An extension of the corresponding value technique in qualitative modeling and simulation

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Abstract

Qualitative simulation programs use tuples of corresponding values of system parameters in order to represent additional information about the relationships among the parameters of the system under consideration. Presently available qualitative simulators [2,5] require that the values appearing in these tuples be points. We show that, by allowing intervals in corresponding value tuples, even more information about the relationships of the system can be represented. This technique eliminates a class of spurious predictions of the QSIM algorithm, which other reported methods cannot detect.

1. BACKGROUND

A number of programs and methodologies for performing various forms of qualitative reasoning about physical systems have been developed [1,2,5,9,10]. In accordance with the underlying principles of naive physics [4], these programs adopt an epistemological scheme in which unknown or irrelevant details about the values and relationships in the modeled physical system are not represented. Parameter values are shown only in terms of their ordinal relationships with previously designated "important" magnitudes (*landmarks*.) The ordered set of landmarks of each parameter is called its *quantity space*, and a parameter magnitude is either a landmark or an open interval between two adjacent landmarks in the quantity space. Exact forms for the functional relationships among the parameters of the system are not given. Generally, such functions are restricted to belong to the families of strictly increasing or decreasing monotonic functions.

To be able to represent more about the "shapes" of these functions, while staying within the limits of the qualitative representation, Forbus [2,3] introduced the technique of using tuples of *corresponding values* of related parameters for such relationships. A corresponding value tuple links a landmark of one parameter with a landmark of the other parameter, therefore fixing a point in the "plot" of the function among the parameters. Consider the classic example where we want to represent the relationship between the amount of liquid in a tank and the pressure at the bottom of the tank. It is known that a strictly increasing monotonic function among these parameters exists. Using the notation and terminology of Kuipers' QSIM algorithm [5], it is known that there is an M+ constraint linking them, i. e.

M+(amount, pressure)

holds.

However, this constraint alone is not sufficient to represent our (admittedly incomplete) knowledge about the considered relationship. Some of the functions that are mapped to this constraint can be seen in Figure 1. Knowing that these two particular parameters should never have negative values, consider only the first quadrant in that figure. Clearly, none of the plotted functions is satisfactory for our example, since they depict cases where one parameter can have the value zero while the other one is nonzero. Qualitative reasoners using only this information about this relationship will produce results which do not correspond to reality.

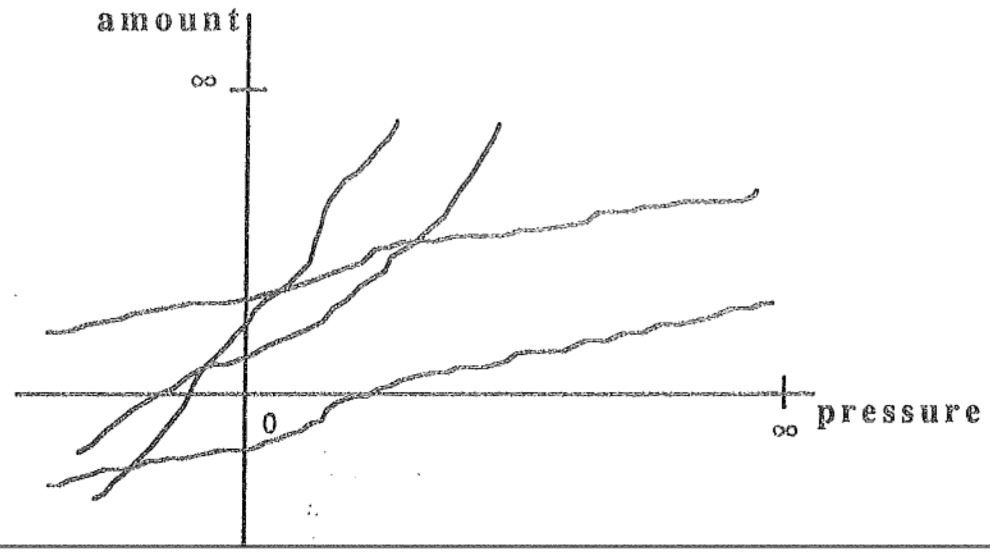

Figure 1. M+(amount, pressure) with no CVs

If one includes the corresponding value (CV) tuple (0,0) associated with the M+ constraint among the parameters in the input, none of the problematic functions of Figure 1 will be considered by the program. Only the set of increasing functions passing through the origin will be represented, which is all one can do with the present amount of knowledge.

2. INTERVAL CORRESPONDING VALUES

Even when such corresponding values are employed, one does not make full use of the qualitative setup to represent available information. We have identified the cause of this to be the insistence [2,3,5] that all magnitudes which appear in CV tuples should be landmarks. We claim that, by changing the definition of corresponding value tuples to include intervals as well as point values, and modifying the qualitative arithmetic routines that operate on these values, a better qualitative reasoner can be obtained. We will demonstrate this on examples from Kuipers' QSIM program [5].

Consider the case where we have two parameters X and Y with a functional relationship f: X → Y, where f is an increasing function, and the following is known about the function and the landmark values of the parameters::

X has two positive landmarks, x1 and x2, such that x1 < x2.

Y has two positive landmarks, y1 and y2, such that y1 < y2.

f(0) = 0

f(x2) = y2

f(x1) > y1

Note that all these are ordinal relationships and are easily representable using the qualitative scheme. But no reasoner using the "classical" corresponding value technique can represent the inequality above. Figure 2 shows three functions which are mapped to the classical representation of f. Two of these are inconsistent with our knowledge of f(x1), however, the CV tuple (x1, (y1,y2)), which embodies that information, is not allowed by the points-only representation, so the program cannot distinguish the three functions.

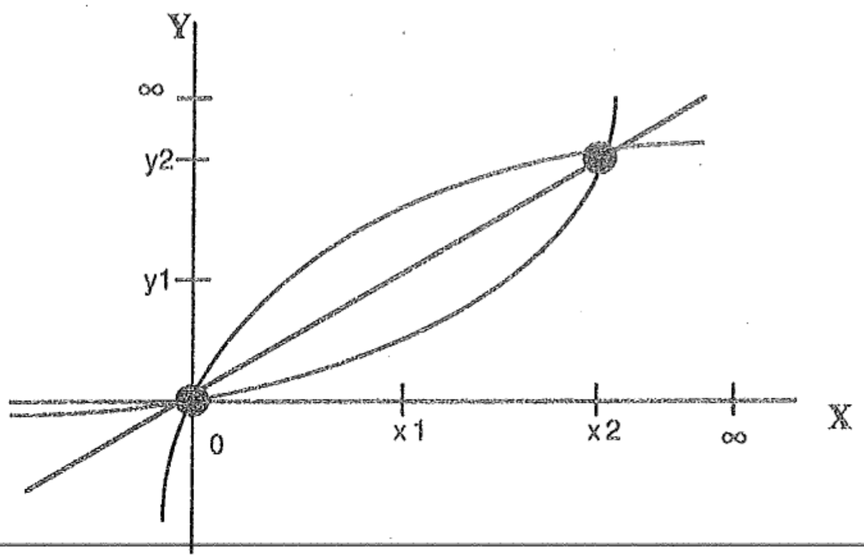

Figure 2. M+(X,Y) with CVs (0,0), (x2,y2)

If intervals were allowed in CV tuples, (x1,(y1,y2)) could also be associated with the M+ constraint, and we would have the (desirable) situation shown in Figure 3.

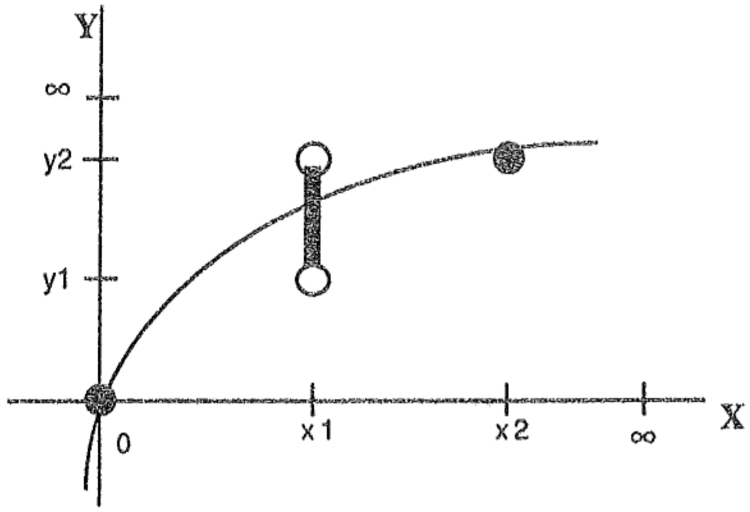

Figure 3. M+(X,Y) with CVs (0,0), (x2,y2) and (x1,(y1,y2))

3. ELIMINATING SPURIOUS BEHAVIORS

We have implemented the modifications entailed by allowing intervals in CV tuples on our version of the QSIM program [9]. An example system, for which "pure" QSIM predicts four spurious behaviors (all of which are detected and eliminated by our version) in addition to the 11 correct possibilities, will be presented now. Consider Figure 4. A little ball is thrown vertically upward from the ground. A small and powerful light source is fixed at a location of a certain height to the left of the point of takeoff of the ball. It is assumed that the ball can never reach the height of the light source. The height, velocity, and acceleration of the ball are parameters Y, V, and A, respectively. A is fixed at a negative landmark. One is also interested in the position of the ball's shadow on the ground, represented by parameter X. 0 (zero) is the point of takeoff of the ball in both X and Y's quantity spaces. The ground is level (i.e. has no "bumps") so that X is a continuous function. The highest altitude that the ball has ever reached before is the landmark alt_rec in Y's quantity space. There is a dead bug lying at a point to the right of the ball's takeoff point. X has the positive landmark bug_pt when the shadow is on the bug. Light travels infinitely fast (for the commonsense time scale at which the system is being viewed, of course.) The set of constraints is that of Table 1. (DERIV(X,Y) simply means that $\frac{dX}{dt} = Y$.) The sign of the time derivative of each parameter is also represented in the table. In this notation, **inc** means +, **std** means **0**, and **dec** means -.

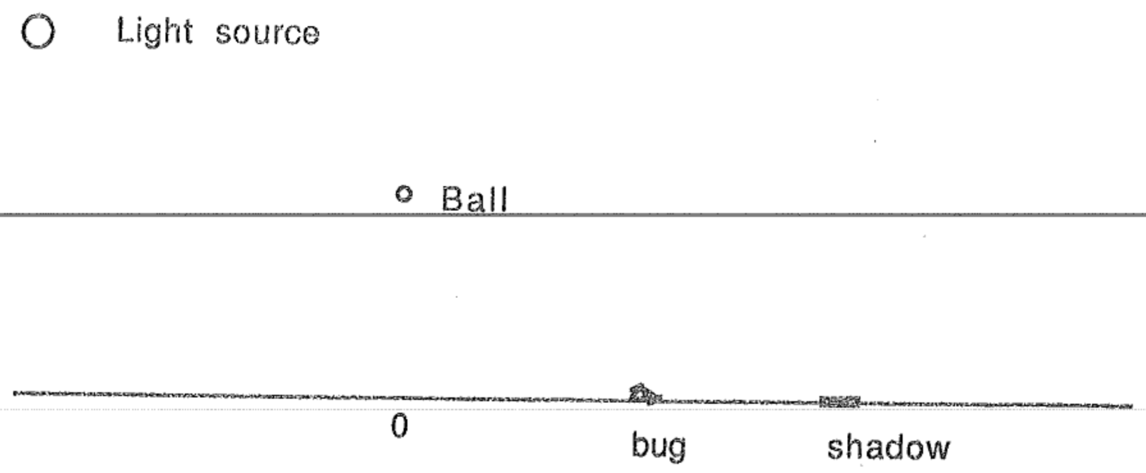

Figure 4. The ball / shadow system

Table 1
Constraints of ball / shadow system

Constraint	CVs
DERIV(V, A)	
DERIV(Y, V)	
M+(X,Y)	(0,0)

The ball is shot up with initial velocity v_0 at t_0. Table 2 contains part of one of the spurious behaviors that pure QSIM predicts. Let us examine this behavior. The ball is shot up at t_0. At t_1, it breaks the old altitude record and goes on climbing. At t_2, when the ball is at a point above alt_rec, its shadow falls on the bug. At t_3, both the ball and its shadow stop for an instant, and their magnitudes at that point are recorded as CVs. After that, the ball starts going down, crossing alt_rec at t_4. But the shadow has still not reached the bug for a second time. This is inconsistent with the available knowledge about the function from Y to X at t_1, so Table 2 contains a spurious behavior.

Our version of QSIM, which uses interval as well as point values in CV tuples, does not predict this spurious behavior. The algorithm is able to compare the X and Y values at time point t_1 with the proposed values at time point t_4. Since the CV tuple (alt_rec,(0,bug_pt)) is inconsistent with the proposed value tuple (alt_rec,(bug_pt,NewX)), (a function does not map a single point to two mutually exclusive intervals,) that proposal for t_4 will be eliminated. For M+ constraints, this check is implemented as follows: If the proposed magnitude tuple is (m_A, m_B), and a CV tuple (p, q) exists, the signs of $(m_A - p)$ and $(m_B - q)$ should be the same. In our example,

$$\text{alt\_rec} - \text{alt\_rec} = \mathbf{0} \neq (\text{bug\_pt},\text{NewX}) - (0,\text{bug\_pt}) = +,$$

so the proposed tuple fails the test.

Table 2
Spurious behavior of ball / shadow system

time	Y	V	A	X
t_0	<0, inc>	<v_0, dec>	<g, std>	<0, inc>
(t_0,t_1)	<(0, alt_rec), inc>	<(0, v_0), dec>	<g, std>	<(0,bug_pt),inc>
t_1	<alt_rec, inc>	<(0,v_0), dec>	<g, std>	<(0,bug_pt),inc>
(t_1,t_2)	<(alt_rec, ∞), inc>	<(0, v_0), dec>	<g, std>	<(0,bug_pt),inc>
t_2	<(alt_rec, ∞), inc>	<(0, v_0), dec>	<g, std>	<bug_pt, inc>
(t_2,t_3)	<(alt_rec, ∞), inc>	<(0, v_0), dec>	<g, std>	<(bug_pt,∞),inc>
t_3	<NewY, std>	<0, dec>	<g, std>	<NewX, std>
(t_3,t_4)	<(alt_rec,NewY),inc>	<(-∞, 0), dec>	<g, std>	<(bug_pt,NewX),dec>
t_4	<alt_rec, dec>	<(-∞, 0), dec>	<g, std>	<(bug_pt,NewX),dec>

Quantity space of X: {-∞, 0, bug_pt, NewX, ∞}

Quantity space of Y: {-∞, 0, alt_rec, NewY, ∞}

Kuipers and his colleagues have reported on various methods of extending QSIM so that it will predict fewer spurious behaviors. All of these approaches involve the addition of new types of constraints to the qualitative vocabulary, making use of the energy or phase properties of the system [6,8], or by making "unsafe" assumptions (which may lead to real possibilities being eliminated) about the shapes of the monotonic functions to automatically calculate values of the higher-order derivatives [7] in the system. Our modification handles a class of spurious behaviors different from the one targeted by these methods. It can be demonstrated [9] that our modified QSIM can eliminate spurious predictions which are not detected by the proposals of [6-8].

4. A STRONGER QUALITATIVE ARITHMETIC

Our implementation of the interval corresponding value feature also involved an improvement to the qualitative arithmetic routines employed during the CV checking phase. In order to check proposed parameter magnitudes for consistency with the previously recorded corresponding values, the QSIM algorithm uses qualitative subtraction and division. When intervals are allowed as corresponding values, one may be faced with a situation where one has to apply these operations to two instances of the same interval magnitude; i. e. one has to evaluate

$$(a,b) - (a,b)$$

or

$$\frac{(a,b)}{(a,b)} .$$

In the general case, these operations give ambiguous results. However, keeping in mind that both operands in the above operations are values of the same parameter, and that QSIM keeps all of the previous values of all parameters for cycle detection purposes, it is possible to determine unambiguous signs for these in some cases. Assume that the qualitative states through which parameter P has passed since the beginning of the simulation are as in Table 3. Suppose now that the arithmetic routine is trying to subtract P's value at t_1 from its proposed value at t_3. Clearly, the result of this operation is unambiguously - (negative), since the parameter has been decreasing in all the time from t_1 to t_3. The extension of this idea to similar situations in which the parameter is increasing, rather than decreasing, and to the division operation is straightforward.

Table 3
Proposed behavior of parameter P

time	P
t_0	<(a,b),dec>
(t_0,t_1)	<(a,b),dec>
t_1	<(a,b),dec>
(t_1,t_2)	<(a,b),dec>
t_2	<(a,b),dec>
(t_2,t_3)	<(a,b),dec>
t_3	<(a,b),dec>

5. CONCLUSION

We presented a method of better exploiting the qualitative representation to obtain tighter qualitative simulations. The ideas explained here have been incorporated into our implementation of QSIM. Case runs and technical details can be found in [9].

REFERENCES

1. de Kleer, J. and Brown, J.S., A qualitative physics based on confluences, *Artificial Intelligence* **24** (1984) 7-83.
2. Forbus, K.D., Qualitative process theory, *Artificial Intelligence* **24** (1984) 85-168.
3. Forbus, K.D., Qualitative physics: Past, present and future, in: D.S. Weld and J. de Kleer (Eds.), *Readings in Qualitative Reasoning About Physical Systems* (Morgan Kaufmann, Los Altos, CA, 1990) 11-39.
4. Hayes, P.J., The second naive physics manifesto, in: J.R. Hobbs and R.C. Moore (Eds.), *Formal Theories of the Commonsense World* (Ablex, Norwood, NJ, 1985) 1-36.
5. Kuipers, B., Qualitative simulation, *Artificial Intelligence* **29** (1986) 289-338.
6. Kuipers, B., Qualitative reasoning: Modeling and simulation with incomplete knowledge, *Automatica* **25** (1989) 571-585.
7. Kuipers, B. and Chiu, C., Taming intractable branching in qualitative simulation, in: *Proceedings IJCAI-87*, Milan, Italy (1987) 1079-1086.
8. Lee, W.W. and Kuipers, B.J., Non-intersection of trajectories in qualitative phase space: A global constraint for qualitative simulation, in: *Proceedings AAAI-88*, Saint Paul, Minn (1988) 286-291.
9. Say, A.C.C., Qualitative System Identification, Ph.D. Dissertation, Department of Computer Engineering, Boğaziçi University, İstanbul, Türkiye (1992).
10. Williams, B.C., Qualitative analysis of MOS circuits, *Artificial Intelligence* **24** (1984) 281-346.