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Semiotic Aspects of Control and Modeling Relations in Complex Systems*

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Abstract

A conceptual analysis of controls and models from a semiotic perspective is provided with the goal of elucidating their nature in complex systems. Atomic control systems and models are described as the paradigmatic forms of systems in relation to their environments. While they share measurement relations, they differ topologically in that control systems are circularly and models linearly related related to their environments. Computation is then introduced in control systems, which motivates hierarchical decompositions and hybrid modeling and control systems. The various relations in complex control systems and models are placed in a semiotic context in terms of constraint relations among various entities, where rules and laws are distinguished as contingent and necessary entailments respectively. Finally selection as a meta-level of constraint is introduced as the necessary condition for semantic relations in control systems and models.

1 Introduction

We are interested in understanding the nature of control and modeling in complex systems from a semiotic perspective: what is the nature of control? what is its relation to semiotic theory? how does the complexity of the control system and of the environment affect the nature of control? and what is necessary and sufficient to achieve control in complex systems? In order to address these questions seriously, we must first develop a coherent set of concepts surrounding control and semiotics in general, and then see how complex situations affect these ideas.

We begin by laying out the conceptual foundations of any control system from a semiotic perspective. We contrast the control relation with the modeling relation, which forms the other canonical relation between a system and its environment. These share the fundamental semiotic measurement or perception functions, but are contrasted by their linear and circular topologies. Hybrid and hierarchical representations are developed, casting the modeling relations within the context of an active control system.

All concepts of control and regulation resonate strongly in the history of systems and cybernetics as developed, for example, by Ashby [1], Powers [11], and Turchin [14]. And in this context, all the relations present in control systems and models can be understood as forms of constraint among classes of phenomena. Semiotically, what is interesting is the nature of the constraint, and in particular the ability of that constraint to be variable at a higher level of analysis. This form of selection of constraint on a pragmatic basis (whether through natural evolution for survival or by human design for function) is the hallmark of semantic relations and the presence of a semiotic system.

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2 Preliminaries: On Definitions

We must first lay out some methodological issues. In particular, we will establish a set of specific definitions related to constraints, control, measurement, semantics, semiotics, and meaning. We do so only for the weak purpose of establishing a specific conceptual frame of reference, not to claim particular semantic ground or meanings as "accurate" or "true".

It should be clear just what is at stake in semantic argument about the meanings of terms. Definition-making is an action of people taken for the specific purpose of parsimoniously capturing appropriate and meaningful distinctions, and identifying them with particular linguistic markers (terms). Further, the purpose of propounding certain definitions within a linguistic community is to bring others to make those same distinctions, and for those terms to be shared among them.

So the purpose of working with definitions is neither to *discover* the "true" meaning of a term nor just to win an argument. Little is at stake in the choice of specific words for specific concepts, except, of course, for the *rhetorical* value gained in the battle of the *politics* of ideas. Nor should semantic argument necessarily go on prior to or be cleanly separated from the rest of an argument. That is, any hope that we would all sit down together, decide on the usage of terms, and only then go on to engage in argument using those terms, is vain. Rather, argument should proceed at both levels complementarily and simultaneously, with a vigorous interplay between argument *within* and *about* the linguistic frame.

The point is that there are vastly more *concepts* that we wish to discuss than there are specific *terms* to use. Therefore the key is to clearly distinguish *senses* of terms from each other, and then appropriately and consistently identify them with specific qualified terms or phrases. So, for example, if two scientists A and B are arguing about the proper use of the term "complexity", they should simply identify two senses complexity$_A$ and complexity$_B$. It may turn out through their discussion that one sense is a case of another, or that a different term (say "organization", or "information") would be more appropriate for one sense or the other. The goal is to reduce the overall set of required terms, where possible, and where not, to achieve the "null consensus" of simply agreeing to disagree. In this way, a linguistic community can move towards a consensual basis for usage and meaning.

3 Simple Control Systems and Models

In systems theory and cybernetics the modeling relation and the control relation serve as two fundamental and distinct classes of relations between a system and its environment, or "the world".

3.1 Simple Control Systems

Consider first a classical control system as shown in Figure 1. In the world (the system's environment) the dynamical processes of "reality" proceed outside the knowledge of the system. Rather, all knowledge of the environment by the system is mediated through the measurement (perception) process, which provides a (partial) representation of the environment to the system. Based on this representation, the system then chooses a particular action to take in the world, which has consequences for the change in state of the world and thereby states measured in the future.

To be in good control, the overall system must form a negative feedback loop, so that disturbances and other external forces from "reality" (for example noise or the actions of other external control systems) are counteracted by compensating actions so as to make the measured state (the representation) as close as possible to some desired state, or at least stable within some region of its state space. If rather a positive feedback relation holds, then such fluctuations will be amplified,

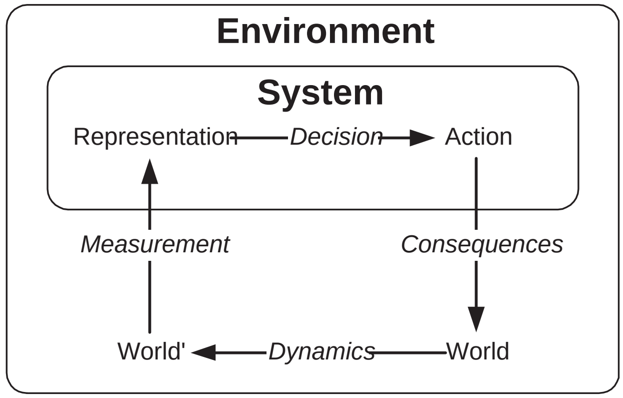

Figure 1: Functional view of a control system.

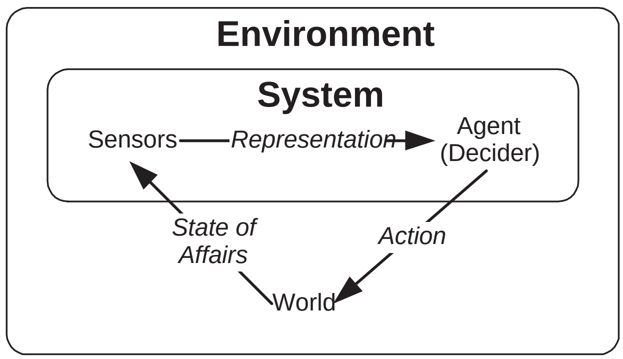

Figure 2: Structural view of a control system.

ultimately bringing some critical internal parameters beyond tolerable limits, or otherwise exhausting some critical system resource, and thus leading to the destruction of the system as a viable entity.

Figure 1 is a functional view of a simple control system, representing the logical relations among certain components of the system and the world: the nodes are logical constructs and the arrows are labeled by the kind of relations which hold between them, or the nature of the constraint one places on the other.

In other words, the measurement function relates a state of the world to a particular representation through one kind of constraint; a decision function (by some agent) relates that representation to the choice of a particular action by another; that action has consequences for the state of the world (through some dynamical constraint); and then in the world other dynamical constraints produce future states of the world.

Alternatively, a structural version of the same diagram can be constructed as shown in Figure 2, representing now the physical entities in the system and the world and how they are structurally related: the nodes are substystems which perform certain physical processes, and the arrows are labeled by how they interact. Thus the physical sensors interact with the state of affairs in the world to produce a representation (token) which is passed to the agent which executes a decision to choose a particular action taken in the world.

Note how generally the functional and structural views are dual: nodes in one are generally arrows in the other, and vice versa.

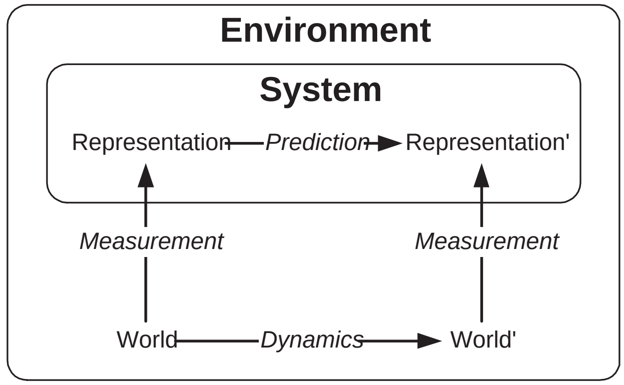

Figure 3: Functional view of the modeling relation.

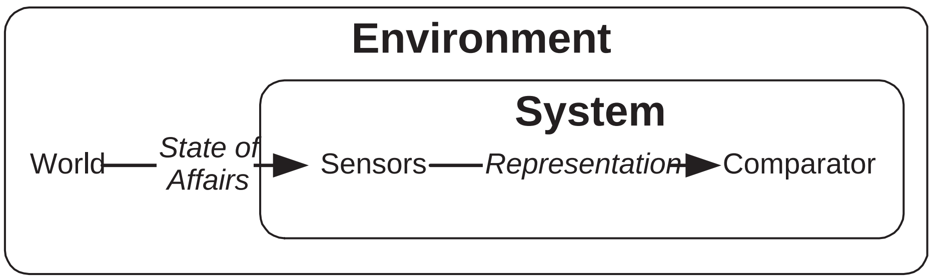

Figure 4: Structural view of the modeling relation.

3.2 Simple Models

Now consider the canonical modeling relation as shown in Figure 3. As with the control relation, the processes of the world are still represented to the system only in virtue of measurement processes. But now the decision relation is replaced by a prediction relation, whose responsibility is to produce a new representation which is hypothesized to be equivalent (in some sense) to some future observed state of the world. To be a good model, the overall diagram must commute, so that this equivalence is maintained.

As with the control system, this is a functional representation, and a structural version is also possible in Figure 4. Here as well the sensors enter into relations with states of affairs in the world and create representations, but these are now sent only to a comparator. There is no relation back from the system to the world.

4 Complex Control

Of course, all of the relations described here are a great deal more complex in real control systems.

4.1 Computation in Control

In particular, typically much more can be done with the measured representation than simply passing it on to the agent for decision about action. It is possible to augment the control system with a computation relation between one representation and another. Thus the representation of the world is acted upon in such a way as to create a new representation. This is shown in Figure 5 in both the functional (left) and structural (right) forms.

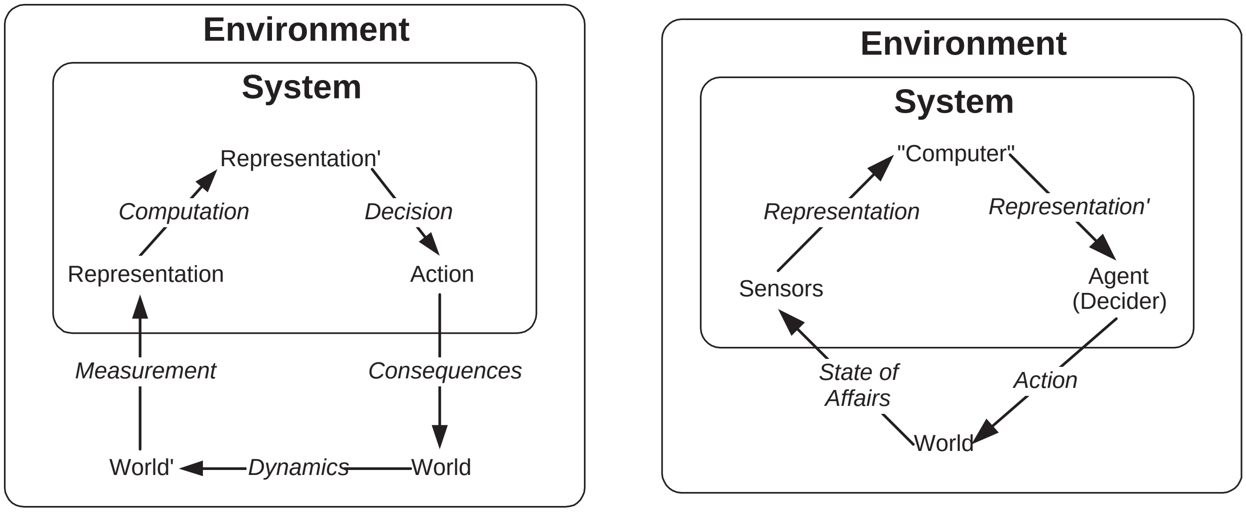

Figure 5: Control system with computation.

In real systems this "computation" could, in fact, be many things, but plays the role of cognition, information processing, or knowledge development. Typically, extra or external knowledge about the state of the world or the desired state of affairs is brought to bear, and provided to the agent in some processed form, for example as an error condition or distance from optimal state. In real systems computations take such forms as the more abstract or combined perceptions in neural organisms or the results of a real computation in machines; but for simplicity here we simply refer to them all as computations. The point is that this second representation$'$ is what is passed to the agent for decision.

4.2 Hierarchical Control

At this point we have recovered the classical view from linear control systems theory, and in particular of Bill Powers [11, 12] system for hierarchical control.[1] As shown in Figure 6, he views the computer as a comparator between the measured state and a hypothetical set point or reference level (goal). This then sends the second representation of an error signal to the agent. He also explicitly includes reference to the noise or disturbances always present in the environment, against which the control system is acting to maintain good control. For us, these are bundled into the dynamics of the world.

Another great virtue of Powers' control theory model is its hierarchical scalability. Figure 7 shows such a hierarchical control system, containing an inner level 1 and the outer level 2. The first key move here is to allow representations to be combined to form higher level representations. In the figure S_1 and S_2 are low distinct level sensors providing low level representations R_1 and R_2 to the inner and outer levels respectively. But R_1 is also sent to the higher level S_3, and together they form a new high level representation R_3.

The second step is the ability for the action of one control system to be the determination of the set-point of another, thus allowing goals to decomposed as a hierarchy of sub-goals. In the figure, the outer level uses R_3 to generate the action of fixing the set point of the lower level.

Notice that the overall topology of the control loop is maintained. While ultimately the lower level is responsible for taking action in the world, it is doing so under the control of the comparison

[1] `http://www.ed.uiuc.edu/csg`

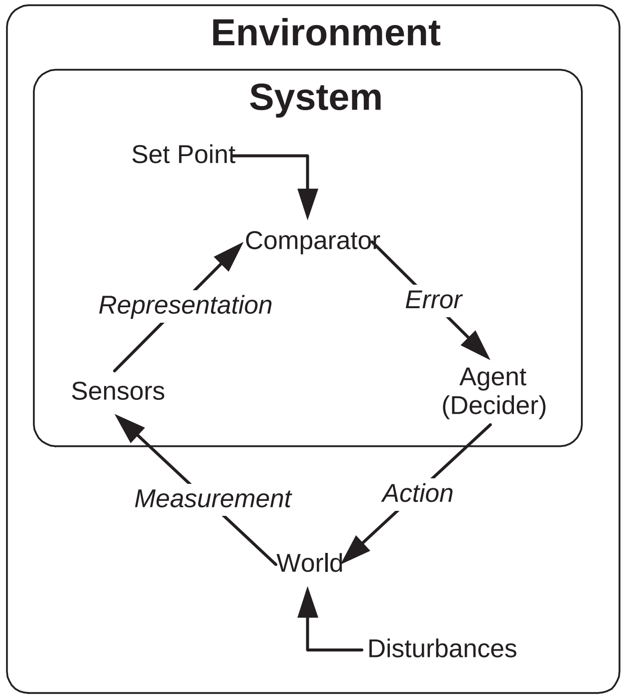

Figure 6: A Powers' control system.

of a high-level goals against a high-level representation. Neural organisms especially are systems of this type, low-level motor and perceptual systems combining to accomplish very high-level tasks. And of course, determination of the outermost goal is not included within Powers' formal model.

5 Hybrid Modeling and Control

As constructed so far, modeling and control are distinct ways in which a system can be related to the world (its environment). Consider a system S in relation to its environment E. Naturally there are two sets of relations $g: E \mapsto S$ from the environment to the system and $f: S \mapsto E$ back from the system to the environment. Then models and control systems are contrasted by their different topological structures. In the modeling relation, only g is present as a measurement function, and thus the structure of a model is fundamentally linear, from the world to the model. But in a control relation, g is present as measurement, but f is also present as the action relation from the system back to the world. Thus control is fundamentally circular, from the system to the world and back again, while models are fundamentally linear, just from the environment to the system.

Yet at the same time they share much in common. In particular, they both hold a measurement relation from the world to the system. And at least in control with computation, there is also a relation where one representation is produced from another, namely computation and prediction respectively.

Yet still the topologies remain distinct, one a looped structure connected to the world, and the other a linear structure from the world to the system. So it is clear that control can be done without computation, modeling, or planning, based strictly on feedback. The difference is that in control the representation of what *is* is compared to what is *wanted*, while in modeling it is compared to what is *expected* (based on the model's predictions).

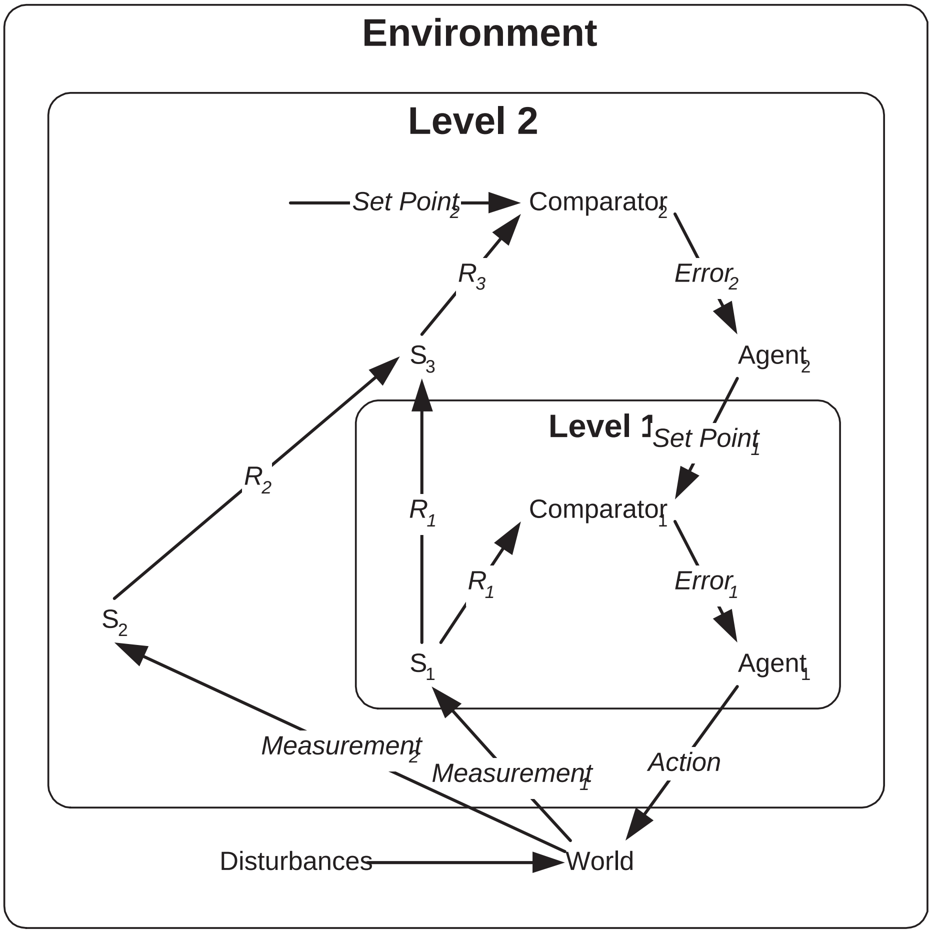

Figure 7: Hierarchical nesting of Powers' control systems.

This form of prediction-less control is what Ashby called "error control" [1]. This he distinguished from "cause control", which involved the prediction of future events to guide actions. We also know cause control as anticipatory [13] or feedforward [7] control. Ashby actually favored cause control, since in principle it could be made perfect (with a perfect model of the world), while error control can only be improved in the limit at infinitesimal lag.

5.1 Mixed Modeling and Control

The simplest way to construct a hybrid control and modeling system is shown in Figure 8. Here the functional view of control with computation is modified to include a further measurement. Essentially this measurement is used to corroborate the results of the computational step.

Functionally the roles have become a bit mixed now, since World$'$ is the source of both the initial sensory input and the corroboratory measurement. In fact, these steps are separated in time. Figure 9 shows both the measurement relations from the world to the system and the action relations from the system back to the world in temporal decomposition.

Notice also that here we introduce the relation between the agent and the representation. In the structural view, this relation is always mediated through the actions of the agent in the world. But here it becomes apparent that functionally this relation actually is the control relation itself. Further notice, as Powers has, that it is not, in fact, the state of the world which is being

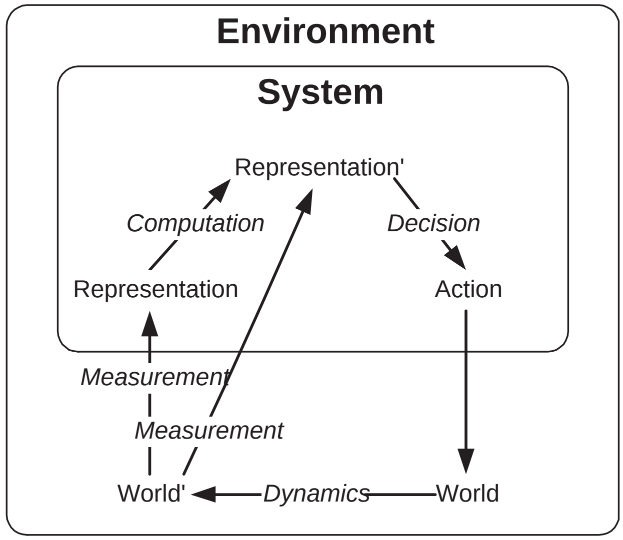

Figure 8: Simple hybrid modeling and control.

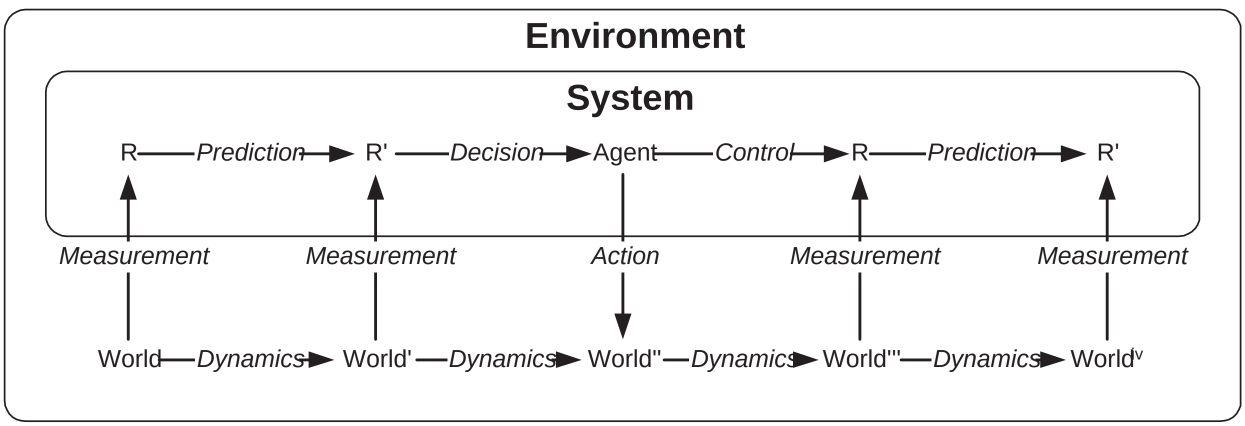

Figure 9: Temporal decomposition of mixed control.

controlled, but rather the *perception* of the state of the world by the system. This fundamental result of constructivism falls out naturally from our descriptions here.

5.2 Anticipatory Control

Usually when we think about cause or anticipatory control there is an embedded model which is used to make a decision as to which action to take. Thus it acts in the role of the agent. This is shown in Figure 10, where now the agent is replaced by an inner system which is *both* a model and a control system (the arrows have been reflected diagonally to ease the drawing). This inner system is a control system in the sense that there are states of its "world", its "dynamics", and an "agent" making decisions.

However, it is also a model in that the states of its "world" are in fact representations, and its "dynamics" is actually a prediction function. The inner system is totally contained within the outer system, and runs at a much faster time scale in a kind of modeling "imagination". The representation R from the sensors is used to instantiate this model, which takes imaginary actions

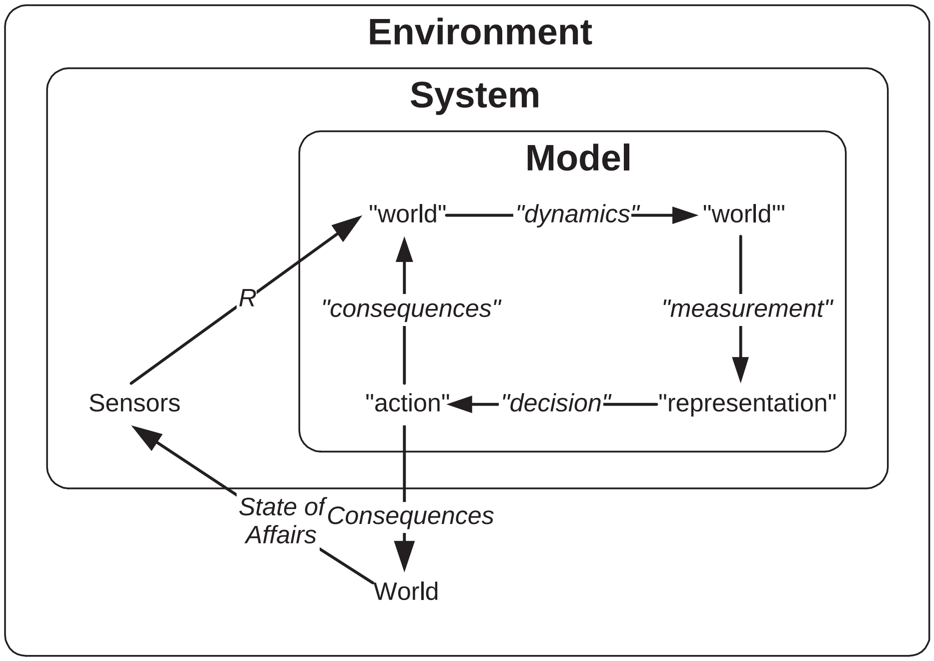

Figure 10: Anticipatory control.

resulting in imaginary stability within the model. Once this stability is achieved, then that action is exported to the real world.

Note that the outer control loop here is simple, lacking computation. In Powers' terms, there is no set point which the state of the internal model is being compared to. But this could be present in a slight elaboration where an imaginary measurement is taken from "world′" and compared to some set point. The outer error signal would then be fed to change the imagined actions inside the model until stability is achieved.

6 Controls and Models as Semiotic Systems

6.1 Traditional Semiotics of Modeling and Control

Models and control systems are frequently both cast in the semiotic context, thereby evoking the distinctions among three distinct classes of semiotic concepts [2, 3]:

Syntactic: Concerning the formal properties of symbol tokens as used in symbol systems.

Semantic: Concerning the interpretation of tokens as their meanings.

Pragmatic: Concerning the use of symbol tokens and their meanings for the overall purposes or survivability of the system.

A traditional view of the roles of syntactic and semantic relations (in particular) are shown in Figure 11. Here the measurement and action functions embody the semantic relations. Together they "ground" the symbols used inside models by connecting them to the world [5]. The syntactic function then becomes the prediction relation which produces one representation from another, or the decision function which produces an action.

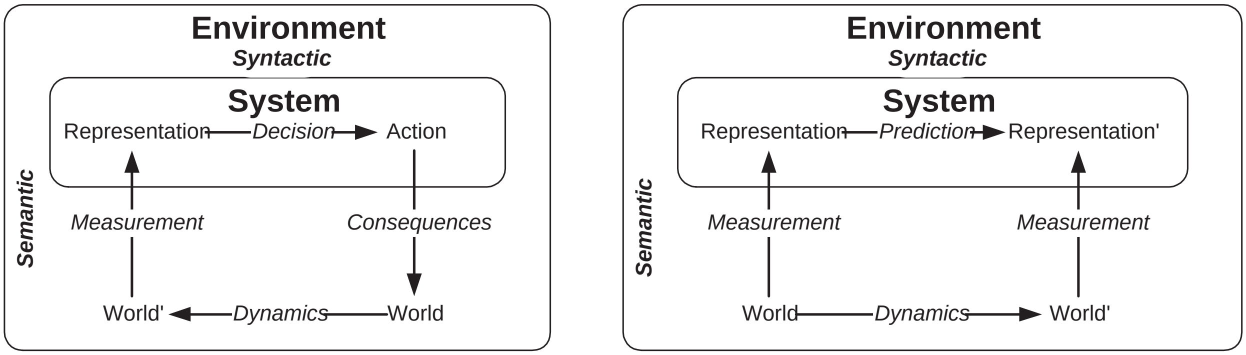

Figure 11: Traditional semiotics of modeling and control.

6.2 Constraints Present in Control and Modeling Relations

However, our view is that this position does not put sufficient restriction on the concept of meaning and semantics, in particular by threatening to "reify" the concept of the *symbol* as *object*, as opposed to *interpretation* of tokens which are *taken as* their meanings as a *process*. On our view, meaning and semantics can only be present in a system when a decision is made to interpret a giving token according to one meaning, and not another, in virtue of a coding constraint which has itself been established contingently by selection.

We will first attempt to identify the presence of all three semiotic categories, and analyze their nature in terms of one of the most fundamental concepts in systems, namely that of variety and constraint.

Measurement: *The constraint placed on tokens by the world.* The production of a token inside the system results from its interaction with the world. In sharp contrast to coding or computation, measurement provides the "grounding" of the symbol tokens. It remains a point of dispute whether measurement is sufficient to provide semantic relations, but it is certainly necessary.

Computation: *The constraint placed on tokens by themselves.* Codings are an expression of syntax, and are usually deterministic. It is essentially string replacement: the presence of one token results in the appearance of another. As Pattee has commented at length [10], coding substitutions are computational, memory-dependent, and rate-independent.

Decision: *The constraint placed on actions by tokens.* Given the presence of a certain representation, either as the result of measurement or of computation, a particular action results.

Dynamics: *The constraint placed on the world by itself.* Effectively the rate-dependent dynamical structure of the universe. These are deterministic at *some* level, even if only within the bounds of some structure of uncertainty (for example the probability distribution of a quantum or classical chaotic process).

6.3 Rules as Contingent Entailments

We have cast all of these relations (measurements, computations, decisions, and dynamics) as forms of constraint. And in fact they all have a high degree of constraint, more or less deterministic. The computation and dynamic relations are the traditional paradigms of this form of determinism. But even measurements are deterministic to the extent that they are reliable and accurate. In other words, given a particular model (a particular set of measurement and prediction relations) or a

x	$f_1(x)$	$f_2(x)$	$f_3(x)$
$+$	d	d	d
$-$	u	u	u
0	n	d	u

Table 1: Functions sufficient for semiotic control.

particular control system (a particular set of measurement, decision, and action relations), there is then very little freedom: a given state of affairs in the world will result in specific representations, predictions, decisions, and actions.

But that is not to say that all these relations are the same *kind* of constraint. In particular, we can distinguish between the kinds of constraints which Pattee calls *laws* and *rules* [9]. Laws are wholly (ontologically) necessary at all levels of analysis, but rules are necessary at one level, and contingent at another: once a particular rule or coding (set of interpretations) is established, then it must be followed, but in general from a perspective outside the system many such interpretations are possible.

This property of rules is the hallmark of semantic systems: that the coding of their symbol tokens act as *contingent functional entailments*, and are thus dually contingent and necessary at complementary levels of analysis. From *within* the symbol system, the token must necessarily be interpreted according to the code, but from *without* we are (or "evolution is") free to choose any coding we please. They are conventional, constructed and interpretable by a certain closed "linguistic community" [8].

This combination of freedom and determinism is not possible with purely physical systems. Indeed, the school of biosemiotics [4] is dedicated, in some sense, to the proposition that the classes of semiotic systems and living systems are equivalent, or at least coextensive [4, 6].

A simplified example will serve to illustrate this point. Let O be a simple organism which lives near an oceanic thermocline with warm water above and cold water below. O acts as a semiotic control system in relation to the thermocline. Its perception is a single critical variable of temperature with states

$$X = \{+ = \text{too hot}, - = \text{too cold}, 0 = \text{just right}\},$$

and it has a single variable action with states

$$Y = \{u = \text{go up}, d = \text{go down}, n = \text{do nothing}\}.$$

The information relation is simply transmission of X to the agent.

There are $3^3 = 27$ possible functions $f\colon X \mapsto Y$, any of which the agent could invoke to make a decision to take a particular action, but only the three shown in Table 1 will result in stable negative feedback control. f_1 is the best default selection, since it minimizes unnecessary action and results in smoother and faster control. But if f is not selected from these three, then positive feedback, not negative feedback, will result, with a corresponding runaway behavior.

There is no fundamental natural law of the universe which requires f to be selected according to the principles of negative feedback. Instead, this selection is *contingent on*, and *results from*, the process by which the system is *constructed.*

6.4 Selection

Thus the presence of rules (contingent functional entailments) in a "good" system, whether an "accurate" model or a "good" control system, implies a level of meta-constraint in addition to those identified in Sec. 6.2, namely the constraint on which rules themselves are viable. In the example above, this constraint can actually be measured information theoretically as $\log_2(27/3) = 3.17$ bits.

The making of *appropriate* choices is exactly the semantic function in a semiotic system. It is on this required "appropriateness" of the choice of the agent that the "intelligence" of the semiotic system rests: a certain action is "correct" in a given context, while another is not. It is only on this basis that meaning or semantics can be said to be present in a control system or a model.

This additional level of constraint is what Pattee calls *selection* [10].

Selection: *The constraint on measurement, computation, and decision by the world.* This new level of constraint is the constraint within the space of all possible rules, in particular of all possible measurements, all possible computations, and all possible actions.

Selection is an example of the pragmatic aspect of semiotic systems, and must be provided by a force acting outside of the system (control system or model) itself. The typical agents of this selection are either natural selection or the decisions provided by the designer.

Thus in a system which has contingent entailments (rules) the pragmatics of the selection of those rules invokes semantic relations of meaning among the components. In our example, it is appropriate to say that for our organism "too hot" actually *means* "go down", and "too cold" actually means "go up". This meaning is present in virtue of the *action* of interpretation provided by the agent. It is the agent which, by manifesting the coding relation f, takes "too hot" to mean "go down", etc.

7 Conclusion: The Challenge for Control in Complex Systems

Above we considered complex control in the sense of "deep" control involving multiple levels of representation or modeling. Ultimately we are interested in considering complex control in the "broad" sense of control among multiple interacting control systems or in complex environments.

As a paradigm, consider the possibility of a form of "social control", where a community of multiple, independent, interacting control systems form a higher-level aggregated control meta-system. This is the situation considered at length by Turchin and called a "meta-system transition" [14], and has been considered by Powers as conflict situations among multiple control systems [11].

Even the simplest such two-element social control system is quite complex, and its analysis is beyond the scope of this paper. Consider, for example, that for each of the component control systems, not only is the reference level (set point) of the other available to it, but in principle the entire other control system is part of its environment. Powers has commented at length on the failure of one control system to be ever able to *truly* control the other in his formal sense, and has suggested that the entire concept of a social control system is invalid.

If control is truly possible among a community of systems, the challenge will be to identify the key components necessary for any control system, in particular the measurement function and reference level. That is, where are the *representations*, where is the *semantics*, at the social level, as distinct from the iterated semantics of the consituent systems? And ultimately, what is the possible nature of *selection*, the source of all meaning, at the social level?

Acknowledgments

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