THREE RADICAL QUIBBLES WITH THE "PROLEGOMENA . . ."

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From my perspective as a mechanical designer and developer of theory and computation tools for mechanical design, Sacks and Doyle have provided a convincing and overdue challenge to qualitative simulation. SPQR is interesting, but involves a reduction from the expressive power of differential equations. Engineers generally need more rather than less expressive power; I am unaware of any successful applications of qualitative simulation in mechanical design. "Prolegomena . . ." explains why in clear and well-supported terms.

Sacks and Doyle rightly restrict themselves to conclusions for which they have evidence; having been asked for my opinion, I feel no such constraint. The following sections argue that Sacks and Doyle are in three ways too conservative. First, they seek only to reform qualitative physics, but no purely qualitative automated physics can be of much value to mechanical designers. Second, they underestimate the extent to which computational capabilities are a potential source of new mathematics. Finally, they do not go far enough in calling for a fusion between AI and non-AI fields.

1. NO *PURELY* QUALITATIVE PHYSICS WILL BE VERY USEFUL TO MECHANICAL DESIGNERS

A qualitative physics presumably uses only representations which do not refer to quantities. Such representations exclude ratios: there is no way in them to say that "x is about two or three times y." They thereby focus attention on the ordering or directional characteristics of the real line; "x is larger than y, but y's derivatives are positive and x's are not, so y will eventually become larger than x."

Engineers, however, depend heavily on quantitative information. The damped harmonic oscillator described in Section 2.5 of Sacks and Doyle is instructive. That SPQR cannot predict its behavior is telling; the example is both simple and fundamental to engineering. For example, the suspension of an automobile is a more complex damped harmonic oscillator. But while Sacks and Doyle suggest a qualitative physics focused on asymptotic behavior, engineers focus on the *quantitative, transient* behavior of the suspension: How far will the car roll in a curve? How rapidly will the oscillations die?

To be sure, most design decisions are made without numeric calculation. But they are not qualitative: the mechanical designer estimates quantities by eye, determining that the shape is well proportioned with respect to the few characteristics that have been calculated. This sense of relative quantities is among the most important of a designer's skills. Another, equally important, is the ability to quickly determine whether a quantity needs to be checked precisely, find a way to do the checking, and make an appropriate trade-off between the precision of the answer and the cost of getting it.

This is not to say that qualitative reasoning is useless, merely that it should be fused with quantitative reasoning. Monotonicity analysis (Papalambros and Wilde 1988) is a powerful technique which uses qualitative information (often manipulated by symbolic mathematical programs (Agogino and Almgren 1987) to guide quantitative optimization.

2. COMPUTATION OFTEN INSPIRES NEW, USEFUL PHYSICAL MATHEMATICS

Sacks and Doyle largely dismiss the first motivation of qualitative simulation: the sense that computation reveals incompleteness in the traditional mathematics of physical reasoning. Conversely, I believe that computation, by dramatically enhancing the power of formalisms, is a powerful inspiration for new physical mathematics.

Chaotic dynamics is the most profound such development thus far. The phase spaces discussed by Sacks and Doyle predate electronic computers, but the current wave of interest in them, and the startling observation that deterministic processes often produce completely unpredictable results, are largely consequences of swift electronic calculation (Glieck 1987). Visualizations of the Mandlebrot set are a striking example. Finite element analysis is another new mathematics, important in engineering in part as a method for determining the response of complex solid structures to loads. It has largely displaced the elegant but limited methods of elasticity by the brute process of dividing the structure into small elements, representing the response of these elements in matrix form, and calculating the overall response by a relaxation method.

Engineering design is potentially a particularly rich source of new mathematics, because while engineering analysis applies basic classical physics to reason about a particular object under particular operating conditions, designers reason about sets of possibilities. The "feature algebra" of (Karinthi and Nau 1991) is one example; given a feature such as a hole in a solid, it determines the set of intermediate features associated with various sequences of machining operations which might be used in producing the solid. Nonmanifold geometries are another example. My own work (Ward and Seering, 1989) is largely devoted to developing formal mathematics for quantitative set-based design reasoning. In part, it involves inverses to interval arithmetic (itself a mathematics inspired by problems in computation). Another aspect of the work can be viewed as specialized theorem proving; yet another addresses issues of distributed decision making.

3. ANY DISTINCTION BETWEEN AI AND NON-AI ENGINEERING, PHYSICS, AND MATHEMATICS IS PERNICIOUS

Ironically, while others struggle to escape discipline boundaries, AI researchers often struggle to create them. Thus, Sacks refers to his work as "qualitative physics" presumably in order to appeal to "qualitative physicists," while as an engineer I would admiringly describe it as "automated physics," fusing quantitative and qualitative aspects. Disciplines facilitate judging research and researchers, but impose limits. I believe AI has been mostly accidently defined, by a few influential theses; the resulting limits are arbitrary, futile and destructive (see also Doyle 1988).

AI researchers seem mostly engaged in creating symbol structures and patterns of manipulation for them, such that the manipulations say useful and interesting things about the world; certainly this description fits qualitative simulation researchers. But it also fits most scientists and engineers; the difference is that AI researchers explicitly orient their symbol structures toward electronic computation. However, this difference is decreasingly important. First, as languages and hardware improve, formalisms depend less on computation, and more on their domains. Second, the computer is becoming a universal and ubiquitous tool. I believe that in time the computational formalizer's skills will be as essential to scientists and engineers as English or algebra. Most physical thinking will be aided by computer, most thinkers obliged to understand computational concepts and limitations. Only a smooth gradation will be observed between the more physically oriented and the more computationally oriented. AI will be lost in the symbioses between humans and computers as the match is lost in a bonfire.

Sacks and Doyle correctly argue that AI should embrace classical mathematics. But the embrace should be neither unidirectional, nor limited to mathematics. My own work is interesting (to me at least) precisely because it applies the formalizing skills of AI to real engineering problems, in the process extending real mathematical methods and capturing real physical reasoning. The work erases boundaries between old and new mathematics, logic and numeric calculation, AI and classical mathematics. Any effort to restrict myself to one "discipline" would have guaranteed failure.

Technological and mathematical knowledge are essential to the high performance of human intelligence in many fields, including the ones in which sophisticated use of computers has been most useful. AI researchers who ignore this knowledge are likely to fall into a cycle of attacking a real problem, developing a formalism which solves a limited version of the problem, proclaiming it as the solution to all problems, then spending the next decade in self-absorbed and futile refinement of the formalism. The authors should replace "qualitative" with "automated" in their title, and extend their thesis to completely dissolve the pernicious distinction between AI versions of mathematics, physics, and engineering, and the real ones.

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