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# Robert Rosen's anticipatory systems

A.H. Louie

A.H. Louie is a mathematical biologist based in Ottawa, Canada.

The author gave two sessions of tutorial on anticipatory systems at *FuMee 1* (2008) in Rovereto, Italy. This article is a condensation and transcription into prose of these sessions' PowerPoint slides. The subject is *Robert Rosen's Anticipatory Systems*. The author's role is that of an expositor, so what is new in this article is the author's presentation and not the scientific content itself, the originality of which, naturally, belongs to Rosen. Aristotle said: "When a thing has been said once it is hard to say it differently." Some repetition of what Rosen has already written (which is worthy of repetition in any case) is unavoidable. Let the acknowledgement "Robert Rosen said it first." be the disclaimer. The compilation, interpretation, and delivery contained in these two tutorial sessions and hence this article, however, are the author's own.

## Abstract

**Purpose** – *This article aims to be an expository introduction to Robert Rosen's anticipatory systems, the theory of which provides the conceptual basis for foresight studies.*

**Design/methodology/approach** – *The ubiquity of anticipatory systems in nature is explained.*

**Findings** – *Causality is not violated by anticipatory systems, and teleology is an integral aspect of science.*

**Practical implications** – *A terse exposition for a general readership, such as the present article, by definition cannot get into too many details. For further exploration the reader is referred to the recent book *More than Life Itself* by the author.*

**Originality/value** – *The topic of anticipatory systems in particular, and methods of relational biology in general, provide important tools for foresight studies. It is the author's hope that this brief glimpse into the world of relational biology piques the interest of some readers to pursue the subject further.*

**Keywords** *Research, Biology, Philosophical concepts*

**Paper type** *Conceptual paper*

## Preview

Robert Rosen instituted a rigorously mathematical treatise on the subject of anticipatory systems, the theory of which provides the conceptual basis for foresight studies. This article is an expository introduction[1]. The ubiquity of anticipatory systems in Nature is explained. An anticipatory system's present behavior depends upon "future states" or "future inputs" generated by an internal predictive model. This apparent violation of causality is, however, simply an illusion. The topic of anticipatory systems in particular, and methods of relational biology in general, provide important tools for forecasting and planning.

## Robert Rosen

Robert Rosen (1934-1998) was for many years one of the world's foremost theoretical biologists. He authored some 250 research papers and a dozen books, concerned with both the development and the implications of the theory underlying biological processes.

He very early began to develop the concept that biology should be based on notions of function rather than structure, and that it was function that was of primary concern in understanding the basis of life and of organism. He subsequently explored the possibilities of building function-based models of biological processes. These turned out to be very different from, and far more general than, reductionistic treatments based on structural ideas. His teacher Nicolas Rashevsky, who initiated the first definitive study in this area, had termed this approach "relational biology".

Among his many publications, these three books may be considered *The Rosen Trilogy*:

1. *Fundamentals of Measurement and Representation of Natural Systems* (1978);
2. *Anticipatory Systems: Philosophical, Mathematical & Methodological Foundations* (1985); and
3. *Life Itself: A Comprehensive Inquiry into the Nature, Origin, and Fabrication of Life* (1991).

Therein lies the comprehensive treatise of Rosen's science. (Henceforth I shall use the abbreviation AS when referring to the book *Anticipatory Systems*, and use the term spelt out in full when referring to the object "anticipatory system" itself[2].)Figure 1

### "What should we do now?"

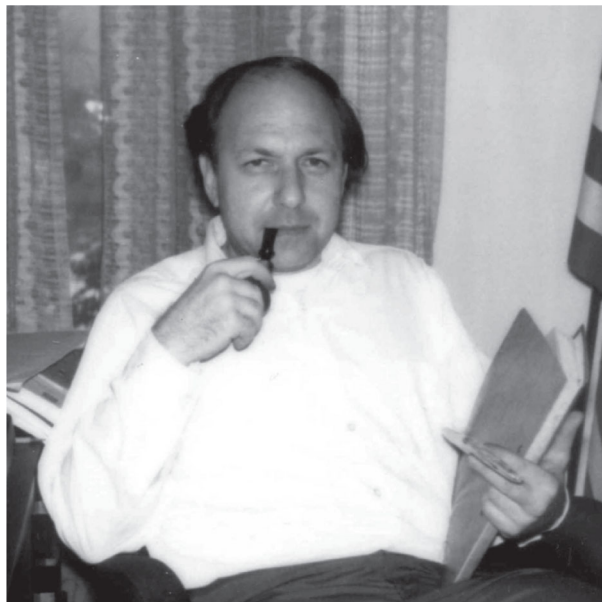
To one degree or another, this "question of *ought*" is the same question the biologist, the economists, the political scientists, the urban planners, the futurists, and many others want to know. However different the contexts in which these questions are posed, *they are all alike in their fundamental concern with the making of policy, and the associated notions of forecasting the future and planning for it*; in short, *foresight*. What is sought, in each of these diverse areas, is in effect a technology of decision-making. But underlying any technology there must be an underlying foundation of basic principles: a science, a *theory*. What is the theory underlying a technology of policy generation? Rosen proposed that this is the theory of anticipatory systems. Note that the *concept* of "anticipation" had not been new (see, for example, Roberto Poli's article in this issue), but the *systemic* study of anticipation was new when Rosen wrote the book on it.

Now what is an anticipatory system? Here is Robert Rosen's definition:

*An anticipatory system is a natural system that contains an internal predictive model of itself and of its environment, which allows it to change state at an instant in accord with the model's predictions pertaining to a later instant.*

Note, in contrast, that a *reactive system* can only react, in the present, to changes that have already occurred in the causal chain, while an *anticipatory system's* present behavior involves aspects of past, present, and future. The presence of a predictive model serves

Figure 1



Robert Rosen (1934-1998)

precisely to pull the future into the present; a system with a “good” model thus behaves in many ways as if it can anticipate the future. Model-based behavior requires an entirely new paradigm, an “anticipatory paradigm”, to accommodate it. This paradigm *extends* – *but does not replace* – the “reactive paradigm” which has hitherto dominated the study of natural systems. The “anticipatory paradigm” allows us a glimpse of new and important aspects of system behavior.

The idea of anticipation in science is controversial, because of “objective causality” pronounced in the “Zeroth Commandment”:

Thou shalt not allow future state to affect present change of state.

Anticipation is almost always excluded from study at every level of system theory[3]. The reasons for this rest on certain basic methodological presuppositions which have underlain “science” in the past few centuries:

- the essential basis on which “genuine scientific inquiry” rests is the principle of *causality* (which an anticipatory systems apparently violates); and
- “true objective science” cannot be argued from final cause (but an anticipatory system seems to embody a form of *teleology*).

We shall debunk these two characterizations of science in some detail below. But let us first consider a few examples of anticipatory systems.

Biology is replete with situations in which organisms can generate and maintain internal predictive models of themselves and their environments, and use the predictions of these models about the future for purpose of control in the present. Much, if not most, biological behavior is model-based in this sense. This is true at every level, from the molecular to the cellular to the physiological to the behavioral, and this is true in all parts of the biosphere, from microbes to plants to animals to ecosystems. But it is not restricted to the biological universe; anticipatory behavior at the human level can be multiplied without end, and may seem fairly trivial: examples range from avoiding dangerous encounters, to any strategy in sports, and even to Linus’s waiting for the Great Pumpkin in the pumpkin patch on Halloween[4]. Model-based behavior is the essence of social, economic, and political activity. An understanding of the characteristics of model-based behavior is thus central to any technology we wish to develop to control such systems, or to modify their model-based behavior in new ways.

It should be clarified that anticipation in Rosen’s usage does not refer to an ability to “see” or otherwise sense the immediate or the distant future – there is no prescience or psychic phenomena suggested here. Instead, Rosen suggests that there must be information about self, about species, and about the evolutionary environment, encoded into the organization of all living systems. He observes that this *information*, as it behaves through time, is capable of acting causally on the organism’s present behavior, based on relations projected to be applicable in the future. Thus, while not violating time established by external events, organisms seem capable of constructing an internal surrogate for time as part of a model that can indeed be manipulated to produce anticipation. In particular, this “internal surrogate of time” must run *faster than real time*. It is in this sense that degrees of freedom in internal models allow time its multi-scaling and reversibility to produce new information. The predictive model in an anticipatory system must not be equivocated to any kind of “certainty” (even probabilistically) about the future. It is, rather, an assertion based on a model that runs in a faster time scale. The future still has not yet happened: the organism has a *model* of the future, but not definitive knowledge of future itself.

## Feedforward

Anticipatory behavior involves the concept of *feedforward*[5], rather than feedback. The distinction between feedforward and feedback is important, and is as follows.

The essence of feedback control is that it is *error-actuated*; in other words, the stimulus to corrective action is the discrepancy between the system’s actual present state and the state

the system should be in. Stated otherwise, a feedback control system must already be departing from its nominal behavior before control begins to be exercised.

In a feedforward system, on the other hand, system behavior is *preset*, according to some model relating present inputs to their predicted outcomes. The essence of a feedforward system, then, is that the present change of state is determined by an anticipated future state, derived in accordance with some internal model of the world.

We know from introspection that many, if not most, of our own conscious activities are generated in a feedforward fashion. We typically decide what to do *now* in terms of what we perceive will be the consequences of our action at some *later* time. The vehicle by which we anticipate is in fact a *model*, which enables us to pull the future into the present. We change our present course of action in accordance with our model's prediction. The stimulus for our action is not simply the present percepts; it is the prediction under these conditions. I emphasize again that "prediction" is *not* prescience, but simply "output of an anticipatory model". Stated otherwise, our present behavior is not just *reactive*; it is also *anticipatory*.

## Model

The essential novelty in Rosen's approach to anticipatory systems is that he considers them as single entities, and relates their overall properties to the character of the models they contain. There have, of course, been many approaches to planning, forecasting, and decision-making, but these tend to concentrate on *tactical aspects* of model synthesis and model deployment in *specific circumstances*. Rosen's AS is not at all concerned with tactics of this type. It deals with, instead, the behavioral correlates arising throughout a system simply from the fact that present behavior is generated in terms of a predicted future situation. It does not consider, for instance, the various procedures of extrapolation and correlation that dominate much of the literature concerned with decision-making in an uncertain or incompletely defined environment. AS is concerned rather with global properties of model-based behavior, regardless of how the model is generated, or indeed of whether it is a "good" model or not. In other words, AS looks at properties of an anticipatory system, not how to build an anticipatory system.

A *model*, defined formally, is a commutative functorial[6] encoding and decoding between two systems in a *modelling relation*[7]. Intuitively, we may just take the common-usage meaning of "model":

- a simplified description of a system put forward as a basis for theoretical understanding;
- a conceptual or mental representation of a thing; or
- an analog of different structure from the system of interest but sharing an important set of functional properties.

Robert Rosen closed AS with these words:

The study of anticipatory systems thus involves in an essential way the subjective notions of good and ill, as they manifest themselves in the models which shape our behavior. For in a profound sense, the study of models is the study of man; and if we can agree about our models, we can agree about everything else.

The crux in the formulation of a theory of anticipatory behavior is the conception of "model". What is the nature of the relation between two systems that allows us to assert that one of them is a model for the other? The essence of this property is that we may learn something new about a system of interest by studying a different system that is its model. Roughly, the essence of a modeling relation consists of specifying an *encoding* and a corresponding *decoding* of particular system characteristics into corresponding characteristics of another system, in such a way that *implication* in the model corresponds to *causality* in the system. Thus in a precise mathematical sense a theorem about the model becomes a prediction about the system. When these remarks are rigorously pursued, the result is a general theory of the modeling relation. This theory has many important implications: to more general situations of metaphor, to the way in which distinct models of a given system are related to

each other, and to the manner in which distinct systems with a common model may be compared.

The situation may be represented by Figure 2.

A modeling relation exists between the natural system  $N$  and the formal system  $F$  when there is a *congruence* between their entailment structures. A *necessary condition* for congruence involves all four arrows, and may be stated as “whether one follows *path c* or *paths ε, i, δ* in *sequence*, one reaches the same destination”. Expressed graphically, this is:

$$\xrightarrow{c} = \xrightarrow{\varepsilon} \xrightarrow{i} \xrightarrow{\delta}.$$

If this relation is satisfied, we say that  $F$  is a *simulation* of  $N$ .

If, in addition, inferential entailment  $i$  is *itself* entailed by the encoding  $\varepsilon$  of causal entailment  $c$ , i.e., if:

$$\left( \xrightarrow{c} \right) \xrightarrow{\varepsilon} \left( \xrightarrow{i} \right)$$

is also satisfied, then we say that  $F$  is a *model* of  $N$ , and  $N$  is a *realization* of  $F$ .

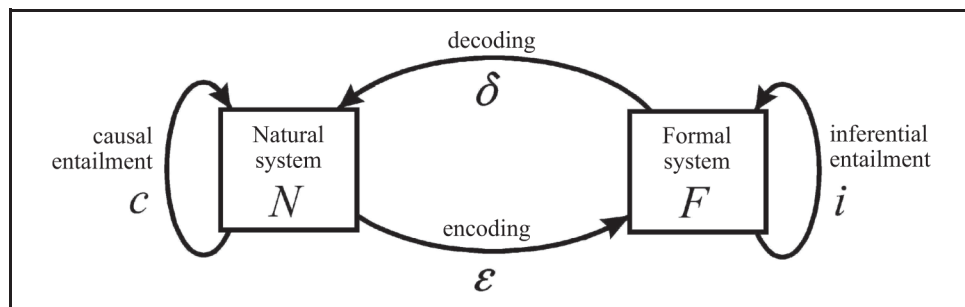
A simulation of a process provides an alternate description of the entailed effects, whereas a model is a special kind of simulation that additionally also provides an alternate description of the entailment structure of the mapping representing the process itself. It is, in particular, easier to obtain a simulation than a model of a process.

Examples are in order. For instance, Claudius Ptolemy's *Almagest* (c. 150 AD) contained an account for the apparent motion of many heavenly bodies. The Ptolemaic system of epicycles and deferents, later with adjustments in terms of eccentricities and equant points, provided good geometric simulations, in the sense that there were enough parameters in defining the circles so that any planetary or stellar trajectory could be represented reasonably accurately by these circular traces in the sky. Despite the fact that Ptolemy did not give any physical reasons why the planets should turn about circles attached to circles in arbitrary positions in the sky, his simulations remained the standard cosmological view for 1,400 years. Celestial mechanics has since, of course, been progressively updated with better theories of Copernicus, Kepler, Newton, and Einstein. Each improvement explains more of the underlying principles of motion, and not just the trajectories of motion. The universality of the Ptolemaic epicycles is nowadays regarded as an extraneous mathematical artifact irrelevant to the underlying physical situation, and it is for this reason that a representation of trajectories in terms of them can only be regarded as simulation, and not as model.

As another example, a lot of the so-called “models” in the social sciences are really just sophisticated kinds of curve-fitting, i.e. simulations. These activities are akin to the assertion that since a given curve can be approximated by a polynomial, it must be a polynomial. Stated otherwise, curve-fitting without a theory of the shape of the curve is simulation; model requires understanding of how and why a curve takes its shape.

Simulation describes; model explains.

**Figure 2** The prototypical modeling relation



Note that in common usage, the two words “simulation” and “model” are often synonyms. Some, alternatively, use “model” to mean mathematical theory, and “simulation” to mean numerical computation. What I have presented above, however, are *Robert Rosen’s definitions*, in precise category-theoretic terms, of these two words.

## Natural law

It can be commonly agreed that no one, whether experimenter, observer, or theorist, does science at all without believing that nature obeys laws or rules, and that these natural regularities can be at least partly grasped by the mind. That nature obeys laws is often subsumed under the notion of *causality*. The articulation of these causal laws or relationships means, in brief, that one can establish a correspondence between events in the world and propositions in some appropriate language, such that the causal relations between events are exactly reflected in implication relations between corresponding propositions.

“Law of Nature”, or Natural Law, consists of two independent parts. The first of these comprises a belief, or faith, that what goes on in the external world is not entirely arbitrary or whimsical. Stated in positive terms, this is a belief that successions of events in that world are governed by definite relations, termed *causality*. Without such a belief, there could be no such thing as science. Causality and general ideas of entailment guarantee a kind of regularity that one expects in nature and in science. Roughly, we are guaranteed that the same causes imply the same effects. Therefore, in the causal world, one sees the operation of laws in terms of which the events themselves may be understood.

The second constituent of Natural Law is a belief that the causal relations between events can be grasped by the mind, articulated and expressed in language. This aspect of Natural Law posits a relation between the syntactic structure of a language and the semantic character of its external referents. This relation is different in kind from entailment within language or formalisms (i.e. implication or inference, which relate purely linguistic entities), and from entailment between events (i.e. causal relations between things in the external world). Natural Law, therefore, posits the existence of entailments between events in the external world and linguistic expressions about those events. Stated otherwise, it posits a kind of *congruence* between implication (a purely syntactic feature of languages or formalisms) and causality (a purely semantic, extra-linguistic constituent of Natural Law).

Summarily, Natural Law makes two separate assertions about the self and its ambience:

1. The succession of events or phenomena that we perceive in the ambience is not arbitrary: there are relations (e.g. causal relations) manifest in the world of phenomena.
2. The posited relations between phenomena are, at least in part, capable of being perceived and grasped by the human mind; i.e. by the cognitive self.

Science depends in equal parts on these two separate prongs of Natural Law. Part 1, that causal order exists, is what permits *science* to exist in the abstract, and part 2, that this causal order can be imaged by implicative order, is what allows *scientists* to exist. Both are required.

In short, the logic, order, and regularity of the universe are intelligible.

## Causality

The concept of anticipation has been rejected out of hand in formal approaches to system theory, because they appear to violate causality. We have always been taught that we must not allow present changes of state to depend on future states; the future cannot affect the present. We now show that this restriction is simply an artifact of the Newtonian reactive paradigm.

However much the languages that we use to construct system models of whatever kind may differ, in detail and emphasis, they all represent paraphrases of the language of Newtonian



mechanics. Two separate ingredients are necessary for the process of system description; they are:

1. a specification of what the system is like at any particular instant of time, with the associated concept of the *instantaneous state* of the system; and
2. a specification of how the system changes state, as a function of present or past states and of the forces imposed on the system, i.e. the *dynamics*.

The characterization of the instantaneous state involves the specification of an appropriate set of *state variables*, while the characterization of how the system changes state involves a specification of the *equations of motion* of the system. Another name of this Newtonian reactive system is “dynamical system”.

Succinctly, the assumptions of the Newtonian paradigm are:

1. A physical system is defined by its constitutive parameters, and is manifested as a sequence of events in space and time. A system behavior is some property of such a sequence.
2. The universe of events can be effectively partitioned into two distinct domains.
3. The first domain is characterized by regularity and order – the province of natural law.
4. In the second domain no perceptible regularity is discernible – the realm of initial conditions.
5. Physics = system laws + initial conditions.

In this context, causality is “past implies present, and present implies future”.

As long as we restrict ourselves to Newtonian dynamical equations under these assumptions, which inextricably involve traditional view of causality, anticipatory systems are clearly excluded from discussion. However, when we proceed to consider systems in terms of relations between input-output pairs of mappings of time, we find that causality needs only dictate natural regularities relating causes and effects, without necessarily including a built-in forward-temporal restraint. Thus anticipatory behavior not only is possible, but, because general input-output relations contain Newtonian dynamics as special cases, it is actually less restrictive and therefore in some sense generic.

## Teleology

We now consider the assertion that anticipatory systems involve teleology or final causes in an essential way, and thus must be excluded from science. Feedforward behavior seems telic, or goal-directed. The goal is in fact built in as part of the model that connects predicted future states and present changes of state. But the very suggestion that a behavior is goal-directed is repellent to many scientists, who regard it as a violation of the Newtonian paradigm.

The formulation of this “teleophobic” assertion goes back to Aristotle’s conception of causality, in which four distinct kinds of “causes” for any physical event are recognized. Adapting this Aristotelian parlance to the above discussion, if we regard the current value of an observable at an instant as such an event, and if we allow only Newtonian dynamical laws to express relations between events, then we may say that:

- the initial conditions are the *material cause* of the event;
- the constitutive parameters of the system are its *efficient cause*; and
- the system laws are its *formal cause*.

This assignment of three of the causes exhausts all the quantities and relations in the Newtonian expression; hence the event can have no room for the fourth, *final cause*. This observation is essentially the entire basis for asserting that scientific explanation (which is posited in advance to be exclusively embodied in reactive relations) cannot involve final



causes. Moreover, since final causes presuppose future states and/or future inputs, we must according to this argument *a fortiori* exclude anticipatory systems.

However, already in physics we find numerous situations in which present events appear to be determined by subsequent ones. Of course, such situations are not directly governed by reactive laws. An obvious example is any system which obeys an “optimality principle”, such as Fermat’s principle in optics or Hamilton’s principle in mechanics; here *the actual path described by a physical process is as much determined by its terminal state as by its initial one*. A similar teleological aspect can be seen in Le Chatelier’s principle in physical chemistry and in Lenz’s law of electricity. These principles express that in case of disturbance, the system develops forces that counteract the disturbance and restore a state of equilibrium; they are derivations from *the principle of minimum effect*. Further, the transition of a system to a state of “minimal free energy”, “maximum entropy”, etc., involves a tacit characterization of such a state as the final cause of motion toward it. Precisely the same situation is encountered in probability theory, where the family of convergence arguments, collectively called the law of large numbers, asserts that limiting probabilities exert an apparent attractive force on the successive steps of a random process, even though those steps are independent. In sum, even though dynamical laws in physics express conventional views regarding causality, they are mathematically equivalent to principles in which a future state acts retroactively on a present change of state.

We should note that hidden teleology by itself is not sufficient to define an anticipatory system. An optimality- or otherwise determined future still constitutes a reactive system. An anticipatory system needs to use the information from its predictive model to change the present, so that a possibly different future from one that is originally predicted may result.

## Anticipatory system

Having analyzed and dispensed with those formal arguments adduced to justify excluding anticipatory systems from system theory, let us now be positive, and construct (necessarily informally in this introductory exposition) a sample anticipatory system with some synthetic arguments.

Let us suppose that we are given a system  $S$  that is of interest.  $S$  may be an individual organism, or an ecosystem, or a social or economic system. For simplicity we shall suppose that  $S$  is an ordinary (i.e. non-anticipatory) dynamical system. As we have seen, this fact allows us to make predictions about the future states of  $S$ , from a knowledge of an initial state and of the system input. Indeed, the dynamical law itself already expresses a predictive model of  $S$ .

But let us embody a predictive model of  $S$  explicitly in another physical system  $M$ . We require that if the trajectories of  $S$  are parameterized by real time, then the corresponding trajectories of  $M$  are parameterized by a time variable that goes *faster than real time*. Thus, any observable on  $M$  serves as a predictor for the behavior of some corresponding observable of  $S$  at that later instant.

We shall now allow  $M$  and  $S$  to be coupled; i.e. allow them to interact in specific ways. For the simplest model, we may simply allow the output of an observable on  $M$  to be an input to the system  $S$ . This then creates a situation in which a future state of  $S$  is controlling the present state transition in  $S$ . But this is precisely what we have characterized above as anticipatory behavior. It is clear that the above construction does not violate causality; indeed, we have invoked causality in an essential way in the concept of a predictive model, and hence in the characterization of the system  $M$ . Although the composite system ( $M + S$ ) is completely causal, it nevertheless will behave in an anticipatory fashion.

Similarly, we may construct a system  $M$  with outputs that embody predictions regarding the inputs to the system  $S$ . In that case, the present change of state of  $S$  will depend upon information pertaining to future inputs to  $S$ . Here again, although causality is in no sense violated, our system will exhibit anticipatory behavior.

From the above remarks, we see that anticipatory behavior will be generated in any system that:

- contains an internal predictive model of itself and/or of its environment; and
- is such that its dynamical law uses the predictions of its internal model in an essential way.

From this point of view, anticipatory systems can be viewed as a special class of adaptive control systems.

There are many another modes of coupling, discussed in AS, which will allow  $S$  to affect  $M$ , and which will amount to updating or improving the model system  $M$  on the basis of the activity of  $S$ . We shall for the present example suppose simply that the system  $M$  is equipped with a set  $E$  of *effectors* that operate either on  $S$  itself or on the environmental inputs to  $S$ , in such a way as to change the dynamical properties of  $S$ . We thus have a situation of the type shown in Figure 3, formulated as an input-output system.

An anticipatory system  $S$  entails the following:

- $S$  possesses a *model subsystem*  $M$ ;
- there is an *orthogonality* between the model  $M$  and the collection of observables of  $S \sim M$ ;
- the rate of change (the *adaptation*) of observables of  $S \sim M$  depends on  $M$ ;
- the effect of the model  $M$  creates a *discrepancy* –  $S$  would have behaved differently if  $M$  were absent; and
- $M$  is a *predictive* model – by looking at a present state of  $M$ , one obtains information pertaining to a future state of  $S$ .

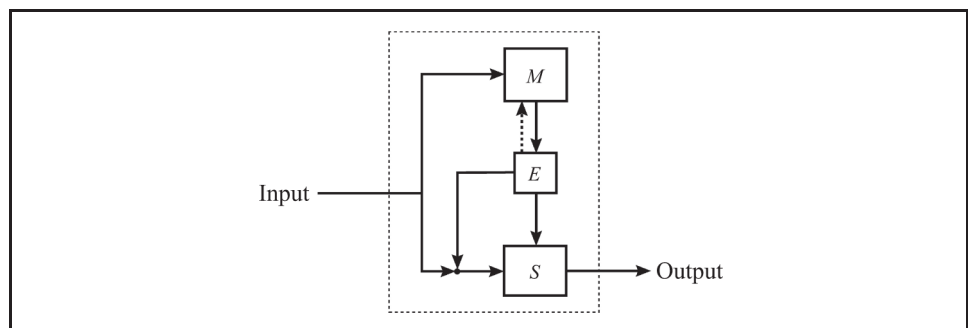
## Errors

A natural system is almost always more than any model of it. In other words, a model is, by definition, incomplete. As a consequence, under appropriate circumstances, the behavior predicted by a model will diverge from that actually exhibited by the system. This provides the basis for a theory of error and system failure on the one hand, and for an understanding of emergence on the other. It is crucial to understand this aspect in any comprehensive theory of control based on predictive models.

Anticipation can fail in its purpose. A study of how planning can go wrong is illustrative; indeed the updating of models from lessons learned is the essence of an anticipatory system. The causes of errors in anticipation may be categorized into:

- bad models;
- bad effectors; and
- side effects.

**Figure 3** Anticipatory system



A bad model can result from technical, paradigmatical, or state-correspondence errors, all due to improper functorial imaging of mappings. In short, faulty encodings lead to faulty models. A proper choice of the internal predictive model  $M$  and the fine tuning of its updating processes are evidently crucial to an anticipatory system's success.

An effector  $E$  is defective when it is incapable of steering  $S$ , when it cannot appropriately manipulate the state variables, or simply when it fails to accordingly react to the information from  $M$ . Thus the careful construction of an anticipatory system also depends on the selection, design, and programming of the effector system  $E$ , as well as on the partitioning of the "desirable" and "undesirable" regions of response.

Side effects arise because, essentially, structures have multiple functions and functions may be carried out by multiple structures. Combined with the fact of incomplete models, the consequence is that, in general, an effector  $E$  will have additional effects on  $S$  to those planned, and the planned modes of interaction between  $E$  and  $S$  will be modified by these extraneous effects.

The diagnosis and treatment of erroneous anticipatory systems are frequently analogous to the procedures used in neurology and psychology.

We may further ask, how does a system generate predictive models? On this point we may invoke some general ontogenic principles, by means of natural selection, to achieve some understanding. And finally, given a system that employs a predictive model to determine its present behavior, how should we observe the system so as to determine the nature of the model it employs?

## Lessons from biology

The conscious generation and deployment of predictive models for the purpose of control are some of the basic intuitive characteristics of intelligence. However, precisely the same type of model-based behavior appears constantly at lower levels of biological organization as well. For instance, many simple organisms are negatively phototropic; they tend to move away from light. Now darkness in itself is physiologically neutral; it has no intrinsic biological significance (at least for non-photosynthetic organisms). However, darkness tends to be correlated with other characteristics that are not physiologically neutral, such as moisture and the absence of sighted predators. The tropism can be regarded biologically as an exploitation of this correlation, which is in effect a predictive model about the environment. Likewise, the autumnal shedding of leaves and other physiological changes in plants, which are clearly an adaptation to winter conditions, are not cued by ambient temperature, but rather by day length. There is an obvious correlation between the shortening day, which again is physiologically neutral in itself, and the subsequent appearance of winter conditions, which again constitutes a predictive model exploited for purposes of adaptive control. Innumerable other examples of such anticipatory preadaptation can be found in the biosphere, ranging from the simplest of tropisms to the most complex hormonal regulation mechanisms in physiology.

Since feedforward or anticipatory control is as ubiquitous as it seems to be, a number of fundamental new questions are posed to us. Among them are the following. Can we truly say we understand the behavior of such a system if we do not know the model employed by the system? How is it possible to determine the character of that model, in terms of measurements or observations performed on the system? More generally, under what circumstances is it possible for a system to contain an internal model of its world? What relations must exist between a set of indicators (environmental signals) and system effectors that will allow an effective feedforward control model to be constructed? How can the behaviors of different systems, perceiving the same set of circumstances but equipped with different models, be integrated? (This last is essentially the problem of conflict and conflict resolution.)

The questions just raised bear directly on the present search for forecasting and planning technologies to guide our behavior in the political, social and economic realms. Tacit in this search is the perception that our society and its institutions can no longer function effectively in

a cybernetic or reactive mode; it must somehow be transformed into a predictive or anticipatory mode. That is, it must become more like an organism, and less like a machine[8].

In dealing with various challenges in our world, properties of biological systems will provide crucial insights. Robert Rosen was fond of saying “the first lesson to be learned from biology is that there are lessons to be learned from biology”. Indeed, considered in an evolutionary context, biology represents a vast encyclopedia of how to solve complex problems effectively; and also of how not to solve them. Biology provides us with existence proofs, and specific examples, of cooperative rather than competitive activities on the part of large and diverse populations. Biology is the science of the commonality of relations, and relationships contain the essential meaning of life. These insights represent natural resources to be harvested, resources perhaps even more important to our ultimate survival than the more tangible biological resources of food and energy. But to reap such a harvest, we need to fabricate proper tools. It is my belief that the conceptions of nature arising from relational biology will help us learn how to make it so.

## Notes

1. A terse exposition for a general readership, such as the present article, by definition cannot get into too many details. It is the author's hope that this brief glimpse into the world of relational biology piques the interest of some readers to pursue the subject further. For further exploration the reader is referred to the recent book *More Than Life Itself* by the author (Louie, 2009).
2. Rosen wrote AS in the first six months of 1979. I became his PhD student just as he finished the first draft. I was one of the first to read it, so I have been associated with the subject right from the beginning. For a variety of external reasons, the book was not published until 1985. The Pergamon Press book is long out of print, although one may be able to find copies in university libraries (or from a resourceful used-book dealer).
3. Note the singular form system in “system theory”: not “systems theory”. This last usage is an error that became accepted when it had been repeated often enough, a very example of “accumulated wrongs become right”. Just think of “set theory”, “group theory”, “number theory”, “category theory”, etc. Of course one studies more than one object in each subject! Indeed, one would say in the possessive “theory of sets”, “theory of groups”, “theory of numbers”, “theory of categories”, ...; one says “theory of systems” for that matter. But the point is that when the noun of a mathematical object (or indeed any noun) is used as adjective, one does not use the plural form.
4. Just in case some readers may not be aware of the reference: Linus is a character from Charles M. Schulz's *Peanuts* (© United Feature Syndicate, Inc.), the most popular comic strip in the world for 50 years. Linus gets one holiday ahead of himself, and anticipates the arrival of the Great Pumpkin on Halloween: “On Halloween night, the Great Pumpkin rises out of the pumpkin patch, and flies through the air with his bag of toys for all the good children in the world!”. This is an example of an anticipatory system in which the predictive model is somewhat faulty, and the faster time line goes a little too fast. For a quick review one may seek out a video of the 1966 television special “It's the Great Pumpkin, Charlie Brown!”.
5. A more proper contrastive word of “feedback” should have been “feedforth”, but “feedforward” is, alas, ingrained terminology in control system theory.
6. For the readers not acquainted with the word “functorial” (it being a concept from the mathematical theory of categories), they may simply take it to mean “pertaining to a mapping that takes into account the processes involved in addition to inputs and outputs”.
7. The topic of my second tutorial session at FuMee 1 was the modeling relation. There is only room in the present article, however, for a small fraction of that particular exposition. The reader is referred to AS (if a copy can be found), Rosen (1991), and Louie (2009) for a detailed treatment of the subject, which is considered by Rosen to be the point of departure of science.
8. As the British geneticist and evolutionary biologist J.B.S. Haldane once said, there are four stages in the development of people's reaction to a new scientific idea: (1) This is arrant nonsense. (2) This is interesting but controversial. (3) This is true, but trivial. (4) I always said so. With regards to Rosen's science, when I was his graduate student 30 years ago, the world was definitely in stage 1; I think it has now progressed to somewhere in stage 2.

## References

- Louie, A.H. (2009), *More than Life Itself: A Synthetic Continuation in Relational Biology*, Ontos Verlag, Frankfurt.
- Rosen, R. (1991), *Life Itself: A Comprehensive Inquiry into the Nature, Origin, and Fabrication of Life*, Columbia University Press, New York, NY.

## Further reading

- Rosen, R. (1978), *Fundamentals of Measurement and Representation of Natural Systems*, North-Holland, New York, NY.
- Rosen, R. (1985), *Anticipatory Systems: Philosophical, Mathematical & Methodological Foundations*, Pergamon Press, Oxford.

## About the author

A.H. Louie is a mathematical biologist. His premier interest is in pure mathematical biology: conception and abstract formulations. This area of research is called relational biology, the school of Nicholas Rashevsky and Robert Rosen. Dr Louie has just finished writing a book on the subject. *More than Life Itself: A Synthetic Continuation in Relational Biology* was published in 2009 by Ontos Verlag.

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