Anticipation—A Spooky Computation

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Robert Rosen, *in memoriam*

Abstract

As the subject of anticipation claims its legitimate place in current scientific and technological inquiry, researchers from various disciplines (e.g., computation, artificial intelligence, biology, logic, art theory) make headway in a territory of unusual aspects of knowledge and epistemology. Under the heading *anticipation*, we encounter subjects such as preventive caching, robotics, advanced research in biology (defining the living) and medicine (especially genetically transmitted disease), along with fascinating studies in art (music, in particular). These make up a broad variety of fundamental and applied research focused on a controversial concept. Inspired by none other than Einstein—he referred to *spooky actions at distance,* i.e., what became known as quantum non-locality—the title of the paper is meant to submit my hypothesis that such processes are related to quantum non-locality. The second goal of this paper is to offer a cognitive framework—based on my early work on mind processes (1988)—within which the variety of anticipatory horizons invoked today finds a grounding that is both scientifically relevant and epistemologically coherent. The third goal of this paper is to identify the broad conceptual categories under which we can identify progress made so far and possible directions to follow. The fourth and final goal is to submit a co-relation view of anticipation and to integrate the inclusive recursion in a logic of relations that handles co-relations.

Keywords: auto-suggestive memory, co-relation, non-locality, quantum semiotics, self-constitution, interactive computation

1 Introduction

Anticipation could become the new frontier in science. Trends, scientific fashions, and priority funding programs succeed one another rapidly in a society that experiences a dynamics of change reflected in ever shorter cycles of discovery, production, and

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consumption. Frontiers mark stark discontinuities that ascertain fundamentally new knowledge horizons. Einstein stated, "No problem can be solved from the same consciousness that created it. We must learn to see the world anew." It is in this respect that I find it extremely important to begin by putting the entire effort into a broad perspective.

2 The Philosophic Foundation of Anticipation is Not Trivial

Philosophical considerations cannot be avoided (provided that they are not pursued as a means in themselves). Robert Rosen (1985) quoted David Hawkins, "Philosophy may be ignored but not escaped." Rosen, whose work deserves to be integrated in current scientific dialog more than was been the case until his untimely death, understood this thought very well.

Anticipation bears a heavy burden of interpretations. As initial attempts (Rosen, 1985; Nadin, 1988; Dubois, 1992) to recover the concept and to give it a scientific foundation prove, the task is difficult. We face here the dominant deterministic view inspired by a model of the universe in which a net distinction between cause and effect can be made. We also face a reductionist understanding of the world, which claims that physics is paradigmatic for everything else. Moreover, we are captive to an understanding of time and space that corresponds to the mathematical descriptions of the physical world: Time is uniquely defined along the arrow from past to future; space is homogeneous. Finally, we are given to the hope that science leads to laws on whose basis we may make accurate predictions. Once we accept these laws, anticipation can at best be accepted as one of these predictions, but not as a scientific endeavor on its own terms.

A clear image of the difficulties in establishing this foundation results from revisiting Rosen's work on anticipatory systems, above all his fundamental work, *Life Itself* (1991). Indeed, his rigorous argumentation, based on solid mathematical work and on a grounding in biology second to none among his peers, makes sense only against the background of the philosophic considerations set forth in his writings. It might not matter to a programmer whether Aristotle's *causa finalis* (final cause) can be ascertained or justified, or deemed as passé and unacceptable. A programmer's philosophy does not directly affect lines of code; neither do disputes among those partial to a certain world view. What is affected is the general perspective, i.e., the understanding of a program's meaning. If the program displays characteristics of anticipation, the philosophic grounding might affect the realization that within a given condition—such as embodied in a machine—the simulation of anticipatory features should not be construed as anticipation *per se*.

The philosophic foundation is also a prerequisite for defining how far the field can be extended without ending up in a different cognitive realm. Regarding this aspect, it is better to let those trying to expand the inquiry of anticipation—let me mention again

Dubois (since 1996) and the notions of incursion and hyperincursion, Holmberg (since 1997) and space aspects—express themselves on the matter. Van de Vijver (1997), among few others (cf. CASYS 98 and the contributions listed in the Program for CASYS 99) has already attempted to shed light on what seems philosophically pertinent to the subject. She is right in stating that the global/local relation more adequately pertains to anticipation than does the pair particular/universal. The practical implications of this observation have not yet been defined.

From my own perspective—based on pragmatics, which means grounding in the practical experience through which humans become what they are—anticipation corresponds to a characteristic of live beings as they attain the condition at which they constitutes their own nature. At this level, predictive models of themselves become possible, and progressively necessary. The thematization of anticipation, which as far as we know is a human being's expression of self-awareness and connectedness, is only one aspect of this stage in the unfolding of our species. According to the premise of this perspective, pragmatics—expressed in what we do and how and why we do what we do—is where our understanding of anticipation originates. This is also where it returns, in the form of optimizing our actions, including those of defining what these actions should be, what sequence they follow, and how we evaluate them. All these are projections against a future towards which each of us is moving, all tainted by some form of finality *(telos),* or at least by its less disputed relative called *intentionality.* The generic *why* of our existence is embedded in this intentionality. The source of this finality are the others, those we interact with either in cooperating or in competing, or in a sense of belonging, which over time allowed for the constitution of the identity called *humanness*. Gordon Pask (1980), the almost legendary cybernetician, called such an entity a *cognitive system.*

2.1 Self-Entailment and Anticipation

In a dialog on *entailment* (cf. http://views.vcu.edu/complex)—a fundamental concept in Rosen's explanation of anticipation—a line originating with François Jacob was dropped: "Theories come and go, the frog stays." (Incidentally, Jacob is the author of *The Logic of Life,* Princeton University Press, 1993). This brings us back to a question formulated above: Does it matter to a programmer (the reader may substitute his/her profession for the word *programmer*) that anticipation is based on the self-entailment characteristic of the living? Or that evolution is the source of entailment? If we compare the various types of computation acknowledged since people started building computers and writing software programs, we find that during the syntactically driven initial phases, such considerations actually could not affect the pragmatics of programming. Only relatively recently has a rudimentary semantic dimension been added to computation. In the final analysis, it does not matter which microelectronics, computer architecture, programming languages, operating systems, networks, or communication protocols are used. For all practical purposes, what matters is that between the world and the computation pertinent to some aspects of this world, the relations are still extremely limited. If a programmer is not just in the business of writing lines of code for a specific application that might improve through a syntactically supported emulation of anticipatory characteristics—think about macros that save typing time by "guessing" which word or expression a user started to type in and "filling in" the letters or words—then it matters that there is something like self-entailment. It matters, too, that the notion of self-entailment supports more adequate explanations of biological processes than any other concept of the physical sciences. On a semantic level, the awareness of self-entailment (through self-associative memory) leads to better solutions in speech and handwriting recognition.

However, once the pragmatic level is reached—we are still far from this—understanding the philosophic implications of the nature and condition of anticipation becomes crucial. The reason is that it is not at all clear that characteristics of the living—self-repair, metabolism, and anticipation—can be effectively embodied in machines. This is why the notion of frontier science was mentioned in the Introduction. The frontier is that of conceiving and implementing life-like systems. Whether Rosen's (M, R)-model, defined by metabolism and repair, or others, such as those advanced in neural networks, evolutionary computation, and ALife, will qualify as necessary and sufficient for making anticipation possible outside the realm of the living remains to be seen. I (Nadin, 1988, 1991) argue for computers with a variable configuration based on anticipatory procedures. This model is inspired by the dynamics of the constitution and interaction of minds, but does not suggest an imitation of such processes. The issue is not, however, reducible to the means (digital computation, algorithmic, non-algorithmic, or heterogenous processing, signal processing, quantum computation, etc.), but to the encompassing goal.

2.2 Specializations

To nobody's surprise, anticipation, in some form or another, is part of the research program of logic, cognitive science, computer science, robotics, networking, molecular biology, genetics, medicine, art and design, nanotechnology, the mathematics of dynamic systems, and what has become known as ALife, i.e., the field of inquiry into artificial life. Anticipation involves semiotic notions, as it involves a deep understanding of complexity, or, better yet, of an improved understanding of complexity that integrates quantitative and qualitative aspects.

It is not at all clear that full-fledged anticipation, in the form of machine-supported anticipatory functioning, is a goal within the reach of the species through whose cognitive characteristics it came into being and who became aware of it. Machines, or computations, for those who focus on the various data processing machines, able to anticipate earthquakes, hurricanes, aesthetic satisfaction, disease, financial market performance, lottery drawings, military actions, scientific breakthroughs, social unrest, irrational human behavior, etc., could well claim total control of our universe of existence. Indeed, to correctly anticipate is to be in control. This rather simplistic image of machines or computations able to anticipate cannot be disregarded or relegated to science fiction. Cloning is here to stay; so are many techniques embodying the once disreputed *causa finalis.* A philosophic foundation of anticipation has to entertain the many questions and aspects that pertain to the basic assertion according to which anticipation reflects part of our cognitive make-up, moreover, constitutes its foundation. Even if Kuhn's model of scientific paradigm change had not been abused to the extent of its trivialization, I would avoid the suggestion that anticipation is a new paradigm. Rather, as a frontier in science, it transcends its many specializations as it establishes the requirement for a different way of thinking, a fundamentally different epistemological foundation.

3 Pro-Action vs. Re-Action

Now that the epistemological requirement of a different way of thinking has been brought up, I would like to revisit work done during the years when the very subject of anticipation seemed not to exist (except in the title of Rosen's book). My claim in 1988 (on the occasion of a lecture presented at Ohio State University) was that anticipation lies at the foundation of the entire cognitive activity of the human being. Moreover, through anticipation, we humans gain insight into what keeps our world together as a coherent whole whose future states stand in correlation to the present state as minds grasp it. Minds exist only in relation to other minds; they are instantiations of co-relations. This is also the main thesis of this paper.

For over 300 years—since Descartes' major elaborations (1637, 1644) and Newton's *Principia* (1687)—science has advanced in understanding what for all practical purposes came to be known as the *reactive modality.* Causality is experienced in the reactive model of the universe, to the detriment of any pro-active manifestations of phenomena not reducible to the cause-and-effect chain or describable in the vocabulary of determinism. It is important to understand that what is at issue here is not some silly semantic game, but rather a pragmatic horizon: Are human actions (through which individuals and groups identify themselves, i.e., self-constitute, Nadin 1997) in reaction to something assumed as given, or are human actions in anticipation of something that can be described as a goal, ideal, or value? But even in this formulation (in which the vocabulary is as far as it can be from the vitalistic notions to which Descartes, Newton, and many others reacted), the suspicion of teleological dynamics—is there a given goal or direction, a final vector?—is not erased. Despite progress made in the last 30 years in understanding dynamic systems, it is still difficult to accept the connection between goal and self-organization, between ideal, or value, and emergent properties.

3.1 Minds Are Anticipations

The mind is in anticipation of events, that is, ahead of them—this was my main thesis over ten years ago. Advanced research (Libet 1985, 1989) on the so-called "readiness potential" supported this statement. In recent years, work on the "wet brain" as well as work supported by MR-based visualization technologies have fully confirmed this understanding. Having entered the difficult dialog on the nature of cognitive processes from a perspective that no longer accepted the exclusive premise of representation —another heritage from Descartes—I had to examine how processes of self-constitution eventually result in shared knowledge without the assumption of a *homunculus*. What seemed inexplicable from a perspective of classical or relativist physics—a vast amount of actions that seemed instantaneous, in the absence of a better explanation for their connectedness—was coming into focus as constitutive of the human mind. Anticipatory cognitive and motoric scripts, from which in a given context one or another is instantiated, were advanced at that time as a possible description for how, from among many pro-active possible courses of action, one would be realized. Today I would call those possible scripts *models* and insist that a coherent description of the functioning of the mind is based on the assumption that there are many such models. Additionally, I would add that learning, in its many realizations, is to be understood as an important form of stimulating the generation of models, and of stimulating a competitive relation among them.[1] In a subtle way, defense mechanisms—from blinking to reflexes of all types—belong to this family. Anticipatory nausea and vomiting (whether on a ship or related to chemotherapy) is another example. The phantom limb phenomenon (sensation in the area of an amputated limb) is mirrored by pain or discomfort before something could have actually caused them. There is a descriptive instance in Lewis Carroll's *Through the Looking Glass*. Before accidentally pricking her finger, the White Queen cries: "I haven't pricked it yet, but I soon shall." She lives life in reverse, which is what anticipation ultimately affords—provided that the interpretation process is triggered and made part of the self-constitutive pragmatics.

3.1.1 Anticipation is Distributed

As recently as this year, results in the study of the anticipation of moving stimuli by the retina (Berry, *et al* 1999) made it clear that anticipation is distributed. The research proved that anticipation of moving stimuli begins in the retina. It is no longer that we expect the visual cortex to do some heavy extrapolation of trajectory (this was the predominant model until recently) but that we know that retinal processing is pro-active. Even if pro-activity is not equally distributed along all sensory channels—some are slower in anticipating than others, not the least because sound travels at a slower

[1] Von Foerster entertains a motto on his e-mail address that is an encapsulation of what I just described: "Act always as to increase the number of choices." (See also 1999.)

speed than light does, for example—it defines a characteristic of human perception and sheds new light on motoric activity.

3.1.2 Knowledge as Construction

But there is also Kelly's (1995) constructivist position, which must be acknowledged by researchers in the psychological foundation of anticipation. The adequacy of our constructs is, in his view, their predictive utility. Coherence is gained as we improve our capacity to anticipate events. Knowledge is constructed; validated anticipations enhance cognitive confidence and make further constructs possible. In Kelly's terms, human anticipation originates in the psychological realm (the mind) and reflects the intention to make possible a correspondence between a future experience and certain of our anticipations (Kelly, 1955; Mancuso & Adams-Weber, 1982). Since states of mind somehow represent states of the world, adequacy of anticipations remains a matter of the test of experience. The basic function of all our representations, as the "fundamental postulate" ascertains, is anticipation (a temporal projection). Alternative courses of action in respect to their anticipated consequences represent the pragmatic dimension of this view.

Observed phenomena and their descriptions are not independent of the assumptions we make. This applies to the perceptual control theory, as it applies to Kelly's perspective and to any other theory. Moreover, assumptions facilitate or hinder new observations. For those who adopted the view according to which a future state cannot affect a present state, anticipation makes no sense, regardless of whether one points to the subject in various religious schemes, in biology, or in the quantum realm. The situation is not unlike that of Euclidean geometry vs. non-Euclidean geometries. To see the world anew is not an easy task!

Anticipation of moving stimuli, to get back to the discovery mentioned above, is recorded in the form of spike trains of many ganglion cells in the retina. It follows from known mechanisms of retinal processing; in particular, the contrast-gain control mechanism suggests that there will be limits to what kinds of stimuli can be anticipated. Researchers report that variations of speed, for instance, are important; variations of direction are not. Furthermore, since space-based anticipation and time-based anticipation have a different metric, it remains to be seen whether a dominance of one mode over the other is established. As we know, in many cases the meeting between a visual map (projection of the retina to the tectum) and an auditory map takes place in a process called *binding*. How the two maps are eventually aligned is far from being a matter of semantics (or terminology, if you wish). Synchronization mechanisms, of a nature we cannot yet define, play an important role here. Obviously, this is not control of imagination, even if those pushing such terms feel more forceful in the *de facto* rejection of anticipation.

Arguing from a formal system to existence is quite different from the reverse argumentation (from existence to formalism). Arguing from computation can take place only within the confines of this particular experience: the more constrained a mechanism, the more programmable it is (as Rosen pointed out, 1991, p. 238). Albeit, reaction is indeed programmable, even if at times it is not a trivial task. Pro-active characteristics make for quite a different task. The most impressive success stories so far are in the area of modeling and simulation. To give only one example: Chances are that your laptop (or any other device you use) will one day fall. The future state—stress, strain, depending upon the height, angle, weight, material, etc.—and the current state are in a relation that most frequently does not interest the user of such a portable device. It used to be that physical models were built and subjected to tests (this applies, for instance, to cars as well as to photo cameras). We can model, and thus to a certain point anticipate, the effects of various possible crashes through simulations based on finite-element analysis. That anticipation itself, in its full meaning, is different in nature from such simulations passes without too much comment. The kind of model we need in order to generate anticipations is a question to which we shall return.

3.2 A Rapidly Expanding Area of Inquiry

An exhaustive analysis of the database of the contributions to fundamental and applied research of anticipation reveals that this covers a wide area of inquiry. In many cases, those involved are not even aware of the anticipatory theme. They see the trees, but not yet the forest. More telling is the fact that the major current directions of scientific research allow for, or even require, an anticipatory angle. The simulation mentioned above does not anticipate the fall of the laptop; rather, it visualizes—conveniently for the benefit of designers, engineers, production managers, etc.—what could happen if this possibility were realized. From this possibilistic viewpoint, we infer to necessary characteristics of the product, corresponding to its use (how much force can be exercised on the keyboard, screen, mouse, etc.?) or to its accidental fall. That is, we design in anticipation of such possibilities. Or we should! I would like to mention other examples, without the claim of even being close to a complete list.

3.2.1 An Example from Genetics

But more than Rosen, whose work belongs rather to the meta-level, it was genetics that recovered the terminology of heredity. Having done so, it established a framework of implicit anticipations grounded in the genetic program. Of exceptional importance are the resulting medical alternatives to the "fix-it" syndrome of healthcare practiced as a "car repair" (including the new obsession with spare parts and artificial surrogates). Genetic medicine, as slow in coming as it is, is fundamentally geared towards the active recognition of anticipatory traits, instead of pursuing the reactive model based on physical determinism. Although there is not yet a remedy to Huntington's disease, myotonic dystrophy, schizophrenia, Alzheimer's disease, or Parkinson's disease, medical researchers are making progress in the direction of better understanding how the future (the eventual state of diagnosed disease) co-relates to a present state (the unfolding of the individual in time). In the language of medicine, anticipation describes the tendency of such hereditary diseases to become symptomatic at a younger age, and sometimes to become more severe with each new generation.

We now have two parallel paths of anticipation: one is that of the disorder itself, i.e., the observed object; the other, that of observation. The elaborations within second-order cybernetics (von Foerster, 1976) on the relation between these paths (the classical subject-object problem) make any further comment superfluous. The convergence of the two paths, in what became known as *eigen* behavior (or *eigen* value), is of interest to those actively seeking to transcend the identification of genetic defects through the genetic design of a cure. After all, a cure can be conceived as a repair mechanism, related to the process of anticipation.

3.2.2 Art, Simulacrum, Fabrication

That art (healing was also seen as a special type of art not so long ago), in all its manifestations, including the arts of writing (poetry, fiction, drama), theatrical performance, and design—driven by purpose (*telos*) and in anticipation of what it makes possible—incorporates anticipatory features might be accepted as a metaphor. But once one becomes familiar with what it means to draw, paint, compose, design, write, sing, or perform (with or without devices), anticipation can be seen as the act through which the future (of the work) defines the current condition of the individual in the process of his or her self-constitution as an artist. What is interesting in both medicine and art is that the imitation can result only in a category of artifacts to be called simulacrum. In other words, the mimesis approach (for example, biomimesis as an attempt to produce organisms, i.e., replicate life from the inanimate; aesthetic mimesis, replicating art by starting with a mechanism such as the one embodied in a computer program) remains a simulacrum. Between simulacra and what was intended (organisms, and, respectively, art) there remains the distance between the authentic and the imitation, human art and machine art. They are, nevertheless, justified in more than one aspect: They can be used for many applications, and they deserve to be valued as products of high competence and extreme performance. But no one could or should ignore that the pragmatics of fabrication, characteristic of machines, and the pragmatics of human self-constitution within a dynamic involving anticipation are fundamentally different.

3.2.3 Learning (Human and Machined-Based)

Learning—to mention yet another example—is by its nature an anticipatory activity: The future associates with learning expectations and a *sui generis* reward mechanism. These are very often disassociated from the context in which learning takes place. That this is fundamentally different from generating predictive models and stimulating competition among them might not be totally clear to the proponents of the so-called computational learning theory (COLT), or to a number of researchers of learning—all from reputable fields of scientific inquiry but captive to the action-reaction model dominant in education. It is probably only fair to remark in this vein that teaching and learning experiences within the machine-based model of current education are not different from those mimicked in some computational form. Computer-based training, a very limited experience focused on a well defined body of information, can provide a cost-efficient alternative to a variety of training programs. What it cannot do is to stimulate and trigger anticipatory characteristics because, by design, it is not supposed to override the action-reaction cycle.

3.2.4 Reward

Alternatively, one can see promise in the formalism of neural networks. For instance, anticipation of reward or punishment was observed in functional neuroanatomy research (cf. Knutson, 1998). Activation of circuitry (to use the current descriptive language of brain activity) running from the medial dorsal thalamus through the anterior cingulate and mesial prefrontal cortex was co-related not to motor response but to personality variations. Accordingly, it is quite tempting to look at such mechanisms and to try to introduce reward anticipation in neural networks procedures as a method of increasing the performance of artificially mimicked decision-making. Homan (1997) reports on neural networks that "can anticipate rewards before they occur, and use these expectations to make decisions." The focus of this type of research is to emulate biological processes, in particular the dopamine-based rewarding mechanism that lies behind a variety of goal-oriented mechanisms. Dynamic programming supports a similar objective. It focuses on states; their dynamic reassessment is propagated through the neural network in ways considered similar to those mapped in the successful enlisting of brain capabilities. Training, as a form of conditioning based on anticipation, is probably complementary to what one would call instinct-based (or natural) action.

3.2.5 Motion Planning

Animation and robot motion planning, as distant from each other as they appear to some of us, share the goal of providing path planning, that is, to find a collision-free path between an initial position (the robot's arm or the arm of an animated character) and a goal position. It is clear that the future state influences the current state and that those planning the motion actually coordinate the relation between the two states. In predictive programs, anticipation is pursued as an evaluation procedure among many possibilities, as in economics or in the social sciences. The focus changes from movement (and planning) to dynamics and probability. A large number of applications, such as pro-active error detection in networks, hard-disk arm movement in anticipation of future requests, traffic control, strategic games (including military confrontation), and risk management prompted interest in the many varieties under which anticipatory characteristics can be identified.

3.3 Aspects of Anticipation

At this point, where understanding the difference between anticipation as a natural entailment process and embodying anticipatory features in machine-like artifacts meet, it is quite useful to mention that expectation, prediction, and planning—to which others add forecasting and guessing—are not fully equivalent to anticipation, but aspects of it. Let us also make note of the fact that we are not pursuing distinctions on the semantic level, but on the pragmatic—the only level at which it makes sense to approach the subject.

3.3.1 Expectation, Prediction, Forecast

The practical experience through which humans constitute themselves in expectation of something—rain (when atmospheric conditions are conducive), meeting someone, closing a transaction, etc.—has to be understood as a process of unfolding possibilities, not as an active search within a field of potential events. Expectation involves waiting; it is a rather passive state, too, experienced in connection with something at least probable. Predictions are practical experiences of inferences (weak or strong, arbitrary or motivated, clear-cut or fuzzy, explicit or implicit, etc.) along the physical timeline from past to the future. Checking the barometer and noticing pain in an arthritic knee are very different experiences; so are the outcomes: imperative prediction or tentative, ambiguous foretelling. To predict is to connect what is of the nature of a datum (information received as cues, indices, causal identifiers, and the like) experienced once or more frequently, and the unfolding of a similar experience, assumed to lead to a related result. It should be noted here that the deterministic perspective implies that causality affords us predictive power. Based on the deterministic model, many predictive endeavors of impressive performance are succesfully carried out (in the form of astronomical tables, geomagnetic data, and calculations on which the entire space program relies). Under certain circumstances (such as devising economic policies, participating in financial markets, or mining data for political purposes), predictions can form a pragmatic context that embodies the prediction. In other words, a self-referential loop is put in place.

Not fundamentally different are forecasts, although the etymology points to a different pragmatics, i.e., one that involves randomness. What pragmatically distinguishes these from predictions is the focus on specific future events (weather forecasting is the best known pragmatic example, that is, the self-constitution of the forecaster through an analytic activity of data acquisition, processing, and interpretation, whose output takes very precise forms corresponding to the intended communication process). These events are subject to a dynamics for which the immediate deterministic descriptions no longer suffice. Whether economic, meteorological, geophysical (regarding earthquakes, in particular), such forecasts are subject to an interplay of initial conditions, internal and external dynamics, linearity, and nonlinearity (to name only a few factors) that is still beyond our capacity to grasp, moreover to express in some efficient computational form. Although forecasts involve a predictive dimension, the two differ in scope and in the specific method. A computer program for predicting weather could process historic data (weather patterns over a long period of time). Its purpose is global prediction (for a season, a year, a decade, etc.). A forecasting algorithm, *if at all possible*, would be rather local and specific: Tomorrow at 11:30 am. Dynamic systems theory tells us how much more difficult forecasting is in comparison with prediction.

Our expectations, predictions, and forecasts co-constitute our pragmatics. That is, they participate in making the world of our actions. There is formative power in each of them. Although expecting, predicting, and forecasting good weather will not bring the sun out, they can lead to better chances for a political candidate in an election. Indeed, we need to distinguish between categories of events to which these forms of anticipation apply. Some are beyond our current efforts to shape events and will probably remain so; others belong to the realm of human interaction. Recursion would easily describe the self-referential nature of some particular anticipations: expected outcome = f(expectation). That such cases basically belong to the category of indeterminate problems is more suspected than acknowledged. Mutually reinforcing expectations, predictions, and forecasts are the result of more than one hypothesis and their comparative (not necessarily explicit) evaluation. This model can be relatively efficiently implemented in genetic computations.

3.3.2 Plans, Design, Management

Plans are the expression of well or less well defined goals associated with means necessary and sufficient to achieve them. They are conceived in a practical experience taking place under the expectation of reaching an acceptable, optimal, or high ratio between effort and result. Planning is an active pursuit within which expectations are encoded, predictions are made, and forecasts of all kind (e.g., price of raw materials and energy sources, weather conditions, individual and collective patterns of behavior, etc.) are considered. Design and architecture as pragmatic endeavors with clearly defined goals (i.e., to conceive of everything that qualifies as shelter and supports life and work in a "sheltered" society: housing, workplace, various institutions, leisure, etc.) are particular practical experiences that involve planning, but extend well beyond it, at least in the anticipatory aesthetic dimension. Every design is the expression of a possible future state—a new chip, a communication protocol, clothing, books, transportation means, medicine, political systems or events, erotic stimuli, meals—that affects the current state—of individuals, groups, society, etc.—through constitution of perceived and acknowledged needs, expectations, and desires. The dynamics of change embodied in design anticipations is normally higher than that of all other known human practical experiences.

Policy, management, and prevention (to name a few additional aspects or dimensions of anticipation) involve giving advance thought, looking forward, directing towards something that as a goal influences our actions in reaching it. All these characteristics are part of the dictionary definitions of anticipation. The various words (such as those just referred to) involved in the scientific discourse on anticipation, i.e., its various meanings, pertain to its many aspects; but they are not equivalent.

3.4 Resilience

It is probably useful to interrupt this account of the many ways through which anticipation penetrates the scientific agenda and to invoke a distinction that, in the beginning, defies our acquired understanding of anticipation, at least along the distinctions made above. In a deceptively light presentation, Postrel (1997) suggests a counterdistinction: resilience vs. anticipation. If the subject were only what distinguishes Silicon Valley from the Boston area, both known as regions of technical innovation and fast economic growth, the two elements invoked—predictable weather patterns, and earthquakes, anything but predictable—we would not have to bother. However, her article presents the political theory of a proficient political scholar, Wildawski (1988), focused on meeting the challenge of risk through anticipation, understood as planning that aspires to perfect foresight, or through resilience, a dynamic response based on providing adjustments. The definitions are quite telling: "Anticipation is a mode of control by a central mind; efforts are made to predict and prevent potential dangers before damage is done. . . . Resilience is the capacity to cope with unanticipated dangers after they have become manifest, learning to bounce back." Not surprising is the inference that "anticipation seeks to preserve stability: the less fluctuation, the better. Resilience accommodates variability. . . ."

We seem to have here a reverse view of all that has been presented so far: Anticipation means to see the world as predictable. But it also qualifies anticipation as being quite inappropriate within dynamic systems, that is, exactly where anticipation makes a difference! Rapid changes, especially unexpected turns of events, seem the congenial weakness of anticipation in this model. (Those critical of the evolution theory refer to *punctuated equilibrium*, i.e., fast change for which evolution theory has yet to produce a convincing account.) Hubristic central planning and over-caution can undermine anticipation. This view of anticipation would also imply that it cannot be properly pursued within open systems or within transitory processes—again, where we could most benefit from it. Resilience depends on spontaneity, serendipity, on the unforeseeable. Wildavsky expressed this in rather sweeping statements: ". . . not only markets rely on spontaneity; science and democracy do as well. . . ." Computations of risk are, of course, also part of the subject of anticipation.

3.5 Synchronization

Yet another element of this methodological overview (far from being complete) is synchronization. It can serve here as a terminological cue, or, to recall Rosen (1991), co-temporality or simultaneity would do. In the canonical description of anticipation—the current state of the system is defined by a future state—one aspect of time, sequentiality or precedence (one instant precedes the other) takes over. Yet in the universe of simultaneous events, we encounter anticipation, not only as it refers to space aspects, but as it takes the form of synchronization mechanisms. Whether in genetic mechanisms, in musical perceptions (where temporality is definitory), or in the perception of the world (I have already mentioned above the way in which the visual and the auditory "map" are brought in sync, the so-called binding problem, i.e., integration of sensory information arriving on different channels), to name just a few, the coordination mechanism is the final guarantor of the system's coherent functioning. As a synchronization mechanism, anticipation means to "know" (the quotation marks are used to identify a way of speaking) when relatively unrelated, or even related, events have to be integrated in order to make sense. It is therefore helpful to consider this particular kind of anticipation as the result of the work of a "conductor" (or switch, for those technically inclined) eliciting the various sound streams originating from independent sources, each operating within its own confines, to merge in a synchronized concert. Cognitively, this means to ensure that what is synchronous in the world is ultimately perceived as such, although information arrives asynchronously in the brain.

Synchronization, as opposed to precedence, is not tolerant of error. Precedence is less restrictive: The cold temperatures that might affect the viability (survival) of a deciduous tree, and the cycle of days and night affected by the cycle of seasons allow for a range. This is why leaves fall over a relatively long time, depending upon tree kinds and configurations (lone trees, groves, forests, etc.). So we learn that not only is there a variety of soft-defined forms of anticipation (weather prediction, even after data collection, processing, and interpretation have made spectacular advances, is as soft as soft gets), but also that there are high precision mechanisms that deserve to be accounted for if we expect to understand, and moreover make use of, anticipatory technologies.

3.6 Some Working Hypotheses

3.6.1 Rosen's Model

Rosen distinguishes the difference between the dynamics of the coupled given object system **S** and the model **M**; that is, the difference between real time in **S** and the modeling time of **M** (faster than that of **S**) is indicative of anticipation. True, time in this particular description ceases to be an objective dimension of the world, since we can produce quite a variety of related and unrelated time sequences. He also remarks that the requirement of **M** to be a perfect model is almost never fulfilled. Therefore, the behavior of such a coupled system can only be qualified as quasi-anticipatory (in which **E** represents effectors through which action is triggered by **M** within **S**); cf. Fig. 1.

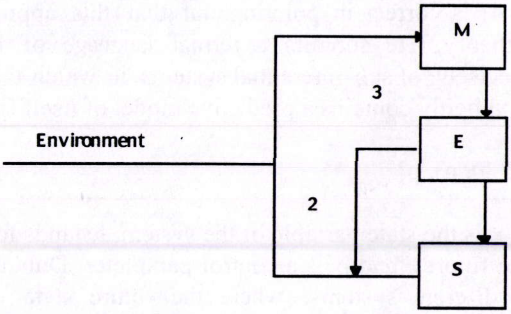

Fig.1: Rosen's model

As aspects of this functioning, Rosen names, rather ambiguously, planning, management, and policies. Essential here are the parametrization of **M** and **S** and the choice of the model. The standard definition, quoted again and again, is that an anticipatory system "contains a predictive model of itself and/or of its environment, which allows it to change state at an instant in accord with the model's predictions pertaining to a later instant" (Rosen 1985, p. 339). The definition is not only contradictory—as Dubois (1997) noticed—but also circular—anticipation as a result of a weaker form of anticipation (prediction) exercised through a model.

Much more interesting are Rosen's examples: "If I am walking in the woods and I see a bear appear on the path ahead of me, I will immediately tend to vacate the premises"; the "wired-in" winterizing behavior of deciduous trees; the biosynthetic pathway with a forward activation. Each sheds light on the distinction between processes that seem vaguely correlated: background information (what could happen if the encounter with the bear took place, based on what has already happened to others); the cycle of day and night and the related pattern of lower temperatures as days get shorter with the onset of autumn; the pathway for the forward activation and the viability of the cell itself. What is not at all clear is how less than obvious weak correlations end up as powerful anticipation links: heading away from the bear ("I change my present course of action, in accordance with my model's prediction," 1985, p. 7) usually eliminates the danger; loss of leaves saves the tree from freezing; forward activation, as an adaptive process, increases the viability of the cell. We have a "temporal spanning," as Rosen calls it. In his example of senescence ("an almost ubiquitous property of organisms," "a generalized maladaptation without any localizable failure in specific subsystems," 1985,

p. 402), it becomes even more clear that the time factor is of essence in the biological realm.

3.6.2 Inclusive Recursion (the Dubois Path)

Dubois (1997, p. 4) is correct in pointing out that this approach is reminiscent of classical control theory. He submits a formal language of inclusive (or implicit) recursion, more precisely, of self-referential systems, in which the value of a variable at a later time (t+1) explicitly contains a predictive model of itself (p. 6):

$$x(t+1) = f[x(t), x(t+1), p), p] \qquad (1a)$$

In this expression, x is the state variable of the system, t stands for time (present, t–1 is the past, t+1 is the future), and p is a control parameter. Dubois starts from recursion within dynamical discrete systems, where the future state of a system depends exclusively on its present and past

$$x(t+1) = f[\ldots x(t-1), x(t), x(t+1), p] \qquad (1b)$$

He further defines incursion, i.e., an inclusive or implicit recursion, as

$$x(t+1) = f[\ldots x(t-2), x(t-1), x(t), x(t+1), \ldots, p] \qquad (2)$$

and exemplifies its simplest case as a self-referential system (cf. 1a and 1b). The embedded nature of such a system (it contains a model of itself) explains some of its characteristics, in particular the fact that it is purpose (i.e., finality, or *telos*) driven.

Having provided a mathematical description, Dubois further reasons from the formalism submitted to the mechanism of anticipation:

The dynamic of the system is represented by

$$\Delta S/\Delta t = [S(t+\Delta t) - S(t)]/\ \Delta t = F[S(t), M(t+\Delta t)] \qquad (3)$$

That of the predictive model is:

$$\Delta M/\Delta t = [M(t+\Delta t) - M(t) = G[M(t)] \qquad (4)$$

In order to avoid the contradiction in Rosen's model, Dubois suggests that

$$\Delta M/\Delta t = [M(t+\Delta t) - M(t)]/\ \Delta t = F[S(t), M(t+\Delta t)] \qquad (5)$$

Obviously, what he ascertains is that there is no difference between the system **S** and the anticipatory model, the result being

$$\Delta S/\Delta t = [S(t+\Delta t) - S(t)]/\ \Delta t = F[S(t), S(t+\Delta t)] \quad (6)$$

which is, according to his definition, an incursive system.

That Rosen and Dubois take very different positions is clear. In Rosen's view, since the "heart of recursion is the conversion of the present to the future" (1991, p. 78), and anticipation is an arrow pointing in the opposite direction, recursions could not capture the nature of anticipatory processes. Dubois, in producing a different type of recursion, in which the future affects the dynamics, partially contradicts Rosen's view.

Incursion (inclusive or implicit recursion) and hyperincursion (an incursion with multiple solutions) describe a particular kind of predictive behavior, according to Dubois. Building upon McCulloch and Pitts (1943) formal neuron and taking von Neumann's suggestion that a hybrid digital-analog neuron configuration could explain brain dynamics, Dubois (1990, 1992) submitted a fractal model of neural systems and furthered a non-linear threshold logic (with Resconi, 1993). The incursive map

$$x(t) = 1 - \mathrm{abs}(1-2x(t+1)) \quad (7)$$

where "abs" means "the absolute value" and in which the iterated x(t) is a function of its iterate at a future time t+1, can subsequently be transformed into a hyper-recursive map:

$$1 - 2x(t+1) = \pm\ (1-x(t)) \quad (8)$$

so that

$$x(t+1) = [1 \pm x(t)-1]/2 \quad (9)$$

It is clear that once an initial condition x(0) is defined, successive iterated values x(t+1), for t=0,1,2,...T, produce two iterations corresponding to the ± sign. In order to avoid the increase of the number of iterated values, i.e., in order to define a single trajectory, a control function u(T–k) is introduced. The resulting hyperincursive process is expressed through

$$x(t+1) = [1 + (1-2u(t+1))(x(t)-1]/2 = x(t)/2 + u(t+1) - x(t) \cdot u(t+1) \quad (10)$$

It turns out that this equation describes the von Neumann hybrid version through the x(t) as a floating point variable and the control function u(t) as a digital variable, accepting 0 and 1 as values, so that the sign + or – result from

$$Sg = 2u(t) - 1, \text{ for } t=1, 2, \ldots T \tag{11}$$

It is tempting to see this hybrid neuron as a building block of a functional entity endowed with anticipatory properties. Let me add here that Dubois has continued his work in the direction of producing formal descriptions for neural net applications, memory research, and brain modeling (1998). His work is convincing, but, again, it takes a different direction from the work pursued by Rosen, if we correctly understand Rosen's warning (1991) concerning the non-fractionability of the (M, R)-system, i.e., its intrinsic relational character. Nevertheless, Dubois' results will be seen by many as another suggestion that the hybrid analog/digital computation better reflects the complexity of the living and thus might support effective information processing for applications in which the living is not reduced to the physical.

3.6.3 Space-Based Computation

Cellular automata, as discrete space-time models, constitute yet another way of modeling anticipation as a space-based computation. More details can be found in the work of Holmberg (1997), who introduces the concept of spatial automata and correctly positions this approach, as well as some basic considerations on the nature of anticipation in technological applications, within systems theory. Not surprisingly, the community of researchers of anticipation is generating further working hypotheses (Julià 1998; Sommer, 1998, addressing intentionality and learnability, respectively). It is very difficult to keep a record of all of these contributions, and even more difficult to comment on works in their incipient phase. Applications of fundamental theoretical anticipatory models are also being submitted in increasing numbers. Dubois himself suggested quite a number of applications, including robotics and neural machines. M y focus is on variable configuration computers (regardless of the nature of computation). Obviously, those and similar attempts (many in the program of the CASYS conferences) are quite different from training in various sports, sports performance (think about anticipation in fencing!), political action, the functioning of the judicial system, the dissemination of writing rules for achieving suspense, the automatic generation of jokes (Barker, 1996), the building of economic models, and so on.

3.6.4 Dynamic Competing Models

Without attempting to submit a full-fledged alternative to either Rosen's or Dubois' anticipation descriptions, I will only mention once more that my own work speaks in favor of a changing set of models and of a procedure for maintaining competition among them.

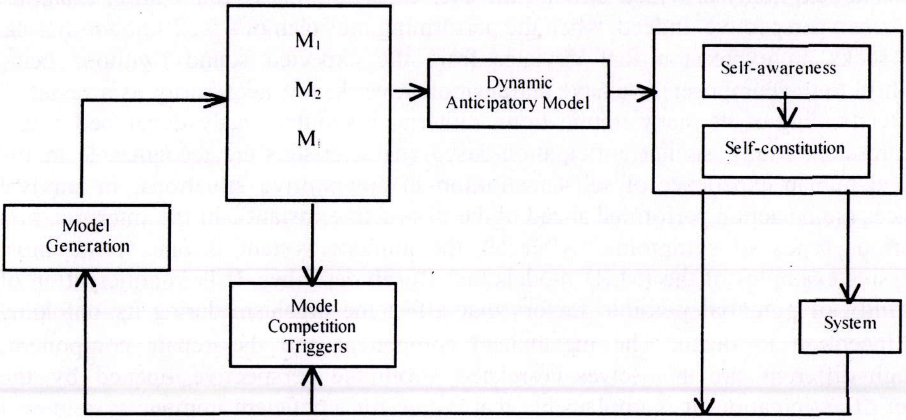

Fig. 2: Changing models and competition among models

Since a diagram is a formalism of sorts, not unlike a mathematical or logical expression, I also reason from it to the dynamics of the system. The diagram ascertains that anticipation implies awareness, and thus processes of interpretation—hence semiotic processes. Mathematical or logical descriptions do not explicitly address awareness, but rather build upon it as a given. Some scientists subsequently commit the error of assuming that because awareness is not explicitly encoded in the formulae, it plays no role whatsoever in the system described. As we shall see in the discussion of the non-local nature of anticipation, quantum experiments suggest that in the absence of the observer, our descriptions of the universe make no sense.

3.6.5 Variability and Computation

To make things even more challenging, there are instances in which anticipation, resulting from the dynamics of natural evolution, is subject to variability, i.e., change. In every game situation, anticipations are at work in a competitive environment. Chess players, not unlike "black-box" traders on the financial or stock markets, as well as professional gamblers, could provide a huge amount of testimony regarding "anticipation as a moving target." In my model of an anticipation mechanism based on a changing number of models and on stimulating competition among them, games can serve as a source of information in the validation process. The mathematics of game theory, not unlike the mathematics of ALife formal descriptions applied to trading mechanisms or to flocking behavior, is in many respects pertinent to questions of anticipation.

What is not explicitly provided through the ever expanding list of application examples is the broad perspective. Indeed, when the performing musician of a well known musical score seeks an expression that deviates from the expected sound (without being unfaithful to the composer), we have anticipation at work: not necessarily as a result of an understanding of its many implications, rather as a spontaneously developed means of expression. Many similar anticipation-based characteristics are recognizable in the practical human experience of self-constitution in competitive situations, in survival instances (some action performed ahead of the destructive instant), in the interpretation of various types of symptoms. After all, the immune system is one of the most impressive examples of the (M,R) models that Rosen describes. It is in anticipation of an infinity of potential possible factors that affect the organism during its unfolding from inception to death. The metabolism component and the repair component, although different, are themselves co-related. From the perspective opened by the subject of anticipation, it is implausible that a cure for a deficient immune system will be found in any place other than its repair function.

In contradistinction, as we shall see, when one searches for information on the World-Wide Web, there is anticipation involved in the mechanism of pre-fetching information that eventually gives the user the feeling of interactivity, even though what technology makes possible is a simulacrum. The question to be asked, but not necessarily answered in this paper, is: To what extent does becoming aware of anticipation, or living in a particular anticipation (of a concert, of a joke, or of an inherited disease), affect our practical experiences of self-constitution, regardless of whether we build a technology inspired by it or only use the technology, or to what extent are such experiences part of the technology? Friedrich Dürrenmatt, the Swiss writer, once remarked (1962, in a play entitled *The Physician Sits*), "A machine only becomes useful when it has grown independent of the knowledge that led to its discovery." This statement will follow us as we get closer to the association between anticipation and computation. It suggests that if we are able to endow machines with anticipatory characteristics (prediction, expectancy, planning, etc.), chances are that our relation to such machines will eventually become more natural. This might change our relation to anticipation altogether, either by further honing natural anticipation capabilities or by effecting their extinction.

The broader picture that results from the examination of what actually defines the field of inquiry identifiable as anticipation—in living systems and in machines—is at best contradictory. To be candid, it is also disconcerting, especially in view of the many so-called anticipation-based claims. But this should not be a discouraging factor. Rather, it should make the need for foundational work even more obvious. One or two books, many disparate articles in various journals, plus the *Proceedings* of the Computing Anticipatory Systems (CASYS) conferences do not yet constitute a sufficient grounding. It is with this understanding in mind that I have undertaken this preliminary overview (which will eventually become my second book on the subject of anticipation).

Since the time my book (1991) was published, and even more after its posting on the World-Wide Web, I have faced colleagues who were rather confused. They wanted to know what, in my opinion, anticipation is; but they were not willing to commit themselves to the subject. It impressed them; but it also made them feel uneasy because the solid foundation of determinism, upon which their reputations were built, and from which they operate, seemed to be put in question. In addition, funding agencies have trouble locating anticipation in their cubbyholes, and even more in providing peer reviews from people willing to jump over their shadow and entertain the idea that their own views, deeply rooted in the paradigm of physics and machines, deserve to be challenged. My research at Stanford University—which constituted the basis for this report—provided a stimulating academic environment, but not many possible research partners. Students in my classes turned out to be far more receptive to the idea of anticipation than my colleagues. The summary given in this section stands as a testimony to progress, but no more than that, unless it is integrated in the articulation of research hypotheses and models for future development.

4 Minds, Knowledge, Computation—a Borgesian Horizon

The anticipatory nature of the mind—and by this I mean the processes of mind constitution as well as mind interaction—together with the understanding of anticipation as a distributed characteristic of the human being, represents an epistemological and cognitive premise. Let us put these ascertainments in the broader perspective of knowledge—the ultimate goal of our inquiry (knowledge at work included, of course). Niels Bohr (1934), well ahead of the illustrious founders of second-order cybernetics or of today's constructivist model of science, risked a rather scandalous sentence: "It is wrong to think that the task of physics is to find out how nature is." He went on to claim that "Physics concerns what we can say about nature." In this vein, we can say that Rosen and others have proven that anticipation is a characteristic of natural processes. We can also take this description and try to make it the blueprint of various applications (some of which were reported above).

4.1 Computation and Prolepsis

Computation is the dominant aspect of the *Weltanschauung* today. It is not only a representation, but also the mechanism for processing representations (for which reason I call the computer a *semiotic engine*). The attempt to reduce everything there is to computation is not new. Science might be rigorous, but it is also inherently opportunistic. That is, those constituting themselves as scientists, (i.e., defining themselves in pragmatic endeavors labeled as science) are human beings living in the reality of a generic conflict between goals and means. Having said this, well aware that

Feyerabend (1975) *et al* articulated this thought even more obliquely, I have to add that anticipation as computation is, from an epistemological perspective, probably more appropriate to our understanding of the concept than what various pre-computation disciplines had to say or to speculate about anticipation.

Between Epicurus' (cf. 1933) term *prolepsis*—rule, or standard of judgment (the second criterion for truth)—and the variety of analytical interpretations leading to the current infatuation with anticipation, there is a succession of epistemological viewpoints. It is not that background knowledge—"the idea of an object previously acquired through sensations" to which Epicurus referred as a necessary condition for understanding—changed its condition from a criterion of truth to a computational entity. After all, computer systems used in speech recognition or in vision involve a proleptic component. (The machine is trained to recognize something identified as such.) Rather, the pragmatic framework changed, and accordingly we constitute ourselves as researchers of the world in which we live by means of computation rather than by means used in Epicurus' physics and corresponding theory of knowledge (the canon, as it is known). What I want to say is that computation and the subsequent attempt to see anticipation as computation are but another description of the world and, particularly in the latter case, of our attempts to form an effective body of knowledge about it. In his discussion of prolepsis, in *Critique of Pure Reason*, Kant (1781) saw it within his description of the world, that is, in the form of "something that can be known *a priori*." In Kant's view, only the "property of possessing a degree" is subject to anticipation. Indeed, in computation we can attach certain weights to various data before the data are actually input. These weights will affect the result and, in many cases, the *art*; that is, the appropriateness of specifying weights influences predictions and forecasts. But no one would infer *à rebours* that Kant saw the world as a computation, or that knowledge was the result of a computational process.

4.2 Evolutionary Computation

The substratum of basic principles on which a theory of anticipation relies (Epicurus, Kant, Rosen, etc.) affects the theory itself, and thus its possible technological implementations. It has not actually been convincingly demonstrated that we can compute anticipation. What has been accomplished, again and again, is the embodiment of anticipatory characteristics, such as prediction, expectation, management, planning, etc., in computer programs. What has also been carried out is the implementation of control mechanisms, and, bringing us closer to our subject, the modeling of selection mechanisms in the now well known genetic computing models inspired by the guiding Darwinian concept. Evolutionary computation might well end up displaying anticipatory characteristics if we take the time and the knowledge needed to apply ourselves to the task. It will not be a spontaneous birth, rather a designed and carefully executed computation. Entailment might prove the critical element, as Rosen's work seems to indicate.

4.2.1 Co-Relation vs. Computation

Once a modeling relation is established between a natural system and a formal one, we can start inferring from the formal system to the natural. Let me mention that here we are in the territory of views that often contradict each other. (For instance, Daniel Dubois and myself are still in dialog over some of the examples to follow.) Neural networks or models of ALife, such as the simulation of collections of concurrently interacting agents, qualify as candidates for such an exercise. However, almost no effort has been made to elucidate the functioning of the causal arrow from the future to the present. In winter, temperatures will fall below the freezing point; leaves fall from deciduous trees in anticipation, but the trigger comes from a different process, i.e., the diminishing length of daylight, which stands in no direct causal relation to the phenomenon mentioned yet again. This is a co-relation of processes, not a computation, or at least not a Turing machine-based computation.

The migration of birds is another example; yet others are the immune system, the sleep mechanism, the blinking mechanism, and the behavior of *Pfiesteria* (the single-cell microorganisms that produce deadly toxins in anticipation of the fish they will eventually kill). But if we want to stick to computation, which is a description different from the one pursued until now, we land in a domain of parallel processes, not very sophisticated, probably even less sophisticated than the level of a UNIX operating system, but of a much higher order of magnitude. We are in what was described as a *big numbers-based reality.* If we could control the process "shorter days," we could eventually graph the inter-relation among the various components at work leading to the shedding of leaves during autumn, or to the sophisticated patterns of behavior of birds preparing for migration.

4.3 Large Numbers and Simple Processes

In respect to brain activity, things are definitely more complicated, but they also fall in the realm of incredibly large numbers applying to rather simple entities and processes. The ongoing CAM-Brain Project (Hugo de Garis, 1994) is supposed to result in an artificial brain of one billion neurons (compare this to the 100 to 120 billion neurons of a *wet* brain implemented) on Field Programmable Gate Arrays. These digital circuits can be reconfigured as the tasks at hand might require. The notion of reconfiguration elicits our understanding of anticipation. Still, it remains to be seen whether the artificial brain will actually drive a robot or only simulate the robot's functioning, as it also remains to be seen whether evolutionary patterns will support vision, hearing, their binding, coordinated movements, and, farther down the line, decision-making. The mind in anticipation of events (as I defined mind) is a lead. If we could parametrize the cognitive process and control the various channels, we could in principle learn more about how neuroactivity precedes moving one's hand by 800 milliseconds, and what the consequences of this forecast for human anticipation abilities are. These are all possible experiments, after each of which we will end up not only with more data (the blessing and curse of our age!), but also necessarily with the desire to gain a better understanding of what these data mean.

If Rosen's hypothesis that anticipation is what distinguishes the biological realm (*life*) from the physical world, it remains to be seen whether we can do more than to compute only particular aspects of it—prediction, expectation, planning, etc.—outside the living. Pseudo-anticipation is already part of our practical experience: satellite launches, virtual surgery, pre-fetching data in order to optimize networks are but three examples of effective pseudo-anticipation. If we could create life, we could study how anticipation emerges as one of its irreducible, or only as one of its specific, properties. Short of this, ALife is involved in the simulation of lifelike processes. Rosen, in defining complexity as not simulatable, comes close to Feynman's (1982) hope that one can best study physics by actually conducting the calculations of the world of physics on the physical entities to be studied. One can call this epistemological horizon Borgesian, knowing that an ideal Borgesian map was none other than the territory mapped.

At this point, we need to arrive at a deeper understanding of what we want to do. Regardless of the metaphor, the epistemological foundation does not change. The knowing subject is already shaped by the implicit anticipatory dimension of mind interaction; in other words, the answer to the question meant to increase our knowledge is anticipated. Computation is as adequate a metaphor as we can have today, provided that we do not expect the metaphor to automatically generate the answers to our many questions. Regardless, the question concerning anticipation in the living and in the non-living is far from being settled, even after we might agree on a computational model or expand to something else, such as co-relation, which could either transcend computation or expand it beyond Turing's universal machine.

5 Revisiting Non-Locality

I took it upon myself to approach these matters well aware that I am advancing in mined territory. Comparisons notwithstanding, such was the situation faced by the proponents of quantum theory. To nobody's surprise, Einstein took quantum mechanics, as developed by Heisenberg, Schrödinger, Dirac, *et al,* under scrutiny, and, well before the theory was even really established, raised objections to it, as well as to Bohr's interpretation. From these objections (the complete list is known as the EPR Paper, 1935, for Einstein, Podolski, and Rosen), one in particular seems connected to the subject of anticipation. Einstein had a major problem with the property of non-locality—the correlations among separated parts of a quantum system across space and time. He defined such correlations as "spooky actions at distance" ("spukhafte Fernwirkungen"), remarking that they have to take place at speeds faster than that of light in order to make various parts of the quantum system match. In simple terms, this spooky action at distance refers to the links that can develop between two or more photons, electrons, or atoms, even if they are remotely placed in the world. One example often mentioned is the decay of a pion (a subatomic particle). The resulting electron and positron move in opposite directions. Regardless how far apart they are, they remain connected. We notice the connection only when we measure some of their properties (well aware of the influence measurement has), their spin, for example. Since the initial pion had no spin, the electron and the positron will have opposite sense spins, so that the net spin is conserved at zero. So, at distance, if the spin of the electron is clockwise, the spin of the positron is counter-clockwise.

It would be out of place to enter here into the details of the discussion and the ensuing developments. Let me mention only that in support of the EPR document, Bohm (1951) tried, through his notion of a local hidden variable, to find a way for the correlations to be established at a speed lower than that of light. He wanted to save causality within quantum predications. Bohm's attempt recalls what the community of researchers is trying to accomplish in approaching aspects of anticipation (such as prediction, expectation, forecast, etc.) with the idea that they cover the entire subject. Bell (1964, 1966) produced a theorem demonstrating that certain experimental tests could distinguish the predictions of quantum mechanics from those of any local hidden variable theory. (Incidentally, physicist Henry P. Stapp, 1991 characterized Bell's theorem as "the greatest discovery of all science.") Again, this recalls by analogy Rosen's position, according to which anticipation is what (among other things) distinguishes the living from the rest of the world. It states that we can clearly discern a particular aspect of anticipation provided in some formal description or in some computer implementation from one that is natural. I mention these two episodes from a history still unfolding in order to explain that what we *say* in respect to nature—as Bohr defined the goal of physics—will be ultimately subjected to the test of our practical experiences. Einstein has been proven wrong in respect to his understanding of non-locality through many experiments that baffle our common sense, but his theory of relativity still stands. Spooky actions at distance are a very intuitive description of how someone educated in the spirit of physical determinism and thinking within this spirit understands how the future impacts the present, or how anticipation computes backwards from the future to the present. He, like many others, preached the need for learning "to see the world anew," but was unable to position himself in a different consciousness than the one embodied in his theory.

As I worked on this text (more precisely, after reworking a draft dated July 22, 1999), Daniel Dubois graciously drew my attention to a number of his research accomplishments pertinent to the connection between anticipation and non-locality. Indeed, over the last seven years, he has applied his mathematical formalism to quite a number of computational aspects of anticipation. Consequently, he was able to establish, by means of incursion and hyperincursion, that the computation pertinent to the membrane neural potential (used as a model of a brain) "gives rise to non-locality effects" (Dubois, 1999). His argument is in line with von Neumann's analogy between the computer and the brain.

But we are not yet beyond a first analogy (or reference). Non-locality is, in the last analysis, distance independent. Furthermore, non-locality is not a limited characteristic of the universe, but a global rule. In the words of Gribbin (1998), non-locality "cuts into the idea of the separateness of things." If the "no-signaling" criterion (energy or information travel no faster than the speed of light) protects the "chain of cause and effect," (effects can never happen before their causes), non-locality ensures the coherence of the universe. Reconciliation between non-locality and causality might therefore be suggestive for our understanding of anticipation. In such a case, the co-relation among elements involved in anticipation can be seen as a computation, but one different in nature from a digital computer, i.e., in a Turing machine. It follows from here that anticipation understood as *co-relation*—a notion we will soon focus on—must be a computation different in type than that embodied in a Turing machine.

5.1 Quantum Semiotics, Link Theory, Co-Relation

Let me preface this section ascertaining that anticipation is a particular form of non-locality, which is quite different from saying that there is non-locality in anticipation. (This is what actually distinguishes my thesis from the results of Dubois.) More precisely, its object is co-relations (over space and time) resulting from entanglements characteristic of the living, and eventually extending beyond the living, as in the quantum universe. These co-relations correspond to the integrated character of the world, moreover, of the universe. Our descriptions ascertain this character and are ultimately an active constituent of this universe. We introduce in this statement a semiotic notion of special significance to the quantum realm: Sign systems not only represent, but also constitute our universe. As with qubits (information units in the quantum universe), we can refer to qusigns as particular semiotic entities through which our descriptions and interpretations of quantum phenomena are made possible.

5.1.1 The Semiotic Engine

As a semiotic engine (Nadin, 1998), a digital computer processes a variety of possible descriptions of ourselves and of the universe of our existence. These descriptions can be indexical (marks left by the entity described), iconic (based on resemblance), or symbolic (established through convention). Anticipatory computation is based on the notion that every sign is in anticipation of its interpretation. Signs are not constituted at the object level, but in an open-ended infinite sign process (semiosis). In sign processes, the arrow of time can run in both directions: from the past through the present to the future, or the other way around, from the future to the present. Signs carry the future (intentions, desires, needs, ideals, etc., all of a nature different from what is given, i.e., all in the range of a final cause) into the present and thus allow us to derive a coherent image of the universe. Actually, not unlike the solution given in the Schrödinger equation, a semiosis is constituted in both directions: from the past into the future, and from the future into the present, and forward into the past. The interpretant (i.e., infinite process of sign interpretation) is probably what the standard Copenhagen Interpretation of quantum mechanics considered in defining the so-called "intelligent observer." The two directions of semiosis are in co-relation. In the first case, we constitute understandings based on previous semiotic processes. In the second, we actually make up the world as we constitute ourselves as part of it. This means that the notion of sign has to reflect the two arrows. In other words, the Peircean sign definition (i.e., arrow from object to representamen to interpretant) has to be "reworded":

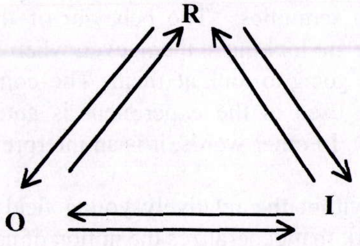

Fig. 3 Qusign definition

The language of the diagram allows for such a "rewording" much better than so-called natural language: The interpretant as a sign refers to something else anticipated in and through the sign. (Peirce's original definition of sign is, "something which stands to somebody in some respect or capacity," 2.228.) Qusigns are thus the unity between the analytical and the synthetic dimension of the sign; their "spin" (to borrow from the description of qubits) can well describe the particular pragmatics through which their meaning is constituted.

5.1.2 Knowing in Advance

The 1930 Copenhagen Interpretation of quantum mechanics (developed primarily by Bohr and Heisenberg) should make us aware of the fact that observation (as in the examples advanced by Rosen, *et al*), measurement (as in the evaluation of learning performance of neural networks), and descriptions (such as those telling us how a certain software with anticipatory features works) are more pertinent to our understanding of what we observe, measure, or describe than to understanding the phenomena from which they derive. To measure is to describe the dynamics of what we measure. The coherence we gain is that of our own knowledge, where dynamics resides as a description. Albeit, the anticipation chain takes the path of something that smacks of backward causality, which the established scientific community excluded for a long time and still has difficulty in understanding. Quantum particle "tunneling"—a phenomenon related to quantum uncertainty and to wave-particle duality—might explain our own existence on the planet, but we still don't know what it means (as Feynman repeatedly stated it, verbally and in writing, 1965). Quite a number of experiments (cf. Raymond Chiao, University of California-Berkeley; Paul Kwiat, University of Innsbruck; Aephraim Steinberg, US National Institute of Standards and Technology, Maryland, among others) ended up confirming that "the way in which a photon starting out on its journey behaves" in different experimental set-ups suggests that anticipation is at work in the quantum realm. They behave (cf. Gribbin, 1999) as if they "knew in advance what kind of experiment they were about to go through." In view of these experiments, Rosen would have a hard time trying to argue that anticipation is a property exclusive of the living. Moreover, we find in such examples the justification for quantum semiotics: "The behavior of the photons at the beam-splitter is changed by how we are looking at them, even when we have not yet made up our minds about how we are going to look at them. The computer-controlled pseudo-random layout of the device used in the experiment is anticipated by the photon," (Gribbin and Chimsky, 1996). In other words, it is an interpretant process.

I should mention here that within the relatively young field of mathematical research called *link theory,* a framework that generalizes the notion of causality is established in a way that removes its unidirectionality (cf. Etter, 1999). The relational aspect of this theory makes it a very good candidate for a closer look at anticipation, in particular, at what I call co-relations.

5.1.3 Coupling Strength

In various fields of human inquiry, the clear-cut distinction between past, present, and future is simply breaking down. No matter how deep and broad grudges against a reductionist physical model (such as Newton's) are, Newtonian dynamics is reversible in time, and so is quantum mechanics. The goal of producing a "unified" description of the universe can be justified in more than one way, but regardless of the perspective, coupling strength is what interests us, that is, what "holds" the "universe" together. This applies to the coherence of the human mind, as it applies to monocellular organisms or to the cosmos at large. It might be that anticipation, in a manner yet unknown to us, plays a role in the coupling of the many parts of the universe and of everything else that appears as coherent to us. Galileian and Newtonian mechanics advanced answers, which were subsequently reformulated and expressed in a more comprehensive way in the theory of relativity (special and general), and afterwards in quantum theories (quantum mechanics, quantum field theory, quantum gravity). In the mechanical universe, to anticipate could mean to pre-compute the trajectory of the moving entity seen as constitutive of broad physical reality. But the causal chain is so tight that the fundamental equation allows only for the existence of recursions (from the present to the future), which we can represent by stacks and compute relatively easily. The past is closed; the future, however, is open, since we can define *ad infinitum* the coordinates of the changing position of a moving entity. No guesswork: Everything is determined, at least up to a certain level of complexity. Relativity does not do away with the openness of the future, but makes it more difficult to grasp. Within black holes, *inherent in the relativistic description but not reducible to them*, time is cyclic. In Einstein's curved space-time, a circular "time-line" (Etter's pun) is no more surprising than a "circle around a cylinder in ordinary space." This, however, leads to a cognitive problem: how to accommodate a cycle with openness. Anticipation related to this description of time is quite different from that which might be associated with a physical-mechanical description.

5.2 Possible and Probable

Quantum theories, as we have suggested, pose even more difficult questions in regard to non-locality, and thus to entanglement. In this new cognitive territory, things get even more difficult to comprehend. Determinism, which means that something is (1) or is not (0) caused by something else, gives way to a probabilistic and/or possibilistic distribution: Something is caused probably (i.e., to a certain degree expressed in terms of probability, that is, statistic distribution) by something else. Or it is caused possibly (in Zadeh's sense, 1977), which is a determination different from probability (although not totally unrelated), by something else. Probabilistic influences can be represented through a transition matrix. Given the relation between two entities A and B and their respective states, we can define a Markov chain, i.e., a transition matrix whose ij^{th} entry is the probability of i given j. Such a chain tells us how influences are strung together (chained) and can serve as a predictive mechanism, thus covering some subset of what we call anticipation.

Recently, weather satellite observations of the density of green vegetation in Africa (an indication of rainfall) were connected through such processes to the danger of an outbreak of Rift Valley Fever, in which Linthicum (1999) devised a metrics based on climate indicators for a forecasting procedure. The "black boxes" chained in such processes have a single input and a single output representing the complete state variable of the system as it changes over time. Climate and health (the risk of malaria, Hanta virus, cholera) are related in more than one way (Epstein, 1999). These examples are less probabilistic than possibilistic. If we pursue possibilities, that is, infer from a *determined* set of what is possible, a different form of prediction can eventually be achieved. Abductive inferences belong to this category and are characteristic of functional diagnosis procedures. Here we have an example of semiotics at work, i.e., abductions on symptoms, not really far from what Epicurus meant by prolepsis.

5.2.1 Linked Incursions

For the aspects of anticipation that belong to a non-deterministic realm, we can further try to link descriptions of the form

$y = f(x)$ or $z = g(w)$ (12a, b)

Indeed, if we substitute y for w, our descriptions become

$y = f(x)$ and $z = g(y)$, that is, $z = g(f(x))$ (13a, b, c)

The result is a functional relation of the composed functions. Without going into the details of Etter's theory, let me suggest that it can serve as an efficient method for encoding a variety of relations (not only in the case of the identity of two variables). If in the functional description we substitute not the variables (w with y, as shown in the example given above) but the relation between them, we reach a different level of relational encoding that can better support modeling. I even suggest that recursions, incursions, and hyperincursions can be defined for co-related events. For example:

$x(t_i+1) = f[x(t_i), x(t_i+1), p]$ (14)

and

$y(t_j+1) = g[y(t_j), y(t_j+1), r]$ (15)

in which time in the two systems is obviously not the same ($t_i \neq t_j$). A co-relation of time can be established, as can a co-relation among the states $x(t_i)$ and $y(t_j)$ or the two systems, through the intermediary of a third system acting as the "conductor," or coordinator, $z(t_i, t_j, t_k)$, i.e., dependent upon both the time in each system and its own time metrics. To elaborate on the mathematics of linked incursions goes beyond the intentions of this paper. Let us not forget that we are pursuing an analysis of the particular ways in which anticipation takes place in the successive unified descriptions of the universe produced so far.

5.2.2 Alternative Computations

In the quantum perspective of a double identity—particle and wave—trajectory is the superposition of every possible location that a moving entity could conceivably occupy. This is where recursivity, in the classic sense, breaks down. I suspect that Dubois was motivated to look beyond recursivity for improved mathematical tools, to what he calls incursion and hyperincursion, for this particular reason. But I also suspect that linked incursions and hyperincursions will eventually afford more results in dealing with various aspects of anticipation and non-locality.

In respect to the explicit statement, prompted by quantum mechanics non-locality, that anticipation could be a form of computation different from that described by a Turing machine, it is only in the nature of the argument to say that a full-fledged anticipation, not just some anticipatory characteristics (prediction, planning, forecasting, etc.) is probably inherent in quantum computation. Rosen recognized early on (1972) that quantum descriptions were a promising path, although among his publications (even more manuscripts belong to his legacy, cf. 1999) there are no further leads in this direction. Efforts to transcend digital computing through quantum computation are significant in many ways. From the perspective of anticipation, I think Feynman's concept comes closer to what we are after: understanding the quantum dynamics not by using a digital computer (as in the tradition of reductionist thinking), but by making use of the elements involved in quantum interactions. As the situation is loosely described: Nature does this calculation all the time! The same thing can be said about protein folding, a typical anticipatory process—a small increase in energy (warming up) drives the folding process back, only in order to have it repeated as the energy decreases. This process might also well qualify as an anticipatory computation, with a particular scope, not reducible to digital computation. (As a matter of fact, protein folding exceeds the complexity of digital computation.) It is an efficient procedure, this much we know; but about how it takes place we know as little as about anticipation itself.

5.2.3 Anticipation as Co-Relation (Or: Co-relation as Anticipation?)

Having advanced the notion of anticipation as a co-relation, I would like to point to instances of co-relation that are characteristic of experiences of practical human self-constitution in fields other than the much researched control theory of mechanisms, economic modeling, medicine, networking, and genetic computing. There is, as Peat (undated) once remarked, a strong concern with "a non-local representation of space" in art and literature. The integration of many viewpoints (perspectives) of the same event illustrates the thought. Reconstruction (in the perception of art and literature) means the realization of a future state (describable as understanding or as coordination of the aesthetic intent with the aesthetic interpretation) in the current state of the dynamic system represented by the work of art or of writing, and by its many interpreters (open-ended process). In Descartes' and Newton's traditions, space and time are local: a taming of artistic expression took place. Peat claims that the "tableau," i.e., the painting, becomes a snapshot in which "motion and change is frozen in a single instant of time. This is a form of objectivity which the concert, the novel, and the diarist express." With the advent of relativity and quantum physics, many perspectives are overlaid. As Peat puts it, "In our century, painting has returned to the non-local order." This holds true for writing (think about Joyce), as well as it does for the dynamic arts (performance, film, video, multimedia). Complementary elements, entangled throughout the unifying body of the work or of its re-presentation, are brought into coherence by co-relations within non-locality-based interactions. Peat goes on to show that communication "cries our for a non-local" description: source and receiver cannot be treated as separable entities. (They are linked, as he poetically describes the process, "by a weak beam of coherent light.") Meaning—which "cannot be associated exclusively with either participant" (n.b., in communication)—could be "said to be 'non-local'."

6 The Relational Path to Co-Relations

That computation, in one of its very many current forms or in a combination of such forms (such as hybrid algorithmic-nonalgorithmic computations), can embody and serve as a test for hypotheses about anticipation should not surprise. Neither should the use of computation imply the understanding that anticipation is ultimately a computation, that it is the *only* form, or the appropriate form, through which we can implement anticipation-based notions. It is an exciting but dangerous path: If everything is described as a computation—no matter how different computation forms can be—then nothing is a computation, because we lose any distinguishing reference. Epistemologically, this is a dead end. Furthermore, it has not yet been established whether information processing is a prerequisite of anticipation or only one means among many for describing it. While we could, in principle, embody anticipatory features in computer programs, we might miss a broad variety of anticipation characteristics. For instance, progress was made in describing the behavior of flocks (cf. The Swarm Simluation System at the Santa Fe Institute). But bird migration goes far beyond the modeled behavioral interrelationships. Trigger information differentials, group interaction, learning, orientation, etc. are far more sophisticated than what has been modeled so far. The immune system is yet another example of a complexity level that by far exceeds everything we can imagine within the computational model. Be all this as it may, our current challenge is to express co-relations, which appear as predefined or emerging relations in a dynamic system, by means of information processing in some computational form, or by means of describing natural entanglements. If we could reach these goals, we would effect a change in quality—from a functional to a relational model. Here are some suggestions for this approach.

6.1 Function and Relation

Relations between two or among several entities can be quite complicated. A solid relational foundation requires the understanding of what distinguishes relation from function. For all practical purposes, functions (also called mappings) can be linear or non-linear. (Of course, further distinctions are also important: They can be many or single-valued, real or complex-valued, etc.) Relations, however, cover a broader spectrum. A relation of dependence (or independence) can be immediate or intermediated. It can involve hierarchical aspects (as to what affects the relation more within a polyvalent connection), as well as order or randomness. Relations, not unlike functions, can be one-to-one, one-to-many, many-to-one, many-to-many. We can define a negation of a relation, a double negation, inverse relation, etc. A full logic of relations has not been developed, as far as I know. Rudimentary aspects are, however, part of what after Peirce (1870, 1883) and Schröder (*The Circle of Operation of Logical Calculus*, 1877) became known as a *logic of relations*. Russell and Whitehead (*Principia Mathematica*, 1910) made further clarifications.

Let us assume a simple case: xRy, in which x stands in relation to y (son of, higher than, warmer than, premise of, etc.). If we consider various aspects of the world and describe them as relationally connected, we can wind up with statements such as xR_1y, zR_2w, etc. In this form, it is not clear that R_i exhausts all the relations between the related entities; neither is it clear to what extent we can establish further relations between two relations R_i and R_j and thus eventually infer from their interrelationship new relations among entities that did not have an apparent relation in the first place. In a wide sense, a relation is an n-ary (n=1, 2, 3....) "connection"; a binary relation is a particular case and means that the relation xRy is true or false for a pair x,y in the Cartesian product XxY. As opposed to functions, for which we have relatively good mathematical descriptions, relations are more difficult to encode, but richer in their encodings. Their classification (e.g., inverse relation, reflexive, symmetric, transitive, equivalent, etc.) is important insofar it leads to higher orders (e.g., a reflexive and transitive relation is called a pre-ordering, while an ordering is a reflexive, transitive, and antisymmetric relation).

6.1.1 N-ary Relations

If we revisit some of the examples of anticipation produced so far in the literature—Rosen's deciduous trees, Peat's communication as a non-local unifying process, Linthicum's and Epstein's metrics of weather data and disease patterns, the cognitive implications of the many competing models from which one is eventually instantiated in an action, or the hyperincursion mechanism developed by Dubois (to name but a few)—it becomes obvious that we have chains of n-ary relations: $xR_i^n y$ (in which R_i^n is a specific R_i n-ary relation); that is, in a given situation, several relations are possible, and from all those possible, some are more probable than others.

To anticipate means to establish which co-relations, i.e., which relations among relations are possible, and from those, which are most probable. Anticipation is a process. It takes place within a system and we interpret it as being part of the dynamics of the system. Observed from outside the system—deciduous trees lose their leaves, birds migrate, tennis players anticipate the served ball—anticipation appears as goal-driven (teleologic). In particular, coherence is preserved through anticipation; or a different coherence among the variables of a situation is introduced (such as playing chess, or predicting market behavior). Pragmatically, this results in choices driven by possibilities, which appear as embodied in future states. The tennis ball is served and has to be returned in a well defined area—and this is an important constraint, an almost necessary condition for the game ever to take place! At a speed of over 100 miles per hour, the served ball is not returned through a reaction-based hit, but as a result of an anticipated course of action, one from among many continuously generated well ahead of the serve or as it progresses. If the serving area is increased by only 10%, chances for anticipation are reduced in a proportion that changes the game from one of resemblance and order to a chaotic, incoherent action that makes no competitive sense. The competition among the various models (all possibilities, but along a probability distribution corresponding to the particular style of the serving player) allows for a successful return, itself subject to various models and competition among them. The whole game can be seen as an unfolding chain of co-relations, i.e., a computation controlled by a range of acceptable parameters. The immune system works in a fundamentally similar fashion. Co-relations corresponding to a wide variety of acceptable parameters are pursued on a continuous basis. Acclimatization, i.e., the way humans adapt to changes in seasons, is but a preservation of the coherence of our individual and collective existence under the influence of anticipated changes in temperature, humidity, day-night cycle, and a number of other parameters, some of which we are not even aware.

6.1.2 Instantiated Co-Relations

But having given the example of an unfolding sequence does not place us in the domain of non-locality. For this we need to distinguish between the diachronic and synchronic axes. A strictly deterministic explanation will always place the anticipated in the sequence of cause-and-effect/action-reaction. The tennis ball is served, days are getting shorter, a virus causes an infection—all seen as causes. In the anticipatory view, the ball is actually not yet served as the sequence of models, from among which one will become the return, started being generated. The anticipation leading to the fall of leaves is the result of a co-relation involving more than one parameter. What appears as a reaction of the immune system is actually also a co-relation involving the metabolism and self-repair function. On the one hand, we have an unfolding over time; on the other, a synchronic relation that appears as an infinitely fast process. In reality we have a co-relation, an intertwining of many relations among a huge number of variables of which we are only marginally, if at all, aware.

Assuming that we have a good description of the n-ary relations R_1^n, R_2^n.... R_i^n, moreover that we can even "relate" relations of a different order (n=3 vs. n=4, for instance), and express this relation in a co-relation, it becomes clear that co-relations are descriptive of higher order relations. For example, two binary relations are identical when their converses are identical. In any sequences of the form xR_iy, zR_jw, uR_kv, etc. we are trying to identify what the relation is among the various relations R_i, R_j, R_k, etc., represented by $R_i R_\alpha R_j$, $R_j R_\beta R_k$, etc. The co-relations, R_α, R_β, R_γ (e.g., son of and daughter of correspond to progeny, but among the co-relations, we will find similarity or distinction, among other things) can apply to the subsets of all R_i (i=1,... n) sharing a certain distinctive characteristic (such as similarity). We can further define referents (Ref) and relata (Rel), as well as a relation between referents or relata denoted as Sg (*Sagitta*, i.e., arrow). By no accident, the arrow can graphically suggest a dynamics from the present to the future (prediction), or the other way around, from the future to the present (anticipation). After Peirce, Tarski (1941) produced an axiomatized theory of relation that, not unlike Boolean logic, could serve as a basis for effective computations of relations and co-relations. It is quite possible that the computation of co-relation could be built around the formalism of quantum computing. In this case, we would operate on the value of the entanglement, not on the state of a particle. It is a task that invites further work. Last but not least, we invite the thought of considering relations among incursions and hyperincursions as a means of testing their descriptive power even more deeply.

6.2 Making Use of the Co-Relation Model

Having advanced this model of anticipation as a form of computation, based on the dynamic generalization of models and on competition among them, and encoded in a formalism that captures co-relations (thus the spirit of non-locality), I would like to present some examples speaking in favor of an understanding of anticipation that occasionally comes close to what I have proposed above. These are not direct applications of the theory I have advanced so far, rather they are suggestive of its possible directions, if not of its meaning.

6.2.1 Anticipatory Document Caching

Incidentally, anticipatory document caching with the purpose of reducing latency on Web transactions is introduced in a language reminiscent of Einstein's observation. "Everyone talks about the speed of light but nobody ever does anything about it." The reason for the provocative introduction is obvious: interactive HTML (i.e., text transmission through the Web) requires at least T-1 connection speeds (i.e., 1.5M bps). Once images are used, the requirement increases to T-3 lines (45M bps). Cross-country interactive screen images push the limit to 155M bps. Places such as the major cities on the West Coast of the USA (San Francisco, Los Angeles) are at least 85 milliseconds away from cities on the East Coast (Boston, New York). Interactivity under the limitations of the speed of light—assuming that we can send data at such speed and on the shortest path—is an illusion. In view of this practical observation, those involved in the design of networks, of communication protocols, of client-server access and the like are faced with the task of reducing the time between access request and delivery. Among the methods used are the utilization of inter-request bandwidth (transfer of unrequested files when no other use is made), proactive requests (preloading a client or intermediate cache with anticipated requests), optimization of topology (checking where files will be best used, combining identical requests and responses over shared links).

What Touch *et al* (1992, 1996, 1998) accomplished is an effective procedure for *providing co-relations*. Evidently, they realize that such correlations cannot rely on a second channel through which requests would travel faster than the information itself. Accordingly, they initiate processes in fact independent of the communication between the client and the remote server. Such processes facilitate an anticipatory behavior based on predictive cues corresponding to the searched information. They also define where in a network of such optimization servers should be placed. I insist upon this mechanism of implementation not only because of its significance for the networked community, but primarily in view of the understanding that anticipatory computation is one of producing meaningful co-relations. The entanglement between the search process and pre-fetching data is *stricto sensu* a pseudo-anticipation. But so are all other implementations known to date. These are all models of possible actions, and it is quite practical to think of generating even more models as the user gets involved in a certain transaction.

6.2.2 Software Design

The same idea was implemented by high-end 3D modeling software (e.g., UNIGRAPHICS), under the guidance of a better understanding of what designers can and would do at a certain juncture in visualizing their projects. The use of computation resources within such programs makes for the necessity to anticipate what is possible and to almost preclude functions and utilities that make no sense at a certain point. This is realized through a STRIM function. Instead of allowing the program to react to any and all possible courses of action, some functions are disabled. Henceforth, the functions essential to the task can take advantage of all available resources. (This is what STRIM makes possible.) It is by all practical means a pro-active concept based on realizing the co-relations within the various components of the program.

6.2.3 Agents Coordination

Another aspect of co-relation is coordination. It can be ascertained that cooperative activities can take place only if a minimum of anticipation—in one or several of the forms discussed so far—is provided. This applies to every form of cooperation we can think of: commerce, work on an assembly line (where anticipation is built in through planning and control mechanisms), the pragmatics of erecting a building, the performing arts, sports.

Coordination is a particular embodiment of anticipation. It can be expressed, for instance, in requirements of synchronization defined to ensure that from a set of possibilities the optimum is actually pursued. Thus, in a given situation, from a broad choice of what is possible, what is optimal is accomplished. The goal is to maximize the probability of successful cooperation. This is achieved by implementing anticipatory characteristics. I would like to mention here as an example the Robo Cup world champion, designed and implemented by Manuela Veleso, Peter Stone, and Michael Bowling (of Carnegie Mellon University). This is an autonomous agent collaboration with the purpose of achieving precise goals (in this case, winning a soccer game between robotic teams) in a competitive environment. Stated succinctly in the words of the authors, "Anticipation was one of the major differences between our team and the other teams," (1998). Let us focus on this aspect and briefly describe the solution. What was accomplished in this implementation is a model of an unfolding soccer game. But instead of the limited action-reaction description, the authors endowed the "players" (i.e., agents) with the ability to maximize their contributions through anticipatory movements corresponding to increasing the team's chance to execute successful passes leading to scoring. It is a relational approach: Agents are placed in co-relation ("taking into account the position of the other robots—both teammates and adversaries") and in respect to the current and possible future positions of the ball. It is evidently a multi-objective description, that is, a dynamic set of models, with what the authors call "repulsion and attraction points." The anticipation algorithm (SPAR, Strategic Positioning with Attraction and Repulsion) contains weighted single-objective decisions. Correctly assuming that transitions among states (i.e., choices among the various models) for each of the cooperating agents takes time (computing cost, in a broader sense), the authors implement the anticipatory feature in the form of selection procedures. The goal is to increase (ideally, to find the maximum) the probability of future collaboration as the game unfolds. The agents are given a degree of flexibility that results in adjustment supposed to enhance the probability of individual actions useful to the team. Additionally, an algorithm was designed in order to allow the "players" (team agents) to position themselves in anticipation of possible collaboration needs among teammates. Individual action and team collaboration are coordinated in anticipation (i.e., predictive form) of the actions of the opponents. At times, though, the anticipatory focus degrades to reactive moves.

Less successful in the competition, but inspired by Rosen's definition, the team of the University of Caen (France) defined the following program: "Anticipation allows the consideration of global phenomena that cannot be treated through a local reactive approach. The anticipation of the actions of the adversary or of its teammates, the anticipation of the change of the other teamplayers' roles, the anticipation of the ball's movements, and the anticipation of conflicts among teammates are some of the forms of anticipation that our system tries to account for," (Stinckwich, Girault, 1999).

6.2.4 Auto-Associative Memories

Along the same line of thought, it is worth mentioning that in the area of cognitive sciences, neural architectures involving auto-associative memories are used in attempts to implement anticipatory characteristics. Such memories reproduce input patterns as output. In other words, they mimic the fact that we remember what we memorize, which in essence we can describe through recursive or, better yet, incursive functions. The association of patterns of memorized information with themselves is powerful because, in remembering, we provide ourselves part of what we are looking for; that is, we anticipate. The context is supportive of anticipation because it supports the human experience of constituting co-relations. We can apply this to computer memory. Instead of memory-gobbling procedures, which hike the cost of computation and affect its effectiveness, auto-associative memory suggests that we can better handle fewer units, even if these are of a bigger size. Jeff Hawkins (1999), who sees "intelligence as an ability ... to make successful predictions about its input," i.e., as an internal measure of sensory prediction, not as a measure of behavior (still an AI obsession) applied his pattern classifier to handprinted-character recognition. The Palm Pilot™ might sooner than we think profit from the anticipatory thought that went into its successful handwriting recognition program that Hawkins authored.

6.3 Interactivity

Such and similar examples are computational expressions of the many aspects of anticipation. Their interactive nature draws our attention towards the very telling distinction between algorithmic and interaction computation. In algorithmic computation, we basically start with a description (called algorithm) of what it takes to accomplish a certain task. The computer—a Turing machine—executes a single thread operation (the van Neumann paradigm of computation) on data appropriately formatted according to syntactic constraints. As such, the process of computation is disconnected from the outside world. Accordingly, there is no room for anticipation, which always results from interaction. In the interactive model, the outside world drives the process: Agents react to other agents; robots operate in a dynamic environment and need to be endowed with anticipatory traits. Searches over networks, not unlike airline ticket purchasing and other interactive tasks, are driven by those who randomly or systematically pursue a goal (find something or let something surprise you).

As Peter Wegner (1996), one of the proponents of interactive computation expresses it, "Algorithms are 'sales contracts' that deliver an output in exchange for an input. A marriage contract specifies behavior for all contingencies of interaction ('in sickness and health') over the lifetime of the object ('till death do us part')." The important suggestion here is that we can conceive of object-based computation in which object operations (two or more) share a hidden state.

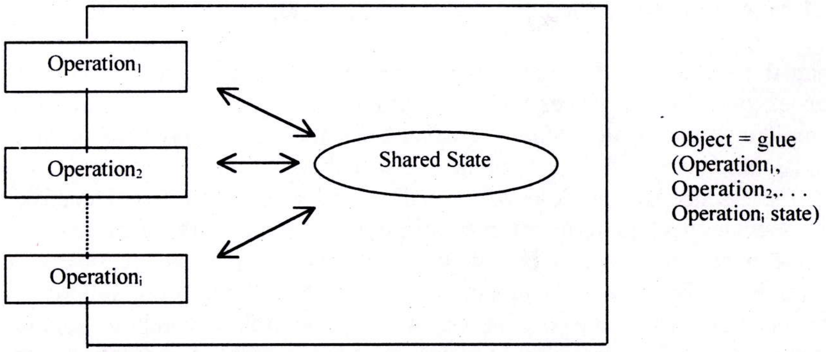

Fig. 4: Interactive computation: the shared state

None of the operations (or processes) are algorithmic, since they do not control the shared state, but participate in an interaction through the shared state. They are also subject to external interaction. What is of exceptional importance here is that the response of each operation to messages from outside depends on the shared state accessed through non-local variables of operations. The non-locality made possible here corresponds to the nature of anticipation. Interactive systems are inherently incomplete, thus decidable in Gödel's sense (i.e., not subject to Gödelian strictures in respect to their consistency). Interactivity requires that the computation remain connected to the practical experiences of human self-constitution, i.e., that we overcome the limitations of syntactically limited processing, or even of semantic referencing, and reach the pragmatic level. Processes in this kind of computation are multi-threaded, open-ended, and subject to predictive or not predictive interactions. The Turing machine could not describe them; and implementation in anticipatory computing machines *per se* is probably still far away.

This brings up, somehow by association, the question of whether the category of artifacts called programs are anticipatory by design or by their condition. The question is pertinent not only to computers, since in the language of modern genetics, programming (as the encoding of DNA, for example) plays an important role. It is, however, obvious that silicon hardware (as one possible embodiment of computers) and DNA are quite different, not only in view of their make-up, but more in view of their condition. If birds are "programmed" for their migratory behavior, then these "programs" are based on entailment schemes of extreme complexity. The same applies even more to the immune system.

6.3.1 Virtual Reality

A special category of interactive computation is represented by virtual reality implementations, all intrinsically pseudo-anticipatory environments of multi-sensorial condition. In the virtual domain, a given set of co-relations can be established or pursued. Entanglement is part of the broader design. Various processes are triggered in a confined space-and-time, i.e., in a subset of the world. Non-locality is a generic metaphor in the virtual realm made possible by the integration of the human subject. Sure, as we advance towards molecular, biological, and genetic computation—where the distinction between real and virtual is less than clear-cut—we reach new levels of pragmatic integration. Evolutionary computation will probably be driven by the inherent anticipatory characteristic of the living. As designs of computation processes at the chromosome level are advanced, a foundation is laid for computation that involves and facilitates self-awareness. Interaction at this level goes deeper than interaction embodied in the examples mentioned above; that is, at this level, mind-interaction-like mechanisms are possible, and thus true anticipation (not just the *pseudo* type) emerges as a structural property.

We are used to the representation of anticipatory processes through models that have a higher speed than the systems modeled: A rocket launch is anticipated in the simulation that "runs" ahead of the real time of the launch. The program anticipates, i.e., searches for all kinds of correlations—the proper functioning of a very complex system consisting of various elements tightly integrated in the whole. We have here, not unlike the case of data pre-fetching, or of integration through search in a space of possibilities, or of auto-associative memory, a mechanism for ensuring that co-relations are maintained above and beyond the deterministic one-directional temporal chain. The more interesting bi-directional chain is not even imaginable in such applications.

The spookiness of anticipatory computation is not only reducible to the speed of interactions that worried Einstein. It also involves a bi-directional time arrow. The account given in this paper, which simultaneously occasioned the advancement of my own model, identifies the many perspectives of the possible frontier in science represented by the subject of anticipation.

7. Conclusion

In order to ascertain anticipatory computation as an effective method, working models that display anticipatory characteristics need to be realized. The examples given herein can be seen as the *specs* for such possible models. Work in alternative computing models is illustrative of what can be done and of the return expected. Co-relations, difficult to deal with once we part from the world of first-order objects, are another promising avenue, as are possibilistic-based computations. Finally, if quantum effects prove to take place also in a world of large scale, anticipation, as entanglement (i.e., co-relation), might turn out to be the binding substratum of our universe of existence.

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