AI Magazine Volume 16 Number 2 (1995) (© AAAI)

Book Reviews

A Review of *Qualitative Reasoning: Modeling and Simulation with Incomplete Knowledge*

Elisha Sacks

Qualitative Reasoning: Modeling and Simulation with Incomplete Knowledge, Benjamin Kuipers, The MIT Press, Cambridge, Massachusetts, 1994, 418 pp., $45.00 (cloth), ISBN 0-262-11190-X.

Qualitative Reasoning: Modeling and Simulation with Incomplete Knowledge describes 15 years of research in the qualitative physics field of AI by the author and his collaborators. Qualitative physics seeks to automate human reasoning about the physical world. The original focus was on the commonsense reasoning that underlies everyday life, such as cooking with stoves, pouring coffee, parking cars, crossing streets, and playing ball. Recent work focuses on expert reasoning about scientific and engineering domains, including circuits, thermodynamics, power plants, chemical plants, and botany. Qualitative physics hypothesizes that commonsense reasoning and expert reasoning are similar enough to justify a unified treatment. The common challenge is to answer qualitative questions about complex systems based on partial knowledge. The cook has only a rough idea of how the stove works; the coffee drinker knows even less about how liquid flows from the pot to the cup; and the engineer must make do with approximate models of machines, plants, and processes.

Kuipers addresses qualitative reasoning about *continuous, finite-dimensional dynamic systems* (hereafter dynamic systems): pieces of the world that are modeled by a finite number of state variables whose time derivatives are continuous functions of their values. Scientists and engineers model many aspects of the world as dynamic systems. They use Newton's laws to model flying balls as systems whose variables are positions and velocities. They use Kirchoff's laws to model circuits as systems whose variables are currents and voltages. They answer questions about dynamic systems by formulating and analyzing the ordinary differential equations that govern their evolution.

Kuipers sees *qualitative reasoning* as the task of formulating and analyzing dynamic systems that model commonsense or expert domains. Like most qualitative physics researchers, he believes that ordinary differential equations are inappropriate for qualitative reasoning because they presuppose complete, precise models of dynamic systems, which are often unrealistic and unnecessary. People cross streets without knowing exactly how fast the traffic is moving or how quickly it can screech to a halt. Engineers design and repair artifacts whose physics are unmanageably complex or incompletely understood. Kuipers extends the language of ordinary differential equations with constructs that encode partial knowledge about variable values and the structure of the equations. The task of qualitative reasoning is to formulate and analyze generalized equations.

The organization of the book roughly follows the progress of Kuipers's research: Chapters 1 through 6 present the basic modeling language and analysis algorithm and illustrate them on a range of case studies. Chapters 7 through 12 present extensions that increase the expressive power of the language and the predictive power of the algorithm. Chapters 13 and 14 describe tools for model building.

The modeling language consists of qualitative differential equations that define the time derivatives of variables as functions of their values. The functions can contain arithmetic operators, symbolic parameters, and functional parameters. For example, one equation for a falling ball is $\ddot{x} = gx$, with $g < 0$, which states that the acceleration of x (the second time derivative) equals a negative constant times x, but a more abstract equation is $\ddot{x} = f(x)$, with $f \in M^-$, which states that the derivative is a monotone-decreasing function of x. The variables and the symbolic parameters take on interval and point values, called *qualitative values,* drawn from a finite partition of the real line. The most common partition is $\{(-\infty,0), 0, (0,\infty)\}$, abbreviated as [–], 0, and [+]. The analysis algorithm computes the sequence of qualitative values of the state variables starting from a given initial state. Given an initial state of x = [+] and $\dot{x} = 0$, it computes a final state of x = [–] and $\dot{x}$ = [–] from either ball equation.

The basic analysis algorithm is a two-stage constraint propagation. The first stage propagates variable values using interval arithmetic. For example, x = [+] and k = [2] imply $\ddot{x}$ =

[2] in both ball equations because $kx = [2]$, and $f(x) = [2]$. The second stage propagates derivative values using calculus rules, such as the intermediate-value and mean-value theorems. For example, the state $< x = 0, \dot{x} = [-] >$ can immediately follow $< x = [+], \dot{x} = [-] >$, but the state $< x = [-], \dot{x} = [-] >$ cannot. The stages repeat until the system reaches a state without any successors or until a state repeats. Terminal states represent asymptotic behavior, whereas repeated states represent periodic behavior. The periodicity is in terms of the space of variable values: It might or might not represent periodic behavior of the physical system. For example, a bouncing ball cycles through the states $< x = [+], \dot{x} = [-] >$ (fall), $< x = 0, \dot{x} = [-] >$ (hit floor), $< x = 0, \dot{x} = [+] >$ (bounce), $< x = +, \dot{x} = [+] >$ (rise), and $< x = [+], \dot{x} = 0 >$ (apex). Periodicity alone of these qualitative states does not determine whether the maximal height increases, is constant, or decreases between bounces.

> *Kuipers sets himself the twin goals of describing his research and writing a textbook. He succeeds brilliantly at the first goal. … However, … the scope is somewhat narrow for a qualitative physics textbook.*

Kuipers extends the language and the analysis algorithm in many ways. He adds a mechanism for creating new qualitative values that represent critical states and comparing their values. For example, the algorithm creates a new state for each apex of the ball and deduces that the heights are equal in a frictionless model. He performs comparative static analysis of quasi-static systems that quickly return to equilibrium after small displacements. The classical example is the balance between supply and demand under slowly changing market conditions. He analyzes systems with multiple operating modes by means of mode-transition rules. For example, the bouncing ball switches from free fall to elastic collision when it hits the ground. He computes numeric bounds on state variables by propagating intervals through equations. He filters behaviors based on higher derivative values, global constraints, and time-scale abstraction. For example, a global constraint that total energy decreases monotonically implies that the ball must bounce ever lower.

The final topic is the automated modeling of physical systems with qualitative differential equations. A first-principles modeler would pick state variables; estimate their range of values; and formulate their governing equations, using the fewest variables and the simplest equations that answer the user's questions. Such a modeler far exceeds the state of the art. Kuipers presents a compositional modeler that takes a high-level model as input and produces an equational model. The program picks standard components from a library that instantiate the high-level objects, links them together to reflect the high-level interactions, and formulates their equations. The approach addresses structured domains with standard components that interact in fixed ways. For example, circuits are often modeled as resistors, capacitors, and inductors that interact using currents and voltages.

Kuipers sets himself the twin goals of describing his research and writing a textbook. He succeeds brilliantly at the first goal. The book is well organized, well reasoned, well written, and well illustrated. The ideas are clearly stated, the formalization is concise and precise, and the algorithms are explained in detail. The numerous examples and figures illustrate every aspect of the research. However, I feel that the scope is somewhat narrow for a qualitative physics textbook.

A broader textbook would contain a fuller discussion of the mathematical theory of the qualitative behavior of dynamic systems, which studies the steady-state behavior of individual systems and the changes in steady-state behavior in system families. Several researchers have developed qualitative analysis programs based on numeric computation guided by the mathematical theory. Kuipers briefly discusses this research in the context of global dynamic constraints and provides many useful references. I recommend *KAM: A System for Intelligently Guiding Numerical Experimentation by Computer* by Kenneth Yip (The MIT Press, 1991) for a lucid introduction to the field.

A broader textbook would contain a discussion of other types of dynamic system beyond ordinary differential equations, especially partial differential equations, which are the norm in science and engineering (heat flow, fluid flow, stress analysis, electrodynamics). More importantly, the book focuses excessively on the simulation of dynamic systems at the expense of other types of reasoning about physical systems, including temporal reasoning, causal reasoning, diagnostic reasoning, reasoning about shape and topology, and reasoning about orders of magnitude. I recommend *Representations of Commonsense Knowledge* by Ernest Davis (Morgan Kaufmann, 1990) for an introduction to these topics.

In summary, Kuipers wrote an excellent summary of his qualitative reasoning research that should benefit students and researchers alike. The clear and detailed exposition makes it a fine course text when supplemented on a few topics.

Acknowledgments

Thanks to Jon Doyle, Leo Joskowicz, Ben Kuipers, Dan Weld, and Mike Wellman for excellent advice on the content and organization of this review.

Elisha Sacks is an associate professor of computer science at Purdue University. He is developing geometric reasoning algorithms for mechanism design, nonlinear dynamics, prosthesis design, geometric constraint solving, and other areas of scientific and engineering computing.