

THE QUALITATIVE REASONING HYPOTHESIS: A RESPONSE TO SACKS' AND DOYLE'S "PROLEGOMENA"

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1. THE CONTROVERSY

I think Elisha Sacks' and Jon Doyle's paper is a valuable contribution to progress in the field of qualitative reasoning for two reasons:

1. It sheds a light on achievements and limitations of current qualitative reasoning techniques and raises the problem of determining the future orientation of the research.
2. It clearly states one proposal for this orientation, which turns out to be wrong.¹

The main statements of their paper are:

1. Research on qualitative reasoning has not fulfilled its claims and not achieved its goal of successfully automating reasoning about a sufficiently broad class of physical systems.
2. The reason for (1) is that its current mainstream (called SPQR by the authors) is too limited and cannot overcome the limitations by simple extensions.
3. The essential limitation of the SPQR approach is that it focuses on transient behavior, whereas experts analyze asymptotic behavior.
4. The way out for qualitative reasoning is to concentrate on modeling experts' use of sophisticated mathematical methods.
5. The sophisticated mathematical models are essentially
 - a. the qualitative theory of dynamic systems and
 - b. numerical analysis.

Our response to these statements is:

1. Yes (although some people may have trouble admitting it).
2. Yes (although some people may have trouble admitting it).
3. If this refers to local state transition analysis versus a global analysis of behaviors, then, yes, it is important, although it is not a new insight.
4. No.
5. a. Oh no.
b. No no no!

2. THE EASY WAY

The obvious and simple way to get rid of the criticism of the paper would be to exploit its unconditioned, unquestioned use of the term "expert." It appears to be almost by definition an analyst of dynamic physical systems who uses differential topology, phase spaces, and numerical analysis; in other words an expert is defined to be a "Sackspert."

¹I very much appreciate the authors' capability to come straight to the point to avoid verbal compromises and to clearly identify controversies, because it supports clarification. It makes me believe that they will accept the style of this response and stand its polemic.

However, according to my experience, only a negligible fraction of people in the world who have significant experience and success in solving problems about physical systems (who are normally called experts) have even heard about phase spaces (think about people designing chips or ships, inventing toasters, repairing clocks, constructing engines, exploring geological formations, analyzing blood-cells, . . . , need more examples?). And even of those who deal with dynamic physical systems and know phase spaces, only a small number actually make frequent use of the techniques.

No, focusing qualitative reasoning on automating a "Sackspert" cannot be a general perspective. But there is a more fundamental position behind the paper which to discuss is worthwhile.

3. THE LIMITATION

The authors state that systems that can be modeled and tasks that can be solved by contemporary qualitative reasoning techniques are only a relatively small part of what once has provided the motivations and goals of the qualitative reasoning enterprise. If one looks at some of the earlier papers in the field and the objectives and expectations stated, one must agree. Sacks and Doyle claim to have discovered a particular reason for the current limitations, namely that SPQR is said to focus on transient behavior instead of following the true "experts" who mainly analyze asymptotic behavior (i.e., fixed points, limit cycles, and the like). Setting aside objections that what to focus on may depend on the system and the task, I think the criticism is not radical enough. Weakness in reasoning about limit cycles has a root which also restricts analysis of transient behavior severely, the mainly local nature of this analysis. In qualitative reasoning, development over time is mostly analyzed by determining step-by-step the possible successors of a state with very weak constraints on sequences of transitions. Although this has been realized a while ago (see Kuipers 1986; Struss 1988*a*), and although there are some attempts for generation and using nonlocal characteristics of change over time (e.g., noncrossing constraints in Lee and Kuipers (1988) and Struss (1988*b*), temporal abstraction in Hamscher (1991), qualitative shapes of functions in Sacks (1985) and Schaefer (1991), one has to admit that their success is limited. In Huberman and Struss (1989), it is pointed out that many of the more global and qualitative characteristics and concepts even cannot be expressed in our modeling vocabulary and, hence, cannot be reasoned about explicitly (such as continuity, linearity, oscillation, convergence, and, indeed, asymptotic behavior). So far, much of the efforts are dedicated to qualitative reasoning in the sense of nonnumeric reasoning about real-valued variables (and to replacing reals by intervals). However, there are many more qualitative features of systems and their behavior, such as how to characterize a "body with a hole," how to distinguish inside and outside of a container (interesting work is described in Randell, Cohn, and Cui 1991), how to reason about sieving pebbles (see Huberman and Struss 1989), etc. There are many open questions and we have a number of choices. A reconsideration of the roots, goals, and perspectives of qualitative reasoning seems to be necessary.

4. THE CROSSROADS

Current work in qualitative reasoning, explicitly or implicitly, proposes a number of directions to follow. I think the following are the most important proposals for focusing the research:

- Investigate the use of quantitative information. ("Obviously, qualitative reasoning loses some information; so adding quantitative information and numerical methods is crucial for progress in the field.")
- Use modern mathematics. ("It provides methods which easily solve the problems qualitative reasoning still struggles with, such as the mass on a spring.")
- Study the existing science of physics. ("After all, it has been developed over hundreds of years and modern technology is a proof that it correctly models what we are after, physical systems.")
- Concentrate on naive physics. ("We are all experts in dealing with physical systems, because we do it quite successfully every second in our lives.")

When analyzing what the right direction is, we do not pretend to find out what the original goal of the field was (this would not produce a unique result, anyway), but assess what the emphasis should be, given our present experience. But no matter which motivation made AI researchers establish a field called qualitative reasoning (or "qualitative physics"), there is a common necessary condition for all of them.

5. THE QUALITATIVE REASONING HYPOTHESIS

This is the hypothesis that there exist *general* concepts and inference schemes that form a basis for various kinds of qualitative reasoning about physical systems (independently of or prior to specialized techniques in particular domains), which, hence, can be analyzed, modeled, and automated *in general*. In other words, this is the assumption that qualitative reasoning can establish a coherent subfield of artificial intelligence. There is some evidence for this hypothesis, since every human being is, to some extent, able to get along with the physical environment without too much consideration of detailed, numerical information. But again, let us admit that, so far, we have not been able to identify a collection of basic concepts and inferences that gets even close to the performance of humans. Do the directions of the crossroads discussed above offer solutions?

6. THE QUANTITATIVE TEMPTATION

"It is not amazing that you do not derive strong, unambiguous results when you throw away the numbers" says a common argument. "Why are you so afraid of exact numbers? If you want to solve a concrete problem, you have to use specific information about it. Solving the problem of how to combine qualitative reasoning methods with numerical information should now be in the focus of the field of qualitative reasoning." There is no doubt that completely solving a particular case of a problem usually requires numerical information and computation. But how can this become the focus of research that tries to figure out how one can reason without this kind of information? (Nobody would use the experience that not everything can best be expressed in natural language and that sometimes graphics is more adequate, as an argument to propose graphical representations as the focus of natural language research.) This would mean that either qualitative reasoning has already solved its main problems or that the qualitative reasoning hypothesis has been refuted, and neither is the case.

Even stronger, we argue that numerical information is useless and meaningless unless we already have a qualitative understanding of the essential relationships. Without this, we would not even be able to determine what numerical information must be obtained in

order to solve a problem. Probably, Sacks and Doyle agree with this statement, since they consider an "informed use of numerical analysis" and state that "the main problem today is interpretation (its) output". As the essential guide for the use and interpretation of numerical data they offer mathematics.

7. THE MATHEMATICAL ILLUSION

We agree that mathematics provides a considerable collection of qualitative concepts, such as continuity, smoothness, bifurcations, and many of its theories are completely qualitative (think, for instance, of topology). In particular, Poincaré developed his theory of differential equations with the explicit goal of deriving qualitative information about systems or ordinary differential equations that cannot be solved analytically. So, why does qualitative reasoning not focus on the automation of mathematical techniques developed on this theoretical basis? This is in fact Sacks' and Doyle's proposal, and they call mathematics "the best known language for formulating and analyzing models." Even if one believes this, it does not imply that mathematics provides the means for *developing the right models and representations*. Nor can mathematics generate an *interpretation* of its result or an intuitive *explanation*. "Just take the equations and analyze them" is no solution, because without an initial qualitative understanding we could not even come up with a schematic picture of a mass on a spring as a representation of a real situation, and we could not note down the variables required to describe it, let alone any equation linking them. All this already presumes a qualitative analysis of the situation which identifies the important entities and the essential descriptive concepts. Although undoubtedly new qualitative information can arise from the analysis of quantitative models, qualitative reasoning is a prerequisite for the construction and use of mathematical models, and this problem should be right in the heart of our field. (The fact that finding appropriate ontologies is part of it and has been an important focus in qualitative reasoning is mainly ignored in the paper.) Sacks and Doyle appear to agree with the latter statement and call "automating the formulation of models" the "central problem for qualitative physics." But then there seem to be two spirits in the paper. While Dr. Sacks advertises that "mathematical concepts and results already available suffice to automate substantial amounts of expert reasoning," Mr. Doyle notices that "the central problem," model building, "is a problem that neither mathematics nor most qualitative physics has addressed." How can then Dr. Sacks claim that "the concepts of advanced mathematics provide formal ways for expressing these underlying assumptions of the modeling process? This can only be true with respect to the entities *in the model*, but not for the concepts that guided the *construction of the model*. The authors propose a process of analyzing and revising models in order to obtain "specific differential equations that capture the features of interest." The problem for qualitative reasoning is to determine *what features are interesting* and essential. The required criteria and the respective reasoning are outside the mathematical world. The authors want to distinguish between "wild behaviors" and "normal behaviors." This has to be done by reference to reality; the physical world decides what is "normal" and what is "wild," not mathematics. Substituting the mathematical model for the real physical system is a widespread problem in science (discussed for instance, in Huberman and Struss 1989). If a model or, rather its analysis, produces the result that the mass on the damped spring might oscillate forever, isn't this ridiculous? The aluminum block on the polished table could oscillate *forever*?! Nonsense.

So, here we are again on the crossroads, noticing that the advertised mathematics is not the main road. It can be a useful tool for formulating models and inferences based on

them, but does not offer much help for the fundamental qualitative analysis of reality that produces and interprets the model. And, if asked to *explain* how a system works, even "Sacksperts" tend to not merely display a third-order differential equation but switch to a different language that has references to the physical world.

8. THE WORLD OF PHYSICS

Does this mean we mainly should import more concepts and techniques from physics and engineering? Actually, it would not hurt. However, many of the arguments about mathematics apply to physics as well. After all, it is one of the most important "customers" of mathematics. And although physics offers an almost exhaustive collection of models of physical systems, it does not offer a model of the modeling process itself. Many physics students have painful experiences because of this. Differential equations and their solutions appear on the professor's slides (and their underlying simplifying assumptions) like the writing on the wall, but it is so hard to rediscover them in a mess of physical objects, some of which are even invisible (e.g., the center of gravity). Physics and engineering do provide many techniques for processing and deriving qualitative information. However, gathering and analyzing these various techniques could only be a first step and not the main purpose of qualitative reasoning. It could only produce a mound of specialized techniques, tied to particular conditions and assumptions and by no means represent the *general* principles of qualitative reasoning postulated by the qualitative reasoning hypothesis. But this could establish the empirical basis for work along this line, which aims at determining the common foundations of the specialized methods, the basic concepts that tie them together and enable us to use them reasonably. But where are these common foundations located, if they are not to be found in mathematics and physics? I believe they can only be found in what is shared by all the specialists and experts working with superficially distinguished techniques in different areas. This is given by what they share with all humans, the capability to act in and reason about the physical world we encounter in our everyday lives, our commonsense reasoning.

9. THE WRONGNESS OF COMMON SENSE

But is this not the opposite pole? Can we really hope to develop useful theories and systems that support engineers and scientists in their sophisticated work, if we ground qualitative reasoning on the fuzzy, uninformed, erroneous reasoning of the man in the street, who believes that a heavy stone falls with a higher speed than a lighter one?! Often, "common sense" is almost used as a synonym for erroneous views on physical reality. No doubt about the influence of modern science and technology on our common perspective of the physical world. But, as a matter of fact, I am convinced that our basic education provided by our (mainly mechanical) environment is not being exorcized once Maxwell's equations have been displayed to us in a physics seminar room. An aeronautics engineer does not perform differently from his 12-year-old son when putting a plank over a creek or when opening a can. Even stronger, I believe that our capabilities in developing and applying advanced theories and technology is ultimately rooted in what has been called "naive physics," in experience gained under a mainly causal, mechanistic view of physical processes, and a portion of spatially oriented analogical reasoning. Where else should it be rooted? Tie a child in front of a slide projector and display differential equations, solution techniques, logical axioms, and deductive rules. Even if you continue over years,