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Evolution as Communication

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ABSTRACT

The *Evolution as Communication* hypothesis posits biological evolution as a specific instantiation of an information communications phenomenon; specifically communications through a channel that is aligned with a time-based space-time dimension and that is unbounded. This implies that biological life can be defined as a communications coding process that maximizes the probability of continuity of information propagation through the time-based, unbounded channel over time. Specific evolutionary phenomena such as reproduction, natural selection, etc., are shown to be well defined within this framework. Testable implications of the hypothesis are discussed.

OVERVIEW

The explanatory success of Darwin's evolutionary framework is indisputable. Nevertheless, there continues to be a nagging feeling that somehow it is not quite the whole story. That nagging feeling manifests itself with regard to several puzzling issues, including the seeming direction of evolutionary "complexity", and the seemingly tautological nature of the driving mechanism of Darwinian evolution natural selection (1). Further, when informed experts disagree on basic definitions (e.g., life) or specific mechanisms (e.g., the locus of selection) associated with a theory, it is a hint that something essential may be missing from our understanding. Contemporary evolutionary theory remains underpinned by the basic Darwinian framework and is clearly an even more powerful framework for explaining the living world. Yet even in today's more robust form, evolutionary theory can perhaps be likened to Newtonian gravitational theory, which, while highly successful as an explanatory model, left uncomfortably unexplained the essential nature of gravity.

Our research suggests that Darwinian evolution may be considered within an extended framework of information theory, or, more specifically, what Shannon called communications theory (2). It is, of course, well understood and accepted that evolution comprises a process of genetic-based information being continually transmitted over time through reproduction (3,4,5). Further, numerous authors have observed that, a product of this biological evolution, human culture, reflects a more recently developed, derivative information transmission phenomenon (3,4).

The Evolution as Communication (EAC) hypothesis summarized in this paper extends well beyond these previous observations on evolution and information theory by fundamentally re-orienting the entire perspective. The perspective that perhaps most anticipates the EAC hypothesis is Yockey's (5) comment that we can "consider evolution as a communication system from past to present and present to future." The EAC hypothesis extends this insight by proposing that evolution in *all* of its biological manifestations can fundamentally be *defined* as a type of communications process. A key corollary of this insight is that what we have historically defined as "life" is most usefully framed as "just" a coding process to ensure continuity of message over time. Further, all other evolutionary-related phenomena such as fitness, reproduction, natural selection, can be comfortably defined in terms of the EAC framework.

Put another way, the historical perspective of biology has been in a sense to place life at the center, with evolution as a derived characteristic of living processes, and the communication of information as a mechanism or outcome of this evolutionary process. This hypothesis turns this model on its head by arguing that evolution is best understood as a specific type of an abstract communication process, and life as we know it is essentially a by-product of this evolutionary communications process. With this new perspective, the concept of evolution is seen to be more "fundamental" than the concept of life and communications (propagation of information) is seen as a more fundamental concept than evolution.

The EAC hypothesis has several key advantages. First, it holds promise for providing additional explanatory power with regard to some of the more puzzling aspects of the living world – for example, the perceived arrow of complexity, and the notoriously "fuzzy" nature of our definitions of life itself. Second, it takes a step toward unifying biological phenomenon with the non-biological background through application of information and communications theory. In other words, it takes a step toward a science of "one nature", in which our sciences of biological phenomena are more explicitly grounded in intrinsic properties of the universe.

COMMUNICATIONS THEORY EXTENDED

Shannon's theory of communication can be thought of as a "special" theory of communication in that it posits certain explicit and implicit assumptions and boundary conditions. Extending beyond Shannon's profound breakthrough, we seek to develop an even more generalized theory of communications. We will do so by taking Shannon's basic framework, boiling it down to its most essential elements, relaxing certain fundamental assumptions of his theory, and examining the results. When we do so, we attain some surprising insights.

First we must consider the question of what we mean by *communications* in its most fundamental sense. We will start with just two of the most fundamental concepts of modern physics: space-time and information. While the essential nature of information and its measurement remains a subject under development (6), for the purposes of this paper we will take information to mean a distinguishable physical state (7,8), and measurable by the Shannon entropy metric (2). Given just the two elemental notions of space-time and information, we can effectively define communications at its most fundamental *as the propagation of information (a "message") through one or more dimensions of space-time*.

Next we tackle the notion of a communications "channel". We will generalize Shannon's notion of a channel by defining it as: *a medium aligned with one or more specific dimensions of space-time through which information (a message) propagates.*

Shannon's breakthrough was determining methods and limits for effectively coding messages through a noisy channel, where the space-time dimension of the channel is implicitly a *spatial* dimension (typically *one* spatial dimension). Since "noise" and "coding" are so central to Shannon's communication theory, we must also carefully define their essential features. At its most basic, we define noise as any phenomenon that *inhibits the propagation of information through a channel*. And at its most basic, the coding of a message is any information-based approach to *maximizing the probability of propagation of a message through a noisy channel.*

So, by abstracting Shannon's model, we have defined a generalized communications process in which information (a message) is propagated through at least one dimension of space-time (a channel) under noisy conditions, facilitated by coding that maximizes the probability of successful message propagation. This generalized communications model can encompass a variety of subsidiary assumptions and boundary conditions.

In that regard, we will diverge from Shannon's specific communications model by relaxing certain assumptions and boundary conditions. Specifically, the explicit or implicit assumptions of Shannon's model that we are particularly concerned with examining are:

- The communications channel is assumed to be bounded
- The communications channel is assumed to be predominantly aligned with a spatial dimension of space-time
- Noise is assumed to be generated only externally to the communications process
- Message coding is assumed to be extrinsic to the communications process

We will next examine each of these assumptions, and discuss the implications for the relaxation of the assumptions and/or boundary conditions. This will lay the groundwork for abstracting Shannon's original model in a way that will yield a framework that is isomorphic with evolutionary and biological phenomena.

Bounded Communications Channel. Shannon assumed a finitely bounded communications channel – bounded both by a finite capacity and bounded by a receiver at the end of the channel. We will not be overly concerned here about assumptions on the bounds of channel capacity. But we will posit a communications channel that is effectively unbounded in the sense that there is no specified receiver.

The lack of boundedness of the channel has an important implication. In Shannon's model the communications success criteria is measured by the fidelity of the message *received* over the noisy channel. In other words, by default the measurement of propagation success is defined in terms of a particular point (the only relevant point – the receiver) of the space-time spatial dimension. However for an unbounded communications channel, the situation is different. The criterion for communications success must be a function of not only the fidelity of the message, but the fidelity of the message at any specified point in the space-time spatial dimension of the communications channel, where the measurement point may be selected from an unlimited number of points along the spatial dimension.

Therefore, given the *a priori* indeterminacy of the point along the spatial dimension at which message fidelity is to be measured, the *continuity* of the message along the unbounded channel must be part of the communications effectiveness equation. Specifically, for unbounded communications channels:

$$E = f(F(p))$$

where:

E = effectiveness of communication over an unbounded channel

F(p) = fidelity of message to original message F(0) at point p

That is, effectiveness of communication is a function of the fidelity of the message being propagated to the original message, measured at any given point in time, p.

It is clear that if the message completely stops, the fidelity of the message is zero after that point. Since we want maximize E = f(F(p)) for any arbitrary point p, continuity of message must always ultimately trump message fidelity for unbounded communications channels.

We can more formally state this notion as a theorem as follows:

Continuity Theorem for Unbounded Communications Channels

For a noisy unbounded channel where message fidelity can be measured at arbitrary points, effective coding processes will ensure continuity of message at the cost of decreased (but > 0) message fidelity.

In other words, the coding process will apply coding methods that dilute the message as required to achieve arbitrarily long propagation through the channel. Further, and importantly, the degree to which the coding process trades-off message fidelity for higher probability of continuity must be a function of the level of noise. That is, the greater the level of noise, the more continuity must be emphasized by the coding process versus fidelity to the original message.

The Continuity Theorem has important implications for associated message coding approaches in unbounded communications channels.

Channel Defined by Spatial Dimension. Shannon implicitly assumed a communications process implied that messages are sent across spatial space-time dimensions. That is certainly a sensible assumption for the human-based telecommunications systems with which Shannon was primarily concerned. But we will premise a communications channel defined, at least primarily, in terms of the *time* dimension of space-time.

Effective message coding in an unbounded, time-based channel must be measured as follows:

E = f(F(t))

where:

E = effectiveness of communication over an unbounded time-based channel

F(t) = fidelity of message to original message F(0) at time t

This again implies that the criteria for success of communications across such an unbounded time dimension-based channel must include an aspect of *continuity*, in addition to message fidelity. Thus:

Continuity Theorem for Unbounded Time-based Communications Channels

For an unbounded time-based channel where message fidelity can be measured at arbitrary points in time, effective coding processes will ensure continuity of message over time at the cost of decreased (but > 0) message fidelity.

And as in the case of the Continuity Theorem for general unbounded channels above, the degree to which the coding process for time-based unbounded channels trades-off message fidelity for higher probability of continuity must be a function of the level of noise.

Noise as a Solely External Phenomenon. Shannon used the term “noise” to describe a phenomenon that reduced the fidelity of the message being transmitted through a communications channel. Let us broaden the concept by assuming noise can be intrinsic to the communications process, rather than just extrinsic. In other words, noise (errors, failures) may be inherent to constituent elements of the communications channel.

By making this assumption, our model integrates classic Shannon communications with the auto-correcting complex systems as described by Von Neumann (9). In such systems errors (noise) have to be continuously corrected for the system to continue to function effectively. These errors may occur during normal operations or when making copies of itself (reproduction). From the perspective of our more generalized notion of communications, we see that Shannon and Von Neumann were just describing different noise sources that can be addressed by applying appropriate information coding approaches.

Coding Extrinsic to the Communications Process. Shannon used the term “coding” to describe information-based approaches to increase the fidelity of a message received over a noisy communication channel. For example, the simplest coding approach is redundancy; the technique of sending multiple copies of the message, or elements of the message, to increase the likelihood of receipt of the original message. A variety of more sophisticated approaches to communications coding are, of course, possible (10).

Shannon implicitly assumed coding was applied extrinsically to the message – specifically by human means and ingenuity. We will premise a coding process intrinsic to the communications process. That is, we premise a self-coding system, in which correcting for the effect of noise is intrinsic to the communications process.

With these alternative assumptions to Shannon’s original model, we have defined a communications process operating in an unbounded time-based channel, with externally and internally generated noise, and that is self-coding. But, as is argued in detail below, what we have also just defined is the essence of biological phenomena!

CORRESPONDENCES BETWEEN EVOLUTION AND COMMUNICATIONS

The relationship between the process of self-coding communications through an unbounded time-based channel and biological evolution can be seen by considering the essential features of each. We take as a basis for comparison the fundamental concepts applied by the Replicator-Mutator Equation. Page and Nowak (11) have demonstrated that the Replicator-Mutator Equation is equivalent to the Price Equation, as well as certain evolutionary game-theoretic models, which collectively serve as the fundamental mathematical bases for evolutionary biology (11). The Replicator-Mutator Equation is of the form:

$$\Delta x_i = \sum_j x_j f_j(\mathbf{x}) q_{ji} - \sum_i f_i x_i$$

where:

x_i = relative abundance of a genetic-based sequence for a trait *i* in a population *P*

f_i = fitness of trait *i*

$\sum_i f_i x_i$ = the average fitness of population *P*

q_{ji} = the probability replication of genetic-based sequence *i* results in sequence *j* (mutation matrix)

$f_j(\mathbf{x})$ = frequency dependent selection and mutation based on the distribution vector $\mathbf{x} = (x_1, . . ., x_n)$ in population *P* (this incorporates evolutionary game dynamics)

Δx_i = rate of change in the genetic-based sequence for a trait *i* over time

It should be noted that although we are applying the Replicator-Mutator Equation to highlight correspondences between biological evolution and our abstract communications model, the Replicator-Mutator Equation makes the simplifying assumption that the fitness landscape remains constant – that is the environment, or in communications terminology, the noise, remains constant. This simplification suggests that although we can apply the Replicator-Mutator Equation or its equivalents to examine correspondences to abstract communications, it is not sufficiently robust to be generally predictive of evolutionary outcomes suggested by the EAC hypothesis.

Table 1 outlines the key correspondences between evolutionary biology interpretations of the basic concepts of the Replicator-Mutator Equation and a communications-based interpretation.

Table 1

Concept	Biological Evolution Interpretation	Communications Interpretation
Population (P)	Set of Organisms at Time *t*	Message Coding Expressions at Time *t*
Genetic Trait (x)	Genetic-Based Trait within Members of Population P	Message or the Coding Expression of Sub-Messages
Fitness (f(x))	Replication Rate of Trait (x) within Population P	Effectiveness of Coding in Propagating a Message Through a Noisy Channel Through Application of Redundancy-based Coding Method
Mutation (q)	Replication Errors	Message Propagation Errors (Reduced Fidelity Due to Noise) and Advantageously used as a Variation-based Coding Method
Population (P')	Set of Organisms at Time *t+1*	Message Coding Expressions at Time *t+1*
P → P'	Evolution of Population During a Unit of Time	Propagation of Coded Messages Through a Noisy Channel During a Unit of Time
x → x'	Selection (Change in Fitness) During a Unit of Time	Effectiveness of Coding Process in Propagating a Message Through a Noisy Channel During a Unit of Time
Adaptation $\sum_j x_j f_j(\mathbf{x}) q_{ji}$	Evolutionary Adaptation	Outcome of Redundancy with Variation-based Message Coding Process

From Table 1 we see that we can create a correspondence between fundamental biological evolution concepts and a self-coding communications process through an unbounded time-based channel. We propose that the evolutionary biology concepts are in fact, a subset of the corresponding communications process interpretations, implying communications is the more basic framework for explaining biological phenomenon.

Particularly noteworthy is that selection and fitness, the two core and intertwined concepts of evolutionary biology, are both seen in the communications interpretation as metrics for the effectiveness of messages to propagate through the noisy communication channel. These twin concepts are central to biological evolution, and yet they seem most slippery to define well. For example, there is the question of what is being selected – the constituent elements (e.g., "selfish DNA') of a genome, the genotype, the phenotype, or a group of phenotypes? Then there is the question of the point in time the selection occurs – is it with respect to the current generation, or with respect to the outcomes of the current generation manifested in the next generation, and so on, *ad infinitum*? The reason for this definitional elusiveness becomes clearer when the concepts are considered in the context of the communications interpretation.

The communications interpretation provides a more abstract, but more robust framework, in that selection and fitness are both considered as applying to *communication coding methods and expressions of those methods*, not, for example, to populations of organisms. So in the communication interpretation, fitness and selection can be defined at multiple levels of message coding method and expression (elements of the genome, the entire genotype, the phenotype, etc.). Further, the communications interpretation reinforces that the concepts of fitness and selection are clearly dependent on the measurement time, and that the twin of concepts of selection and fitness are fundamentally ill-defined without such a time-based qualifier. This important fact is likely the root cause of the nagging feeling that selection and fitness in the basic Darwinian interpretation constitute something of a tautology.

Another example of the corresponding evolution biology interpretation being a subset of the communications interpretation is related to noise. Clearly mutations are a manifestation of noise in the communication sense. We might term this "intrinsic" noise as we defined above. But extrinsic noise is at work too, and the selection of traits over time is a function of this extrinsic noise.

We conclude then, that, evolutionary biology is best viewed as a *form* of the abstract communications model we have developed.

EVOLUTION AS COMMUNICATION-BASED DEFINITIONS

The correspondence between the fundamental aspects of the generalized communication framework and biological phenomenon in Table 1 can be extended. The isomorphism between abstract communications and biological phenomenon encourages us to actually *define* biological phenomenon as an abstract communications process – a communications process that is intrinsic to the way our universe works.

Following is a summary re-framing of evolutionary aspects of biological phenomena within the context of EAC terminology.

Evolution. The process of propagating self-coded messages through a noisy unbounded communication channel, where the channel is aligned with the time dimension.

Environment. A noise source that is extrinsic to a specific message coding system.

Fitness. A time-dependent metric of the effectiveness of the communications coding in propagating a message through the noisy time dimension-based communications channel.

Natural Selection. A time-dependent realization of the fitness metric.

Adaptation. Changes to message coding methods that enhance message propagation effectiveness, i.e., maximize continuity of the message while maintaining as much message fidelity as possible.

Life. Message coding instantiations of a self-coding communication process across a noisy unbounded time-based channel (and where, for "life as we know it", the spatial environment of the channel is an earth-like environment).

Genotype. A message coding structure for effective propagation of the constituent information elements of the genome.

Phenotype. A message coding structure for effective propagation of genotypical elements.

Mutation. Reduced fidelity of a message due to noise.

Reproduction (Asexual). A message coding method that relies on the most basic of all message coding techniques – message redundancy, augmented with noise-combating variation generated from mutation. Reproduction can therefore be thought of as a message amplifier.

Sexual Reproduction. A more sophisticated recombinant variation-based message coding method that combines the coding technique of message redundancy with a greater level of noise mitigating message variation than can be generated by asexual reproduction.

Speciation. The outcome of variation-driving coding processes (e.g., mutation, sexual reproduction) wherein variation among an ensemble of coded messages is so great that recombinant variation-based coding is no longer fully possible.

EVOLUTION AS COMMUNICATION AND ITS CODING PROCESSES

Of course, without noise there is no need for coding at all to propagate information. Therefore, for a noiseless time-based channel, there is no need for replication of message (redundancy-based coding); perfect fidelity of message is guaranteed, in perpetuity.

However, in our universe, noise is the rule. The fundamental approach to coding messages propagating through noisy channels is to apply redundancy. In its most basic form, this means replication of messages. For time-based channels, this implies message replication over time.

One can imagine that for channels in which noise is highly constrained, replication with perfect fidelity could be an effective coding approach. But for most situations, we would imagine that such a coding method is vulnerable to the challenge that certain types of noise could cause not only specific individual replicas to succumb to the noise, but also the entire class of messages expressed by the replicas, no matter how many replicas were extant.

It is not surprising then, that an examination of biological phenomena suggests coding approaches that rely on redundancy enabled by replication remain a core method, but are augmented by important extensions. Two redundancy-based coding method extensions find significant application in biological evolution. The first approach can be termed "variational" coding, and the second approach can be termed "multi-level" coding. By a variational coding approach we mean a process where messages are replicated without complete fidelity, thereby enhancing message variation. By multi-level coding, we mean that a source code is mapped to another code, and that code may be mapped to yet another code, and so on, each code having a fundamentally different expression in the environment. Both of these extended coding approaches are consistent with the Continuity Theorem as they maximize probability of continuity over time, but at the cost of message fidelity.

It has been well noted that coding against noise clearly occurs at multiple levels of expression of biological phenomenon. At the level of the genome, it is well established that the genetic code is arranged to minimize the effect of genetic noise (5). Further, duplicated genes, a redundancy-based coding approach, is also well known (5). But phenotypic reproduction should also be considered a coding process based on redundancy with variation (and in the case of sexual reproduction, also incorporating recombinant variational coding). In general, biological phenomena is characterized by multiple levels of expression, each level challenged by noise, and each level therefore applying a coding technique to successfully combat noise.

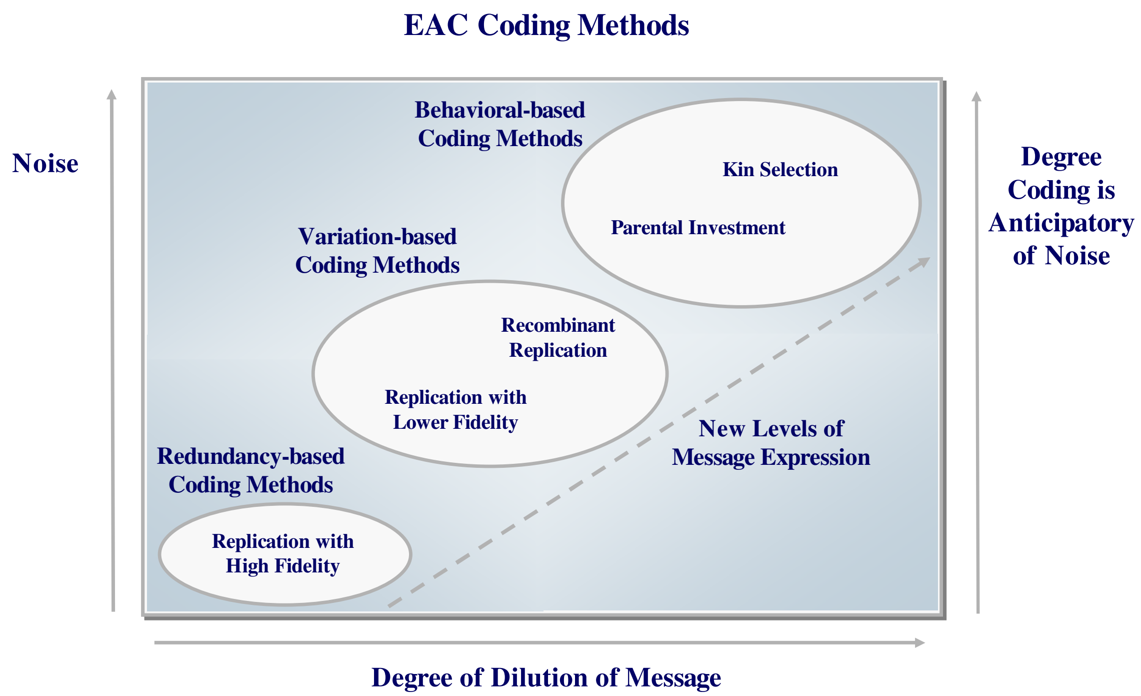
But why are there multiple levels of biological expression to begin with? We propose that the development of multiple levels of biological expression is itself is a manifestation of the coding strategy. In particular, perhaps the most amazing "trick" of biological evolution is that the coding approach is able to convert noise at one level (e.g., genetic-level noise) into a useful coding approach at the next level (e.g., phenotypic variation). This very sophisticated coding trick is what constitutes much of the seeming "magic" of life. The continuing development of new levels of evolutionary expression is also the reason we perceive an arrow of complexity over long periods of time. Further, we as humans are part of a more recent manifestation of the magic trick, in which the effect of phenotypic noise is converted to a positive effect at an information level above the phenotype itself – an extended phenotype phenomenon we typically call "culture."

The magic trick of multi-level coding is a direct consequence of the unboundedness of the abstract communications process, which implies continuity is the most important criterion of communication success, followed by the degree of fidelity of the original message. The coding process applies its multi-level expression tricks, as well as variation enhancing recombinant tricks (e.g. sexual reproduction), in combating noise and thereby maximizing the probability of message continuity, even at the expense of message dilution. It should be noted that a by-product of variational coding approaches is speciation; which is the outcome of variation-driving processes where the variation becomes significant enough that there are barriers to sexual reproduction.

The EAC Hypothesis provides a deeper theoretical underpinning of the benefits of sexual reproduction (i.e., variational coding) that have been confirmed in the field (12); and more generally, the benefits of phenotypic diversity in noisy environments. In fact, recent modeling results confirm earlier conjectures that the greater the environmental noise (fluctuations in environmental conditions), the more advantageous phenotypic diversity (13). Further, this recent modeling work confirms the intuition that for environments with sufficiently high levels of noise, phenotypes that are able to directly respond behaviorally to environmental noise, even taking into account a cost penalty for such responsive capabilities, are advantaged versus phenotypes that rely solely on variation (stochastic) propagation (13). These results are a strong confirmation of why multi-level expressions of coding are generated.

Moreover, as will be explored below in more detail, the EAC Hypothesis highlights a deeper integration of biological phenomena. Specifically, as depicted in Figure 1, the Continuity Theorem implies that a continuum of phenomena including asexual reproduction, sexual reproduction, parental investment, and kin selection are all manifestations of a coding process that maintains continuity of message at an increasing cost of diluting the message. The degree to which message continuity is emphasized by the coding process versus message fidelity is a function of the level of noise over time. And in addition to decreased message fidelity, the coding response to noise over time also includes coding methods that are more "anticipatory" of noise as depicted in Figure 1.

Figure 1



IMPLICATIONS AND PREDICTIONS

Hypotheses are only useful if they are testable. In this section some testable implications of the EAC Hypothesis are explored.

To reiterate, a key implication of EAC is that the Continuity Theorem drives a coding process that continuously trades-off continuity of message and fidelity of message, but that continuity must ultimately trump fidelity. But this coding trade-off is a function of the level and nature of the noise that the coding process must counteract.

This simple insight serves to help connect several different concepts of evolutionary biology, and suggest directions for extensions of current models. For example, it permits an integrated view of evolutionary phenomena in which a coding "choice" must be made among methods that are dilutive of the genetic-based message, but that maximize probability of message continuity. These genetically dilutive approaches include asexual reproduction (with mutation), sexual reproduction, but also include concepts such as parental investment, kin selection and other forms of altruistic behaviors. EAC suggests that all such genetically dilutive methods must be a function, at least in part, of the level and nature of the expected noise with which the coding process must deal. In other words, EAC suggests that where noise over time is low, more emphasis on coding that preserves message fidelity as much as possible can be expected (e.g., asexual reproduction). Where noise over time is high, successful coding methods will sacrifice more message fidelity to maximize message continuity through the noisy channel.

As mentioned above, empirical evidence (12) and mathematical modeling results (10,13) confirm a relationship between noise levels (environmental variations) and the coding choice of sexual reproduction (and corresponding increased phenotype diversity) versus asexual reproduction. Specifically, these results demonstrate that the higher the level of noise over time, the relatively more effective the message dilutive approach of sexual reproduction versus asexual reproduction. But the same logic should hold for any behavior-based coding method that is message dilutive, including altruistic behaviors that sacrifice own reproductive success in exchange for increasing the probability of successful continuity of more dilutive messages. EAC predicts such trade-offs must be a function of noise levels, and not just other variables such as degree of kinship. This implication for kin selection is expanded in the following discussion.

Kin Selection: Kin selection refers to the phenomenon of biological relatives mutually influencing fitness. It has been historically assumed that kin selection was guided the following basic relationship, known as Hamilton's rule:

$rb > c$

where:

r = the genetic relatedness of the recipient to the altruistic actor

b = the additional reproductive benefit gain by the recipient of the altruistic act

c = the reproductive cost to the actor of performing the altruistic act

It has been recently argued by Wilson (14) that Hamilton's rule should include a group fitness component as follows:

$(rb_k + b_e) > c$

where:

r = the genetic relatedness of the recipient to the altruistic actor

b_k = the additional reproductive benefit gain by the kin recipient of the altruistic act

b_e = the additional reproductive benefit gain by the group encompassing the kin recipient and the altruistic actor

c = the reproductive cost to the actor of performing the altruistic act

Wilson argues that environmental factors may have more of an effect than kinship factors, and the benefits may accrue more at the group level than at the kinship level depending on these environmental conditions. More recently Foster et al (15) argue against Wilson's position; in effect, defending the original Hamilton rule, but also acknowledging Wilson's point on ecological and environmental factors being an important influence on altruistic behaviors.

EAC suggests that the compromise offered by Foster et al is on the right track, but with the extension that the relevant environmental factor is specifically the level of environmental noise or uncertainties. The higher the (expected) noise or uncertainties, the more altruism we should expect. EAC is supportive of Foster et al's point that r>0 must still hold for true altruism, but interpreting relatedness most broadly may not obviate Wilson's argument.

Thus, the EAC hypothesis would suggest modification of Hamilton's equation or Wilson's extension as follows:

$r^*bn > c$

where:

r* = the expected genetic relatedness of the recipient to the altruistic actor

b = the additional reproductive benefit gain by the recipient of the altruistic act

c = the reproductive cost to the actor of performing the altruistic act

n = level of environmental noise or uncertainty

So EAC predicts it must be the case that n>0 for altruism to occur, and the greater the degree of noise, the greater the degree of altruism that can be expected to occur for a given level of r and b.

Fitness Horizons: Fitness in evolutionary biology is typically defined as reproductive success; i.e., in the terminology of EAC, continuity of message to the next generation with some degree of message fidelity. And this measurement of fitness in biological terms includes not just the existence of offspring, but the number of offspring; i.e., in the terminology of EAC, the degree of redundancy-based coding of the message in the next generation.

However, it follows from the Continuity Theorem that biological fitness must be measurable over arbitrary time horizons. Therefore the classic Darwinian criterion of fitness as reproductive success can be seen as just a first approximation based on measuring fitness within the context of the next unit of time horizon. EAC implies that we should expect to see evolutionary manifestations that are consistent with fitness measured over an unbounded time horizon. These manifestations can be expected at different level of biological message coding or expression.

A verifiable implication of this expectation relates to genetic changes that confer measurable benefits only in later generations. EAC predicts that the greater the level of noise over time, the more advantageous for genetic variability that manifests as a benefit only in subsequent generations. In these subsequent generations the latent variability would have the potential to become a beneficial coding expression when either 1) additional genetic changes enable a beneficial expression, or 2) the nature of the environmental noise is such that the trait becomes beneficial.

Another verifiable implication relates to phenotypic behaviors that benefit descendants beyond the next generation. This general concept may be included within the kin selection model described above, but a subtle implication of the Continuity Theorem is that given a trade-off between a behavior that will assist a relative in a later generation versus a relative in an earlier generation, where the two relatives have exactly the same level of kinship, the behavior that benefits the later generation would be expected to be selected. And the degree to which this generational bias will be invoked should be a function of environmental uncertainty (noise). (And, of course, a special case of this phenomenon is parental investment, in which the parent is the earlier generation relative and the offspring is the later generation relative.)

- **Multi-level Selection:** EAC deals with the issue of the unit of biological selection somewhat orthogonally to classic evolutionary biology, as EAC implies that the ultimate unit of selection is the coding process itself, comprising coding methods (e.g., reproduction methods, levels of expression, etc.), as well as specific expressions (e.g., genomes associated with specific organisms) of the coding methods. EAC is therefore generally supportive of selection effects occurring at different coding expression levels; for example, at the level the genotype, at the level of elements of the genotype, and at the level of the phenotype. Seen from the perspective of EAC then, the important insight that selfishness or cooperativeness can be ascribed at the level of the genome (3) could just as well apply to certain *elements* of the genome (for example, the so called “selfish DNA”, such as transposons), but also to coding expressions that are above the level of the genotype. Nevertheless, in accordance with the gene-centered evolutionary perspectives popularized by Dawkins (3), EAC predicts selection to be driven primarily “bottom-up” – that is lower level expressions are derivatively selected based on the selection of higher level coding expressions. The Continuity Theorem suggests that all of these aspects of evolutionary selection could just as well come under the label of the “The Selfish Message” – fidelity of the message is compromised only to maximize the probability of message continuity.

In fact, EAC suggests an integrative framework for biological, behavioral and cultural phenomena. Behaviors and collective behaviors (extended phenotype or culture) can also be considered manifestations of the message coding process – specifically new levels of coding expression. Hence, the concept of memes originally proposed by Dawkins (3) can viewed as part of the communications coding continuum, rather than just an example of an evolutionary process operating on different “stuff.”

- **Defining Life:** EAC illuminates the nature of the fuzziness in our historical definitions of life. The root cause of the fuzziness stems from considering life the central concept. The essence of the concept of life comes into focus when life is not posited as the central concept, but rather a derivative concept based on generalized communications and evolution. That is, life is an instantiation of a generalized communication/evolutionary process.

EAC can therefore be applied to provide some new perspectives of the fuzzy boundaries of life. For example, by EAC definitions, clearly biological viruses should be considered life. Viruses are an instantiation of an evolutionary process, including self-coding processes (i.e., biological viruses mutate, propagate, and adapt). The question has arisen whether computer viruses should be considered life as well (4). Well, by the EAC definition it is an instantiation of an evolutionary, self coding process, just as is a biological virus. On the other hand the evolutionary medium is a digital computer rather than an earth-like environment, so it is not "life as we know it."

What about prions (infectious proteins)? Here there is no evidence of self-coding, and therefore prions cannot be considered an instantiation of an evolutionary process, and hence not, by EAC definitional correspondences, life. But prions might very well satisfy the criteria of alternative abstract communications models.

Arrow of Complexity: There has been a contentious debate as to whether there actually has been an increase in biological complexity over time (here we can take complexity to be measured by minimum description length or algorithmic complexity). The reason for the contention seems to be that although by simple observation it seems obvious that biological life is more complex presently, than, say, a billion years ago, there appears to be nothing in the Darwinian natural selection algorithm to necessarily drive toward more or less complexity (this point was particularly emphasized by Stephen Gould). So, armed with just standard Darwinian natural selection, we are left with either dismissing the seemingly intuitively obvious, or concluding that any actual measurable increase in complexity over long periods of time is just random drift, which presumably could reverse itself at any time.

EAC, on the other hand, supports a discernable arrow of biological complexity that most fundamentally derives directly from the Continuity Theorem. Specifically, the Continuity Theorem implies increasingly "anticipatory" coding schemes should prevail over time so long as noise levels continue at sufficiently high levels.

For example, high variation recombinant coding schemes (e.g., sexual reproduction) are more anticipatory of future noise levels than are schemes based solely of mutation-based variation coding. i.e., asexual reproduction (10,12). Further, higher level coding expressions such as phenotypes and associated behaviors are more anticipatory of future noise levels than lower level expressions (13). In each of these cases, there is clearly an energy cost associated with the more anticipatory coding process, but its ability to maintain continuity through future noisy environments more than makes up for the cost penalty. And this process inevitably leads to more "computationally-intensive" coding over time, which leads to our perception of an arrow of complexity.

The trend of increasingly complexity is likely, to some degree, self-reinforced as a consequence of expressions of increasingly sophisticated coding methods themselves constituting new sources and types of noise. For example, the application of a multi-level coding technique as described above, in which noise at one level is converted to a useful coding at a higher level of message expression implies a process of coding methods built on other coding methods, which implies an increasing complex environment.

The self sustaining, unbounded time-based communications process can be usefully considered an "information wave" that propagates through the time dimension of space-time. The wave analogy may be particularly apt with regard to the way new levels of coding continuously form from underlying layers over time. The self-sustaining aspect of the wave, which is the most counterintuitive aspect, is driven by the ability of the coding process to combat noise (increasing entropy) through sophisticated coding means that includes the method of converting noise at one level of message expression to useful coding at a higher level of message expression. Of course, net entropy of the extended system is still increased in accordance with the second law of thermodynamics, but the information wave generates complexity (reduces Shannon entropy) locally at the expense of increased entropy external to the wave.

Integrating Across Scientific Boundaries: By underpinning evolutionary phenomenon with a generalized communications/information process, and defining life as a particular instantiation of this evolutionary phenomenon, EAC provides a framework that can assist in moving closer toward unifying the sciences.

It has been commonly assumed for at least half a century that the bridge between physics and biology has something to do with information. But although it has been generally assumed that information is the bridge between the living and non-living worlds, the exact nature of the linkage have proved difficult to discern.

Conceptually leaping directly from physics to biology has delivered limited insights. Applying a generalized and integrated theory of communications and evolution as has been presented here seems a promising basis for the scientific integration of the living and non-living aspects of our universe.

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