Evolution as Context-driven Actualization of Potential[1]

Liane Gabora
Center Leo Apostel for Interdisciplinary Studies, Vrije Universiteit Brussel,
and Department of Psychology, University of California, Berkeley, liane@berkeley.edu
and

Diederik Aerts
Center Leo Apostel for Interdisciplinary Studies and Department of Mathematics
Vrije Universiteit Brussel, Brussels, Belgium, diraerts@vub.ac.be

ABSTRACT

While natural selection is often viewed as synonymous with evolution, it is widely felt to be inadequate as a theory of biological evolution; moreover, historically the concept of evolution has not been limited to biology. We propose an integrative framework for characterizing how entities evolve, in which evolution is viewed as a process of context-driven actualization of potential (CAP). Processes of change differ according to the degree of nondeterminism, and the degree to which they are sensitive to, internalize, and depend upon a particular environment or context. The approach enables us to embed phenomena across multiple disciplines into a broader conceptual framework. It suggests that the dynamical evolution of a quantum entity as described by the Schrödinger equation is not fundamentally different from change provoked by a measurement often referred to as collapse but a limiting case, with only one way *to* collapse. The biological transition to coded replication is seen as a means of preserving structure in the face of context, and sexual replication as a means of increasing potentiality thus enhancing diversity through interaction with context. The integrative framework sheds light on biological concepts like selection and fitness, reveals how exceptional Darwinian evolution is as a means of 'change of state', and clarifies in what sense culture (and the creative process underlying it) is and is not Darwinian.

KEYWORDS
acquired characteristics, context, culture, environment, evolution, fitness, natural selection, nondeterminism, potential, selection.

[1] Published as: Gabora, L. and Aerts, D. (2005). Evolution as a context-driven actualization of potential. *Interdisciplinary Science Reviews 30*, pp. 69-88.

1 INTRODUCTION

The term evolution is often construed as shorthand for Darwinian evolution—a process of descent with modification, wherein a species adapts to an environment through iterations of replication with random variation followed by natural selection. Darwin's theory united previously disparate phenomena, and paved the way for further inquiry. However, it contributes little to our understanding of developmental and ecological processes. Also, applications of Darwinism in the social sciences have not caught on, suggesting there is more going on in the evolution of cultures and economies than natural selection. Moreover, the concept of evolution extends beyond the biological and social sciences; physicists use the term to refer to dynamical change of state in the absence of a measurement, without implying that natural selection is involved. Thus natural selection is only part of the picture of how entities evolve.

This paper outlines how the concept of evolution has been used in different fields, summarizes the limitations of neo-Darwinism as a general theory of evolution, and sketches what a general theory of evolution might look like. The basic idea is that all entities evolve through a reiterated process of *interaction* with a context; thus the process is referred to as context-driven actualization of potential, or *CAP*. By "potential" we do not mean determined or preordained; in fact, the actual is but a realized fraction of the spectrum of what is potential. Indeed, different forms of evolution differ according to the degree of nondeterminism, as well as degree of contextuality and retention of context-driven change. The CAP framework has been applied in a detailed or technical manner to specific domains such as physics (Aerts 2002) and creativity (Gabora & Aerts, in press). The goal of this paper is to show what can be learned by uniting physical, biological, and cultural change under a single evolutionary scheme.

The value in such a unifying vision is not universally agreed upon. While some believe it to play a vital role in scientific explanation (Friedman 1974; Kitcher 1981, 1993; Pitt 1988); others warn that it leads to oversimplification and distortion (Dupre 2002). Without actively engaging in this debate, we note that the framework proposed here was not sought after, but landed so to speak on our doorstep. Indeed it has already born fruit: it suggests a unifying scheme for the two kinds of change in quantum mechanics, offers a fresh perspective on issues such as selection and fitness in biology, and clarifies how the concept of evolution applies to culture and creative thought.

2. LIMITATIONS OF THE NEODARWINIAN FRAMEWORK

This section outlines the limitations of natural selection as a theory of how biological organisms evolve, and shows that it runs into even more serious problems when applied to other fields.

2.1 Evolution of Biological Form

Darwin's theory of natural selection threw light on the perplexing question of why some traits thrive at the expense of others. With what has come to be called the neo-Darwinian paradigm, the basic idea of random variation and natural selection has been vastly extended by knowledge of the underlying genetic mechanisms, and mathematical formalization by population biologists. However, it is becoming increasingly evident that neo-Darwinism, powerful though it is, cannot account for all, or perhaps even most, biological change (*e.g*. Boone *et. al*. 1998; Kauffman 1993; Schwartz 1999). The concept of natural selection offers little in the way of explanation for biological forms and phenotypes arise in the first place. (One can ask, for example, if natural selection is such a powerful tool for describing biological change, what can it tell me about the fitness of the offspring I would have with one healthy mate as opposed to another.) Moreover, non-Darwinian processes—such as autopoiesis (Varela 1979), emergence (Chandler & Van de Vijver 1999; Kampis 1991; Rosen 1985), symbiosis (Margulis & Fester 1991), punctuated equilibrium (Eldridge & Gould 1973) and epigenetic mechanisms (Newman & Muller 1999)—play a vital role. In emergent and epigenetic processes, form unfolds because of how any one part functions *in the context of* not just the other parts, but potentially a host of unpredictable factors external to the entity which in turn affect interactions amongst parts. Moreover, the generation of variation is not completely random; convergent pressures are already at work *prior* to the physical realization of organisms. First, mating is often *assortative*—mates are chosen on the basis of traits they possess or lack, rather than at random—and relatives are avoided as mates. Second, since Cairns' (1988) initial report, there is increasing evidence and acceptance of *directed mutation*, where the frequency of beneficial mutations is much higher than chance, particularly in environments to which an organism is not well adapted. Furthermore, the concept of fitness, a cornerstone of the neo-Darwinian enterprise, is problematic (Krimbas 2004). In sum, there is more going on in evolution than random variation and natural selection.

2.2 Cultural Evolution

Culture too is often said to be a process of evolution, at least in the general sense of change in response to environmental constraint such that new solutions grow out of and build upon old ones (Campbell 1960, 1965, 1987, 1990; Csanyi 1989; Cziko 1997; Gabora 1996; Hofbauer & Sigmund 1988; Hull 1988; Lumsden & Wilson 1981; Plotkin 1997). Inspired by Dawkins' (1982) notion of *universal Darwinism*—the idea that natural selection is not restricted to the physical structure of organic life, but could work with other underlying materials—natural selection has been adapted to develop mathematical (Boyd & Richerson 1985; Cavalli-Sforza & Feldman 1981; Schuster & Sigmund 1983) and computational (Gabora 1995; Spector & Luke 1996) models of cultural evolution. It has also been applied less formally to units of culture referred to as memes (Aunger 2000; Blackmore 1999, 2000; Dawkins 1976; Dennett 1995; Gabora 1996) and to the analysis of growth and change in economics (Borgers 1997; Borkar *et. al*. 1998; Metcalfe 2001; Rivkin 2001; Saviotti & Mani 1995; Witt 1992), financial markets (Farmer & Lo 1999), social customs (Durham 1991), and artifact design (Lake 1998). These studies occasionally fall under attack (Gould 1991; Hallpike 1986; Jeffreys 2000; Perkins 1998; Pinker 1997; Sternberg 1998), but are more often simply ignored. Common reasons for rejecting a Darwinian approach in these fields are that ideas are not generated randomly but strategically, cultural artifacts are not self-replicators, and cultural evolution is Lamarckian while biological evolution is not. Thus, not only does natural selection fail to provide an integrative framework for biology, but it has not had significant impact when applied to the social sciences.

2.3 Creative Thought

Cognition too has been described in Darwinian terms. While some philosophers describe the growth of knowledge as Darwinian in the sense that conjectures must be refutable, *i.e*. able to be selected against (Popper 1963; Lorenz 1971), Campbell (1960, 1965, 1974, 1987) went further, arguing that a stream of creative thought is a Darwinian process. The basic idea is that we generate new ideas through variation and selection: 'mutate' the current thought in a multitude of different ways, select the variant that looks best, mutate *it* in various ways and select the best, and so forth, until a satisfactory idea results. Thus he viewed thought as a series of tiny selections. This view has been extended, most notably by Simonton (1998, 1999a, b), but have not caught fire. As Pinker (1997) puts it, "a complex meme does not arise from the retention of copying errors... The value added with each iteration comes from focusing brainpower on improving the product, not from retelling or recopying it hundreds of thousands of times in the hope that some of the malaprops or typos will be useful." Indeed attempts to develop it formally must fail, because natural selection theory, as mathematically formulated by population geneticists, requires multiple, distinct, simultaneously-actualized replicators that differ in their rate of replication. Not only is a thought or idea not a replicator (Gabora 2004), but each thought changes the context against which the *next* is evaluated; they are not simultaneously selected amongst (Gabora & Aerts, in press). Creative thought is more a matter of honing in on an initially vague idea by redescribing successive iterations of it from different real or imagined perspectives. Is there nevertheless some sense in which thought can be said to evolve?

2.4 Evolution of Objects and Particles

Let us now look at what is meant by the term 'evolution' in physics. The central mathematical object in quantum mechanics is a complex Hilbert space, a vector space over the field of complex numbers. Unit vectors of this space represent states of a particle. A measurement of a particle is described by a self-adjoint operator, which is a linear function on the Hilbert space. A self-adjoint operator always has a set of special states associated with it, the *eigenstates*[1]. An eigenstate does not change under the influence of the measurement described by the self-adjoint operator. However, if the particle is in a genuine *superposition state*[2] (which can be written as a linear superposition of eigenstates[3]) then the change of state provoked by the measurement is such that this superposition state changes to one of the eigenstates of the self-adjoint operator representing the measurement. This change of state from a superposition state to an eigenstate is referred to in the quantum jargon as *collapse*. Evolution is what happens in the absence of collapse. Thus, evolving is what the quantum entity is doing when no measurement is taking place. This evolution is described by the Schrödinger equation, and it is considered a fundamentally different kind of change from 'collapse' under the influence of a measurement.

Clearly physicists are using the term 'evolution' to refer to something quite different from how it is used in the biological or social sciences. Yet in all cases it refers to a process of change, and there is a concern for the history of change, both internal and external to the entity, and how that history affects and reveals itself in the entity's present structure.

3. EVOLUTION AS CONTEXT-DRIVEN ACTUALIZATION OF POTENTIAL

We have seen that the neoDarwinian paradigm does not provide a complete account of evolution, not in biology, nor elsewhere where the term is used. We now present a more general scheme for change of the state of an entity under the influence of a context.

3.1 Deterministic versus Nondeterministic Change of State

Since we do not always have perfect knowledge of the state of the entity, the context, and the interaction between them, a general description of an evolutionary process must be able to cope with nondeterminism. Evolutionary systems differ with respect to the degree of determinism involved in the changes of state that the entity undergoes. Consider an entity—whether it be physical, biological, mental, or some other sort—in a state $p(t_i)$ at an instant of time t_i. If it is under the influence of a context $e(t_i)$, and we know with certainty that $p(t_i)$ changes to state $p(t_{i+1})$ at time t_{i+1}, we refer to the change of state as *deterministic*. Newtonian physics provides the classic example of deterministic change of state. Knowing the speed and position of a ball, one can predict its speed and position at some time in the future. In many situations, however, an entity in a state $p(t_i)$ at time t_i under the influence of a context $e(t_i)$ may change to any state in the set $\{p_1(t_{i+1}), p_2(t_{i+1}), \ldots, p_n(t_{i+1}), \ldots\}$. When more than one change of state is possible, the process is *nondeterministic*.

3.1.1 Nondeterminism with respect to State of Entity

Nondeterministic change can be divided into two kinds. In the first, the nondeterminism originates from a lack of knowledge concerning the state of the entity $p(t_i)$ itself. This means that deep down the change is deterministic, but since we lack knowledge about what happens at this deeper level, and since we want to make a model of what we know, the model we make is nondeterministic. This kind of nondeterminism is modeled by means of a stochastic theory that makes use of a probability structure that satisfies the axioms of Kolmogorov.

3.1.2 Nondeterminism with respect to Context

Another possibility is that the nondeterminism arises through lack of knowledge concerning the context $e(t_i)$, or how that context *interacts* with the entity.[4] In this case, the mathematical structure of the situation is entirely different. It has been proven that when there is a lack of knowledge about the context, or how the context interacts with the entity, the stochastic model to describe this situation necessitates a non-Kolmogorovian probability model; a Kolmogorovian probability model (such as is used in population genetics) cannot be used (Aerts 1986; Accardi, 1982; Aerts & Aerts, 1994; Pitowsky, 1989; Randall & Foulis 1976). It is only possible to ignore the problem of incomplete knowledge of context if all contexts are equally likely, or if context has a temporary or limited effect. Because the entity has the potential to change to many different states (given the various possible states the context could be in, since we lack precise knowledge of it), we say that it is in a *potentiality state* with respect to context. This is schematically depicted in Figure 1.

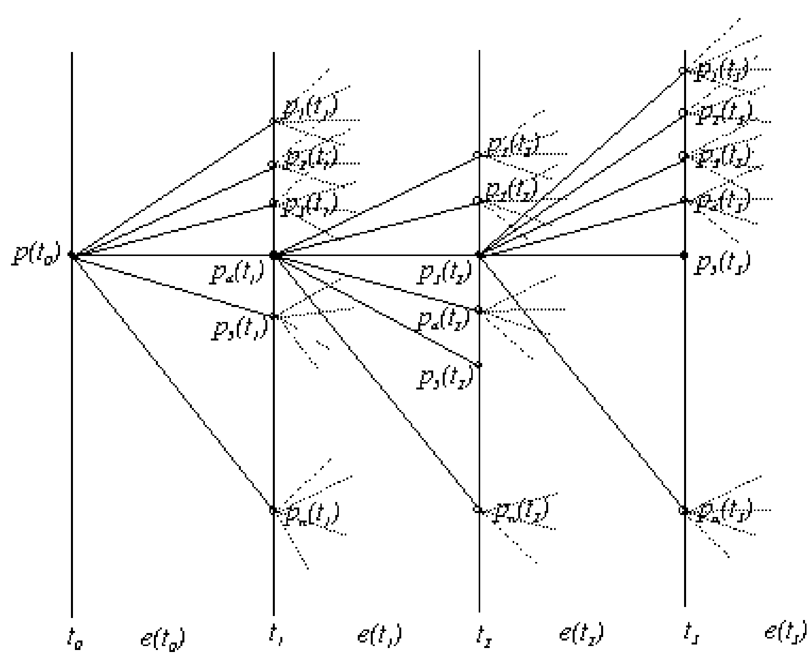

Figure 1. Graphical representation of a general evolution process. Contexts $e(t_0)$, $e(t_1)$, $e(t_2)$ and $e(t_3)$ at times t_0, t_1, t_2, and t_3,

are represented by vertical lines. States of the entity are represented by circles on vertical lines. At time t_0 the entity is in state $p(t_0)$. Under the influence of context $e(t_0)$, its state can change to one of the states in the set $\{p_1(t_1), p_2(t_1), p_3(t_1), p_4(t_1), \ldots, p_n(t_1), \ldots\}$. These potential changes are represented by thin lines. Only one change actually takes place, the one represented by a thick line, *i.e.* $p(t_0)$ changes to $p_4(t_1)$. At time t_1 the entity in state $p_4(t_1)$ is under the influence of another context $e(t_1)$, and can change to one of $\{p_1(t_2), p_2(t_2), p_3(t_2), p_4(t_2), \ldots, p_n(t_2), \ldots\}$. Again only one change occurs, *i.e.* $p_4(t_1)$ changes to $p_3(t_2)$. The process then starts all over again. Under the influence of a new context $e(t_2)$, the entity can change to one of $\{p_1(t_3), p_2(t_3), p_3(t_3), p_4(t_3), \ldots, p_n(t_3), \ldots\}$. Again only one change happens: $p_3(t_2)$ changes to $p_5(t_3)$. The dashed lines from states that have not been actualized at a certain instant indicate that much more potentiality is present at time t_0 than explicitly shown. For example, if $p(t_0)$ had changed to $p_2(t_1)$ instead of $p_4(t_1)$, which was possible at time t_0, then context $e(t_1)$ would have exerted a different effect on the entity at time t_1, such that a new vertical line at time t_1 would have to be drawn, representing another pattern of change.

We stress that a potentiality state is not *predetermined*, just waiting for its time to come along, at least not insofar as our models can discern, possibly because we cannot precisely specify the context that will come along and actualize it. Note also that a state is only a potentiality state *in relation to* a certain (incompletely specified) context. It is possible for a state to be a potentiality state with respect to one context, and a deterministic state with respect to another. More precisely, a state that is deterministic with respect to a context can be considered a limit case of a potentiality state, with zero potentiality.

3.1.3 The Role of Lack of Knowledge

In reality the universe is so complex we can never describe with complete certainty and accuracy the context to which an entity is exposed, and how it interacts with the entity. There is always some possibility of even very unlikely outcomes. However, there are situations in which we can predict the values of relevant variables with sufficient accuracy that we may consider the entity to be in a particular state, and other situations in which there is enough uncertainty to necessitate the concept of potentiality. Thus a formalism for describing the evolution of these entities must take into account the *degree of knowledge* we as observers have about the context.

3.1.4 A Mathematics that Describes both Contextual and Uncontextual Change

We have seen that a description of the evolutionary trajectory of an entity may involve nondeterminism with respect to the state of the entity, the context, or how they interact. An important step toward the development of a complete theory of evolution is to find a mathematical structure that can incorporate all these possibilities.[5] There exists an elaborate mathematical framework for describing the change and actualization of potentiality through contextual interaction that was developed for quantum mechanics. However it has several limitations, including the linearity of the Hilbert space, and the fact that one can only describe the extreme case where change of state is *maximally* contextual. Other mathematical theories, such as state-context-property (SCOP) systems, lift the quantum formalism out of its specific structural limitations, making it possible to describe nondeterministic effects of context in other domains (Aerts 1993; Aerts & Durt 1994; Foulis & Randall 1981; Foulis *et al.* 1983; Jauch 1968; Mackey 1963; Piron 1976, 1989, 1990; Pitowsky 1989; Randall & Foulis 1976, 1978). The original motivation for these generalized formalisms was in fact theoretical (as opposed to the need to describe the reality revealed by experiments). In the SCOP formalism, for instance, an entity is described using a state space, and a set of measurements or contexts, and the algebraic structure of the state space is given by a the set of atoms of a complete lattice (they play the role of the rays of a complex Hilbert space in quantum mechanics). Measurements are described by Boolean morphisms on the lattice (they play the role of the self-adjoint operators in quantum mechanics). With these formalisms it is possible to describe situations with *any* degree of contextuality. In fact, classical and quantum come out as special cases: quantum at the one end of extreme contextuality, and classical at the other end of extreme lack of contextuality (Piron 1976; Aerts 1983). This is why it lends itself to the description of context-driven evolution.

Let us look briefly at how CAP is used to describe the trajectory of an entity undergoing nondeterministic contextual change of state. The change of state may in turn evoke a change in its context, or in the sort of context it is subsequently susceptible to, or the context may change of its own accord. Under the influence of a (possibly new) context, it undergoes another change. For example, let us say that the state of the entity has already changed from to $p_0(t_0)$ to $p_4(t_1)$. More explicitly, starting from state $p_4(t_1)$, under the influence of context $e(t_1)$, the entity changes to a different state by time t_2. Again there are many potential states it could change to. We denote this set of states $\{p_1(t_2), p_2(t_2), \ldots, p_n(t_2), \ldots\}$. At time t_2, one of these states, for example $p_3(t_2)$, actualizes. And so forth, recursively. The states $p(t_0), p(t_1), p(t_2), \ldots, p(t_i), \ldots$ constitute the trajectory of the entity through state space, and describe its evolution in time. Thus, the general evolution process is broadly construed as the incremental change that results from recursive, *context-driven actualization of potential,* or CAP. A model of an evolutionary process may consist of both *deterministic segments*, where the entity changes state in a way that follows predictably given its previous state and/or the context to which it is exposed, and/or *nondeterministic segments,* where this is not the case.

3.2 Degree of Sensitivity to Context

Besides degree of nondeterminism and whether it stems from lack of knowledge concerning entity or context, another parameter that differentiates evolving entities is the degree of *sensitivity to context*, or more precisely, the degree to which a change of state of the context evokes a change of state in the entity. The degree of sensitivity to context can vary from not just one entity to another but also from one environment to another. In one environment, a given entity may be completely adapted. This environment rarely affords context(s) that induce a change of state, or the changes of state it induces may be small. In another environment, the same entity may barely survive. This environment affords context(s) that induce frequent or large-scale change.

3.3 Degree to which Context-driven Change is Retained

Sensitivity to context is just one facet of contextuality. An entity may be sensitive—readily undergo change of state due to context—but through regulatory mechanisms or self-replication have a tendency to return to its previous state. An example of a situation where context-driven change is retained is a rock breaking in two. An example where it is not retained is the healing of an injury.

3.4 Context Independence

The extent to which a change of context threatens the survival of the entity can be referred to as *context dependence.* The degree to which an entity is able to withstand, not just its *particular* environment, but *any* environment, can be referred to as *context independence*. Sensitivity to and retention of context can lead, in the long run, to *either* context dependence or context independence. This could depend on the variability of the contexts to which an entity is exposed. A static, impoverished environment may provide contexts that foster specializations tailored to *that* particular environment, whereas a dynamic, rich, diverse environment may foster more general coping mechanisms. Thus for example, a species that develops an intestine specialized for the absorption of nutrients from a certain plant that is abundant in its environment exhibits context dependence, whereas a species that becomes increasingly more able to consume *any* sort of vegetation exhibits context independence.

Whether an entity exhibits context dependence or independence may simply reflect what one chooses to define as the entity of interest. If an entity splits into multiple 'versions' of itself (as through reproduction) each of which adapts to a different context and thus becomes more context dependent, when all versions are considered different lineages of one *joint* entity, that joint entity is becoming more context-*independent*. Thus for example, while different mammalian species are becoming more context dependent, the kindom as a whole is becoming more context independent.

4. WAYS THE UNIVERSE HAS FOUND OF ACTUALIZING POTENTIAL

We now look at how different kinds of evolution fit into the above framework, and how their evolutionary trajectories differ with respect to the these parameters introduced in the previous section. They are all means of actualizing potential that existed due to the state of the entity, the context, and the nature of their interaction, but differ widely with respect to these parameters.

4.1 Evolution of Physical Objects and Particles

We begin by examining three kinds of change undergone by physical entities. The first is the collapse of quantum particles under the influence of a measurement. The second is the evolution of quantum particles when they are not measured. The third is the change of state of macroscopic physical objects.

4.1.1 Nondeterministic Collapse of a Quantum Particle

As mentioned in section 2.2.4, the change of state of a quantum particle under the influence of a measurement is referred to as collapse. We saw that a measurement is described by a self-adjoint operator which has a set of eigenstates associated with it, states that do not change under the influence of the measurement. Thus an eigenstate is deterministic with respect to a measurement. The probability that a genuine superposition state collapses to a particular eigenstate is related to the weight of the vector representing the superposition state in its linear sum over the vectors representing the eigenstates. In general (depending on how many weights are non-zero), many of the eigenstates are possible states to collapse to under the influence of this measurement. In other words, the collapse is non-deterministic. This means that a genuine superposition state is a state of potentiality with respect to the measurement. This suggests that what we refer to as a context is the same thing as what in the standard quantum case is referred to as a measurement.

Thus a quantum entity exists in a superposition state, and a measurement causes it to collapse nondeterministically to an eigenstate of that measurement. The specifics of the measurement constitute the context that elicit in the entity one of the states that were previously potential for it. Its evolution cannot be examined without performing measurements—that is, introducing contexts—but the contexts themselves unavoidably affect its evolution. Clearly the evolution of a quantum particle is an extreme case of nondeterministic change, as well as of context sensitivity and internalization, because its state at any point in time reflects the context to which it is exposed. It is not an example of context dependence, since presumably the quantum entity does not require these measurements for its survival.

4.1.2 Evolution of Quantum Particles

The other mode of change in standard quantum mechanics is the dynamical change of state that takes place when no measurement is executed, which as mentioned in section 2.2.4 is referred to as 'evolution'. This is the effect of the fields that are present in the rest of the universe and that steer the change of state of the quantum entity, as described by the Schrödinger equation. There is sensitivity to (and possibly internalization of) context, but it is deterministic. Specifically, if the quantum entity at a certain time t_0 is in state $p(t_0)$, and the only change that takes place is this dynamical change governed by the Schrödinger equation, then the state $p(t_i)$ at any time t_i later than t_0 is determined.

For historical reasons, physicists think of a measurement not as a context, but as a process that gives rise to outcomes that are read off the measurement apparatus. In this scheme of thought, the simplest measurements are assumed to be those with two possible outcomes. A measurement with one outcome is rightly not thought of as a measurement, because if the same outcome always occurs, nothing has been compared and/or measured. However, when measurements are construed as contexts, we see that the measurement with two possible outcomes is not the simplest change possible. It is the deterministic evolution process—which can in fact be conceived as a measurement with one outcome, namely always the same—that is the simplest kind of change. This means that in quantum mechanics the effect of context on change is as follows:

- When the context is the rest of the universe, its influence on the state of a quantum entity is deterministic, as described by the Schrödinger equation.
- When the context is a measurement, its influence on a genuine *superposition state* is *nondeterministic,* described as a process of collapse with nonzero potentiality.
- When the context is a measurement, its influence on an *eigenstate* is *deterministic*, described as a process of collapse with zero potentiality.

Thus, under the CAP framework, the two basic processes of change in quantum mechanics are united; what has been referred to as evolution is not fundamentally different from collapse. They are both processes of actualization of potentiality under the influence of a context. In evolution there is only one possible outcome, and it is therefore deterministic, whereas in collapse, until the state of the entity becomes an eigenstate, there is more than one possible outcome, and it is therefore nondeterministic.

4.1.3 Evolution of Classical Physical Entities

Classical physical entities are the paradigmatic example of lack of sensitivity to and internalization of context, and deterministic change of state. However, theorists are continually expanding their models to include more of the context surrounding an entity in order to better predict its behavior, which suggests that things are not so tidy in the world of classical physical objects as Newtonian physics suggests. Many macro-level physical entities exhibit the kind of structure found in quantum mechanics, including entanglement as indicated by the violation of Bell inequalities (Aerts *et al*. 2000). Moreover, it has been shown this is due to the existence of situations in which change of state of the entity cannot be predicted due to lack of knowledge of how it interacts with its context (Aerts 1983, 2002).

4.2 Biological Evolution

This section is also divided into three parts. The first concerns the earliest life forms, prior to the genetic code. The second concerns organisms after coded replication was established but prior to sexual reproduction. The third concerns sexually reproducing organisms.

4.2.1 The Earliest Life Forms

Early life forms were more sensitive to context and prone to internalize context than present-day life because their replication took place not according to instructions (such as a genetic code), but through happenstance interactions. In Kauffman's (1993) model of the origin of life, polymers catalyze reactions that generate other polymers, increasing their joint complexity, until together as a whole they form something that can more or less replicate itself.[6] The set is *autocatalytically closed* because although none of the polymers can catalyze its own replication, each polymer can catalyze the replication of some other polymer in the set, and likewise, its own replication is catalyzed by some other member of the set. Since each polymer is getting duplicated somewhere in the set, eventually multiple copies of all polymers exist. So long as the set contains at least one copy of each kind of polymer, it can self-replicate, and continue to do so indefinitely, or at least until it changes so drastically that its self-replicating structure breaks down. (Notice that 'death' of such life forms is not a particularly noticeable event; the only difference between a dead organism and an alive one is that the alive one continues to spawn new replicants.) Replication is far from perfect, so 'offspring' are unlikely to be identical to their 'parent'. Different chance encounters of polymers, or differences in their relative concentrations, or the appearance of new polymers, could all result in different polymers catalyzing a given reaction, which in turn altered the set of reactions to be catalyzed. Context was readily internalized by incorporating elements of the environment, thus there was plenty of room for heritable variation.

4.2.2 Genetic Code Impedes Retention of Context in Lineage

Perhaps the most significant transition in the history of life was the transition from uncoded, self-organized replication through an autocatalytic process, to replication as per instructions given by a genetic code. We saw that prior to coded replication, a change to one polymer would still be present in offspring after budding occurred, and this could cause other changes that have a significant effect on the lineage further downstream. There was nothing to prohibit inheritance of acquired characteristics. But with the advent of explicit self-assembly instructions, acquired characteristics were no longer passed on to the next generation; thus the process became more constrained, robust, and shielded from external influence. (Thus for example, if one cuts off the tail of a mouse, its offspring will have tails of a normal length.) A context-driven change of state of an organism only affects its lineage if it impacts the generation and survival of progeny (such as by affecting the capacity to attract mates, or engage in parental care). Clearly, the transition from uncoded to coded replication, while ensuring the fidelity of replication, decreased long-term sensitivity to and internalization of context, and thus the capacity for context independence. Since one generation was almost certainly identical to the next, the evolution process became more deterministic. As a result, in comparison with entities of other sorts, biological entities are resistant to the internalization and retention of context-driven change. Though the term 'adaptation' is most closely associated with biology, biological form is resistant to adaptation. This explains why it has been possible to develop a theory of biological evolution that all but ignores the problem of incomplete knowledge of context. As we saw earlier, it is possible to ignore the problem of context if all contexts are equally likely, or if context has a limited effect on heritability. In biology, since acquired traits are not heritable, the only contextual interactions that exert much of an effect are those that affect the generation of offspring. Thus it is because classical stochastic models work fine when lack of knowledge concerns the state of the entity and not the context that natural selection has for so long been viewed as adequate for the description of biological evolution.

4.2.3 Effect of Sexual Reproduction

With the advent of sexual reproduction, the contextuality of biological evolution increased. Consider an organism that is heterozygous for trait X with two alleles *A* and *a*. The potential of this *Aa* organism gets actualized differently depending on the context provided by the genotype of the organism's mate. In the context of an *AA* mate, the *Aa* organism's potential becomes constrained to include only *AA* or *Aa* offspring. In the context of an *aa* mate, the *Aa* organism has the potential for *Aa* or *aa* offspring, and once again some of this potential might get actualized. And so forth. But while the mate *constrains* the organism's potential, the mate is necessary to *actualize* some of this potential in the form of real physical offspring. In other words, the genome of the mate simultaneously makes *some* aspects of the *Aa* organism's potentiality possible, and *others* impossible. An organism exists in a state of potentiality with respect to the different offspring (variants of itself) it could produce with a particular mate. In other words, a mate constitutes a context for which an organism is a state of potentiality. One can get away with ignoring this to the extent that one can assume mating is random. Note that since a species is delineated according to the capacity of individuals to mate with one another, speciation can be viewed as the situation wherein one variant no longer has the potential to create a context for the other for which its state is a potentiality state with respect to offspring. A species can be said to be adapted to the extent that its previous states *could have* collapsed to different outcomes in different contexts, and thus to the extent to which its form *reflects* the particular contexts to which it *was* exposed. Note also that although over time species becomes increasingly context dependent, collectively they are becoming more context *in*dependent. (For virtually any ecological niche there exists *some* branch of life that can cope with it.)

Some (*e.g.* Gould 2002) argue for expansion of the concept of selection to other hierarchical levels, *e.g.* group selection. We agree with Kitcher (2004: 8) that 'despite the vast amount of ink lavished upon the idea of "higher-order" processes', once we have the causal story, it's a matter of convention whether we say that selection is operating at the level of the species, the organism, the genotype, or the gene. It is not the concept of selection that needs expansion, but the embedding of selection in a framework for how change can occur. The actual is but the realized fragment of the potential, and selection works *only* on this fragment, what is already actual. We can now return to our question about what natural selection has to say about the fitness of the offspring you might have with one healthy mate as opposed to another. The answer is of course, nothing, but why? Because the situation involves actualization of potential and nondeterminism with respect to context, and as we have seen, a nonclassical formalism is necessary to describe the change of state involved. The CAP perspective also clarifies why fitness has been so hard to nail down. We agree with Krimbas (2004) that fitness is a property of neither an organism, nor an environment, but emerges at the interface between them, and changes from case to case. However we do not go along with his conclusion that it is merely a conceptual device, devoid of any substancial physical counterpart. The view of fitness that emerges here is not far in spirit from the "two-faced" (Sober 2001) or propensity (Brandon & Beatty 1984; Mills & Beatty 1979) view, except that potential fitness incorporates all possible evolutionary trajectories under all possible contexts, and actual fitness refers only to the realized segment of this potentiality.

4.3 Change of Cognitive State in a Stream of Thought

Recall from section 2.3 Campbell's attempt to apply selection theory to thought. However, selection theory requires multiple, distinct, simultaneously-actualized states. In cognition, each thought or cognitive state changes the 'selection pressure' against which the next is evaluated; they are not simultaneously selected amongst. The mind can exist in a state of potentiality, and change through interaction with the context to a state that is genuinely new, not just an element of a pre-existing set of states. Creative thought is a matter of honing in on an idea by redescribing successive iterations of it from different real or imagined perspectives; *i.e.* actualizing potential through exposure to different contexts. Once again, the description of contextual change of state introduces a non-Kolmogorovian probability distribution, and a classical formalism such as selection theory cannot be used. Thus an idea certainly changes as it gets mulled over in a stream of thought, and indeed it appears to evolve, but the process through which it evolves is not Darwinian (For in-depth discussion with examles see Gabora & Aerts, in press). Campbell's error is to treat a set of *potential*, contextually elicited states of *one* entity as if they were *actual* states of a *collection* of entities, or possible states with no effect of context, even though the mathematical structure of the two situations is completely different. In a stream of thought, neither are all contexts equally likely, nor does context have a limited effect on future iterations. So the assumptions that make classical stochastic models useful approximations do not hold.

4.4 Cultural Evolution

In this section we look at how cultural evolution fits into the CAP framework.

4.4.1 Culture Evolves Without a Self-Assembly Code

The basic unit of culture has been assumed to be the behavior or artifact, or the mental representations or ideas that give rise to concrete cultural forms. The meme notion further implies that these cultural units are replicators (Dawkins 1976). However, an idea or artifact is not a replicator because it does not consist of self-assembly instructions; it may *retain* structure as it passes from one individual to another, but does not *replicate* it. Looking at cultural evolution from the CAP framework we are led to ask: what is *really* being impacted by context when individuals tell stories, share theories, expose attitudes, and so forth? It is not necessarily any one particular meme; it is often a snapshot or 'contextually induced collapse' of ones view of how the world hangs together, a spontaneous reflection of ones model of reality, or *worldview*. A worldview is not merely a collection of discrete ideas or memes (nor do ideas or memes form an interlocking set like puzzle pieces) because each context impacts it differently; concepts and ideas are always colored by the situation in which they are evoked (Barsaolou 1982; Gabora & Aerts 2002). Indeed it has been argued that a worldview is a replicator (Gabora 2004). We saw that living organisms prior to the genetic code—a pre-RNA set of autocatalytic polymers—were *primitive replicators* because they generate self-similar structure, but in a self-organized, emergent, piecemeal manner, Eventually, for each polymer, there existed another that catalyzed its formation. Since there was no self-assembly instructions to copy from, there was no explicit copying going on. The presence of a given catalytic polymer, say polymer X, simply speeded up the rate at which certain reactions took place, while another catalytic polymer, say Y, influenced the reaction that generated X. Just as polymers catalyze reactions that generate other polymers, retrieval of an item from memory can trigger another, which triggers yet another and so forth, thereby cross-linking memories, ideas, and so forth into a conceptual web. Like Kauffman's (1993) autocatalytic sets of poymers, the result can be described as a connected closure structure (Gabora & Deses, in press). Elements of a worldview are regenerated through social learning. Since as with Kauffman's origin of life scenario the process occurrs in a self-organized, piecemeal autocatalytic manner, through bottom-up interactions rather than a top-down code, worldviews like the earliest life forms replicate with low fidelity, and their evolution is highly nondeterministic.

4.4.2 Inheritance of Acquired Traits in Culture

As with the earliest pre-DNA forms of life, characteristics of a worldview acquired over a lifetime are heritable. We hear a joke and, in sharing it with others, give it our own slant. We create a disco version of Beethoven's Fifth Symphony and a rap version of that. The evolutionary trajectory of a worldview makes itself known indirectly via the behavior and artifacts it manifests under the influence of the contexts it encounters. (For example, when you explain how to change a tire, certain facets of your worldview are revealed, while your playing of a piano concerto reveals other facets.)

Because acquired traits are heritable in culture, the probability of splitting off into multiple variants is high. These variants can range from virtually identical to virtually impossible to trace back to the same 'parent' idea. They affect, and are affected by, the minds that encounter them. For example, books can affect all the individuals who read them, CDs can affect all the individuals who play them, movies can affect all the individuals who watch them, and so forth, and these individuals subsequently provide new contexts for the possible further evolution of the ideas they described and stories they told.

5. CONCLUSIONS

While replication with variation and selection of particulate traits has served as an adequate description of evolution for some time, it is not general enough to provide a full description of how entities evolve. The reason selection is a significant part of the story in biology owes to the unusual means of perpetuating form using a self-assembly code, different versions of which get selected amongst for replication, and the death of individuals and the contextually-elicited change accrued over a lifetime. But even in biology, selection is far from a complete theory of evolution. It can explain why certain forms propagate while others die out, but it cannot explain how biological form arises in the first place. Moreover, organisms are not the only entities that evolve. Physical, cognitive, and cultural entities undergo a similar process of incremental adaptation to the constraints imposed by an environment. There is no reason evolution need involve selection, except as a special case.

This paper introduced a general framework for characterizing how entities evolve through context-driven actualization of potential (CAP). By this we mean:

- An entity has the *potential* to change in different ways under different contexts.
- Some aspects of this potentiality are actualized when the entity undergoes a change of state through *interaction with the particular context* it encounters.
- The interaction between entity and context may also change the context, and the constraints and affordances it offers the entity.
- Thus the entity undergoes another change of state, and so forth, recursively.

When evolution is construed as the incremental change that results from recursive, context-driven actualization of potential, the domains through which we have carved up reality can be united under one umbrella. Quantum, classical, biological, cognitive, and cultural evolution appear as different ways in which potential that is present due to the state of an entity, its context, and the nature of their interaction, is recursively actualized. They differ according to the degree of:

- Sensitivity to context.

- Internalization of context.
- Dependence upon a particular context.
- Nondeterminism due to lack of knowledge concerning the state of the entity.
- Nondeterminism due to lack of knowledge concerning the state of the context.

The reason potentiality and contextuality are so important stems from the fact that we inevitably have incomplete knowledge of the universe in which an entity is operating. Specifically, one is forced to think in terms of potentiality when the state of the entity of interest and/or the context that affects it are in constant flux, or undergoing change at a resolution below that which we can detect, but which has an effect on what emerges at the entity-context interface. This gives rise in a natural way to nondeterministic change. Nondeterminism that arises through lack of knowledge concerning the state of the entity can be described by classical stochastic models (Markov processes) because the probability structure is Kolmogorovian. However, nondeterminism that arises through lack of knowledge concerning the interaction between entity and context introduces a non-Kolmogorovian probability model[7] on the state space, thus necessitating a nonclassical formalism. Historically, the first nonclassical formalism science produced was the quantum formalism. This formalism has since been generalized to describe situations involving nonlinearity, and varying degrees of contextuality.

Without going over in detail how different processes of change 'appear' in the CAP framework, let us briefly review some of the more surprising or illuminating outcomes, starting at the most micro level and working our way up in scale.

It has been thought that the two modes of change in quantum mechanics—dynamical evolution of the quantum entity as per the Schrödinger equation, and the collapse that takes place when the quantum entity is measured—were fundamentally different. However, when the measurement is seen to be a context, we notice that it is always a context that could actualize the potential of the entity in different ways. Indeed, if one knows the outcome with certainty one does not perform a measurement; it is only when there is more than one possible value that a measurement is performed. Thus the two modes of change in quantum mechanics are united; the dynamical evolution of a quantum entity as per the Schrödinger equation reduces to a collapse for which there was only one way *to* collapse (i.e. only one possible outcome), hence a deterministic collapse. This also holds for the deterministic evolution of classical entities. This constitutes a true paradigm shift, for evolution and collapse have been thought to be two fundamentally different processes.

Looking at biological evolution from the CAP perspective, self-replication appears as a means of testing the integrity of an entity—or rather different *versions* of an entity—against different contexts. While individuals and even species become increasingly context-dependent, the joint entity of living organisms becomes increasingly context-*in*dependent.The genetic code afforded primitive life protection against contextually-induced disintegration of self-replication capacity, at the cost of decreased diversity. The onset of sexual reproduction increased the potentiality of a lineage, and thus possible trajectories for biological form. The CAP framework supports the notion that fitness is neither a property of an organism, nor of an environment, but emerges at the interface between them. The concept of potential fitness includes all possible evolutionary trajectories under all possible contexts. Since it involves nondeterminism with respect to context, unless context has a limited effect or all possible contexts are equally likely, a nonclassical formalism is necessary to describe the novel form that results when an organism interacts with its environment in a way that makes some of its potential became actual (where actual fitness refers only to the *realized* segment of its potentiality). It now becomes clear why natural selection has been able to tell us much about changes in frequencies of existing forms, but little about how new forms emerge in the first place!

The same argument holds for what happens in a stream of creative thought. The mathematical formulation of the theory of natural selection requires that in any given iteration there be multiple distinct, actualized states. In cognition however, each successive mental state changes the context in which the next is evaluated; they are not simultaneously selected amongst. Creative thought is a matter of honing in on an idea by redescribing successive iterations of it from different real or imagined perspectives; actualizing potential through exposure to different contexts. Thus selection theory is not applicable to the formal description of a stream of thought, and to the extent that creative thought powers cultural change, it is of limited applicability there as well. Once again, a nonclassical formalism is necessary.

The notion of culture as a Darwinian process probably derives from the fact that the means through which a creative mind manifests itself in the world—language, art, and so forth—exist as discrete entities such as stories and paintings. This can lead to the assumption that discrete creative artifacts in the world spring forth from corresponding discrete, pre-formed entities in the brain. This in turn leads to the assumption that novelty gets generated through that most celebrated of all change-generating mechanisms, Darwinian selection, and that ideas and artifacts must therefore be replicators. However, an idea or artifact is not a replicator because it does not consist of coded self-assembly instructions, and thus does not make copies of itself. Moreover, ideas and artifacts do not arise out of separate, distinct compartments in the brain, but emerge from a dynamically and contextually modifiable, web-like memory structure, a melting pot in which different components continually merge and blend, get experienced in new ways as they arise in new contexts and combinations. The CAP perspective suggests instead that the basic unit and the replicator of culture is an integrated network of knowledge, attitudes, ideas, and so forth; that is, an internal model of the world, or worldview, and that ideas and artifacts are how a worldview reveals itself under a particular context.

The CAP framework provides a perspective from which we can see why the neo-Darwinian view of evolution has been satisfactory for so long, and it wasn't until after other processes become prominently viewed in evolutionary terms that the time was ripe for potentiality and contextuality to be taken seriously. We also see how unique the genetic code is, and the consequent lack of retention of context-driven change. Indeed, the effects of contextual interaction in biology are in the long-run largely invisible; context affects biological lineages only by influencing the number and nature of offspring. Natural selection is such an exceptional means of change, it is no wonder it does not transfer readily to other domains. Note that it is often said that because acquired traits are inherited in culture, culture should not be viewed in evolutionary terms. It is ironic that this critique also applies to the earliest stage of biological evolution itself. What was true of early life is also true of the replication of worldviews: acquired characteristics can be inherited. Modern life is unique in this sense. Perhaps it is only because Darwinian evolution is such an *unusual* form of evolution that it got so much attention it cornered the word 'evolution'. We stumbled upon the least contextual form of evolution, called it evolution, and then proceeded with a 'theory of evolution' that all but excluded context.

ACKNOWLEDGMENTS

This research was supported by Grant G.0339.02 of the Flemish Fund for Scientific Research.

NOTES

---

[1] For the sake of mathematical completeness, we mention that this is only the case when the operator has a point spectrum. Measurements described by operators without a point spectrum must be treated in a more sophisticated way, but this is of no relevance to the points made here.

[2] Each state that is not an eigenstate is in fact a superposition state.

[3] This is a consequence of the vector space structure of the set of states, and the fact that the set of eigenstates forms a basis of this vector space.

[4] Yet another possibility is that the nondeterminism is ontological *i.e*. the universe is at bottom intrinsically nondeterministic. In this case, it can be shown (Aerts 1994) that the mathematical structure necessary to model the situation is equivalent to the mathematical structure needed to model the situation where the nondeterminism arose through lack of knowledge of the context. This means that the situation of ontological indeterminism is also described by the CAP framework.

[5] This story has a precedent. The same problem arose in physics in the last century. Classical mechanics could describe situations where the effect of the measurement was negligible, but not situations where the measurement intrinsically influenced the evolution of an entity. This is because it does not provide a way of coping with contextuality (except in the initial conditions or in an ad hoc way, by introducing an additional model of perturbation). Modern classical theories, such as chaos and complexity, though they provide a means of transcending reductionism, still have this limitation.

[6] The reason this works is because when polymers interact, the number of different polymers increases exponentially, but the number of reactions by which they can interconvert increases faster than their total number. Thus, as their diversity increases, so does the probability that some subset of the total reaches a critical point where there is a catalytic pathway to every member.

[7] For example Bayes' formula for conditional probability is not satisfied.

REFERENCES

Accardi L. and Fedullo A.: 1982, 'On the statistical meaning of complex numbers in quantum mechanics', *Nuovo Cimento*, 34(7), 161-172.

Aerts D.: 1983, 'Classical Theories and Nonclassical Theories as a Special Case of a more General Theory', *Journal of Mathematical Physics* 24, 2441-2454.

Aerts D.: 1986, 'A possible explanation for the probabilities of quantum mechanics', *Journal of Mathematical Physics,* 27, 202-210.

Aerts D.: 1993, 'Quantum Structures Due to Fluctuations of the Measurement Situations', *International Journal of Theoretical Physics* 32, 2207–2220.

Aerts D.: 1994, 'Quantum structures, separated physical entities and probability', *Foundations of Physics* 24, 1227-1259.

Aerts D.: 2002, 'Being and change: foundations of a realistic operational formalism', in Aerts D., Czachor M. and Durt T. (eds.), *Probing the Structure of Quantum Mechanics: Nonlinearity, Nonlocality, Probability and Axiomatics*, World Scientific, Singapore, pp. 71-110.

Aerts D. and Aerts S.: 1994, 'Applications of quantum statistics in psychological studies of decision processes', *Foundations of Science* 1, 85-97.

Aerts D., Aerts S., Broekaert J. and Gabora L.: 2000a, 'The Violation of Bell Inequalities in the Macroworld', *Foundations of Physics* 30, 1387–1414.

Aerts D. and Durt T.: 1994, 'Quantum, Classical, and Intermediate, an Illustrative Example', *Foundations of Physics* 24, 1353-1368.

Aunger R.: 2000, *Darwinizing Culture*, Oxford University Press, Oxford.

Barsalou L.W.: 1982, 'Context-independent and Context-dependent Information in Concepts', *Memory & Cognition* 10, 82-93.

Blackmore S.: 1999, *The Meme Machine*, Oxford University Press, Oxford.
Blackmore S.: 2000, 'The Power of Memes', *Scientific American* 283(4), 52-61.
Boone J. Smith E., Dennett D., and Earle T.: 1998, 'Is it Evolution Yet? A Critique of Evolutionary Archaeology', *Current Anthropology* 39(3) June, S141-74.
Borger T. and Sarin R.: 1997, 'Learning through Reinforcement and the Replicator Dynamics', *Journal of Economic Theory* 77, 1-14.
Borkar V.S., Jain S. and Rangarajan G.: 1998, 'Dynamics of Individual Specialization and Global Diversification in Communities', *Complexity* 3(3), 50-6.
Boyd R. and Richerson P.J.: 1985, *Culture and the Evolutionary Process*, University of Chicago Press, Chicago, IL.
Brandon R.N. and Beatty, J.: 1984, 'The Propensity Interpretation of "Fitness" – No Interpretation is No Substitute', *Philosophy of Science* 51, 342-347.
Cairns J., Overbaugh J. and Miller J.: 1988, 'The Origin of Mutants', *Nature* 335, 142-145.
Campbell D.T.: 1960, 'Blind Variation and Selective Retention in Creative Thought as in Other Knowledge Processes', *Psychological Review* 67, 380-400.
Campbell D.T.: 1965, 'Variation and Selective Retention in Socio-cultural Evolution', in Barringer H.R. , Blanksten G.I. , and Mack R.W. (eds), *Social Change in Developing Areas: A Reinterpretation of Evolutionary Theory*, Schenkman, Cambridge, MA.
Campbell D.T.: 1987, 'Evolutionary Epistemology', in Radnitzky G. and Bartley III W.W. (eds.) *Evolutionary Epistomology: Rationality, and the Sociology of Knowledge*, Open Court, LaSalle, IL.
Campbell D.T.: 1990, 'Levels of Organization, Downward Causation, and the Selection-theory Approach to Evolutionary Epistemology', in Greenberg G. and Tobach E. (eds.) *Theories of the Evolution of Knowing*, Erlbaum, Hillsdale, NJ.
Cavalli-Sforza L.L. and Feldman M.W.: 1981, *Cultural Transmission and Evolution: a Quantitative Approach*, Princeton University Press, Princeton.
Chandler J. and Van de Vijver G.: 1999, *Closure: Emergent Organizations and their Dynamics*. Vol. 901 of Annals of the New York Academy of Sciences.
Csanyi V.: 1989, *Evolutionary Systems and Society: A General Theory of Life, Mind and Culture*, Duke University Press, Durham, NC.
Cziko G.: 1995, *Without Miracles: Universal Selection Theory and the Second Darwinian Revolution*, MIT Press, Boston, MA.
Dawkins R.: 1976, *The Selfish Gene*, Oxford University Press, Oxford.
Dawkins R.: 1982, *The Extended Phenotype*, Oxford University Press, Oxford.
Dennett D.: 1995, *Darwin's Dangerous Idea*, Simon & Schuster, New York.
Dupre J.: 2002, 'The Lure of the Simplistic', *Philosophy of Science* 69, S284-203.
Durham W.H.: 1991, *Coevolution: Genes, Culture, and Human Diversity*, Stanford University Press, Stanford, CA.
Eldridge N. and Gould S.J.: 1973, 'Punctuated Equilibrium: An Alternative to Phyletic Gradualism', in Schopf T. (ed.) *Models in Paleobiology*, San Francisco: Freeman, Cooper and Co., pp. 82-115.
Farmer D. and Lo A.W.: 1999, 'Frontiers of Finance: Evolution and Efficient Markets', *Proceedings of the National Academy of Sciences USA* 96, 9991-9992.
Foulis D., Piron C., and Randall C.: 1983, 'Realism, Operationalism and Quantum Mechanics', *Foundations of Physics* 13(813), 813-841.
Foulis, D. and Randall, C.: 1981, 'What are Quantum Logics and what Ought they to Be?', in Beltrametti E. and van Fraassen B. (eds.), *Current Issues in Quantum Logic* 35, Plenum, New York.

Friedman M.: 1974, 'Explanation and Scientific Understanding', *Journal of Philosophy* 71(19). Reprinted in Pitt (ed.), *Theories of Explanation*, 1988, Oxford University Press, Oxford.
Gabora L.: 1995, 'Meme and Variations: A Computer Model of Cultural Evolution', in Nadel L. and Stein D. (eds.), *1993 Lectures in Complex Systems*, Addison-Wesley, Boston, pp. 471-86.
Gabora L.: 1996, 'A Day in the Life of a Meme', *Philosophica,* 57, 901-938.
Gabora L.: 2004, 'Ideas are not Replicators but Minds Are', *Biology and Philosophy* 19(1), 127-143.
Gabora L. and Aerts D.: 2002b, 'Contextualizing Concepts using a Mathematical Generalization of the Quantum Formalism', *Journal of Experimental and Theoretical Artificial Intelligence* 14, 327 – 358. http://www.vub.ac.be/CLEA/liane/papers/jetai.pdf
Gabora L. and Aerts, D.: in press, 'Creative Thought as a Non-Darwinian Evolutionary Process', *Journal of Creative Behavior*.
Gabora L. and Deses D.: in press, 'Evolution of Worldviews through Conceptual Closure', *Studies in Language*, special issue on evolutionary epistomology, culture, and language.
Gould S.J.: 1991, *Bully for Brontosaurus: Reflections in Natural History*, pp. 63-66, W.W. Norton & Company, New York.
Gould S.J.: 2002, *The Structure of Evolutionary Theory*, Harvard University Press, Cambridge, MA.
Hallpike C.R.: 1986, *The Principles of Social Evolution*, Clarendon Press, Oxford.
Hofbauer J. and Sigmund K.: 1988, *The Theory of Evolution and Dynamical Systems*, Cambridge University Press, Cambridge.
Hull D.L.: 1988, *Science as a Process: An Evolutionary Account of the Social and Conceptual Development of Science*, University of Chicago Press, Chicago, IL.
Jauch J.: 1968, *Foundations of Quantum Mechanics*, Addison-Wesley, Reading, MA.
Jeffreys M.: 2000, 'The Meme Metaphor', *Perspectives in Biology and Medicine* 43(2), 227-242.
Kampis G.: 1991, Self-*Modifying Systems in Biology and Cognitive Science: A New Framework for Dynamics, Information and Complexity*, Pergamon Press, New York.
Kauffman S.: 1993, *Origins of Order*, Oxford University Press, New York.
Kitcher P.: 1981, 'Explanatory Unification', *Philosophy of Science* 48, 507-31.
Kitcher P.: 1993, *The Advancement of Science: Science Without Legend*, Oxford University Press, New York.
Kitcher P.: 2004, 'Evolutionary Theory and the Social uses of Biology', *Biology and Philosophy* 19(1), 1-15.
Krimbas C.B.: 2004, 'On Fitness', *Biology and Philosophy* 19(2), 185-204.
Lake M.: 1998, Digging for Memes: The Role of Material Objects in Cultural Evolution, in C. Renfrew & C. Scarre (eds.), *Cognition and Material Culture: The Archeology of Symbolic Storage*, McDonald Institute Monographs, pp. 77-88.
Lorenz K.: 1971, *Studies in Animal and Human Behavior*, Harvard University Press, Cambridge, MA.
Lumsden C. and Wilson E.: 1981, *Genes, Mind, and Culture: The Coevolutionary Process*, Harvard University Press, Cambridge, MA.
Mackey G.: 1963, *Mathematical Foundations of Quantum Mechanics*, John Benjamin, Reading, MA.
Margulis, L. and Fester R.: 1991, *Symbiosis as a Source of Evolutionary Innovation*, MIT Press, Cambridge, MA.
Metcalfe J. S.: 2001, 'Consumption, Preferences, and the Evolutionary Agenda', *Journal of Evolutionary Economics* 11(1), 37-58.
Mills S. And Beatty J.: 1979, 'The Propensity Interpretation of Fitness', *Philosophy of Science* 46, 263-286.

Newman S.A. and Müller G.B.: 1999, ‘Morphological Evolution: Epigenetic Mechanisms’, in *Embryonic Encyclopedia of Life Sciences*, Nature Publishing Group, London.
Perkins D.N.: 1998, ‘In the Country of the Blind: An Appreciation of Donald Campbell's Vision of Creative Thought’, *Journal of Creative Behavior* 32(3), 177-91.
Pinker S.: 1997, *How the Mind Works.* Norton, New York.
Piron C.: 1976, *Foundations of Quantum Physics*, W.A. Benjamin, Reading, MA.
Piron C.: 1989, ‘Recent Developments in Quantum Mechanics’, *Helvetica Physica Acta* 62(82), 439-68.
Piron C.: 1990, *Mécanique Quantique: Bases et Applications*, Press Polytechnique de Lausanne, Lausanne, Switzerland.
Pitowsky I.: 1989, ‘Quantum Probability, Quantum Logic’, *Lecture Notes in Physics 321*, Springer, Berlin.
Pitt J.C.: 1988, *Theories of Explanation*, Oxford University Press, New York.
Plotkin H.: 1997, *Darwin Machines and the Nature of Knowledge*, Harvard University Press, Cambridge, MA.
Popper K.R.: 1963, *Conjectures and Refutations*, Routledge & Kagen, London.
Randall C. and Foulis D.: 1976, ‘A Mathematical Setting for Inductive Reasoning’, in Hooker C. (ed.), *Foundations of Probability Theory, Statistical Inference, and Statistical Theories of Science III*, 169, Reidel, Dordrecht, The Netherlands.
Randall C. and Foulis D.: 1978, ‘The Operational Approach to Quantum Mechanics’, in Hooker C. (ed.), *Physical Theories as Logico-Operational Structures* 167, Reidel, Dordrecht, The Netherlands.
Rivkin J.W.: 2001, ‘Reproducing Knowledge: Replication without Imitation at Moderate Complexity’, *Organizational Science* 12(3), 274-293.
Rosen R.: 1985, *Anticipatory Systems: Philosophical*, *Mathematical & Methodological Foundations*. Oxford, New York.
Saviotti, P.P. and Mani, G.S.: 1995, ‘Competition, Variety, and Technological Evolution: A Replicator Dynamics Model’, *Journal of Evolutionary Economics* 5(4), 369-92.
Schuster, P. and Sigmund, K.: 1983, ‘Replicator Dynamics’, *Journal of Theoretical Biology* 100, 533-38.
Schwartz J.H.: 1999, *Sudden Origins*, Wiley, New York.
Simonton D.K.: 1998, ‘Donald Campbell’s Model of the Creative Process: Creativity as Blind Variation and Selective Retention’, *Journal of Creative Behavior* 32(3), 153-58.
Simonton D.K.: 1999a, *Origins of Genius: Darwinian Perspectives on Creativity*, New York: Oxford.
Simonton D.K.: 1999b, ‘Creativity as Blind Variation and Selective Retention: Is the Creative Process Darwinian?’, *Psychological Inquiry* 10, 309-28.
Sober E.: 2001, ‘The Two Faces of Fitness, in R. Singh, C.B. Krimbas, D. Paul, and J. Beatty (eds.) *Thinking About Evolution*, Cambridge University Press, Cambridge, pp. 309-321.
Spector L. and Luke S: 1996, ‘Culture Enhances the Evolvability of Cognition’, in Cottrell G. (ed.) *Proceedings of the Eighteenth Annual Conference of the Cognitive Science Society*, , pp. 672-77, Lawrence Erlbaum Associates, Mahwah, NJ.
Sternberg R.J. and Lubart T.I.: 1995, *Defying the Crowd: Cultivating Creativity in a Culture of Conformity*. Free Press, New York.
Varela F.: 1979, *Principles of Biological Autonomy*, Elsevier/North-Holland, New York.
Witt, U.: 1992, ‘Evolutionary Concepts in Economics’, *Eastern Economic Journal* 18, 405-19.