought from the earliest days. A seasoned philosopher might point out that my discussion so far represents a banal exercise: the regurgitation of commonplace ideas from a mishmash of science, philosophy and history. But isn't that how it has to be: a viewpoint that arises naturally from my argument? Because of the role of translational processing in interpretation of semantic content, the mind can only accommodate ideas that it is already

equipped to deal with. The adage that there are no new ideas, just a rehashing of the old, becomes a truism. However, it is in the rehashing that progress is made, and Shannon's distinction between the engineering problems and semantic content provides a fresh perspective on this process. From the arguments above, it should be clear that any "idea" entering our consciousness does so as a result of translational processing, and our appreciation depends on a linkage to other ideas already in residence. The availability in a particular mind of a particular combination of observations and old ideas in a particular spatiotemporal context is unique to a particular individual, and the re-ordering of those ideas in new patterns depends on the particular experience of that individual and on critical choice. It is this re-ordering, the "mutation" of old ideas, that is a potential source of philosophical renewal, providing the grist for the evolutionary mill. Whether or not the new combinations are useful or have any original meaning is determined by their resonance in a wider social context.

Evolutionary Epistemology

The philosophical perspective developed here has clear parallels in Popper's Three Worlds model and his objective knowledge epistemology [37,38], Campbell's evolutionary epistemology [39], and Dawkins' memes [13,36,40].¹⁴ My supra-phenotypical semantic inheritance is recognizable in Popper's extrasomatic World 3 (Figure 12), but arrived at from a new direction. However, the "insubstantial" nature of semantic content makes possible a clearer distinction between the mind, and both the phenomenal world and that of the external semantic inheritance. The semantic traffic between the three worlds reflects a sophisticated translation process that is not well understood. However, as already recognized by Aristotle, the higher processing through which we interpret primary sensory input seems similar to the processing through which we interpret "images" stored in the brain, or the semantic content of the external semantic heritage, in books, movies, art, science, math, music, poetry, etc. The data from the real world that impinge on our sense organs are purely physical, though they can act as carriers of messages. What we describe as entering our minds, what appears to us as perception, and what becomes meaningful is the result of translational processing at many levels, from the innate on up.¹⁵

Similarly, because of the insubstantial nature of semantic content, all perception of the external semantic heritage must also be the result of translational processing of data introduced via a thermodynamic vehicle. The semantic heritage itself is *passive* in the sense that all the apparently dynamic aspects of World 3 are engendered by translational traffic between individual human minds and between minds and the knowledge banks. Despite the enormous impact of the semantic inheritance, the human mind is still the only vehicle for active

¹⁴In summary, memes are self-replicating mental agents: "The haven all memes depend on reaching is the human mind, but a human mind is itself an artifact created when memes restructure a human brain in order to make it a better habitat for memes. The avenues for entry and departure are modified to suit local conditions, and strengthened by various artificial devices that enhance fidelity and prolixity of replication: native Chinese minds differ dramatically from native French minds, and literate minds differ from illiterate minds. What memes provide in return to the organisms in which they reside is an incalculable store of advantages—with some Trojan horses thrown in for good measure..." Daniel Dennett [56] (quoted by Dawkins in *Viruses of the Mind* [40]).

¹⁵In addition to Dennett's treatment [56], further complexities of the human brain with its many levels of processing are discussed in the context of the contributions of emotions to homeostasis and the wider social milieu by Antonio Damasio [92] in *Looking for Spinoza*, which also has a nice account of Spinoza's life.

change in the semantic heritage.¹⁶ The factors that guarantee further development are the uniqueness of each mind, access, and selection.

The information storage and retrieval aspects of the “engineering side” pop up in different disguises: as DNA processing in World 1, as memory and processing in World 2, and as the many invented methods for storing information that stabilize the semantic heritage of World 3. However, the semantic content in the brain must be as insubstantial as semantic content in DNA, or on paper or in digital format. It is available for examination only because it can be transiently trapped in a thermodynamic form. The distinguishing features on the engineering side are the mechanisms for handling storage and transmission. As Popper, Campbell, and Dawkins have all emphasized, both at the DNA level, and in the brain, two aspects of information transfer are essential for evolution to occur: a high degree of fidelity in archival storage and transmission and a degree of mutability to provide the working stuff for selection. From the wider evolutionary perspective, life can be seen as a set of mechanisms, driven mainly by absorption of light in photosynthesis, through which thermodynamic potential can be exploited for self-replication, through translation and transmission of semantic content, with selection of spontaneous variants to provide the mechanism for change. For most of the biosphere, the semantic content involves DNA, and its direct or indirect translational products. For human kind, the whole apparatus of culture and civilization provides an additional channel. Our “advance” over the last few millennia has come about because of evolution in this latter mode: the supra-phenotypical semantic heritage.

Parallels with Popper's Objective Knowledge

Arguments about the nature of reality have occupied a central position in philosophical debate at least since pre-Platonic days [34,37–39,41,42]. It seems to me quite interesting to revisit this enduring argument in the light of the dual aspects of information content. The struggles of Bishop Berkeley with the world as illusion, and Dr. Johnson's cry of pain as he kicked the stone,¹⁷ seem freshly illuminated by the light of Shannon's distinction between semantic content and the engineering problem. The evolutionary perspective developed above lands me firmly in the realist camp as expounded by Popper/Campbell/Bartley (though other philosophers seem to view realism through several different prisms). We might suppose that, in the light of the insubstantial nature of semantic content, our individual zeitgeist is a transparency. But, of course, this is only part of the picture. The mental constructs through which we recognize the world are the products of a mind that owes both its being and becoming to the biological context of an evolved phenotype and the socio-ecological context of a civilization. In this wider framework of the shaping of the human mind, we can perhaps, without insult to Descartes, extend his idea to embrace our wider debt: *cogito ergo sumus* brings the

¹⁶We should note that this unique position may already be shifting as computers take on a more direct role in interpretation of the physical world, through deposition of data in the knowledge bases, and through predictive calculations, in molecular dynamics modelling, for example. The question of whether computers can be designed to emulate the human brain has been much discussed. Both Penrose [69] and Putnam [34] reject the idea and certainly make a strong case against believing that a classical Turing machine can perform this function. In so far as a Turing machine is designed to be error-free, I would agree. On the other hand, it seems that if a computer is to emulate the mind, it should be treated like a newborn child and allowed to learn about the world, make mistakes, feel pain and pleasure, and develop its own opinions. Without the evolutionary potential for “error”—some capacity for the mutation of semantic input—a computer will never be able to contribute original ideas. Of course, these requirements provide some hardware and software challenges, but steps in this direction are underway [93].

¹⁷From Boswell's *Life of Johnson*: “After we came out of the church, we stood talking for some time together of Bishop Berkeley's ingenious sophistry to prove the nonexistence of matter, and that every thing in the universe is merely ideal. I observed, that though we are satisfied his doctrine is not true, it is impossible to refute it. I never shall forget the alacrity with which Johnson answered, striking his foot with mighty force against a large stone, till he rebounded from it—‘I refute it thus.’” The recent series of movies starting with “The Matrix” provides an exploration of “Brain in a Vat” themes that follow an anti-realist approach similar to Berkeley's, but with a machine intelligence replacing God (see Hilary Putnam [34] and <http://www.uwichill.edu.bb/bnccde/ph29a/putnam.html> for the brain-in-a-vat reference).

rest of us into the picture. Necessarily, our debt extends back through time and to the whole biosphere and embraces the physical world.

The lack of a thermodynamic context for semantic content raises epistemological questions, both in relation to our perception of everyday reality, and in relation to the nature of the scientific enterprise. Although all hypotheses are generated in the semantic realm, they are tested in the observable, phenomenal, thermodynamic world, which provides the context for their evaluation. A hypothesis that fails to account for well-authenticated properties of the observable world needs to be discarded or modified. Popper developed this idea through his falsification approach. Popper's view was largely a response to what he saw as a crisis of “certainty” in philosophy, which arose from assaults from many fronts on the deterministic view of science and its philosophical underpinnings following the successes of Newtonian mechanics. Demonstrations of the limits of inductive logic dating back to Hume (or earlier, to the skeptics), the introduction of Darwin's ideas, the beginnings of psychology, the limitations of language, and the failure of logical positivism to find a solution to the problem of “truth,” were compounded by the difficulties introduced by quantum uncertainties and relativistic views of space and time. By the mid-20th century, a philosophical view was established (associated with contributions from, among others, Frege, Carnap, Quine, Gödel, and the early Wittgenstein [43]), that verification was not an appropriate target for the scientific enterprise. Popper [44] pointed out that even though this may be so, we could at least know when a hypothesis was inadequate, because of its failure in prediction of future observation. He framed this idea through his falsification criterion: a hypothesis has value only if it does account for “the facts,” and if criteria for testing are built in as “risky” predictions. Popper recognized the need for some epistemological foundation and suggested that this could be based on the recognition of an external observable world governed by invariant laws: his World 1. He found support for such a base in biological evolution and in the extension of evolutionary ideas to the domain of hypothesis testing. Popper believed that science could establish a reliable description of this world by an iterative process of investigation based on a testing against observable reality. He got into trouble with his philosophical colleagues [34,45,46] on a number of counts, to some extent because his critics failed to notice his distinction between the logic of the falsification approach and the practice of working scientists. Popper recognized that the latter was inevitably more complex because of practical difficulties and factors such as human fallibility and the imprecision of the knowledge base. But to the pedantic, examination of historical cases suggested that the mechanism of falsification just didn't always work as advertised; in practice, a strong hypothesis could survive after falsification because it still seemed to work pretty well. At a more formal level, following Tarski's formulation of a semantic theory of truth [47], Popper attempted to extend the idea of falsification by suggesting an algorithm for scoring the truth content of a hypothesis, which was suggested to contain inconsistencies [34,45,46]. Another area in which Popper got onto trouble was in use of his falsification approach to provide a demarcation between science and non-science. Popper proposed that a good scientific hypothesis must include predictions that allow unambiguous tests. If a hypothesis was framed in such a way as to allow wriggle room through ad hoc additions that could explain away inconsistencies: it wasn't science. His critics pointed out that science in practice often adopts the latter strategy as an expedient for progress. An alternative line of demarcation can be framed in the light of the second principle suggested in my statement of purpose above.

“Relative truth”

An alternative scenario for revolutions in science was introduced by Kuhn [48], in which normative science—successful science, conducted according to established paradigms—accounts for the main flow of the scientific enterprise, but gets shocked out of its rut by paradigm shifts that are incommensurable with current thinking and which are rare and

disruptive. A period of dispute follows after which social consent determines acceptance (or otherwise) of the shift, and the system settles back into a productive complacency. In my view, both Popper and Kuhn have something interesting to contribute. Kuhn recognized the importance of a social element, and his revolutionary scenario certainly fits some major shifts in scientific opinion, including Mitchell's chemiosmotic revolution. The properties of semantic transmission, the nature of our daily "conversations," and the mechanism of education discussed above, lead to the necessity of a similar social involvement. However, Kuhn scants the epistemological complexities, which Popper deals with quite effectively. The philosophical community seems to have decided that the two views were contradictory rather than complementary, projected this as a Kuhn/Popper war, and declared Kuhn the victor. The outcome seems to have been, at least in the United States, that the mainstream of philosophical discussion has passed Popper by, the baby of falsification, and the evolutionary framework, have both been thrown out with the bathwater, and his views have been eclipsed (but see Miller [49] for a defense).¹⁸

An influential scenario favored in some circles has been a view of truth that removes it from any firm pinning to external reality [46,50,51]. Kuhn's social context has been combined with a mishmash of ideas from the later Wittgenstein to produce a distortion of the scientific method, most notably in the self-serving "Strong Programme in the Sociology of Knowledge" from Bloor [50] and the Edinburgh group, in which congruity with reality is abandoned and truth is relative and determined by social consent. At least some blame must also attach to Rorty [52], who took a similar neo-pragmatic approach that rejected realistic philosophies. He regards the scientific enterprise as a game, useful perhaps, but beyond the dignity of the serious philosopher. Rorty defines realistic philosophy in terms of a correspondence theory of truth, but this seems a bit of an Aunt Sally, whose knock-down has been used to tar all realistic philosophies. Feyerabend's semantic instability [46] recognized the mutability of ideas, but he later extended his thinking in an anarchistic direction that also contributed to the fashion for "relative truth." Popper has been viewed as adhering to a correspondence theory of truth, but his attitude was more provisional. His embrace of falsifiability was explicitly in response to

¹⁸See for instance the books by Kuhn [48], Rorty [52], Kenny [43], Kripke [94], Feyerabend [46], and Bloor [50]. Putnam [34] has an equitable critique of Rorty. For a more direct response to Bloor, see Slezak [95] (also available on-line at: http://hps.arts.unsw.edu.au/hps_content/staff_homepages/p_slezak_site/Article%20Links/1994/Slezak_Bloor_2nd_Look_1994.pdf). The antirealist, constructivist, view has also been championed by Fine [51], with more thought, but still through the prism of a highly restricted correspondence theory of truth.

In my view, because of the problems in philosophy identified by the mid-20th century, discussions of the nature of truth in the philosophical, scientific, or everyday meaning, are bound to be somewhat futile, even when conducted against an evolutionary background. To this extent, a pedantic adherence to a "correspondence theory of truth" is indefensible. However, this does not mean that we have to abandon attempts to relate experience to an external reality. To avoid the pitfalls of inductive circularity, an external reality governed by invariant laws should perhaps be presented formally as a hypothesis, in which our understanding is provisional. Since the assumption of an external reality forms the external pegging for most of the inductive circles that form our knowledge base, I believe it is fairly secure. A statement that "T is true" then represents a hypothesis that T is congruent with that reality. Perhaps we can pin discussion down by acknowledging a reality that allows for an observation-based exploration, recognize that there are bound to be shades of agreement as to what it all means, and accept that an approach to a consensus involves an evolution guided by utility rather than absolutes. Some of my own favorite quotations speak to the subject: Einstein's restatement of Occam's Razor: "Things should be kept as simple as possible, but not simpler"; Chesterton's definition of paradox as "Truth standing on her head to get attention"; and an adage from the early days of the chemiosmotic battleground: "The heat of the controversy is inversely proportional to the hardness of the data." This latter reflects a general observation that, if a hypothesis survives the falsification test often enough, people stop arguing about it. Finally, I offer with some hesitation a remark of Peter Mitchell's: "The trouble with most scientists is not that they don't have good memories, but that they don't have good forgetories." I gathered from conversation that what he meant was something like the following: To be effective, a working scientist must be selective in terms of what data and interpretations he or she takes seriously. Data is often conflicting, and interpretations are often misleading. The selection filters (sorting algorithms) used are not just straightforward applications of logic. Instead they represent a sophisticated balancing act that must also include subjective elements: personal judgments of a colleague's intellectual worth, scientific integrity, disinterestedness, etc. We might set against this Richard Feynman's remark: "To guess what to keep and what to throw away takes considerable skill. Actually it is probably merely a matter of luck, but it looks as if it takes considerable skill." The messiness of science is a reflection of the humanity of scientists. The success of the enterprise comes from the application of "reconciliation devices" such as the perspective achieved over time, summarized as the "Truth Will Out Device (TWOD)" by Gilbert and Mulkay [54]. Time allows the mechanism of falsification to play itself out against new experience: Popper's idea in action. The dud hypotheses are weeded out.

recognition of the slippery nature of truth—the limitations of inductive logic preempt the view required by a strict correspondence theory—and Tarski's resort to meta-languages was itself an attempt to deal with these difficulties. Popper's evolutionary epistemology seemed to provide a pathway out of this impasse. Meanwhile, the ogre of relative truth has permeated much of our culture and social thinking, and has, in the Bush administration, been incorporated quite explicitly into policy at the highest political levels [53], leading to a noticeable decline in the nation's standing among the international community.

The Impact on Science

Most scientists are unaware of this disjointed view of truth, seen as a “philosophical horror show” by Putnam [34], and soldier bravely on in Popper's blithe spirit, mainly because it reflects well their everyday experience of the utility of a testing of hypothesis. In my view, this uncomplicated approach is quite appropriate; formalization of ‘the scientific method’ is difficult because “scientific knowledge” is a moving target. The practice of science occurs in a context of observation, hypothesis, and measurement, in which incomplete knowledge is the norm. Technical advances allow the application of new methods of measurement, which introduce a new observational background against which hypothesis must be tested and renewed, refined or discarded. All this is conducted in an environment of peer review which can be far from ideally disinterested. The account by Gilbert and Mulkay [54] of the controversy leading to eventual acceptance of Mitchell's chemiosmotic hypothesis provides an interesting overview of the sociological side. Nevertheless, the method of science works in the long run; viewed in the evolutionary context, it is clear that science has aided those societies that have recognized the benefits in exploitation of resources; economic prosperity and survival through martial sophistication are not bad tests of congruity with reality [35]. In a wider view, the testing of life against the external thermodynamic world by survival of extant forms represents ~4 billion years of exploration of the nature of the real world in terms of physical and chemical interactions that have allowed the survivors to exploit thermodynamic potential. This exploration, and its more recent extension through deliberate, conscious experiment, hypothesis testing, and exploitation of the artifacts of civilization, provides an epistemological foundation of some security that should not be lightly discarded. Although the details are provisional, we *can* have some confidence that there's a real world out there and that it has followed invariant laws for those 4 billion years (and longer, because our knowledge of the early cosmos is based on the same laws), even though our understanding of those laws must be provisional.

Universal Darwinism—Memes as Units of Semantic Content

The insubstantial nature of semantic content has obvious implications for any discussion of the mind; as noted earlier, consideration of similar insubstantialities in different forms and under different names has driven philosophical speculation down the centuries. More recently, Dawkins [13,36,40] has introduced the notion that the basic building blocks of knowledge are selfish, mental agents that are transferred from mind to mind, and replicate through imitation, for which he coined the name memes [14]. The idea was introduced as the last chapter of *The Selfish Gene* [13] and borrowed by association the central tenets of that treatment. Dawkins' brilliance makes the idea almost irresistible; it has an appealing simplicity and recognizes an evolutionary potential that allows a useful extension of ideas from genetics and their application to cultural transmission. The meme theme has been exploited in a substantial literature (see for instance Blackmore's enjoyable account [55] and reference therein). Dennett [56], in a wide-ranging and insightful exploration of consciousness, has invoked the idea of memes among a set of hypotheses to account for the peculiar properties of the human mind.

After a strong beginning, the field of memetics has fizzled; it is held back by lack of a cohesive idea of just what a meme is and by a disappointing lack of practical application. However, memes seem to show the same lack of thermodynamic consequence as semantic content, and it seems productive to view them simply as units of semantic content involved in information transmission at the cultural level. Neither Dawkins nor Dennett explicitly recognized the insubstantial nature of memes, but the question of their nature cannot be adequately addressed without such recognition. If memes are units of semantic content, then it should be clear from the above discussion that they could only “infect” minds already prepared to decode them. Simple “imitation,” no matter how we stretch it, does not describe this process adequately. Without a mind and the history of its evolution, there would be no memes. Memes did not spring from nowhere: they originated in minds. They can be transmitted only through the agency of thermodynamic carriers, the physicochemical mechanisms already discussed above. They have value and significance only after translation and interpretation and in the context of an appropriate education. We must therefore view memetics against an evolutionary and an educational/social background. This was at least partly recognized by Dawkins and Dennett in their discussions of the evolutionary significance, the developmental modeling through education, and the role of “mutation” of memes in cultural progress; a similar theme is developed further by Blackmore [55]. However, all these discussions have been in the framework of the replicator role, the “selfish replicator” scenario, and the *analogy* with genes. Without a common feature, this analogy is tenuous. A common theme is provided by the more general view proposed here, which recognizes semantic transmission as the element binding these two replicators—indeed as a fundamental aspect of Universal Darwinism (Figure 13)—and suggests that the nature of the evolutionary process is determined by the need for *both* the “engineering side,” which has a well-defined physical context that I have lumped under thermodynamic, and semantic content, which introduces no thermodynamic burden, has value only in context, and requires translational processing.

There are some simple memes that behave as advertised: fads and fashions or that commercial jingle you can't get out of your head; for example—Dave Barry has called such mental dross Brain Sludge. However, as discussed in detail by Dennett [56], the mental processes underlying consciousness come in many variants, from the innate functions on up. These operate on a massively parallel scale, with different time constants for different sensory components, and the level of complexity is further compounded by interferences from psyche and the hormones [15]. Both Dawkins and Dennett certainly recognize different levels of complexity; both build wider potential into the concept through the mutability of memes and by suggesting additional interactions between memes that provide links to the richer context of evolutionary epistemology [37–39,41], and Blackmore [55] explicitly recognizes the debt to Popper. Nevertheless, something is missing. Perhaps the argument is distorted by the unfortunate choice of “selfish” as a descriptor, with its anthropocentric overtones, and implications of individual choice. Dawkins has expended some effort in a revisionist shift to a position in which the “selfish replicator” has become a “selfish cooperator,” introducing a schizophrenic element to the discussion, leading to confusion between several different properties, which might be clarified by recognizing the role of semantic transmission and its two components.

Consciousness: The Nature of Semantic Content Does Not Force us to a Dualistic View

Dennett's treatment of consciousness centers on the use of experimental data from cognitive neurosciences [57] to explore the nature of consciousness. An initial objective is deflation of the idea of an insubstantial Central Controller operating the curtains in a Cartesian Theatre, a concept associated with the dualistic view of mind as immaterial and distinct from the substantial body. To achieve this, Dennett must use a strictly materialistic approach. The treatment depends on analysis of the complexity of processing, its highly parallel nature, the

different timescales of conscious and subconscious processing, and the potential for “advanced” behavioral patterns inherent in the combinatorial possibilities. The memes become part of a metaphorical bestiary that serves as a replacement for the Central Controller: memes of different sorts, agents, homunculi and demons, all competing in a sort of Brueghelian hinterland underlying consciousness (Figure 14). Both here, and in his treatment of epiphenomena, Dennet fails to notice the substitution of one immaterial entity by another. If memes are to do their thing while retaining their insubstantial status, what about these other ghosts? Do we have to resurrect dualism? Dennett does a nice job of making a highly technical area accessible to the outsider, and the resort to metaphor is well justified in this context. But “Consciousness Explained”? It seems to me necessary to face up to the insubstantial nature of semantic content before considering the matter settled. I want therefore to re-emphasize how the properties of semantic transmission impose constraints on mental mechanisms. We can recognize the insubstantial nature of semantic content without recourse to a traditional dualistic view as long as we keep in mind that, in addition to semantic content, semantic transmission *requires* a carrier, encoding, and a translational machinery, and that these “engineering” aspects have thermodynamic components, even if the meaning does not. These physical components tie the process to the real world. There is a duality in play here, but not one that requires us to abandon scientific enquiry. The features that led to the idea of a distinction between mind and body are due to the conjoined participation of two components in a single process.

The idea developed earlier, that all evolving systems must operate through semantic transmission, has an obverse: only systems that are evolving have need of a semantic inheritance. Only life has meaning; meaning only has significance in the context of evolving systems. However, the meaning—the semantic content—can only have expression in the context of a thermodynamic framework, can only be transmitted through the medium of a thermodynamic carrier, and can only be appreciated via a translational machinery. Although the extraordinary features of the mind lie in its ability to make manifest the insubstantial, there's nothing unnatural about this. The semantic content of genes and memes share the same insubstantial property, so we could perhaps also marvel at how the phenotype reflects the insubstantial message of the genotype. We should recognize that both translational feats are remarkable. Perhaps it is because we know so much about the engineering side and are so used to being ourselves the embodiment of the genetic message that we do not see this latter face of evolution as exceptional. Or perhaps it is because of the difference in linkage between the transfer of semantic content and the translational machinery needed for further maturation. The linkage is tight in reproduction by cell division (the genotype is copied, and half the somatic machinery follows the copy) and becomes looser in sexual reproduction (the female gamete carries with it the somatic machinery, but the male is just a chemical carrier of semantic content) and separate in the supra-phenotypical case (memes require a thermodynamic carrier, but depend on finding a brain). To reinforce Dawkins' “viruses of the mind” idea [40], it's worth noting that reproduction of viruses follows a similar pattern: the semantic content is carried by the RNA or DNA, but the carrier has to find a host with a translational machinery.

Keeping Track of the Insubstantial

I have suggested above that the mind has the ability to make manifest the insubstantial; it also has the ability to invest with meaning the spatiotemporal evolution of the environment. These seemingly miraculous functions are in a sense quite primitive. We can dissect at a biochemical level the mechanisms that provide unsophisticated versions of these functions, for example in the bacterial response to gradients discussed above. Competing biochemical processes, with time constants for activation, refreshment and decay, make possible the detection of environmental variables represented by spatiotemporal gradients that determine behavior. It takes no great stretch of imagination to see that similar principles might underlie the more sophisticated behaviors that we recognize as consciousness.

Consciousness is usually discussed in an anthropocentric context. However, it seems likely that the underlying mechanisms of our perception machine are quite primitive and common at least to all vertebrates. Any organism that has the ability to focus attention in a time-adaptive fashion and relate behavior to associative memory has the need for the same mechanisms that drive our more sophisticated apparatus. The differences lie in the sophistication of linkages to memory. In any case, the lack of thermodynamic consequence of semantic content (or of memes) gives rise to a necessity for some representation in “thermodynamic” form of any semantic or sensory component that makes it through to the perception machine. Since the semantic content is inaccessible to measurement, the more immediate task in trying to understand consciousness is to take advantage of the tools available that explore the linkage to physical or chemical processes. We can keep track of this “invisible man” through his footprints in the snow, through observation of the manifestations of this thermodynamic linkage. Techniques like fMRI (functional magnetic resonance imaging), EROS (event-related optical sensing; see Figure 15), and the electromagnetic recording of neuronal activity [58] take advantage of these physical manifestations.

While the initial translation of physicochemical input must be hard-wired, the upper echelons of our processing depend on learned associations retained in memory; we recognize a dog because we learned about dogs from the family, or from Dick and Jane. The mechanisms of memory, either short or long term, are still unknown, but whatever hardware is used, there has to be some physicochemical linkage that can operate rapidly and reversibly, both with the later stages of translational processing of sensory input and with the mechanisms that allows us to be conscious of an external world. These latter are also unknown, but are likely related to the ~40-Hz gamma rhythms involved in higher mental activity. Since the focus of attention can shift on this time scale, the slate must be constantly refreshed and updated both from memory and from sensory input. The thermodynamically stable encoding of meaning in the “perception machine” is *necessarily* transitory. Because perception is subject to modulation by memory, the two must share common linkages; memory and sensory input must both have connections that allow refreshment, comparison, and updating of the apparatus for consciousness. From the time scale, the entire apparatus must function in the time domain of cell excitability, so that even if long-term memory involves protein synthesis or cellular remodeling, it must also be accessible to those rapid, reversible linkages. Because the basic machinery of perception is relatively primitive, it seems likely that it is seated in a relatively primitive region of the brain, perhaps the thalamus rather than the cortex [58–60]. Since the whole set of mechanisms is realized in a highly parallel, spatially delocalized architecture, the linkages to memory and the cortex must be governed by local preprocessing elements associated with local memory modules. There is no reason why these should not be quite widely dispersed on an anatomical scale, but, in order to be part of a coherent mechanism of perception, they do need to share common communication channels and to be controlled by a common synchronization.

Consciousness of Self

The reversible-linkage mechanism outlined above offers a “black-box” solution to the “insubstantial” nature of consciousness, a highly parallel set of processing functions that link memory and sensory input to perception of an internal “image” in a mechanism that is “refreshed” by editing and updating functions, perhaps through mediation of the gamma rhythms. But this still fails to *explain* our perception of meaning or the illusion of self.

Dawkins' introduction of the idea of memes in the last chapter of *The Selfish Gene* [13] was so tongue-in-cheek, that Susan Blackmore [55] at her first reading “dismissed the idea ... as no more than a bit of fun.” The simple message on a preliminary reading seemed to be that individual memes have a purpose of their own that is independent of (and can subvert) that of the mind. This view does not do justice either to the complexities of thought or to the extent

to which we determine our thought processes. Indeed, toward the end of the chapter, Dawkins recognized this in a discussion of how “our conscious foresight—our capacity to simulate the future in imagination—could save us from the worst selfish excesses of the blind replicators” [13]. In later publications [22,61], Dawkins has emphasized the selfish cooperator face of the gene analog and developed the more subtle point that, after any change through mutation, the gene has to survive in the context a variable set of gene buddies, which are exchanged among a population. Selection pressure occurs at several levels. An essential requirement is efficient integration of the gene product into a metabolic machine, because, without an efficient functional whole, any “local” advantage conferred by a particular mutation would be worthless. Selection in the context of an external ecology works on this functional whole, but now in the context of a population. Transferring this idea to the meme makes for an evolution of memes in the context both of cohabitation in a meme population in the individual mind and of an external culture, so that the fate of an individual meme is subsumed under the survival of a composite whole. We might think of the mind as a dynamic aggregate of these composite memes, integrated into a greater whole that we experienced as self. Blackmore [55] suggests that this sense of self is an illusion and that we are at the mercy of the memes; “we” are our memes, no more, no less—an echo of Hume's view of the self as just a bundle of perceptions. Dennett recognizes that the Joycean virtual machine of his model of consciousness would be a zombie unless it had evolved with the potential for adaptive behavior, mutation of ideas, a mechanism for distilling meaning from the Brueghelian subconscious, and a personal and social identity.

As I see it, at some level we need to recognize that there is a willfulness to mental processing, a sense of self reinforced by its survival potential. Popper [38] had earlier suggested that our ability to manipulate models in the mind allows us to discard unworkable ones without getting killed for them—“Good tests kill flawed theories; we remain alive to guess again”—an idea echoed in Dawkins' remark above. We seek out information and informed sources. Saul Bellow's character in *The Dean's December* [62] has a nice remark to the effect that he likes living in the mid-West because “... By the time the latest ideas reach Chicago they're worn thin and easy to see through.” The sophistication of our sensory processing depends absolutely on what we have learned from life; Bellow's novel is, at one level, an exploration of this theme (as indeed is much of our greatest literature). Organized thought is an extended set of coupled processes, in which different components, facts, ideas, filters, Kantian maxims, Campbell's vicars, etc., play different mechanistic roles. New facts and old ideas are reshuffled and new relationships are tested in the mind using *sorting* algorithms; we talk of “weighing the facts” and an “informed mind.” These adaptive filters are not genetically linked. They are learned, necessarily in an incremental fashion. We do not expect a child to have the same discrimination as an adult. The sorting aids are just as much a part of the semantic inheritance as the facts and ideas involved in the shuffling process; they are the very stuff of our education in its wider meaning. As Dennett [56] notes, a sufficiently complex virtual machine could be imagined to explain much of our mental complexity. However, the lumping of all aspects of this complexity under the memetic heading seems to me to be overstretching the idea. We could of course recognize different classes of meme: idea memes, filter memes, memory memes, vicar memes, etc., but then we would quickly reach a condition in which the term meme and the concept become redundant. Indeed, Dennett's resort to metaphor seems a recognition of this dilemma. Without wishing to detract from the utility of memetics and the fruitfulness of the idea, the features that make sense can be subsumed under the insubstantial nature of all semantic content. The accusation, also leveled against Popper's three-world model, that this resurrects duality, can be defused, as noted already, by a recognition that the semantic component is *necessarily* coupled to the “engineering” side.¹⁹

The sorting tools available include the rules of grammar and syntax, mathematics, and logic; the physical laws; moral laws like the Golden Rule; the democratic ideals that in part derive

from it; and belief systems. The internal mental process is iterative—a sorting and rearranging that is to some extent unconscious—with intermediate hypotheses tested against an evolving model maintained in the mind, appropriate to the area under consideration. The important point is that as our education evolves, we are more and more capable of making a *choice*, including that of which sorting aids to use, and we exercise our critical faculties. However amorphous my “self” is in terms of anatomical locality, “I” appear to direct my own focus of attention. Clearly, the self has an unhappy tendency to muddle things up; Blackmore [55] has a nice chapter on subjugating memes by meditation, very much along the lines of Buddhist practice, and this might well provide a mechanism for release from self, with therapeutic benefits (to reduce *nirvana* to the prosaic). However, abdication of self is not a proven recipe for a successful society. Rather than ascribing the illusion of self to the complex interactions between squabbling memes in a meme playground, it seems to me more productive to view the mind as a meme stud farm. Then I can go out and rustle up that pretty memetics mare and sire her with that strapping Shannon stallion, and pretty soon I'll have a fine bunch of frisky semantic foals that others might be interested in. Rather than a wimpy acquiescence in the dominance of memes, let's corral them and lick them into a self that we can be proud of! That way, we can expect to be held responsible for our decisions, expect others to be responsible for theirs, and maybe get back a society that values responsibility rather than excuse.

“Sorting AIDS” and the Survival of Societies

My third quibble with the simple memetic view is in the evolutionary mode. As originally expressed, this borrowed from Dawkins' selfish gene hypothesis the idea that the replicator (gene or meme) was the driving agent. Of course, it is clear in each case that the semantic content is the component of information transmission passed between successive generations and that its thermodynamic representation is therefore necessarily the entity that endures, the point that I think Dawkins intended. Taking the view that information transfer requires both message and vehicle and recognizing that the former is insubstantial propels us to a perspective in which the replicator is inseparable from its thermodynamic context, and its evolution is inseparable from an ecological context. For the meme, this surely involves a testing of man and his mind and the complex ideas it produces, against the world experienced as real, rather than survival of any selfish meme. The emphasis has to be shifted to the more sophisticated version of the meme as a composite whole. Along these lines, Dawkins and Dennett both integrate the fate of memes with that of their hosts (a meme that leads its bearer to disaster won't last long in the meme pool), but this leaves one wondering if there is any sense in imagining the meme as an “independent” evolutionary entity, as seems to be championed by Blackmore. Certainly (unless we want to explore supernatural possibilities), no meme can exist independently of its thermodynamic context, and an extended thermodynamic matrix of interacting entities (an external world, people and their minds, books, computers, etc.) is needed for meme exchange, selection, and conservation. The ecological niches for meme competition are the individual mind and societies. But this idea is no more than Popper's three worlds reformulated.

We offer our thoughts to “the world” for a wider testing against “reality.” That the reality includes a social and educational context that might be hostile, wrong, or muddled does not detract from the willful nature of the process. However, the nature of our local reality will certainly affect the outcome. The particular culture has consequences for the individual; poor Bruno at the stake comes to mind.²⁰ In the longer terms, choice of sorting aids also has

¹⁹This idea is not new. As Parmenides puts it, “Therefore thinking, and that by reason of which thought exists, are one and the same thing, for thou wilt not find thinking without the being from which it receives its name” [96]. Despite the general perception of his role as the modern source of the dualistic view, the same idea can even be recognized in Descartes' writings. He discussed the close and intimate union between mind and body. His observation that matter occupies space but that thought does not might be seen as an early version of my suggestion that semantic content cannot be evaluated through physical measurement.

consequences for the survival of the culture sponsoring them. A civilization or social group is defined as much by the sorting aids it condones as by anything. The sorting rules of any particular society have the status of, for example, the rule books for Wittgenstein's "language games," or similar scenarios from justificational epistemologies; they determine what is acceptable to the club. Choice of sorting aids on both the individual and societal sides is at the heart of the social contract.

It seems to me no accident that the most successful exploitation of physical and intellectual resources in the modern world has occurred in the context of democratic societies. The continuous application of human endeavor needed to maintain our highly unstable complex societies is best served through the willing participation of its members. "Willingness" can be engendered through different mechanisms; religion, nationalism, and totalitarian fervor have obviously worked in the past. But—and this is the view championed by Popper—in democratic societies, the feedback loops between government and the people, and freedom to choose, open up possibilities for error correction that seem to have a longer term advantage. An important component of the struggle for democracy has been the idea that people put more effort into tasks from which they receive a benefit. This implies choice, and hence the explicit recognition of liberties, responsibilities, and, as famously expounded in the Declaration of Independence, the "pursuit of happiness." Democratic mechanisms allow for evolution of the sorting rules condoned by society. In contrast, societies based on fundamentalist religious or totalitarian principles, in which new ideas have to pass a litmus test against dogma, are doomed to the same stagnation as pervaded the Middle Ages. The sorting tools inculcated at the madrassah, or at Bob Jones University,²¹ are not designed to broaden either the limits of experience or the chronognostic range (Figure 16).

Standing on the Shoulders of Giants

It is in the context of perception that I want to return to the chronognostic theme introduced above. The graph of Figure 17 can be thought of as a plot of subjective time against objective time. Our objective measurement of time is calibrated to the ticking of the cosmic clockwork. The "arrow of time" on that scale is changed not a jot by our insignificant meddling. Our subjective experience is more elastic. The initial slope of the graph represents the modest stretching of perception as the biosphere evolved, linked to the increased sophistication in the entropic delay introduced as complexity increased. The change in slope represents a more dramatic stretching of subjective time resulting from our evolution in the supra-phenotypical domain. A similar graph could have been presented showing the increase in effective force available for manipulation of the environment and would show a similar change in slope. The correlation between these two trends highlights the link between chronognostic range and the power we wield, but the slope begs the question of where we're headed.

We take our perception of time so much for granted that its implications become invisible, so much so that even in the discussions of evolutionary epistemology, its role is largely implicit (though Popper gives it some prominence [37,38]). However, it is only in the context of chronognosis that behavior has meaning; only through congruity with a polarity of time that

²⁰Giordano Bruno was burned at the stake for his support of the Copernican hypothesis, including his extension of the universe beyond the "immobile sphere" of the firmament (to give us a view of the stars as other suns with their own planets, people, and gods) and for his suggestion that the Creator could not be less than this larger creation. "On January 20 of the first year of the new century (1600) Pope Clement VIII ordered that Bruno be handed over to secular authorities for punishment. Sentence is read on February 8th: Bruno is declared an impenitent, obstinate and pertinacious heretic, to be stripped of priesthood and expelled from the Church, and his works to be publicly burned at the steps of St. Peters and placed on the Index of Forbidden Books. Bruno replies: 'Perhaps you who pronounce my sentence are in greater fear than I who receive it.'" The secular authorities burned Bruno as well (taken from <http://members.aol.com/Pantheism0/brunlife.htm>).

²¹This from the BJU Web page: "The Opportunity Place: A liberal arts, non-denominational Christian university, BJU stands without apology for the old-time religion and the absolute authority of the Bible."

spatiotemporal behavior makes sense. Life and evolution represent an exploration of the nature of the physical world in which predictive success has determined survival.

Recalling Olsen's coin-tossing "miracle," it is pertinent to note that two views of the same experience lead to different evaluations. From a statistical perspective, the outcome was prosaic. From the temporal perspective, the sequence was extraordinary. We can view life from these two perspectives: from the statistical, we get the Ronald Reagan view of biology: "If you've seen one redwood, you've seen them all" and from the evolutionary, every living creature is the unique fruition of a 4-billion-year experiment. Chronognosis is the most immediate sorting agent through which a new form or new hypothesis is tested against the physical world. This view of temporal perception seems almost tautological, being built into the whole concept of cause and effect. Indeed, for Kant, the perception of time was a priori, obtained directly from intuition, a view that seems well supported by the recent work on biological clocks. At the molecular level, evolutionary mechanism is predicated on temporal polarity: the central role of *sequence* in allowing an *ordering* of base pairs, or of amino acids, which underlies combinatorial amplification and information *processing*, and selection rules that allow *evolution* to occur; the very ideas and the physical realities they represent are imbedded in time. As noted already above, the temporal context of life and evolution means that the combinatorial possibilities at the metabolic and ecological levels are greatly expanded by the increased dimensionality. At the primitive level, a bacterium won't reach its food if it misreads the gradient. Similarly, at higher levels, the everyday experience of time is what compels all action and reaction. At the human level, our sophistication enables us to entertain philosophical paradoxes around time (Figure 17), but does not relieve us of the "tyranny of time" in controlling our daily lives. Our whole apparatus of perception is based on our chronognosis, and this linkage operates all the way from the innate to the full flowering of intellect. However, it is our ability to anticipate the future more successfully than other species that has led both to our present success and to our present peril as unthinking wielders of power.

The development of a modern view of time and space, including other aspects of evolution and the "biological arrow of time," has been discussed with insight by many others [17,30,31,33, 35–39,41,63–69]. I will not embellish my own discussion in these areas further, except to note that our appreciation of time engages the highest levels of our understanding. The brief history of time that emerges from the biological perspective is in a sense more inclusive than that from the cosmological view. Thanks to these authors and their kind, what we know of the cosmos and of time are now parts of the common semantic heritage. The mind of a Panini, a Socrates, a Dante, a Bacon, a Shakespeare, or an Einstein may be extinguished, but bits of each have spilled out into the external semantic inheritance to help us on the road to a deeper understanding. They are immortalized in the wider context of our society—their souls go marching on.²² These are the giants whose shoulders we stand on.²³ Our extensions of the limits of experience and of our chronognostic range are all part and parcel of the same thing: the evolution of the biosphere to take advantage of the thermodynamic opportunities available, through refinement of the semantic heritage, and increased combinatorial complexity. Within this framework, we have developed an understanding of our universe as having an independent

²²Albert Einstein's (1934) address to a group of children: "My dear children: I rejoice to see you before me today, happy youth of a sunny and fortunate land. Bear in mind that the wonderful things that you learn in your schools are the work of many generations, produced by enthusiastic effort and infinite labor in every country of the world. All this is put into your hands as your inheritance in order that you may receive it, honor it, and add to it, and one day faithfully hand it on to your children. Thus do we mortals achieve immortality in the permanent things which we create in common. If you always keep that in mind you will find meaning in life and work and acquire the right attitude towards other nations and ages."

²³Bernard of Chartres (d. c.1130): "We are like dwarfs on the shoulders of giants, so that we can see more than they, and things at a greater distance, not by virtue of any sharpness of sight on our part, or any physical distinction, but because we are carried high and raised up by their giant size." Quoted by John of Salisbury in *The Metalogicon* (1159; from [97]). This famous metaphor was also used by Isaac Newton in a letter to Robert Hooke (1676). There is a sneaking suspicion, because of the hostility between the two and Hooke's small stature, that the sweeping vision of Bernard's phrase was not all that Newton had in mind.

physical existence in space, governed by time-independent laws.²⁴ We have developed formal descriptions through which we can interpret the direction of time and the temporal behavior of matter in a way that has allowed us to exploit our environment to further our own advantage. As with all such models, these views are conjectural and will change, but it seems likely that the mechanism of a testing against the realities of the thermodynamic world will continue to provide a pathway for further refinement.

Postscript

The reader who has borne with me so far will not need to be reminded that with extension of the limits of our experience comes a linked responsibility. We can no longer invoke religion in assigning responsibility for our behavior with respect to those aspects of our interactions with the natural world for which we claim an understanding. A remarkable feature that emerges from the above discussion is the impact that the essentially biological functions represented by the extensions of human behavior in the supra-phenotypic domain have had on the very system that has generated them. The extraordinary developments of the past century accompanying the advances in science, computation and technology, and their exploitation in the service of human kind have left us in an unprecedented situation. The “effortless” semantic content, shared as the collective wisdom of our civilizations, is in stark contrast to the way in which it has enabled our species to direct energy into a remodeling of this world. This in turn has put an obvious strain on our relation to the rest of the biosphere and our physical environment. Over the past few decades, our meddling has changed not just the biosphere, but the whole balance of energy fluxes through which the biosphere is maintained. Ozone depletion from the catalytic effects of halogenated hydrocarbons was a near-catastrophe, which, despite the international response, will be with us for decades. Global warming from the increased levels of CO₂ accompanying burning of hydrocarbon reserves will have profound effects on ecology and is already melting ice-caps and raising the levels and increasing the acidity of our ocean. In the United States, these warning signs have been passed off by ignorant politicians as inconsequential,²⁵ so that the profligate consumption continues unabated. Perhaps if we pause to reflect on the intimacy of our relationship with the biosphere, the delicate balance with the atmosphere and oceans, and the fragility of our highly ordered world, we might recall ourselves to recognition of our responsibilities. No one will preserve our world if we don't.

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²⁴The view of time in modern physics is tied to controversial issues in both cosmology and quantum mechanics. In terms of the local universe, the constraints of conventional physics and relativity set well-defined limits on measurements through which a hypothesis can be tested. However, some interpretations of quantum mechanics (and its extension to string theory), and some cosmological theories, include multiworld/multiuniverse models in which the present impossibility of measurement limits the epistemological certainties. Hypotheses are then so much less constrained (as is well recognized by some in the physics community [98]) that one wonders if they would pass the tests implicit in the Jones ruling (see footnote 13). See http://www.life.uiuc.edu/crofts/papers/Epistemology_and_QM.pdf for a naive biologist's perspective.

²⁵One is tempted to observe that some politicians behave as if they have the chronognostic range of hollyhocks. The spinless kowtowing of the Bush administration and its supporters in Congress to the rapacious demands of commercial interest, especially in energy policies that exacerbate the effects of global warming, is likely to haunt us far into the future. Diamond [63] in *Collapse* underlines how a limited chronognostic range can spawn bad policy. The estimate of chronognostic range (above) might be an insult to the biennial hollyhock; Diamond has an account of the priorities of the early Bush administration that suggests a range of just 90 days.

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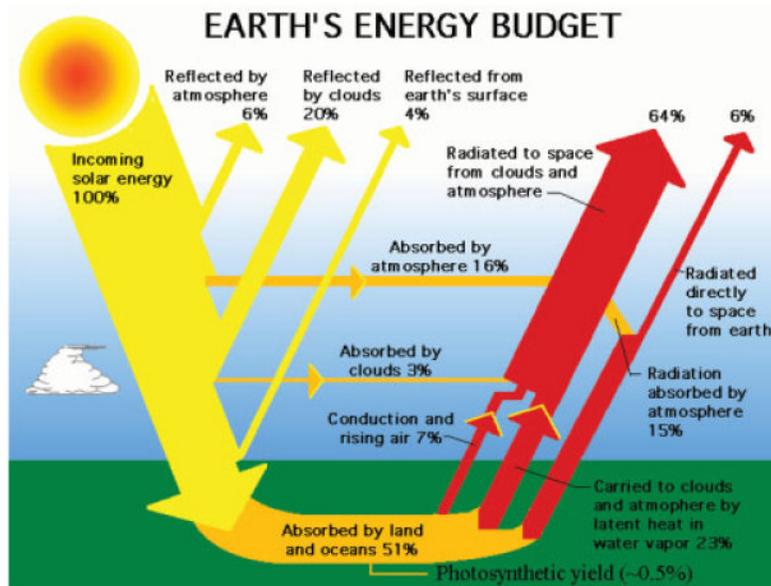


FIGURE 1. Scheme to show how the solar energy intercepted by the earth is redistributed. The photosynthetic yield of ~0.5% is available for consumption by animals, fungi, and bacteria, and sustains the biosphere, but is eventually lost to space as IR radiation (Adapted from <http://asd-www.larc.nasa.gov/erbe/components2.gif>). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

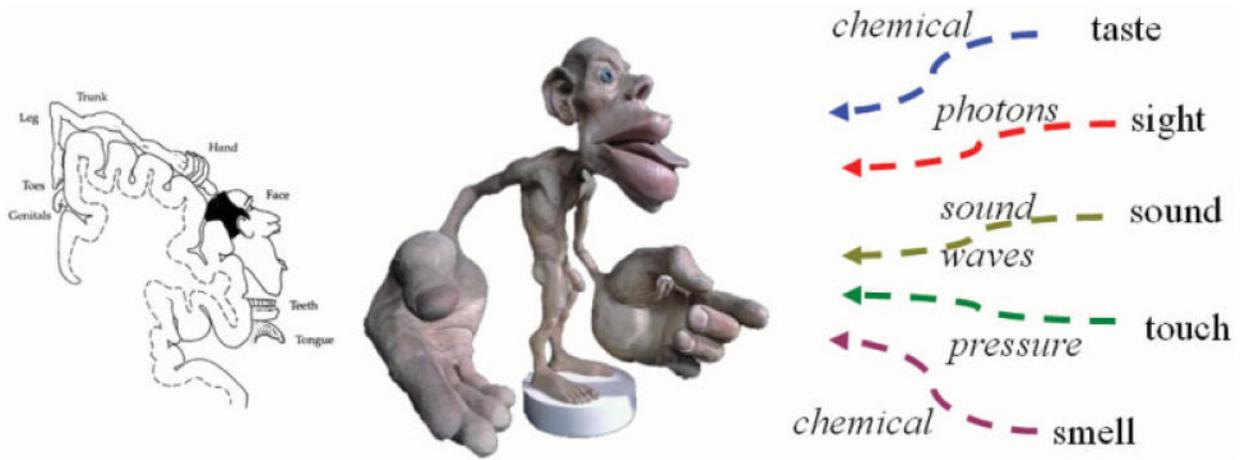


FIGURE 2.

The mind, its external interfaces, and the thermodynamic carriers for sensory and semantic input. Penfield's sensory homunculus, projected on the cortex of the brain (left), or as a model distorted in proportion to the area of the cortex concerned with touch (middle), and the physical or chemical vehicles that impinge on different sensory interfaces (right). (The model is in the Natural History Museum, London, and has been released to the public domain. Models for other senses could be constructed along similar lines). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

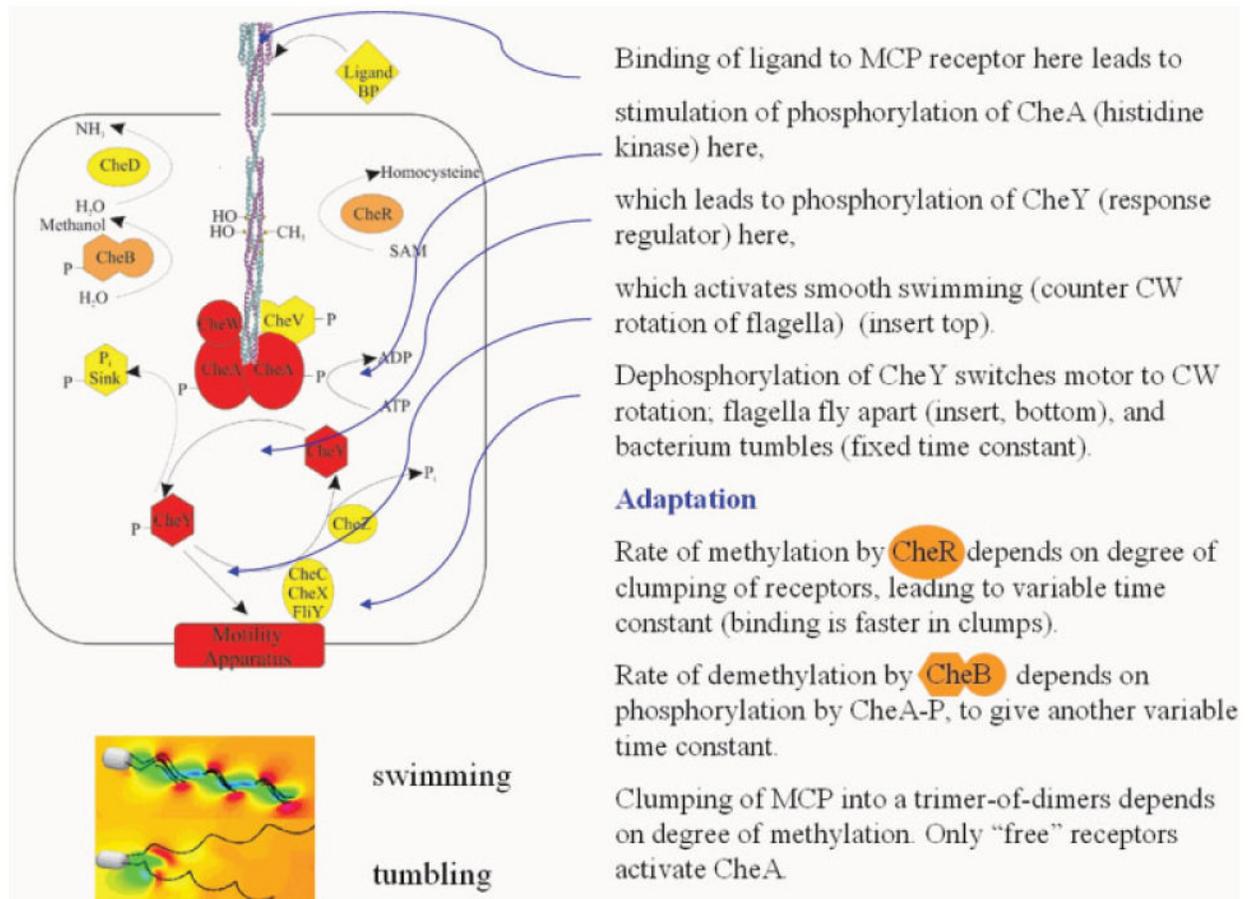


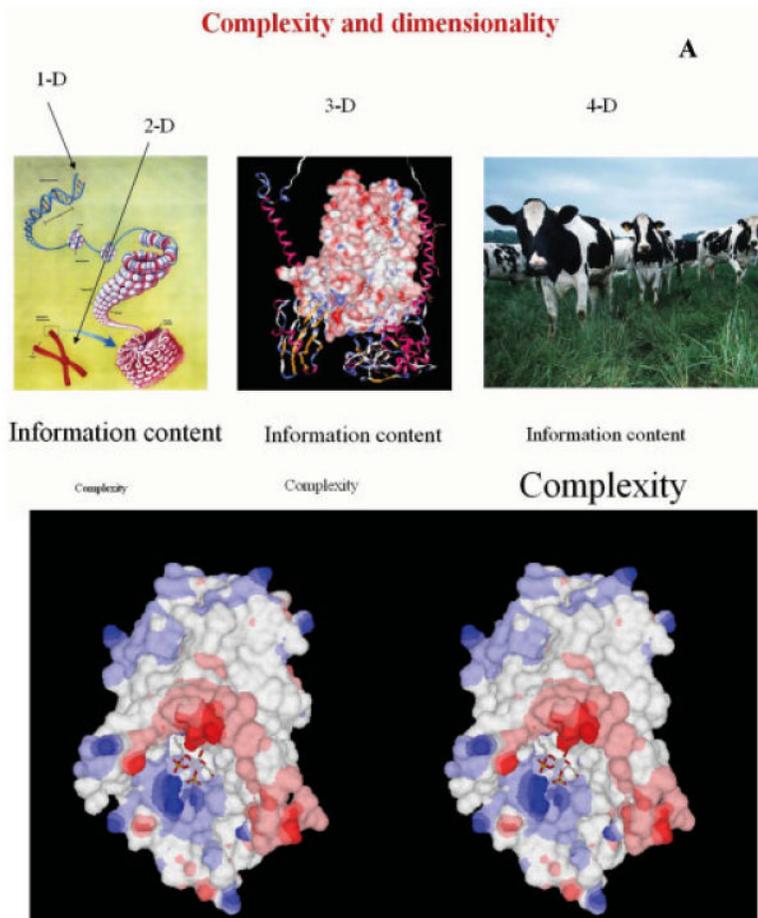
FIGURE 3.

Dissecting the biochemical machinery underlying bacterial chemotaxis. The apparatus through which the bacterium detects changes in gradients includes the following elements. Detection of attractant or repellent molecules through a chemoreceptor (MCP), which transmits a signal across the cell membrane; the subsequent triggering of a signal transmission cascade through a two-component histidine kinase (CheA) and response regulator (CheY) system; and modulation of flagella response (insert, lower left). This involves phosphorylation of CheY (catalyzed by CheA) or dephosphorylation (CheC, CheZ) to change the direction of rotation. An essential component of the mechanism is *adaptation*, a biochemical process with variable time constants involving methylation (catalyzed by CheR), and demethylation (catalyzed by CheB) by reversible esterification of acidic side chains in the receptor, which modulate the degree of aggregation, likely by neutralizing the coulombic repulsion from like charges. This leads to deactivation or activation of the signal transmission pathway. The precise role varies between species, but the system can be regarded as involving competing decay and refresh pathways, in which the time constants for some functions are under control by the state of activation of the receptor. This allows recognition of gradients—changes in local concentration—with a time scale on the seconds-to-minutes range. Details of mechanism vary in different bacterial families; the scheme here is appropriate for *Bacillus subtilis*, in which an additional mechanism for amidation and deamidation (CheD) of the acidic residues also contributes. An interesting variant recently reported [99,100] is an activation of a similar CheA kinase through binding of sensory rhodopsin II to its membrane partner HtrII on photoactivation in haloarchaea. Art work adapted from Ref. 85 by addition of a serine receptor dimer model from Ref. 84.



FIGURE 4.

Pierre Simon Laplace (1749–1827) and the deterministic view: “We ought to regard the present state of the universe as the effect of the antecedent state and as the cause of the state to follow. An intelligence knowing all the forces acting in nature at a given instance, as well as the momentary positions of all things in the universe, would be able to comprehend the motions of the largest bodies as well as the lightest atoms in the world, provided that its intellect were sufficiently powerful to subject all data to analysis; to it nothing would be uncertain, the future as well as the past would be present to its eyes ...”. Laplace, 1820, *A philosophical essay on probabilities*. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

**FIGURE 5.**

Top: Combinatorial complexity on going from one to four dimensions. Left, the double helix contains two complementary copies of the genome with identical information content. In bacteria, this single genome restricts dimensionality to 1D, but in sexual reproduction additional combinatorial levels are opened, effectively in 2D, by chromosomal crossover. The 3D level (middle) is represented by the bc_1 complex catalytic core (PDB ID 2bcc, 3bcc) [101], with the cytochrome b subunit surface colored to show its physicochemical surface (as electrostatic potential: red, negative; blue, positive). This complex has two catalytic sites for oxidation or reduction of ubiquinone species (or binding of inhibitory mimics), internal pockets for binding of four metal centers (3 hemes and an iron-sulfur cluster), two external catalytic interface for interaction with a mobile domain of the iron-sulfur protein, a hydrophobic membrane interface, several interfaces for interaction with other subunits, and a dimeric interface. Bottom: The adenine nucleotide translocator (PDB ID 1okc). The surface is colored to show electrostatic potential. This stereo view (for crossed-eye viewing) allows a glimpse into the pocket where adenine nucleotide binds, which is occupied here by the inhibitor carboxyatractyloside. This protein is thought to act in dimeric form to exchange ADP^- for ATP^- across the mitochondrial membrane through large conformational changes; the surface is quite complex and shows not only the internal binding pocket, but also two aqueous polar interfaces, a hydrophobic collar that interfaces with the membrane lipid, and a dimeric interface.

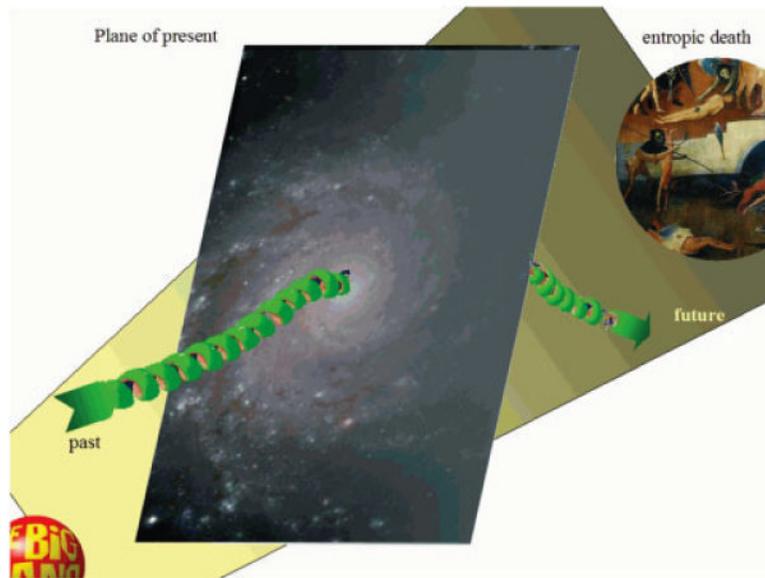


FIGURE 6.

The arrow of time. The arrow is shown as a spiral (represented by an α -helix) passing from the past through the "plane of present" to the future. The "plane of present" is represented by a spiral galaxy (with a period long compared to human timescales). Start- and end-points are the big bang, and "entropic death" (represented metaphorically by a detail from "Hell" by Hieronymus Bosch). There would of course be none of those discernable gradients in a universe at equilibrium). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

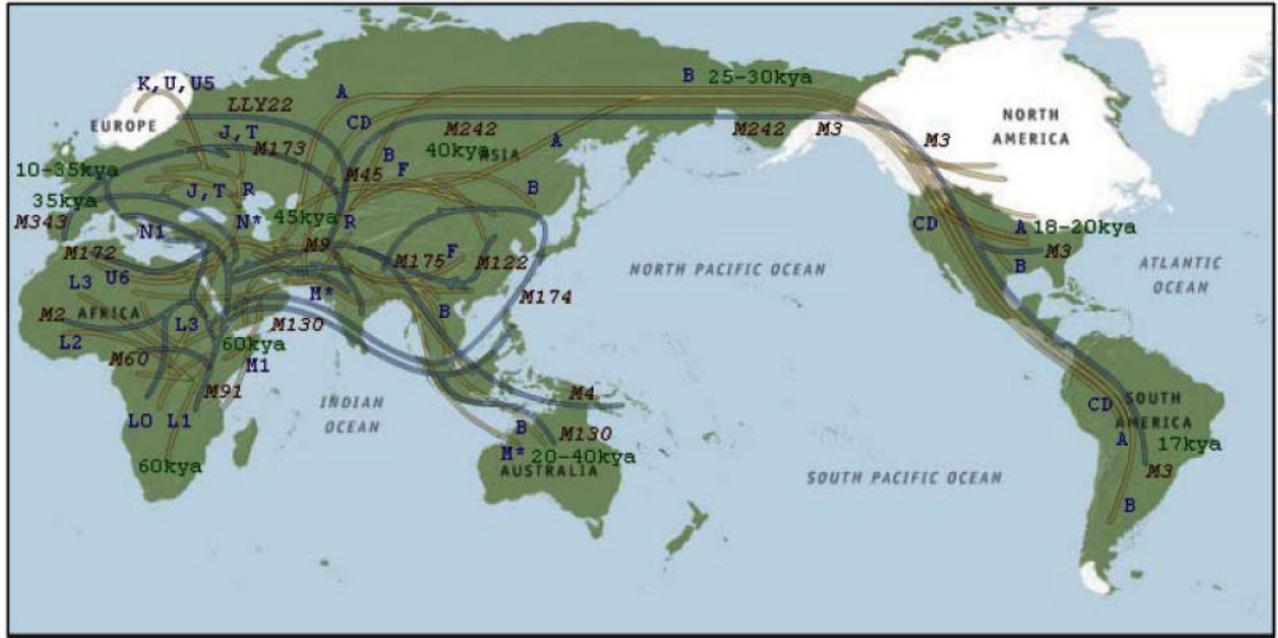


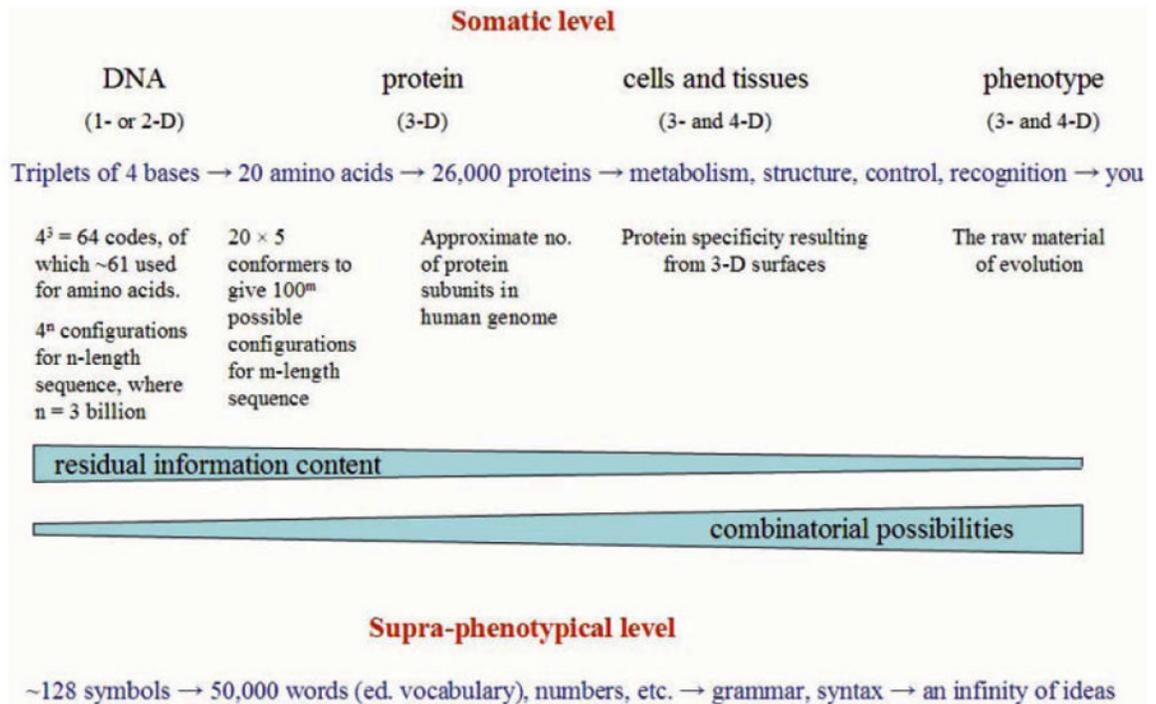
FIGURE 7.

The exodus from Africa. The origins of all modern human populations can be traced back to ancestors from Africa, through comparison of sequences of mitochondrial DNA (female lines, or “Eve”, beige), and DNA from the “Y” chromosome (male lines, or “Adam”, cyan). Migrations from Africa date back ~70,000 years, providing an anthropocentric start to our history. The blue lettering indicates major mitochondrial lineages, the dark red italic lettering shows Y-chromosomal lineages, and the dark green numbers followed by kya show that arrival time in thousands of years ago. Only lineages dating back to the period 35–40 kya are shown), and the land masses and glaciation (white) reflect this time period. This Figure was constructed using data made available through the National Geographic Society's Genographic Project web pages (<https://www3.nationalgeographic.com/genographic/index.html>), and this informative and interesting site is gratefully acknowledge.



FIGURE 8.

Lascaux cave drawings, and similar cave art and figurines from the pre-historic era, represent early examples of the representation in physical form of semantic content abstracted from the mind (image from Wikipedia, <http://en.wikipedia.org/wiki/Image:Lascaux2.jpg>) [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

**FIGURE 9.**

Scheme to illustrate the levels of combinatorial complexity arising from increased dimensionality following semantic translation at the somatic level (top). The residual information content refers to that originating from the genome at conception; in metazoans, the mature phenotype obviously contains many diploid copies, but most of these are not involved in reproduction, and only half the original is passed on in each haploid gamete. The estimated number of protein coding genes (~24,000) represents <2.5% of the genome. A smaller fraction encodes RNA directly involved in the translational machinery. A much larger fraction (probably >80%) is transcribed, and from its characteristics is likely involved in determination of tissue specificity, ontogenic sequencing, etc. For a recent review, see 104. The combinatorial possibilities expand with dimensionality more dramatically than shown; the vertical axis of the schematic should be thought of as on a log scale. Complexity inherent in language (bottom). The representation of complex thought in literature, conversation, etc. depends on the combinatorial exploitation of a relatively small number of symbols in sentences whose structure encodes meaning. The ideas (memes) are the units of semantic transmission, and the complexity of our culture depends on the translational processing and mutation in individual minds (not shown). Similar schemes could be shown for mathematics, logic, music, etc. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

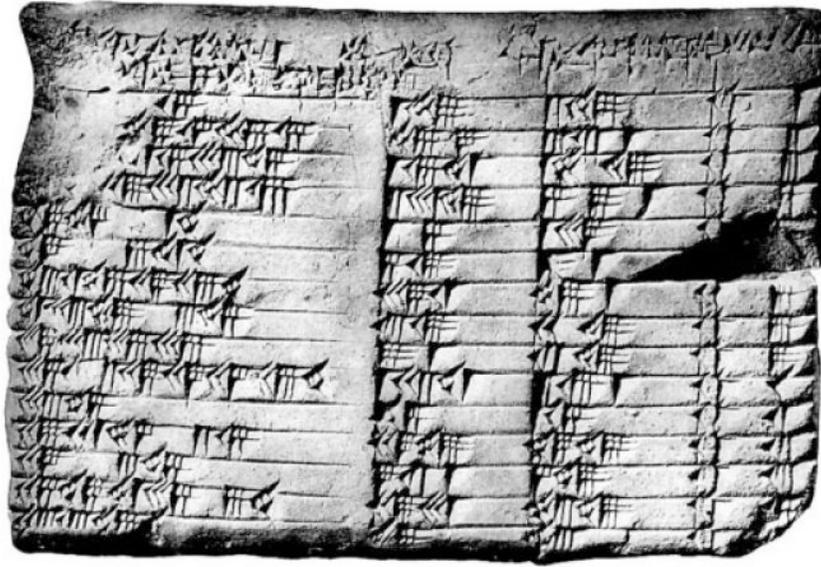


FIGURE 10. Cuneiform tablet from Ancient Babylon (~1700 BC) showing Pythagorean triplets. Plimpton 322 from the Plimpton collection (Columbia University) (image from Wikipedia, http://en.wikipedia.org/wiki/Image:Plimpton_322.jpg). For much of the information about the development of mathematics, I am indebted to the MacTutor Web site (see Supplementary Sources for URL).



FIGURE 11.

The Council of Nicaea. Bishop Nicholas forcefully argues for the homoousian cause (Sistine Chapel fresco). The transformation of St. Nicholas into Santa Claus is a nice example of memetic mutation (see text). Image courtesy of St. Nicholas Center (www.stnicholascenter.org), which has a nice account. The forcefulness of Bishop Nicholas was not just verbal! [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

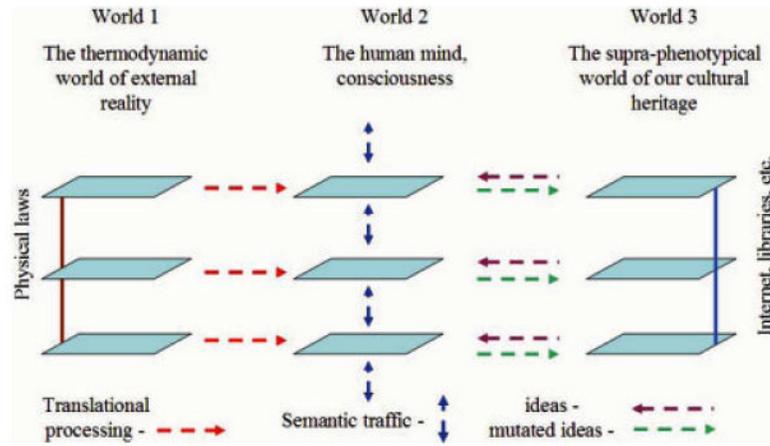
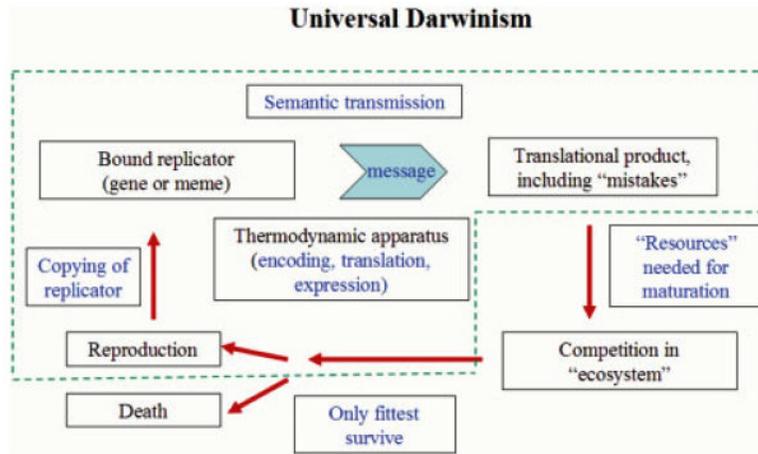


FIGURE 12.

Popper's Worlds 1, 2, and 3, expanded into three dimensions. We see ourselves as individual minds (World 2). Our perception of the physical World 1 might be unique (arrows from left showing sensory input), but we all experience the same world, tied by physical laws. Our "conversations" (central column) involve exchanges in which translational processing, access to associative memory, mutation of ideas, etc. are so rapid as to appear automatic. The semantic heritage of World 3 (right) appears dynamic, but is static except for the horizontal exchanges with individual minds. The Internet traffic is a relatively new feature, but we depend on a copying function that is error-free, so the vertical exchanges indicated do not change the heritage. However, the speed of exchanges via the Internet is contributing to an acceleration in exploration of combinatorial possibilities made possible by the horizontal exchanges with minds. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

**FIGURE 13.**

Scheme to show the role of semantic transmission in Darwinian evolution. All evolving systems follow the same pattern in which the meaning of a thermodynamically encoded message is transmitted via a translational machinery to allow reproduction. The overall process is subject to error, so that the translational product may include "mutations." The translational product is tested in an "ecosystem" against competitors. Products that survive reproduce, thus propagating the more successful traits, leading to improvement. In reproduction (enclosed by dashed line), the step for semantic transmission is shown as separate from that for the copying of the replicator to accommodate obvious difference in the degree of linkage for different forms. The tightness of linkage decreases in the order: bacteria reproduction by cell division; asexual reproduction in the protista; sexual reproduction in the metazoan; and supra-phenotypical inheritance. In all cases, the transmitted message needs to find itself in a competent translational environment. However, the linkage between transfer of the message and the translational apparatus also depends on the case considered, in a similar order (see text for explanation). The mature phenotype is reproduced *after* whatever mutation changes it, so that what looks like a cycle in this 2D representation would project to a 3D version (see Figure 12) and a spiral through time in 4D (see Figure 6). All processes that we perceive as cyclical are spirals through time, with pitches and lengths spanning many orders of magnitude. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]



FIGURE 14.

Detail from “The Fall of the Rebel Angels” by Pieter Bruegel the Elder, from the Webmuseum, Paris (<http://www.ibiblio.org/wm/paint/auth/bruegel/>). Dennett's treatment of the states underlying consciousness [56] involves demons, homunculi, memes, and other agents, a metaphor nicely illustrated by Bruegel's painting. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

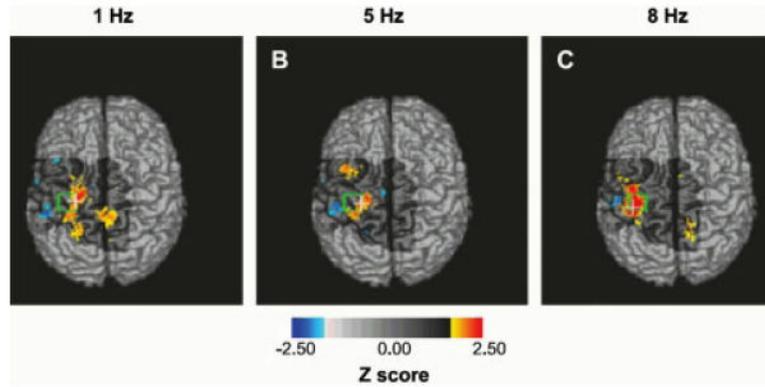


FIGURE 15.

EROS maps showing cortical neuronal activity measured noninvasively through changes in near infrared transmission. The optical apparatus measures IR transmission through the brain cortex from outside the skull. Here, the stimulus was a thumb-twitch, elicited by electrical stimulation of the wrist, and maps are similar for different repetition frequency (top). The responses occur at 16–32 ms after stimulation. Events on this time scale are obviously registered (since they induce the response seen), but are probably not yet consciously perceived. The Z score represents differences from baseline. The darker gray shows the area monitored. The brain image was from structural MRI, used to determine the brain area corresponding to the response. Similar maps can be measured following sensory stimulation by sight or sound, but these elicit responses with greater latency, and in areas dependent on sensory and semantic context. The time scale of measurement here is fast enough for exploration of the mechanisms underlying consciousness (from Maclin et al. [102]; reprinted with permission from Elsevier).

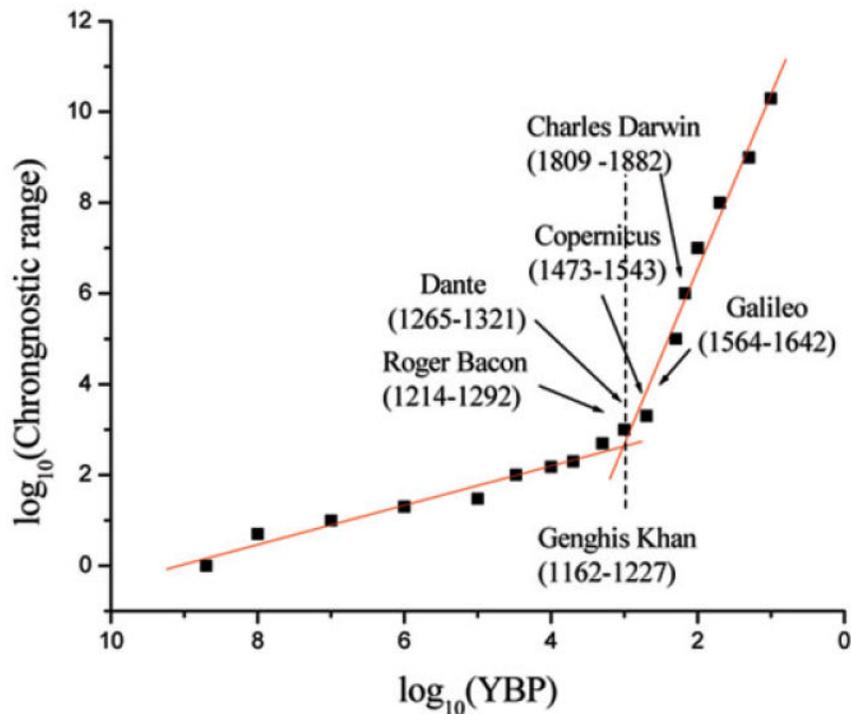


FIGURE 16.

The relation between chronognostic range and evolution of the biosphere. The plot of chronognostic range (CR, in years) against years before the present (YBP) is shown on a log vs. log scale to accommodate the many orders of magnitude involved. The slope in the early part of the graph reflects the contribution from advances in behavioral complexity. A few “markers” will illustrate the approach. The bacterial world was constrained by the biochemical processes discussed in the text (CR in the seconds range; see also Figure 3). As evolution led to more advanced forms, the temporal perception lengthened, perhaps to the lifetime for an advanced vertebrate. But even in the case of early human societies, the range was constrained to a few 100 years and was limited by oral transmission. With the development of archival information storage, this was extended into the thousands of years range. The change in slope reflects an acceleration arising from the development of a supra-phenotypical semantic heritage. The choice of points is biased, since the latter part of the plot is based on developments in the civilization of Europe and the West. However, in Western thought, it was not until the Copernican revolution, Bruno, and Galileo that our perception of the universe was stretched further than the Greco-Roman-Arabic Ptolemaic tradition, and not until Darwin that our temporal range was stretched beyond the “biblical limit.” In modern times, this range is determined by cosmological time scales, accessible to interpretation though advances in our understanding of astronomy and its relativistic scales of time and distance. The graph reveals a dramatic change in slope in the mid-13th century. A strong case is made by Jack Weatherford in *Genghis Khan and the Making of the Modern World* [103] that the flowering of intellectual life in the 14th century owed much to the spread of ideas after the establishment of the Mongol Empire. This opened trade routes that facilitated an exchange of ideas and culture between Europe, the Islamic Empires, and East Asia. Subsequent developments leading to the astonishing slope must include the dawn of humanism, the reformation, the development of literature in the vernacular, the renaissance, the age of exploration, the spread of printing in the West, and the emergence of a rational science from the constraints of dogma. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]



FIGURE 17.

Paradoxes of time: meme selection at the machine level? A small sample of the images delivered by Google in response to *arrow of time*; the recall of associative images from the Web represents a second-hand dipping into a pool of images deposited by human agency. Left: “Time flies like an arrow”, and middle: “Fruit flies like a banana”, both from Harvey Galleries (www.harveygallery.com/, reproduced with kind permission of Henry Harvey); right: the CPLEAR experiment (www.cern.ch/cplear/) to test charge, parity, time (CPT) invariance, reproduced with kind permission from CERN. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]