successor-state axiom can say that the tub is empty before the action and full when the action is done, but it can’t talk about what happens during the action. It also can’t easily describe two actions happening at the same time—such as brushing one’s teeth while waiting for the tub to fill. To handle such cases we introduce an approach known as event calculus.

The objects of event calculus are events, fluents, and time points. \( At(Shankar, Berkeley) \) is a fluent: an object that refers to the fact of Shankar being in Berkeley. The event \( E_1 \) of Shankar flying from San Francisco to Washington, D.C., is described as

\[
E_1 \in \text{Flyings} \land \text{Flyer}(E_1, Shankar) \land \text{Origin}(E_1, SF) \land \text{Destination}(E_1, DC)
\]

where \( \text{Flyings} \) is the category of all flying events. By reifying events we make it possible to add any amount of arbitrary information about them. For example, we can say that Shankar’s flight was bumpy with \( Bumpy(E_1) \). In an ontology where events are \( n \)-ary predicates, there would be no way to add extra information like this; moving to an \( n+1 \)-ary predicate isn’t a scalable solution.

To assert that a fluent is actually true starting at some point in time \( t_1 \) and continuing to time \( t_2 \), we use the predicate \( T \), as in \( T(At(Shankar, Berkeley), t_1, t_2) \). Similarly, we use \( Happens(E_1, t_1, t_2) \) to say that the event \( E_1 \) actually happened, starting at time \( t_1 \) and ending at time \( t_2 \). The complete set of predicates for one version of the event calculus\(^4\) is:

\[
\begin{align*}
T(f, t_1, t_2) & \quad \text{Fluent } f \text{ is true for all times between } t_1 \text{ and } t_2 \\
\text{Happens}(e, t_1, t_2) & \quad \text{Event } e \text{ starts at time } t_1 \text{ and ends at } t_2 \\
\text{Initiates}(e, f, t) & \quad \text{Event } e \text{ causes fluent } f \text{ to become true at time } t \\
\text{Terminates}(e, f, t) & \quad \text{Event } e \text{ causes fluent } f \text{ to cease to be true at time } t \\
\text{Initiated}(f, t_1, t_2) & \quad \text{Fluent } f \text{ become true at some point between } t_1 \text{ and } t_2 \\
\text{Terminated}(f, t_1, t_2) & \quad \text{Fluent } f \text{ cease to be true at some point between } t_1 \text{ and } t_2 \\
t_1 < t_2 & \quad \text{Time point } t_1 \text{ occurs before time } t_2
\end{align*}
\]

We can describe the effects of a flying event:

\[
E = \text{Flyings}(a, \text{here, there}) \land \text{Happens}(E, t_1, t_2) \Rightarrow \\
\text{Terminates}(E, At(a, \text{here, there}), t_1) \land \text{Initiates}(E, At(a, \text{there}), t_2)
\]

We assume a distinguished event, \( \text{Start} \), that describes the initial state by saying which fluents are true (using \( \text{Initiates} \)) or false (using \( \text{Terminated} \)) at the start time. We can then describe what fluents are true at what points in time with a pair of axioms for \( T \) and \( \neg T \) that follow the same general format as the successor-state axioms: Assume an event happens between time \( t_1 \) and \( t_3 \), and at \( t_2 \) somewhere in that time interval the event changes the value of fluent \( f \), either initiating it (making it true) or terminating it (making it false). Then at time \( t_4 \) in the future, if no other intervening event has changed the fluent (either terminated or initiated it, respectively), then the fluent will have maintained its value. Formally, the axioms are:

\[
\begin{align*}
\text{Happens}(e, t_1, t_3) \land \text{Initiates}(e, f, t_2) \land \neg \text{Terminated}(f, t_2, t_4) \land t_1 \leq t_2 \leq t_3 \leq t_4 \Rightarrow \\
T(f, t_2, t_4) \\
\text{Happens}(e, t_1, t_3) \land \text{Terminates}(e, f, t_2) \land \neg \text{Initiates}(f, t_2, t_4) \land t_1 \leq t_2 \leq t_3 \leq t_4 \Rightarrow \\
\neg T(f, t_2, t_4)
\end{align*}
\]

\(^4\) Our version is based on Shanahan (1999), but with some alterations.