Abstraction by Time-Scale in Qualitative Simulation*

(Extended Abstract)

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February 9, 1987

Abstract

Qualitative simulation faces an intrinsic problem of scale: the number of limit hypotheses grows exponentially with the number of parameters approaching limits. We present a method called *Time-Scale Abstraction* for structuring a complex system as a hierarchy of smaller, interacting equilibrium mechanisms. Within this hierarchy, a given mechanism views a slower one as being constant, and a faster one as being instantaneous. A perturbation to a fast mechanism may be seen by a slower mechanism as a displacement of a monotonic function constraint. (In the full paper, we demonstrate the time-scale abstraction hierarchy using the interaction between the water and sodium balance mechanisms in medical physiology, an example drawn from a larger, fully implemented, program.) Where the structure of a large system permits decomposition by time-scale, this abstraction method permits qualitative simulation of otherwise intractibly complex systems.

This is an extended abstract of a paper submitted to AAAI-87.

*This research was supported in part by the National Science Foundation through grants DCR-8512779 and DCR-8602665, and by the National Library of Medicine through NIH Grants LM 04374, and LM 04515.

1 The Problem of Scale

Qualitative simulation is a promising method for reasoning with incomplete knowledge about the structure and behavior of physical systems [de Kleer and Brown, 1984; Forbus, 1984; Kuipers, 1984, 1985, 1986]. The structure of a system is described in terms of a collection of continuous parameters and constraints among them. Behavior is described in terms of changes to position and direction in qualitative *quantity spaces.* Such a constraint model may be derived from a component-connection description [deKleer and Brown, 1984], from a process-view description [Forbus, 1984], or be given as part of the problem-solver's model of the domain [Kuipers, 1984; Kuipers and Kassirer, 1984]. The advantage of these qualitative reasoning methods is their ability to express and reason with incomplete knowledge of functional relationships. For example, one may say that wind resistance increases monotonically with velocity, without needing to know or assume their exact relationship: $resistance = M^+(velocity)$.

A fundamental operation in qualitative simulation is *limit analysis*: when several variables are changing, and moving toward limiting values, the constraints are analyzed to determine which limits may be reached, and hence which qualitative states may come next. For the small to moderate-sized systems examined thus far in the literature, the natural constraint model is often sufficiently powerful to limit the possibilities to a reasonable set.

Unfortunately, there is an intrinsic problem of scale. When dealing with a large system, the number of changing variables moving toward limits may be very large. The set of global limit hypotheses grows exponentially with the number of variables. If two variables in the system do not interact, the temporal reasoning methods of Williams [1986] may be able to isolate them. However, we are frequently faced with large systems consisting of variables that *do* interact, which appear intractible to current qualitative reasoning methods.

Numerous examples throughout AI and computer science demonstrate that a powerful method fo· handling a complex problem is to impose a modular, hierarchical structure that allows it to be solved in pieces of a manageable size. In order to apply this method, we need to define a valid hierarchical structure that breaks a complex system into a collection of tractible mechanisms. The structure must also support a discipline for moving the focus of attention among the individual mechanisms in the hierarchy, and a mapping relation for communicating information meaningfully among the mechanisms. This paper presents one such structure.

We have encounterd this problem of scale in our studies of the expert physician's knowledge of human physiology, especially the systems whereby the body regulates its sodium and water balances [Kuipers and Kassirer, 1984; Kuipers, 1985]. The examples presented in this paper will draw on our models of these physiological mechanisms, but the techniques have more general applicability to qualitative modeling and simulation of large-scale systems.

2 Time-Scale Abstraction

Looking at expert physicians for our inspiration, we observe that although the human regulatory systems are immensely complicated, the experts reason effectively about them by focusing on one aspect at a time. One important method for distinguishing closely related mechanisms within the same large system is the time-scale at which they operate.

These observations lead us to define the concept of *time-scale abstraction* applied to a complex system made up of interacting equilibrium mechanisms:

> *If a complex system can be decomposed into equilibrium mechanisms that operate at widely separated time-scales, then a particular mechanism can view a faster one as being instantaneous, and a slower one as being constant.*

When a faster mechanism views a slower one as constant, the slower one can simply be treated as a source of values for certain parameters. When a slower mechanism views a faster one as instantaneous, a relation among shared variables may be treated by the fast mechanism as the result of a process over time, and by the slow mechanism as a functional relationship. (Figure 1)

**** Detailed water and sodium balance example omitted near here. ****

**** (1) Two ways to view a process. near here. ****

3 Communicating Across Time-Scales

In order to use a hierarchical model linked by time-scale abstraction for qualitative simulation of a complex system, information must be transmitted through shared variables among mechanisms operating at different time-scales.

3.1 The Pattern of Shifting Focus

We need a discipline for shifting the focus of attention among different time-scales and for making valid use of previously derived information in subsequent computations. The two directions of shift in focus from a given mechanism require different methods.

- **Faster to Slower.** Given an initial perturbation to its environment, qualitative simulation predicts the resulting equilibrium state of the fast mechanism, and shifts attention to the next slower one. The final values of parameters that are shared with the slower mechanism can be treated as part of the initial state of the slower mechanism. There are also effects on the constraints which will be treated in the next section.

- **Slower to Faster.** After a slower mechanism has reached equilibrium, the environment it provides for a faster mechanism may have changed. However, the faster mechanism, by definition, must have tracked the slower mechanism on its way to equilibrium. Thus, the fast mechanism is already in equilibrium, and simulation is not necessary. By combining the values of shared variables, the fact that the mechanism is in equilibrium, and other context information, a complete description of the equilibrium state of the fast mechanism can be derived by propagation.

Figure 2 shows the pattern of control for a three-level time-scale hierarchy, deriving the effect of an initial perturbation throughout the system. Upward arrows initiate simulation to a new equilibrium, and downward arrows initiate propagation to a complete description of an existing equilibrium state. The algorithm is as follows. After simulating a mechanism, QSIM identifies the faster mechanisms which share parameters with the current mechanism, and propagate that information to determine the equilibrium state of the faster mechanism. Once this is done, the slower mechanisms sharing parameters are identified. The current values of parameters shared with this mechanism are used to define the initial state for it to be simulated. The process repeats recursively.

**** (2) Pattern of control figure near here. ****

In order for the abstraction hierarchy to support correct simulation, control of the focus of attention must be combined with an appropriate interpretation of information from one level of the hierarchy, as viewed from another. In particular, if some change causes a fast mechanism to behave abnormally, this is viewed from the slower mechanism as a displacement of a monotonic function.

3.2 Changing the Monotonic Function Constraints

A change to a fast mechanism may be seen by a slower mechanism as a shift in a monotonic function constraint. (Figure 3) This is discussed in detail in the AAAI-87 paper, but omitted here.

**** (3) monotonic relation + shift near here. ****

3.3 Implementation Considerations

The time-scale abstraction methods have been implemented as extensions to QSIM[1], currently (2-1-87) reasoning about a three-level time-scale hierarchy consisting of the water and sodium balance mechanisms and the Starling equilibrium mechanism governing the balance of water between the plasma and interstitial compartments [Kuipers and Kassirer, 1984]. A preliminary model of control of heart rate and output has also been developed in isolation [Kuipers and Kassirer, 1985] and is being incorporated into the hierarchy. The ultimate purpose of this physiological model is to support "deep model" reasoning and hypothesis testing in medical diagnosis.

The extensions required to the knowledge given to QSIM are quite minor:

[1] As with our previous work, the program demonstrating the capabilities described in this paper is available to interested researchers. The program, named Q, is an extended version of QSIM implemented in Common Lisp. Please contact the author.

- The time-scale ordering of the mechanisms making up a system is given explicitly. Shared variables and shifted corresponding values are computed automatically when information is mapped from one mechanism to another.
- In order to map a qualitative value from one mechanism description to another, the landmarks in the quantity space have explicitly associated meanings, such as zero, infinity, or normal, which can be matched across two symbol structures representing the same quantity space.
- At the moment, with a small hierarchy, simulation continues until all related mechanisms have been considered. With a large knowledge base, a method for cutting off simulation at some lowest level of detail will be required.

4 Conclusions

In the medical physiology domains we have discussed, the natural system appears to have a suitable modular structure for imposing a time-scale hierarchy. This is not necessarily always the case. Perrow [1984] argues that certain engineered systems such as nuclear power plants are simply too complex and highly interactive for human comprehension, especially under emergency circumstances. For some systems, we suspect that the modularity by time-scale necessary for this kind of hierarchical structure does not exist, and cannot validly be imposed.

In this paper, we have presented methods for qualitative simulation of complex systems that can be structured as a time-scale hierarchies of interacting mechanisms. Another important application of time-scale abstraction, discussed in [Kuipers, 1987], is the use of the abstracted view of a process to determine the cause of a branching behavioral prediction, identifying a new distinction in the quantity space of some independent variable, and making the simulation deterministic.

We believe that these results, along with other recent developments in qualitative simulation (e.g. Williams [1986], Weld [1986], and Kuipers and Chiu [1987]), are significant steps towards robust qualitative reasoning methods capable of being applied to complex problems in the real world.

5 References

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Acknowledgments

My long-time medical collaborator, Dr. J. P. Kassirer, MD, of the New England Medical Center, has guided my attempts to become literate in medical physiology. He deserves major credit for the correct parts of the medical knowledge incorporated here. I am responsible for any errors.

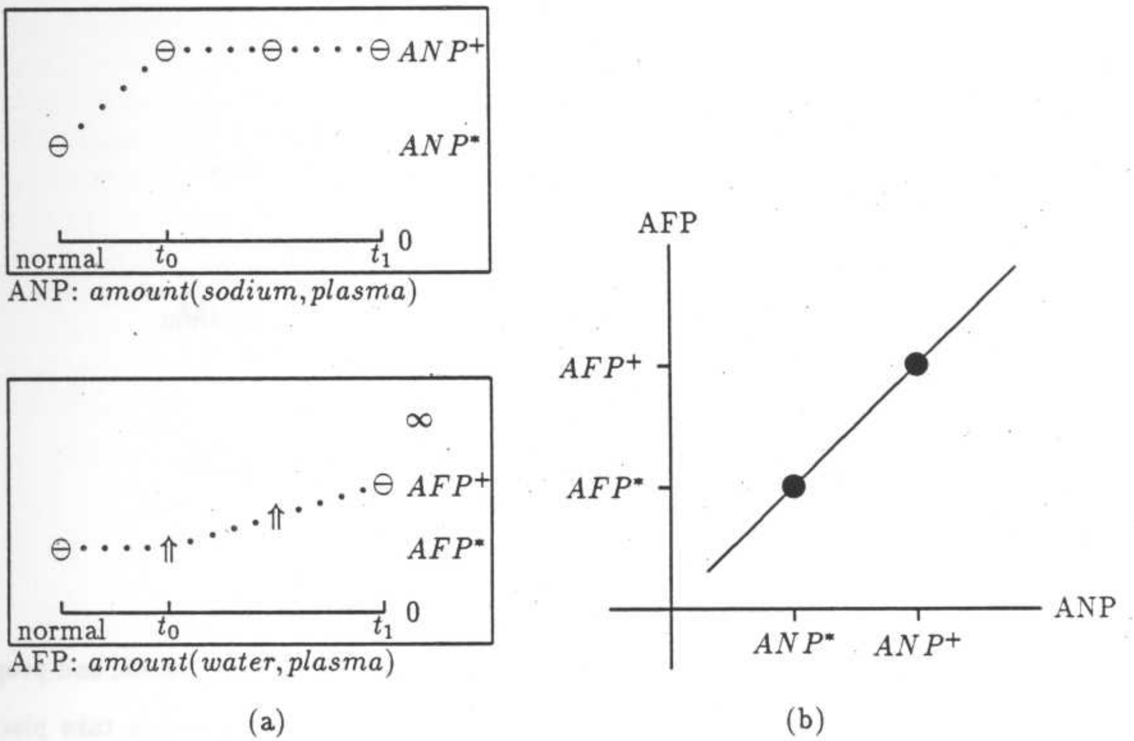

Figure 1: The relationship between ANP and AFP

- (a) From the point of view of the Water Balance mechanism a change to ANP *causes* a subsequent change to AFP.
- (b) From the point of view of the Sodium Balance mechanism, the monotonic function constraint $AFP = M^+(ANP)$ requires the two parameters to change together.

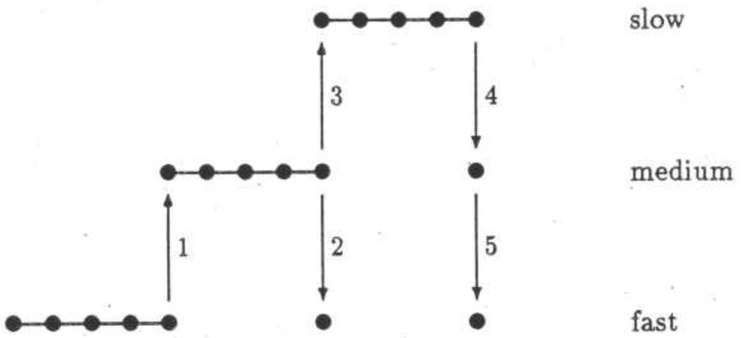

Figure 2: Control of focus of attention.

Each bead represents a qualitative state, so simulation produces a string of beads, and propagation of an equilibrium state produces a single bead. Changes in focus of attention take place in the sequence shown. (1) The equilibrium state of the fastest mechanism provides values for initializing a simulation of the next slower mechanism. (2) The final state of the second simulation is first used to propagate a new equilibrium state for the fastest mechanism. (3) Then values from both faster mechanisms are available to initialize the slowest mechanism. And so on.

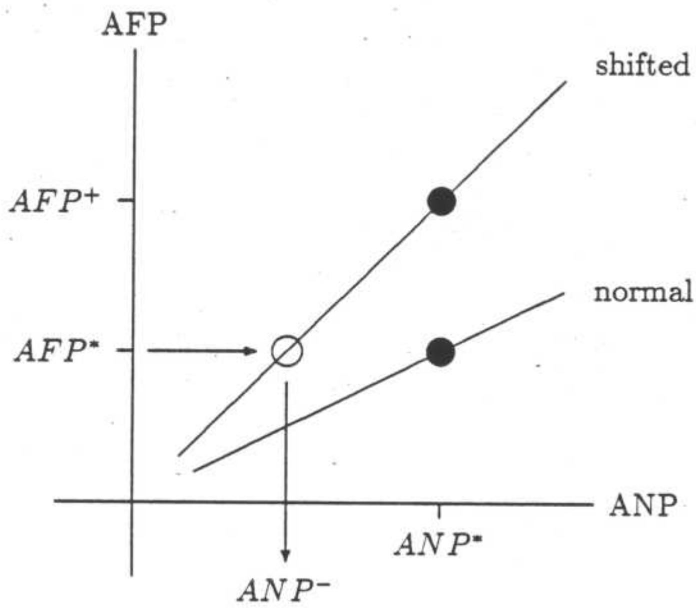

Figure 3: Normal and shifted monotonic function constraints.

The sodium balance mechanism moves to bring AFP back to its normal value AFP^*. If the relation $AFP = M^+(ANP)$ is shifted upward, ANP will reach equilibrium at a value lower than normal, $ANP^- < ANP^*$.