Rethinking Logics of Action and Time

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***Abstract*—It is over thirty years since I developed interval temporal logic and the accompanying logic of action and time. Overall, these theories have held up well and, with some extensions over the years, have remained useful in our work on AI planning/reasoning systems and natural language understanding. Recently I have become interested in systems that can learn by reading, and specifically, that can learn necessary conditions for event occurrence from reading dictionary definitions. This task adds new constraints on the form of the temporal logic we need. In this talk, I will review our earlier work on temporal logic and then look at the problems that have forced a recent generalization of the formalism in order to allow compositional construction of event definitions from natural language definitions.**

***Keywords*-Temporal Logic; Models of Events and Action**

I. Background

My original formulations of actions and time still seem valid today, and form the underpinnings of our new work. The major claim in this work was that eventualities (reified states, events and activities) define stretches of time (*time intervals*) over which they are realized (i.e., where states hold and events occur). Studying these temporal projections of eventualities lead to the interval theory of time. Critical to this theory was stepping away from the standard physics interpretation of time as a continuous dense ordering modeled on the real numbers. The most prominent departure of the interval model was the preeminence of the meets relation, where one interval is entirely before another and yet there is no time between them and they share no time in common. Allen & Hayes (1990) show how the complete interval logic can be derived from the *meets* relation, yielding the thirteen possible interval relations introduced in Allen (1984). The Allen & Hayes model also introduced the notion of *moments*, which are minimal intervals of time. Moments have no subintervals and represent a conceptual snapshot of time. Nothing can change within a moment, otherwise it could be subdivided and thus would be a true interval rather than a moment! In essence, moments capture the limits of our perception (or the measuring capabilities of devices we invent). They bear many similarities to the notion of states (in STRIPS-like planning models) or situations (in the situation calculus). For those that worry about points, Allen & Hayes also derive a notion of points, defined as the "places" where two intervals meet. Points have no duration, and so are distinct from intervals (and moments), but we can define a notion of some property holding at a point indirectly by saying that there is an interval over which the property is true that contains the point.

Given this logic of time, we construct a logic of events by associating eventualities with times. For states (or properties), we have a predicate $\textsc{Holds}(p, t)$ that asserts the property p holds over an interval t. A key property of $\textsc{Holds}$ is homogeneity, namely if a property holds over T then it also holds over all subintervals of T, i.e.,

$$\forall o, P, t \;.\; \textsc{Holds}(P(o), t) \supset [\forall t' \subseteq t . \textsc{Holds}(P(o), t')]$$

For events, the predicate OCCURS was used, where OCCUR(e, t) asserts that event e occurred over time t. This relation only holds for the minimum time over which the event can be said to occur, and thus an event occurrence uniquely defines its time of occurrence and the homogeneity property definitely does not hold!

II. Recent Developments

Recently, we have been working on systems that can automatically derive common sense knowledge from definitions. For instance, in Allen & Teng (2013) we focused on what is needed to be able to capture an adequate definition of the notion of *change* from the compositional interpretation of its definition *becoming different*. In tackling this problem, several significant issues arose that forced further development of the temporal logic. First, we needed a notion of *scales* (e.g., hotter/colder, happier/sadder, color, etc), as being different must mean that the objects differ on some relevant dimension, captured by the scale. Without scales the notion of *different* reduces to simple inequality, which is not an intuitively satisfactory formulation. If one defined *different* in this way, then no two distinct things could ever be similar as they are not equal.

With such a notion of scales in hand, we can formalize the property that one object A is different than another object B in a fairly satisfactory way. But in defining the notion of *change* it is the *same* object that is being compared, just at

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different times. In other words, an object X changes at time t if it is different after t than it was before t! Our previous temporal logics had no way of directly comparing an object at different times since times were associated with properties and events, not objects. To handle this, we introduce a new function that takes an object and a time and denotes that object over that time, e.g., $x@t$ represents "object x over time t". We refer to these as *temporally situated objects*. Thus, *John is Happy today* might be written as

$$\textsc{TrueOf}(\mathit{john}@\mathit{today}, \mathit{Happy})$$

Where TRUEOF plays the same role as HOLDS in our old logic, where this would have been expressed as $\textsc{Holds}(\mathit{Happy}(\mathit{john}), \mathit{today})$. For unary properties, these two formulations are equivalent and thus notational variants of each other. For binary relations, however, the situation is very different. For example, we might express *I am different today from yesterday* as:

$$\textsc{TrueOf2}(\mathit{me}@\mathit{yesterday}, \mathit{me}@\mathit{today}, \mathit{Different})$$

This fact cannot be expressed using the HOLDS predicate with its single temporal argument. The notion that objects are temporally situated and properties are not is in stark contrast to standard temporal logics in which objects are atemporal and properties change over time. As is usual the case whenever I work on temporal logic, this insight is not new, and such formulations have long been discussed in philosophy, going back to before Whitehead (1929).

We also introduce a predicate EXISTS that defines the temporal range of an object, i.e., when the temporally situated object $o@t$ exists. For instance, if I was born in 1983, then $\textsc{Exists}(\mathit{me}@\mathit{1984})$ and $\textsc{Exists}(\mathit{me}@\mathit{1982})$ both hold. With this extension, we can also now define concepts such as creation and destruction, with were always problematic in the old formalism.

In this talk I will discuss these and other issues that have arisen as we try to take the notion of compositional interpretation of definitions seriously.

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