CHAPTER

The Commonsense Law of Inertia

5

A quality of the commonsense world is that objects tend to stay in the same state unless they are affected by events. A book sitting on a table remains on the table unless it is picked up, a light stays on until it is turned off, and a falling object continues to fall until it hits something. This is known as the commonsense law of inertia. This chapter discusses the representation of the commonsense law of inertia in the event calculus. We retrace the development of the DEC axioms, and we discuss the enforcement of the commonsense law of inertia and the release of fluents from inertia.

5.1 REPRESENTATION OF THE COMMONSENSE LAW OF INERTIA

How should we represent the commonsense law of inertia? Let us consider a version of the event calculus with integer time, using the example of turning on a light. We first represent the effects of events; we represent that, if a light is turned on, then the light will be on at the next timepoint:

$$Happens(TurnOn(l), t) \Rightarrow HoldsAt(On(l), t+1) \tag{5.1}$$

Suppose two lights are off at timepoint 0, and the second light is turned on at timepoint 0:

$$\neg HoldsAt(On(Light1), 0) \tag{5.2}$$
$$\neg HoldsAt(On(Light2), 0) \tag{5.3}$$
$$Happens(TurnOn(Light2), 0) \tag{5.4}$$
$$Light2 \neq Light1 \tag{5.5}$$

We can show that the second light will be on at timepoint 1.

Proposition 5.1. *If* $\Sigma = (5.1)$, $\Delta = (5.4)$, $\Omega = (5.5)$, *and* $\Gamma = (5.2) \wedge (5.3)$, *then* $\Sigma \wedge \Delta \wedge \Omega \wedge \Gamma \vdash HoldsAt(On(Light2), 1)$.

Proof. From (5.1) and (5.4), we have $HoldsAt(On(Light2), 1)$. ■

5.1.1 FRAME PROBLEM

What can we say about the first light? We would like to reason that, because we were not told that the first light was turned on, it will still be off: $\neg HoldsAt(On(Light1), 1)$. Sadly, this does not follow from the domain description $\Sigma \wedge \Delta \wedge \Omega \wedge \Gamma$. The trouble is that we have represented which fluents change truth value when an event occurs but we have not represented which fluents do not change truth value. The problem of representing and reasoning about which fluents do not change when an event occurs is known as the *frame problem*. Several types of axioms have been proposed for specifying when fluents do not change truth value.

5.1.2 CLASSICAL FRAME AXIOMS

A *classical frame axiom* represents that a given fluent does not change when a given event occurs. For example, we represent that, if light l is off and a different light is turned on, then l will still be off:

$$\begin{gathered} \neg HoldsAt(On(l_1), t) \wedge \\ Happens(TurnOn(l_2), t) \wedge \\ l_1 \neq l_2 \Rightarrow \\ \neg HoldsAt(On(l_1), t+1) \end{gathered} \tag{5.6}$$

We can then show that after the second light is turned on, the first light is off.

Proposition 5.2. *If* $\Sigma = (5.1)$, $\Delta = (5.4)$, $\Omega = (5.5)$, $\Gamma = (5.2) \wedge (5.3)$, *and* CFA = (5.6), *then* $\Sigma \wedge \Delta \wedge \Omega \wedge \Gamma \wedge \text{CFA} \vdash \neg HoldsAt(On(Light1), 1)$.

Proof. From (5.2), (5.4), (5.5), and (5.6), we have $\neg HoldsAt(On(Light1), 1)$. ∎

Unfortunately, classical frame axioms are unable to cope with several events occurring at one timepoint. For instance, if we are also given that the first light is turned on at timepoint 0:

$$Happens(TurnOn(Light1), 0) \tag{5.7}$$

then inconsistency results.

Proposition 5.3. *If* $\Sigma = (5.1)$, $\Delta = (5.4) \wedge (5.7)$, $\Omega = (5.5)$, $\Gamma = (5.2) \wedge (5.3)$, *and* CFA = (5.6), *then* $\Sigma \wedge \Delta \wedge \Omega \wedge \Gamma \wedge \text{CFA}$ *is inconsistent.*

Proof. From (5.2), (5.4), (5.5), and (5.6), we have

$$\neg HoldsAt(On(Light1), 1) \tag{5.8}$$

From (5.1) and (5.7), we have $HoldsAt(On(Light1), 1)$, which contradicts (5.8). ∎

Notice also that, if we remove (5.4), then we are unable to conclude $\neg HoldsAt(On(Light1), 1)$. Classical frame axioms were developed for use within the situation calculus, which is discussed in Section 16.1. They are only useful in the event calculus if exactly one event occurs at each timepoint.

5.1.3 EXPLANATION CLOSURE AXIOMS

Another type of axiom, an *explanation closure axiom*, represents that a given fluent does not change unless certain events occur. For example, we represent that, if a light is off and the light is not turned on, then the light will still be off:

$$\begin{gathered} \neg HoldsAt(On(l), t) \wedge \\ \neg Happens(TurnOn(l), t) \Rightarrow \\ \neg HoldsAt(On(l), t+1) \end{gathered} \tag{5.9}$$

If we had

$$\neg Happens(TurnOn(Light1), 0)$$

then we could show $\neg HoldsAt(On(Light1), 1)$ from (5.2) and (5.9). But this does not yet follow from the domain description. An additional mechanism is required to limit events to those that are known to have occurred.

5.1.4 MINIMIZING EVENT OCCURRENCES

We use the mechanism of circumscription described in Section 2.6 to minimize event occurrences, by minimizing the extension of the *Happens* predicate. This gives us the desired result. If the first and second lights are initially off and the second light is turned on, then the first light will still be off:

Proposition 5.4. *Let* $\Sigma = (5.1)$, $\Delta = (5.4)$, $\Omega = (5.5)$, $\Gamma = (5.2) \wedge (5.3)$, *and* $ECA = (5.9)$. *Then we have* $\Sigma \wedge CIRC[\Delta; Happens] \wedge \Omega \wedge \Gamma \wedge \mathrm{ECA} \vdash \neg HoldsAt(On(Light1), 1)$.

Proof. From $CIRC[\Delta; Happens]$ and Theorem 2.1, we have

$$Happens(e, t) \Leftrightarrow (e = TurnOn(Light2) \wedge t = 0)$$

From this and (5.5), we have $\neg Happens(TurnOn(Light1), 0)$. From this, (5.2), and (5.9), we have $\neg HoldsAt(On(Light1), 1)$. ■

5.1.5 INTRODUCTION OF *INITIATES* PREDICATE

So far, this method requires us to enumerate all explanation closure axioms for the domain such as (5.9). We can avoid this by introducing the predicate $Initiates(e, f, t)$, which represents that, if event e occurs at timepoint t, then fluent f will be true at $t + 1$:

$$\begin{aligned} &Happens(e, t) \wedge Initiates(e, f, t) \Rightarrow \\ &HoldsAt(f, t + 1) \end{aligned} \tag{5.10}$$

We can then generalize the explanation closure axiom (5.9) into:

$$\begin{aligned} &\neg HoldsAt(f, t) \wedge \\ &\neg\exists e\, (Happens(e, t) \wedge Initiates(e, f, t)) \Rightarrow \\ &\neg HoldsAt(f, t + 1) \end{aligned} \tag{5.11}$$

Now suppose that instead of (5.1), we have

$$Initiates(TurnOn(l), On(l), t)$$

In order to show $\neg HoldsAt(On(Light1), 1)$ from $\neg HoldsAt(On(Light1), 0)$, we must show

$$\neg\exists e\, (Happens(e, 0) \wedge Initiates(e, On(Light1), 0))$$

From the circumscription of *Happens* in (5.4), we have

$$Happens(e, 0) \Leftrightarrow e = TurnOn(Light2)$$

Thus we require:

$$\neg Initiates(TurnOn(Light2), On(Light1), 0)$$

But this does not yet follow from the domain description. We require a method to limit the effects of events to those that are known.

5.1.6 MINIMIZING EVENT EFFECTS

Again we use circumscription, this time to minimize the effects of events, by minimizing the extension of *Initiates*. We can again show, this time using *Initiates*, that after turning on the second light, the first light will still be off:

Proposition 5.5. *Let* $\Sigma = (5.12)$, $\Delta = (5.4)$, $\Omega = (5.5)$, $\Gamma = (5.2) \wedge (5.3)$, *and* $D1 = (5.10) \wedge (5.11)$. *Then we have* $CIRC[\Sigma; Initiates] \wedge CIRC[\Delta; Happens] \wedge \Omega \wedge \Gamma \wedge D1 \vdash \neg HoldsAt(On(Light1), 1)$.

Proof. From $CIRC[\Sigma; Initiates]$ and Theorem 2.1, we have

$$Initiates(e,f,t) \Leftrightarrow \exists l\,(e = TurnOn(l) \wedge f = On(l)) \tag{5.12}$$

From $CIRC[\Delta; Happens]$ and Theorem 2.1, we have

$$Happens(e,t) \Leftrightarrow (e = TurnOn(Light2) \wedge t = 0) \tag{5.13}$$

From (5.12) and (5.5), we have

$$\neg Initiates(TurnOn(Light2), On(Light1), 0)$$

From this and (5.13), we have

$$\neg \exists e\,(Happens(e,0) \wedge Initiates(e, On(Light1), 0))$$

From this, (5.2), and (5.11), we have $\neg HoldsAt(On(Light1), 1)$. ■

These are the beginnings of DEC. The axiom (5.11) is similar to DEC6, and (5.10) is the same as DEC9.

5.1.7 INTRODUCTION OF *TERMINATES* PREDICATE

Along similar lines, we introduce the predicate $Terminates(e,f,t)$, which represents that, if event e occurs at timepoint t, then fluent f will be false at $t+1$. We have an axiom similar to DEC5 and one that is the same as DEC10:

$$\begin{gathered} HoldsAt(f,t) \wedge \\ \neg \exists e\,(Happens(e,t) \wedge Terminates(e,f,t)) \Rightarrow \\ HoldsAt(f,t+1) \end{gathered} \tag{5.14}$$

$$\begin{gathered} Happens(e,t) \wedge Terminates(e,f,t) \Rightarrow \\ \neg HoldsAt(f,t+1) \end{gathered} \tag{5.15}$$

5.1.8 DISCUSSION

The effects of events are enforced by (5.10) and (5.15), whereas the commonsense law of inertia is enforced by (5.11) and (5.14). In the conjunction of axioms EC, the effects of events are enforced by EC14 and EC15, whereas the commonsense law of inertia is enforced by EC9, EC10, EC14, and EC15. For instance, EC14 specifies that a fluent f that is initiated by an event that occurs at timepoint t_1 is true at timepoint $t_2 > t_1$ provided that $\neg StoppedIn(t_1, f, t_2)$, which by EC3 is equivalent to

$$\neg\exists e, t\,(Happens(e,t) \land t_1 < t < t_2 \land Terminates(e,f,t))$$

Notice that EC14 and EC15 enforce both the effects of events and the commonsense law of inertia. EC14 and EC15 enforce the commonsense law of inertia after a fluent has been initiated or terminated by an occurring event, whereas EC9 and EC10 enforce the commonsense law of inertia in all cases. If, for example, the truth value of a fluent is known at timepoint t, then EC9 and EC10 can be used to determine the truth value of the fluent after timepoint t.

Some redundancy exists between, say, EC9 and EC14, because after a fluent is initiated by an occurring event, both EC9 and EC14 specify that the fluent is true until it is terminated by an occurring event. This redundancy is not present in the conjunction of axioms DEC.

5.2 REPRESENTING RELEASE FROM THE COMMONSENSE LAW OF INERTIA

We may not always wish the commonsense law of inertia to be in force. In this section, we describe how fluents can be released from the commonsense law of inertia and then, at a later time, can again be made subject to this law.

5.2.1 EXAMPLE: YALE SHOOTING SCENARIO

We start by considering the example of shooting a turkey. If a gun is loaded at timepoint 1 and used to shoot a turkey at timepoint 3, then the gun will fire and the turkey will no longer be alive. This simple example assumes that the shooter does not miss. In this case, the fact that the gun is loaded is subject to the commonsense law of inertia.

This example is due to Steve Hanks and Drew McDermott. If an agent loads a gun, then the gun will be loaded:

$$Initiates(Load(a,g), Loaded(g), t) \tag{5.16}$$

If a gun is loaded and agent a_1 shoots the gun at agent a_2, then a_2 will no longer be alive:

$$\begin{gathered} HoldsAt(Loaded(g), t) \Rightarrow \\ Terminates(Shoot(a_1, a_2, g), Alive(a_2), t) \end{gathered} \tag{5.17}$$

If a gun is loaded and an agent shoots the gun, then the gun will no longer be loaded:

$$\begin{gathered} HoldsAt(Loaded(g), t) \Rightarrow \\ Terminates(Shoot(a_1, a_2, g), Loaded(g), t) \end{gathered} \tag{5.18}$$

Consider the following observations and narrative. Initially, the turkey is alive and the gun is not loaded:

$$HoldsAt(Alive(Turkey), 0) \tag{5.19}$$
$$\neg HoldsAt(Loaded(Gun), 0) \tag{5.20}$$

Nathan loads the gun at timepoint 0, waits at timepoint 1, and shoots the turkey at timepoint 2:

$$Happens(Load(Nathan, Gun), 0) \tag{5.21}$$
$$Happens(Wait(Nathan), 1) \tag{5.22}$$
$$Happens(Shoot(Nathan, Turkey, Gun), 2) \tag{5.23}$$

We can then show that the turkey will no longer be alive at timepoint 3.

Proposition 5.6. *Let* $\Sigma = (5.16) \wedge (5.17) \wedge (5.18)$, $\Delta = (5.21) \wedge (5.22) \wedge (5.23)$, $\Omega = U[Load, Wait, Shoot] \wedge U[Loaded, Alive]$, *and* $\Gamma = (5.19) \wedge (5.20)$, *and* $\mathrm{D2} = (5.10) \wedge (5.11) \wedge (5.14) \wedge (5.15)$. *Then we have*

$$CIRC[\Sigma; Initiates, Terminates, Releases] \wedge CIRC[\Delta; Happens] \wedge$$
$$\Omega \wedge \Gamma \wedge \mathrm{D2} \vdash \neg HoldsAt(Alive(Turkey), 3)$$

Proof. See Exercise 5.3. ■

5.2.2 RELEASING FROM INERTIA

By contrast, consider a gun that is loaded at timepoint 1 and whose chamber is spun at timepoint 2. If the trigger is pulled at timepoint 3, then the gun may or may not fire (the chamber may still be spinning). We may model this by specifying that, after the gun's chamber is spun, the gun's readiness to shoot is released from the commonsense law of inertia. Then, at any given timepoint after the gun's readiness to shoot is released, the gun may or may not be loaded.

This models a chamber that continues to spin, so that at any given timepoint after the chamber is spun, the gun may or may not be ready to shoot, independently of whether it is ready to shoot at other timepoints. Thus, if the domain of the timepoint sort is the integers and the gun's readiness to shoot is released for n timepoints, then there are 2^n classes of models. (We might instead wish to model a chamber that spins only for an instant. For a way of doing this, see Section 9.1.1.)

We now introduce the *Releases* and *ReleasedAt* predicates. $Releases(e, f, t)$ represents that, if event e occurs at timepoint t, then fluent f will be released from the commonsense law of inertia at $t + 1$. $ReleasedAt(f, t)$ represents that fluent f is released from the commonsense law of inertia at timepoint t. Thus, we have

$$Happens(e, t) \wedge Releases(e, f, t) \Rightarrow ReleasedAt(f, t + 1) \tag{5.24}$$

This is DEC11. We can use *Releases* and *ReleasedAt* to represent our uncertainty about whether a given fluent is true or false at a given timepoint.

We incorporate *ReleasedAt* into (5.14) and (5.11), which gives us the following revised generalized explanation closure axioms:

$$\begin{gathered} HoldsAt(f,t) \wedge \neg ReleasedAt(f,t) \wedge \\ \neg \exists e\, (Happens(e,t) \wedge Terminates(e,f,t)) \Rightarrow \\ HoldsAt(f,t+1) \end{gathered} \tag{5.25}$$

$$\begin{gathered} \neg HoldsAt(f,t) \wedge \neg ReleasedAt(f,t) \wedge \\ \neg \exists e\, (Happens(e,t) \wedge Initiates(e,f,t)) \Rightarrow \\ \neg HoldsAt(f,t+1) \end{gathered} \tag{5.26}$$

(5.25) is DEC5 and (5.26) is DEC6.

Thus at any given timepoint a fluent either is, or is not, subject to the commonsense law of inertia. When a fluent is subject to the commonsense law of inertia, its truth value will be the same as its previous value, unless the fluent is true and it is terminated by an occurring event or the fluent is false and it is initiated by an occurring event. When a fluent is released from the commonsense law of inertia, its truth value may or may not be the same as it was previously. That is, its truth value may fluctuate.

5.2.3 RESTORING INERTIA

We have so far specified how a fluent becomes released from the commonsense law of inertia. We must also specify how a fluent is again made subject to this law. Although we could add an *Unreleases* predicate, it is convenient to allow *Inititates* and *Terminates* to serve this role because, when a fluent is made subject to the commonsense law of inertia, its truth value is usually also specified.

We have an axiom stating that, if a fluent is initiated or terminated by an event that occurs at timepoint t, then the fluent will no longer be released from the commonsense law of inertia at $t+1$:

$$\begin{gathered} Happens(e,t) \wedge (Initiates(e,f,t) \vee Terminates(e,f,t)) \Rightarrow \\ \neg ReleasedAt(f,t+1) \end{gathered} \tag{5.27}$$

This is DEC12.

5.2.4 EXPLANATION CLOSURE AXIOMS FOR *RELEASEDAT*

So far, we have specified when *ReleasedAt* changes truth value, using (5.24) and (5.27). We have not specified when this predicate does not change truth value. We therefore add the following two generalized explanation closure axioms for *ReleasedAt*:

$$\begin{gathered} ReleasedAt(f,t) \wedge \\ \neg \exists e\, (Happens(e,t) \wedge (Initiates(e,f,t) \vee Terminates(e,f,t))) \Rightarrow \\ ReleasedAt(f,t+1) \end{gathered} \tag{5.28}$$

$$\begin{gathered} \neg ReleasedAt(f,t) \wedge \\ \neg \exists e\, (Happens(e,t) \wedge Releases(e,f,t)) \Rightarrow \\ \neg ReleasedAt(f,t+1) \end{gathered} \tag{5.29}$$

(5.28) is DEC7 and (5.29) is DEC8.

5.2.5 EXAMPLE: RUSSIAN TURKEY SCENARIO

This example is due to Erik Sandewall. We modify the example in Section 5.2.1 as follows. If a gun is loaded and an agent spins the gun, then the gun's readiness to shoot will no longer be subject to the commonsense law of inertia:

$$HoldsAt(Loaded(g), t) \Rightarrow Releases(Spin(a, g), Loaded(g), t) \tag{5.30}$$

Instead of waiting at timepoint 1, Nathan spins the gun:

$$Happens(Spin(Nathan, Gun), 1) \tag{5.31}$$

Notice that given axioms (5.15), (5.27), and (5.29), axiom (5.18) ensures that, after a loaded gun is fired, the gun is no longer loaded and $Loaded(Gun)$ is no longer released from the commonsense law of inertia.

The fluent term $Alive(Turkey)$ is subject to the commonsense law of inertia at all times:

$$\neg ReleasedAt(Alive(Turkey), t) \tag{5.32}$$

Only initially is $Loaded(Gun)$ subject to the commonsense law of inertia:

$$\neg ReleasedAt(Loaded(Gun), 0) \tag{5.33}$$

We can then show that there are two possible outcomes: (1) If the gun is loaded at timepoint 2, then the turkey will no longer be alive at timepoint 3, and (2) if the gun is not loaded at timepoint 2, then the turkey will still be alive at timepoint 3.

Proposition 5.7. *Let* $\Sigma = (5.16) \wedge (5.17) \wedge (5.18) \wedge (5.30)$, $\Delta = (5.21) \wedge (5.31) \wedge (5.23)$, $\Omega = U[Load, Spin, Shoot] \wedge U[Loaded, Alive]$, *and* $\Gamma = (5.19) \wedge (5.20) \wedge (5.32) \wedge (5.33)$, *and* $D3 = (5.10) \wedge (5.15) \wedge (5.24) \wedge (5.25) \wedge (5.26) \wedge (5.27) \wedge (5.28) \wedge (5.29)$. *Then we have*

$$\begin{aligned} &CIRC[\Sigma; Initiates, Terminates, Releases] \wedge \\ &CIRC[\Delta; Happens] \wedge \Omega \wedge \Gamma \wedge D3 \wedge HoldsAt(Loaded(Gun), 2) \\ &\vdash \neg HoldsAt(Alive(Turkey), 3) \end{aligned} \tag{5.34}$$

as well as

$$\begin{aligned} &CIRC[\Sigma; Initiates, Terminates, Releases] \wedge \\ &CIRC[\Delta; Happens] \wedge \Omega \wedge \Gamma \wedge D3 \wedge \neg HoldsAt(Loaded(Gun), 2) \\ &\vdash HoldsAt(Alive(Turkey), 3) \end{aligned} \tag{5.35}$$

Proof. See Exercise 5.4. ■

In the Russian turkey scenario, release from the commonsense law of inertia is used to model nondeterminism. Nondeterminism is discussed further in Chapter 9. Release from the commonsense law of inertia is also useful for representing indirect effects (discussed in Chapter 6) and continuous change (discussed in Chapter 7).

5.3 RELEASE AXIOMS

A fluent is released from the commonsense law of inertia as follows.

Definition 5.1. If γ is a condition, α is an event term, β is a fluent term, and τ is a timepoint term, then

$$\gamma \Rightarrow Releases(\alpha, \beta, \tau)$$

is a ***release axiom***. This represents that, if γ is true and α occurs at τ, then β will be released from the commonsense law of inertia after τ.

A fluent is again made subject to the commonsense law of inertia as follows. We represent that, if γ is true and α occurs at τ, then β will no longer be released from the commonsense law of inertia after τ using a positive or negative effect axiom:

$$\gamma \Rightarrow Initiates(\alpha, \beta, \tau)$$
$$\gamma \Rightarrow Terminates(\alpha, \beta, \tau)$$

In the *Inititates* case, the fluent will become true and not released; in the *Terminates* case, the fluent will become false and not released.

In EC, a fluent is released for times greater than the time of the releasing event and is not released for times greater than the time of the initiating or terminating event. In DEC, a fluent is released starting one timepoint after the time of the releasing event and is not released starting one timepoint after the time of the initiating or terminating event. For example, suppose we have $Releases(Rel, Fluent, t)$, $Happens(Rel, 1)$, $Initiates(Init, Fluent, t)$, and $Happens(Init, 4)$. Figure 5.1 shows when *Fluent* is released using the conjunction of axioms EC; Figure 5.2 shows when *Fluent* is released using DEC.

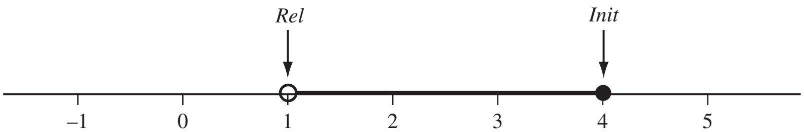

FIGURE 5.1

Released fluent in EC.

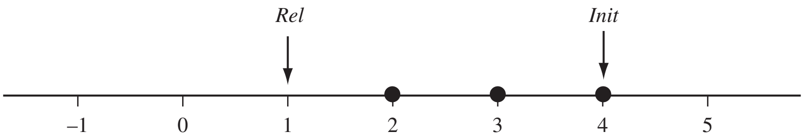

FIGURE 5.2

Released fluent in DEC.

BIBLIOGRAPHIC NOTES

Frame problem

The frame problem was first described by McCarthy and Hayes (1969, p. 487). According to Shanahan (1997b), "McCarthy relates that he was reading a book on geometry at the time he coined the term 'frame problem,' and that he thought of the frame problem as analogous to that of choosing a co-ordinate frame" (p. 25). Hayes (1971) defines a frame as "a classification of statements into groups which are independent in the sense that an action may alter members of one group without affecting any of the other groups" (p. 497). See also the discussions of McCarthy (1977, p. 1040) and Lifschitz (1990b, p. 366). An introduction to the frame problem is provided by Shanahan (2002), and a book-length treatment is provided by Shanahan (1997b). Earlier book-length discussions are provided by Brown (1987), Pylyshyn (1987), and Ford and Pylyshyn (1996).

Frame axioms

Frame axioms were introduced by McCarthy and Hayes (1969, pp. 484 and 485). Hayes (1971) was apparently the first to call them " 'frame' axioms" (p. 514). We use the term *classical frame axiom* from Kautz and Selman (1996, p. 1197) to distinguish the frame axioms of McCarthy and Hayes from explanation closure axioms. Classical frame axioms were originally written in the situation calculus. Using Reiter's notation, a sample classical frame axiom is:

$$on(d_2, s) \wedge d_1 \neq d_2 \supset on(d_2, do(turn\_off(d_1), s))$$

Using Shanahan's notation, the same axiom is written as:

$$Holds(On(d_2), s) \wedge d_1 \neq d_2 \rightarrow Holds(On(d_2), Result(TurnOff(d_1), s))$$

To handle e events and f fluents, on the order of $2 \cdot e \cdot f$ classical frame axioms are required (Reiter, 2001, p. 22).

Kowalski (1974, 1979, pp. 133-146) introduces a way of combining classical frame axioms that relies on representing that fluent $F(x_1, \ldots, x_n)$ is true in situation σ as $Holds(F(x_1, \ldots, x_n), \sigma)$ rather than $F(x_1, \ldots, x_n, \sigma)$. See the discussions of Nilsson (1980, pp. 311-315) and Shanahan (1997b, pp. 231-241). Using Shanahan's notation, suppose we have the effect axiom:

$$\neg Holds(On(d), Result(TurnOff(d), s))$$

We can then use a single frame axiom:

$$Holds(f, s) \wedge f \neq On(d) \rightarrow Holds(f, Result(TurnOff(d), s))$$

instead of several frame axioms:

$$Holds(On(d_2), s) \wedge d_1 \neq d_2 \rightarrow Holds(On(d_2), Result(TurnOff(d_1), s))$$
$$Holds(Broken(d_1), s) \rightarrow Holds(Broken(d_1), Result(TurnOff(d_1), s))$$
$$\vdots$$

Explanation closure axioms were first proposed by Haas (1987), who called them "domain-specific frame axioms" (p. 343). They were further developed and named "explanation-closure" axioms by Schubert (1990, p. 25). E. Davis (1990) proposed similar axioms for "framing primitive events by fluents" (p. 206). Using Reiter's situation calculus notation, a sample explanation closure axiom is:

$$on(d,s) \land \neg on(d, do(a,s)) \supset a = turn\_off(d)$$

which corresponds to the single effect axiom:

$$\neg on(d, do(turn\_off(d), s))$$

Pednault (1989) proposed two constraints to facilitate the generation of classical frame axioms: (1) separate effect axioms must be written for each fluent, and (2) the effects of actions must be completely specified by the effect axioms.

Synthesizing the proposals of Haas, Schubert, E. Davis, and Pednault, Reiter (1991; 2001, pp. 28-32) provided a method for automatically constructing explanation closure axioms given a set of effect axioms. To handle f fluents, on the order of $2 \cdot f$ explanation closure axioms are required (Reiter, 2001, p. 27). Explanation closure axioms were first used in the event calculus by Shanahan and Witkowski (2004). Axioms DEC5, DEC6, DEC7, and DEC8, which resemble explanation closure axioms extended to allow fluents to be released from the commonsense law of inertia, were introduced by Mueller (2004a). Our review of classical frame axioms and explanation closure axioms is loosely based on that of Ernst, Millstein, and Weld (1997, pp. 1170 and 1171). The form of explanation closure axiom we give,

$$\begin{gathered} HoldsAt(F,t) \land \neg Happens(E_1,t) \land \cdots \land \neg Happens(E_n,t) \Rightarrow \\ HoldsAt(F,t+1) \end{gathered}$$

is logically equivalent to the form usually given:

$$\begin{gathered} HoldsAt(F,t) \land \neg HoldsAt(F,t+1) \Rightarrow \\ Happens(E_1,t) \lor \cdots \lor Happens(E_n,t) \end{gathered}$$

Shanahan (1996, pp. 684 and 685, 1997b, pp. 315-330) introduced the forced separation version of the event calculus in which *Inititates*, *Terminates*, and *Releases* are circumscribed separately from *Happens* and the observation (*HoldsAt*) formulas and event calculus axioms are outside the scope of any circumscription. The technique of forced separation derives from the following previous proposals: (1) the filtered preferential entailment or filtering of Sandewall (1989b, 1994, pp. 213-215, 242, and 243), in which minimization is applied to effect axioms ("action laws") but not to observation formulas, which in turn derives from the preferential entailment of (Shoham 1988, p. 76); (2) the proposal of Crawford and Etherington (1992) to separate the description of the system from the observations; (3) the extension of Sandewall's techniques by Doherty and Łukaszewicz (1994) and Doherty (1994), in which circumscription is applied to schedule statements involving the *Occlude* predicate but not to observation statements or to the nochange axiom, as discussed in Section 16.2.1; (4) the method of Kartha and Lifschitz (1995), in which circumscription is applied to effect axioms and state constraints but not to observation formulas (Shanahan, 1997b, pp. 315-318); and (5) the method of F. Lin (1995), in which the *Caused* predicate is minimized using circumscription or predicate completion.

E. Davis (1990) discusses the need for axioms of "nonoccurrence of extraneous events" (p. 208) when using explanation closure axioms. The rationale for the use of circumscription over less powerful methods is given by Shanahan (1998):

> *We could use negation-as-failure (or rather, say, predicate completion). Using circumscription does allow for the addition of, for example, disjunctive facts, however. Predicate completion is only defined for a certain class of theories. Event [*sic*] though this class encompasses most of what we're interested in, there doesn't seem any point in ruling out exceptions. (p. 329)*

Commonsense law of inertia

The phrase *commonsense law of inertia* was originated by John McCarthy (personal communication, May 18, 2005; Lifschitz, 1987c, p. 186). The phrase appears to have been first used in print by Lifschitz (1987a, p. 45; 1987c, p. 186). Hanks and McDermott (1987) mention the "inertia of the world" (p. 395) and attribute the phrase "inertial property of facts" (p. 394) to John McCarthy. Fluents subject to the commonsense law of inertia are sometimes called "frame fluents" (Lifschitz, 1990b, p. 370; R. Miller & Shanahan, 2002, p. 471) or are said to be "in the frame" (Lifschitz, 1990b, p. 369; R. Miller & Shanahan, 2002, p. 474) or to "belong to the frame" (R. Miller & Shanahan, 1996, p. 67).

Yale shooting scenario

The Yale shooting scenario was introduced by Hanks and McDermott (1985; 1986; 1987, pp. 387-390), who use the scenario to point out problems with McCarthy's (1984a, 1986) initial attempt at solving the frame problem using circumscription. The scenario and the various treatments of it are discussed at length by Shanahan (1997b). The scenario is also discussed by Reiter (2001, pp. 43-46) and Sandewall (1994, pp. 151 and 152, 197-201). Sun (1995, p. 589) points out that most solutions incorrectly predict that a person who is not shot will be alive forever. This problem could be avoided in a probabilistic treatment—see Section 17.3. The Russian turkey scenario was introduced by Sandewall (1991, 1994, pp. 155 and 156) and is discussed by Kartha and Lifschitz (1994, p. 344) and Shanahan (1997b, pp. 299-301).

Release from inertia

Release from the commonsense law of inertia and the *Releases* predicate were introduced into the event calculus by Shanahan (1997b, pp. 299-301), drawing on the occlusion or **X** predicate of Sandewall (1989b, sec. 6; 1994, chap. 11) and the **releases** construct of Kartha and Lifschitz (1994, p. 344). The *ReleasedAt* predicate was incorporated into the event calculus by R. Miller and Shanahan (1999, pp. 17-19, 2002, pp. 471-474). The *ReleasedAt* predicate is similar to the occlusion or **X** predicate of Sandewall. A precursor to *ReleasedAt* is the *Frame* predicate of Lifschitz (1990b, p. 370), which we may relate to *ReleasedAt* via the axiom

$$Frame(f) \Leftrightarrow \forall t\, \neg ReleasedAt(f, t)$$

Based on McCarthy's (1984a, 1986, 1987) earlier proposals, Lifschitz (1990b, p. 370) proposes the following axiom for the situation calculus:

$$Frame(f) \wedge \neg Ab(f, a, s) \supset Holds(f, Result(a, s)) \equiv Holds(f, s)$$

which is an ancestor of the following axioms for the event calculus (R. Miller & Shanahan, 2002, p. 466):

$$\begin{aligned} HoldsAt(f, t_2) &\leftarrow [HoldsAt(f, t_1) \wedge t_1 < t_2 \\ &\wedge Frame(f) \wedge \neg Clipped(t_1, f, t_2)] \\ \neg HoldsAt(f, t_2) &\leftarrow [\neg HoldsAt(f, t_1) \wedge t_1 < t_2 \\ &\wedge Frame(f) \wedge \neg Declipped(t_1, f, t_2)] \end{aligned}$$

EXERCISES

5.1 List three everyday scenarios in which the commonsense law of inertia is not in force.

5.2 Sketch out event calculus representations of the scenarios you listed in Exercise 5.1.

5.3 Prove Proposition 5.6.

5.4 Prove Proposition 5.7.

5.5 (Research Problem) Pursue the proposal of Lifschitz (1990b, p. 372) to have several frames in which the commonsense law of inertia holds.