The Epistemology of Physical System Modeling

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Modeling and simulation have been typically pursued in isolation. When a model of a complex system is reported in the literature, there is a considerable emphasis on the end result, the model. On the other hand, many works on simulation assume the existence of models, and focus on developing representations and reasoning about the models in the representations. However, not every physical system has its models ready to use for problem-solving tasks and constructing adequate models is not trivial. Choosing a simulation method is also dependent on the kinds of models available, the creation of which in turn depends on the knowledge available and its representation. A model of a physical system is normally created by the person studying the system with considerable time and effort spent. But a hand-crafted model is often error-prone and difficult to modify to solve a similar problem about other physical systems.

Our work is motivated by three goals: (1) examining the process of model-building and simulation, as well as the types of knowledge and their representation required to perform the process or to evaluate the process and its results; (2) automating the process of model-building and simulation to reason about moving objects; and (3) making the modeling process as general as possible so that common knowledge can be shared and reused instead of being duplicated.

Consider, for example, a spring with one end attached to a fixed point and the other end attached to a block. If the block is pulled from its equilibrium position and released, it shows oscillatory motion on a straight line. This harmonic oscillator is a common textbook example which is frequently used in qualitative physics research. It is well known that the oscillator has one degree of freedom, i.e., displacement of the block from its equilibrium position. However, if the block is pulled *and* rotated from its equilibrium position before being released, predicting its behavior is not as simple as before. Is the motion going to be still oscillatory? More interesting questions include: (1) What if a spring is attached to a corner of a block instead of the center of the face? (2) What if a block attached to a spring is put in arbitrary position and orientation before being released? (3) What if two blocks are connected by a spring? (4) What if multiple blocks connected by multiple springs are put in arbitrary positions and orientations?

Different forms of these problems require spatial reasoning to formulate equations of motion, in particular the ability to reason explicitly about vector quantities and moving frames of reference. Many qualitative physics approaches which can solve the linear harmonic oscillator problem cannot handle the more complex problems we describe above because they lack this spatial reasoning ability.

We have developed an automated modeling and simulation system called ORACLE. Knowledge is represented with general model fragments in a purely declarative, neutral, algorithm-independent form; most of the knowledge is just the same fundamental equations that appear in any standard text on the subject, with their implied semantics of vectors and frames of references. Starting with the basic, simple knowledge, ORACLE generates a powerful model and simulator which can be used to predict the motion of a physical system with multiple moving objects in arbitrary configurations. Evidence of the generality of the ORACLE approach across different types of physical systems was demonstrated by the experimental results of testing it on spring-block systems in a variety of configurations, sailboats in fluids, and composite objects of rigid bodies. ORACLE can also model many other types of physical systems with no or minor changes, including multiple rigid bodies connected by springs, propeller-driven airplanes, and spinning balls. This extensibility to a broad class of physical systems is possible for several reasons. First, knowledge is represented in a general form and instantiated later for particular situations so that common knowledge can be shared and reused. Second, instead of using a special purpose method intended to handle a certain class of physical systems only, a general method is used to construct and simulate models; model fragments relevant to a physical system being modeled are identified and composed to formulate a model, and the model is applied to solve a problem.