CHAPTER

Indirect Effects of Events

6

Suppose that a book is sitting on a table in a living room and an agent is in the living room. Normally, when the agent walks out of the room, the book remains in the living room; but, if the agent picks up the book and walks out of the living room, then the book is no longer in the living room. That is, an indirect effect or ramification of the agent walking out of the living room is that the book the agent is holding changes location. The problem of representing and reasoning about the indirect effects of events is known as the *ramification problem*. This chapter presents several methods for representing indirect effects and dealing with the ramification problem in the event calculus. We discuss the use of effect axioms, primitive and derived fluents, release axioms and state constraints, effect constraints, causal constraints, and trigger axioms.

6.1 EFFECT AXIOMS

One way of representing indirect effects is to represent them the same way that direct effects are represented, namely, using positive and negative effect axioms.

6.1.1 EXAMPLE: CARRYING A BOOK

An agent picks up a book; the book then moves along with the agent. We start with the following spatial theory. If an agent walks from room r_1 to room r_2, then the agent will be in r_2 and will no longer be in r_1:

$$Initiates(Walk(a, r_1, r_2), InRoom(a, r_2), t) \tag{6.1}$$

$$r_1 \neq r_2 \Rightarrow Terminates(Walk(a, r_1, r_2), InRoom(a, r_1), t) \tag{6.2}$$

An object is in one room at a time:

$$HoldsAt(InRoom(o, r_1), t) \land HoldsAt(InRoom(o, r_2), t) \Rightarrow r_1 = r_2 \tag{6.3}$$

If an agent is in the same room as an object and the agent picks up the object, then the agent will be holding the object:

$$HoldsAt(InRoom(a, r), t) \land HoldsAt(InRoom(o, r), t) \Rightarrow Initiates(PickUp(a, o), Holding(a, o), t) \tag{6.4}$$

If an agent is holding an object and the agent lets go of the object, then the agent will no longer be holding the object:

$$\begin{aligned}&HoldsAt(Holding(a,o),t) \Rightarrow\\&Terminates(LetGoOf(a,o),Holding(a,o),t)\end{aligned} \tag{6.5}$$

We then represent the indirect effects of walking while holding an object using positive and negative effect axioms. If an agent is holding an object and the agent walks from room r_1 to room r_2, then the object will be in r_2 and will no longer be in r_1:

$$\begin{aligned}&HoldsAt(Holding(a,o),t) \Rightarrow\\&Initiates(Walk(a,r_1,r_2),InRoom(o,r_2),t)\end{aligned} \tag{6.6}$$

$$\begin{aligned}&HoldsAt(Holding(a,o),t) \wedge r_1 \neq r_2 \Rightarrow\\&Terminates(Walk(a,r_1,r_2),InRoom(o,r_1),t)\end{aligned} \tag{6.7}$$

Now consider the following observations and narrative. Nathan and the book start out in the living room:

$$\neg ReleasedAt(f,t) \tag{6.8}$$

$$HoldsAt(InRoom(Nathan,LivingRoom),0) \tag{6.9}$$

$$HoldsAt(InRoom(Book,LivingRoom),0) \tag{6.10}$$

Nathan picks up the book and walks into the kitchen:

$$Happens(PickUp(Nathan,Book),0) \tag{6.11}$$

$$Happens(Walk(Nathan,LivingRoom,Kitchen),1) \tag{6.12}$$

We also have

$$LivingRoom \neq Kitchen \tag{6.13}$$

We can then show that the book will be in the kitchen.

Proposition 6.1. *Let* $\Sigma = (6.1) \wedge (6.2) \wedge (6.4) \wedge (6.5) \wedge (6.6) \wedge (6.7)$, $\Delta = (6.11) \wedge (6.12)$, $\Omega = U[Walk,PickUp,LetGoOf] \wedge U[InRoom,Holding] \wedge (6.13)$, $\Psi = (6.3)$, *and* $\Gamma = (6.8) \wedge (6.9) \wedge (6.10)$. *Then we have*

$$\begin{aligned}&CIRC[\Sigma;Initiates,Terminates,Releases] \wedge CIRC[\Delta;Happens] \wedge\\&\Omega \wedge \Psi \wedge \Gamma \wedge \mathrm{EC} \vdash HoldsAt(InRoom(Book,Kitchen),2)\end{aligned}$$

Proof. From $CIRC[\Sigma;Initiates,Terminates,Releases]$ and Theorems 2.1 and 2.2, we have

$$Initiates(e,f,t) \Leftrightarrow \tag{6.14}$$

$$\begin{aligned}&\exists a,r_1,r_2\,(e = Walk(a,r_1,r_2) \wedge f = InRoom(a,r_2)) \vee\\&\exists a,o,r\,(e = PickUp(a,o) \wedge\\&f = Holding(a,o) \wedge\\&HoldsAt(InRoom(a,r),t) \wedge\\&HoldsAt(InRoom(o,r),t)) \vee\end{aligned}$$

$$\exists a, o, r_1, r_2\ (e = Walk(a, r_1, r_2) \wedge$$
$$f = InRoom(o, r_2) \wedge$$
$$HoldsAt(Holding(a, o), t))$$

$$Terminates(e, f, t) \Leftrightarrow \tag{6.15}$$

$$\exists a, r_1, r_2\ (e = Walk(a, r_1, r_2) \wedge$$
$$f = InRoom(a, r_1) \wedge$$
$$r_1 \neq r_2) \vee$$
$$\exists a, o\ (e = LetGoOf(a, o) \wedge$$
$$f = Holding(a, o) \wedge$$
$$HoldsAt(Holding(a, o), t)) \vee$$
$$\exists a, o, r_1, r_2\ (e = Walk(a, r_1, r_2) \wedge$$
$$f = InRoom(o, r_1) \wedge$$
$$HoldsAt(Holding(a, o), t) \wedge$$
$$r_1 \neq r_2)$$

$$\neg Releases(e, f, t) \tag{6.16}$$

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

$$Happens(e, t) \Leftrightarrow \tag{6.17}$$
$$(e = PickUp(Nathan, Book) \wedge t = 0) \vee$$
$$(e = Walk(Nathan, LivingRoom, Kitchen) \wedge t = 1)$$

From (6.17) and EC3, we have

$$\neg StoppedIn(0, Holding(Nathan, Book), 1) \tag{6.18}$$

From (6.16) and EC13, we have

$$\neg ReleasedIn(0, Holding(Nathan, Book), 1) \tag{6.19}$$

From (6.11) (which follows from (6.17)), (6.9), (6.10), (6.4) (which follows from (6.14)), $0 < 1$, (6.18), (6.19), and EC14, we have

$$HoldsAt(Holding(Nathan, Book), 1) \tag{6.20}$$

From (6.17) and EC3, we have

$$\neg StoppedIn(1, InRoom(Book, Kitchen), 2) \tag{6.21}$$

From (6.16) and EC13, we have

$$\neg ReleasedIn(1, InRoom(Book, Kitchen), 2) \tag{6.22}$$

From (6.12) (which follows from (6.17)), (6.20), (6.6) (which follows from (6.14)), $1 < 2$, (6.21), (6.22), and EC14, we have $HoldsAt(InRoom(Book, Kitchen), 2)$, as required. ■

6.1.2 DISCUSSION

The advantage of the method of using effect axioms to represent indirect effects is its simplicity. The disadvantage of this method is that more axioms may be required than with other methods. For example, suppose we add *Run* as another way of getting from one room to another:

$$Initiates(Run(a, r_1, r_2), InRoom(a, r_2), t)$$

$$r_1 \neq r_2 \Rightarrow Terminates(Run(a, r_1, r_2), InRoom(a, r_1), t)$$

Previously we represented the indirect effects of walking while holding an object. Now we must represent the indirect effects of running while holding an object as well:

$$HoldsAt(Holding(a, o), t) \Rightarrow$$
$$Initiates(Run(a, r_1, r_2), InRoom(o, r_2), t)$$
$$HoldsAt(Holding(a, o), t) \Rightarrow$$
$$Terminates(Run(a, r_1, r_2), InRoom(o, r_1), t)$$

The indirect effects of changing rooms do not come for free.

6.2 PRIMITIVE AND DERIVED FLUENTS

Another way of dealing with the ramification problem is to divide fluents into two categories: *primitive fluents*, or fluents directly affected by events, and *derived fluents*, or fluents indirectly affected by events. The truth value of a primitive fluent is determined by effect axioms, whereas the truth value of a derived fluent is determined by state constraints. The derived fluent is released from the commonsense law of inertia at all times, so its truth value is permitted to vary and is determined by state constraints.

6.2.1 EXAMPLE: DEVICE

We start with some positive and negative effect axioms. If an agent switches on a device, then the device will be switched on:

$$Initiates(SwitchOn(a, d), SwitchedOn(d), t) \tag{6.23}$$

If an agent switches off a device, then the device will no longer be switched on:

$$Terminates(SwitchOff(a, d), SwitchedOn(d), t) \tag{6.24}$$

If an agent plugs in a device, then the device will be plugged in:

$$Initiates(PlugIn(a, d), PluggedIn(d), t) \tag{6.25}$$

If an agent unplugs a device, then the device will no longer be plugged in:

$$Terminates(Unplug(a, d), PluggedIn(d), t) \tag{6.26}$$

We use a state constraint to represent the fact that a device is on whenever the device is switched on and the device is plugged in:

$$\begin{gathered} HoldsAt(On(d),t) \Leftrightarrow \\ HoldsAt(SwitchedOn(d),t) \land HoldsAt(PluggedIn(d),t) \end{gathered} \tag{6.27}$$

The order in which the device is switched on and plugged in does not matter. The device will be on once it is both switched on and plugged in.

Unlike the use of effect axioms for representing indirect effects, when we add other events that initiate or terminate *SwitchedOn*, we do not have to add any further axioms. The state constraint (6.27) represents an indirect effect of *SwitchedOn*, no matter how *SwitchedOn* is initiated or terminated. The same is true for *Plugged In*.

Consider the following observations and narrative. Initially, the device is neither switched on nor plugged in:

$$ReleasedAt(On(d),t) \tag{6.28}$$

$$\neg ReleasedAt(SwitchedOn(d),t) \tag{6.29}$$

$$\neg ReleasedAt(PluggedIn(d),t) \tag{6.30}$$

$$\neg HoldsAt(SwitchedOn(Device1),0) \tag{6.31}$$

$$\neg HoldsAt(PluggedIn(Device1),0) \tag{6.32}$$

Then Nathan switches on and plugs in the device:

$$Happens(SwitchOn(Nathan,Device1),0) \tag{6.33}$$

$$Happens(PlugIn(Nathan,Device1),1) \tag{6.34}$$

We can show that the device will then be on.

Proposition 6.2. *Let* $\Sigma = (6.23) \land (6.24) \land (6.25) \land (6.26)$, $\Delta = (6.33) \land (6.34)$, $\Omega = U[SwitchOn, PlugIn] \land U[SwitchedOn, PluggedIn, On]$, $\Psi = (6.27)$, *and* $\Gamma = (6.28) \land (6.29) \land (6.30) \land (6.31) \land (6.32)$. *Then we have*

$$\begin{aligned} &CIRC[\Sigma; Initiates, Terminates, Releases] \land CIRC[\Delta; Happens] \land \\ &\Omega \land \Psi \land \Gamma \land \mathrm{EC} \vdash HoldsAt(On(Device1),2) \end{aligned}$$

Proof. From $CIRC[\Sigma; Initiates, Terminates, Releases]$ and Theorems 2.1 and 2.2, we have

$$\begin{aligned} &Initiates(e,f,t) \Leftrightarrow \\ &\exists a,d\,(e = SwitchOn(a,d) \land f = SwitchedOn(d)) \lor \\ &\exists a,d\,(e = PlugIn(a,d) \land f = PluggedIn(d)) \end{aligned} \tag{6.35}$$

$$\begin{aligned} &Terminates(e,f,t) \Leftrightarrow \\ &\exists a,d\,(e = SwitchOff(a,d) \land f = SwitchedOn(d)) \lor \\ &\exists a,d\,(e = Unplug(a,d) \land f = PluggedIn(d)) \end{aligned} \tag{6.36}$$

$$\neg Releases(e,f,t) \tag{6.37}$$

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

$$\begin{aligned}&Happens(e,t) \Leftrightarrow \\ &(e = SwitchOn(Nathan, Device1) \wedge t = 0) \vee \\ &(e = PlugIn(Nathan, Device1) \wedge t = 1)\end{aligned} \tag{6.38}$$

From (6.38), (6.36), and EC3, we have

$$\neg StoppedIn(0, SwitchedOn(Device1), 2) \tag{6.39}$$

From (6.37) and EC13, we have

$$\neg ReleasedIn(0, SwitchedOn(Device1), 2) \tag{6.40}$$

From (6.33) (which follows from (6.38)), (6.23) (which follows from (6.35)), $0 < 2$, (6.39), (6.40), and EC14, we have

$$HoldsAt(SwitchedOn(Device1), 2) \tag{6.41}$$

From (6.38) and EC3, we have

$$\neg StoppedIn(1, PluggedIn(Device1), 2) \tag{6.42}$$

From (6.37) and EC13, we have

$$\neg ReleasedIn(1, PluggedIn(Device1), 2) \tag{6.43}$$

From (6.34) (which follows from (6.38)), (6.25) (which follows from (6.35)), $1 < 2$, (6.42), (6.43), and EC14, we have

$$HoldsAt(PluggedIn(Device1), 2) \tag{6.44}$$

From (6.41), (6.44), and (6.27), we have $HoldsAt(On(Device1), 2)$. ■

6.3 RELEASE AXIOMS AND STATE CONSTRAINTS

Another method of dealing with the ramification problem involves temporarily releasing a fluent from the commonsense law of inertia. First, we release the fluent, and we make the fluent subject to a state constraint while it is released. Later, we make the fluent subject to the commonsense law of inertia again.

6.3.1 EXAMPLE: CARRYING A BOOK REVISITED

An agent picks up a book. While the agent is holding the book, its location is not subject to the commonsense law of inertia. Instead, its location varies with the location of the agent holding it.

We modify the example in Section 6.1.1 to use release axioms and state constraints instead of effect axioms. If an agent picks up an object, then the room of the object will be released from the commonsense law of inertia:

$$Releases(PickUp(a, o), InRoom(o, r), t) \tag{6.45}$$

Whenever an agent is holding an object, if the agent is in one room, then the object is also in that room:

$$\begin{aligned}&HoldsAt(Holding(a,o),t)\land\\&HoldsAt(InRoom(a,r),t)\Rightarrow\\&HoldsAt(InRoom(o,r),t)\end{aligned}\tag{6.46}$$

If an agent is in a room and the agent lets go of an object, then the object will be in the room, and the fact that the object is in that room will no longer be released from the commonsense law of inertia:

$$\begin{aligned}&HoldsAt(InRoom(a,r),t)\Rightarrow\\&Initiates(LetGoOf(a,o),InRoom(o,r),t)\end{aligned}\tag{6.47}$$

Unlike with the use of effect axioms for representing indirect effects, if we add running as another way of moving from room to room, we do not have to add any further axioms. The state constraint (6.46) represents an indirect effect of an agent's location, no matter how the agent's location is changed.

Suppose we have the following observations and narrative. At first, Nathan and the book are in the living room:

$$\neg ReleasedAt(f,t)\tag{6.48}$$

$$HoldsAt(InRoom(Nathan,LivingRoom),0)\tag{6.49}$$

$$HoldsAt(InRoom(Book,LivingRoom),0)\tag{6.50}$$

Then Nathan picks up the book and walks into the kitchen:

$$Happens(PickUp(Nathan,Book),0)\tag{6.51}$$

$$Happens(Walk(Nathan,LivingRoom,Kitchen),1)\tag{6.52}$$

We also have the fact that the living room and the kitchen are not the same room:

$$LivingRoom\neq Kitchen\tag{6.53}$$

We can show that the book will end up in the kitchen.

Proposition 6.3. *If* $\Sigma=(6.1)\land(6.2)\land(6.4)\land(6.5)\land(6.45)\land(6.47)$, $\Delta=(6.51)\land(6.52)$, $\Omega=U[Walk,PickUp,LetGoOf]\land U[InRoom,Holding]\land(6.53)$, $\Psi=(6.3)\land(6.46)$, *and* $\Gamma=(6.48)\land(6.49)\land(6.50)$, *then*

$$\begin{aligned}&CIRC[\Sigma;Initiates,Terminates,Releases]\land CIRC[\Delta;Happens]\land\\&\Omega\land\Psi\land\Gamma\land\mathrm{EC}\vdash HoldsAt(InRoom(Book,Kitchen),2).\end{aligned}$$

Proof. From $CIRC[\Sigma;Initiates,Terminates,Releases]$ and Theorems 2.1 and 2.2, we have

$$\begin{aligned}&Initiates(e,f,t)\Leftrightarrow\\&\exists a,r_1,r_2\,(e=Walk(a,r_1,r_2)\land f=InRoom(a,r_2))\lor\\&\exists a,o,r\,(e=PickUp(a,o)\land\\&f=Holding(a,o)\land\\&HoldsAt(InRoom(a,r),t)\land\\&HoldsAt(InRoom(o,r),t))\lor\end{aligned}\tag{6.54}$$

$$
\begin{aligned}
&\exists a, o, r\,(e = \mathit{LetGoOf}(a, o) \wedge \\
&f = \mathit{InRoom}(o, r) \wedge \\
&\mathit{HoldsAt}(\mathit{InRoom}(a, r), t)) \\
&\mathit{Terminates}(e, f, t) \Leftrightarrow && (6.55)\\
&\exists a, r_1, r_2\,(e = \mathit{Walk}(a, r_1, r_2) \wedge \\
&f = \mathit{InRoom}(a, r_1) \wedge \\
&r_1 \neq r_2) \vee \\
&\exists a, o\,(e = \mathit{LetGoOf}(a, o) \wedge \\
&f = \mathit{Holding}(a, o) \wedge \\
&\mathit{HoldsAt}(\mathit{Holding}(a, o), t)) \\
&\mathit{Releases}(e, f, t) \Leftrightarrow && (6.56)\\
&\exists a, o, r\,(e = \mathit{PickUp}(a, o) \wedge f = \mathit{InRoom}(o, r))
\end{aligned}
$$

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

$$
\begin{aligned}
&\mathit{Happens}(e, t) \Leftrightarrow && (6.57)\\
&(e = \mathit{PickUp}(\mathit{Nathan}, \mathit{Book}) \wedge t = 0) \vee \\
&(e = \mathit{Walk}(\mathit{Nathan}, \mathit{LivingRoom}, \mathit{Kitchen}) \wedge t = 1)
\end{aligned}
$$

From (6.57), (6.55), and EC3, we have

$$\neg \mathit{StoppedIn}(0, \mathit{Holding}(\mathit{Nathan}, \mathit{Book}), 2) \tag{6.58}$$

From (6.56) and EC13, we have

$$\neg \mathit{ReleasedIn}(0, \mathit{Holding}(\mathit{Nathan}, \mathit{Book}), 2) \tag{6.59}$$

From (6.51) (which follows from (6.57)), (6.49), (6.50), (6.4) (which follows from (6.54)), $0 < 2$, (6.58), (6.59), and EC14, we have

$$\mathit{HoldsAt}(\mathit{Holding}(\mathit{Nathan}, \mathit{Book}), 2) \tag{6.60}$$

From (6.57) and EC3, we have

$$\neg \mathit{StoppedIn}(1, \mathit{InRoom}(\mathit{Nathan}, \mathit{Kitchen}), 2) \tag{6.61}$$

From (6.57) and EC13, we have

$$\neg \mathit{Released}(1, \mathit{InRoom}(\mathit{Nathan}, \mathit{Kitchen}), 2) \tag{6.62}$$

From (6.52) (which follows from (6.57)), (6.1) (which follows from (6.54)), $1 < 2$, (6.61), (6.62), and EC14, we have $\mathit{HoldsAt}(\mathit{InRoom}(\mathit{Nathan}, \mathit{Kitchen}), 2)$. From this, (6.60), and (6.46), we have $\mathit{HoldsAt}(\mathit{InRoom}(\mathit{Book}, \mathit{Kitchen}), 2)$. ■

6.4 EFFECT CONSTRAINTS

Another way of representing indirect effects is to use universally quantified formulas involving *Initiates* and *Terminates*.

Definition 6.1. If γ is a condition, δ_1 and δ_2 are *Initiates* or *Terminates*, α is an event term, β_1 and β_2 are fluent terms, and τ is a timepoint term, then

$$(\gamma \wedge \delta_1(\alpha, \beta_1, \tau)) \Rightarrow \delta_2(\alpha, \beta_2, \tau)$$

is an ***effect constraint***.

6.4.1 EXAMPLE: CARRYING A BOOK REVISITED

Consider again the example in Section 6.1.1. We may represent the indirect effects of walking from one room to another using effect constraints:

$$\begin{gathered} HoldsAt(Holding(a,o),t) \wedge \\ Initiates(e, InRoom(a,r),t) \Rightarrow \\ Initiates(e, InRoom(o,r),t) \end{gathered} \tag{6.63}$$

$$\begin{gathered} HoldsAt(Holding(a,o),t) \wedge \\ Terminates(e, InRoom(a,r),t) \Rightarrow \\ Terminates(e, InRoom(o,r),t) \end{gathered} \tag{6.64}$$

Unfortunately, we cannot use predicate completion and Theorems 2.1 and 2.2 to compute $CIRC[(6.1) \wedge (6.2) \wedge (6.4) \wedge (6.5) \wedge (6.63) \wedge (6.64); Initiates, Terminates, Releases]$, because *Initiates* is contained in the antecedent of (6.63) and *Terminates* is contained in the antecedent of (6.64). (This can be handled by answer set programming—see Section 15.3.4.) Instead we simply use (6.63) and (6.64) to derive the effect axioms in Section 6.1.1 that represent the indirect effects. From (6.63) and

$$Initiates(Walk(a, r_1, r_2), InRoom(a, r_2), t)$$

we have

$$\begin{gathered} HoldsAt(Holding(a,o),t) \Rightarrow \\ Initiates(Walk(a, r_1, r_2), InRoom(o, r_2), t) \end{gathered}$$

which is (6.6). From (6.64) and

$$r_1 \neq r_2 \Rightarrow Terminates(Walk(a, r_1, r_2), InRoom(a, r_1), t)$$

we have

$$\begin{gathered} HoldsAt(Holding(a,o),t) \wedge r_1 \neq r_2 \Rightarrow \\ Terminates(Walk(a, r_1, r_2), InRoom(o, r_1), t) \end{gathered}$$

which is (6.7).

6.5 CAUSAL CONSTRAINTS

Michael Thielscher devised the electronic circuit shown in Figure 6.1 in order to point out problems with solutions to the ramification problem based on dividing fluents

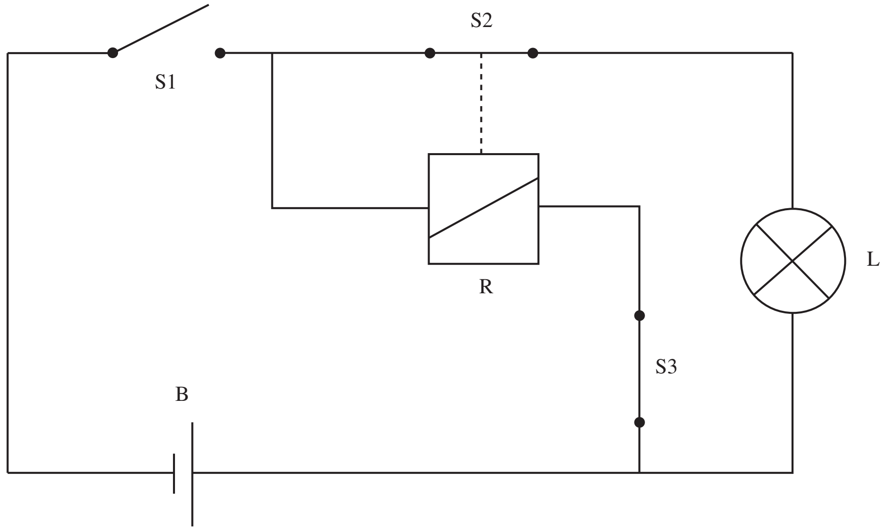

FIGURE 6.1

Thielscher's circuit (Thielscher, 1996, p. 19).

into primitive and derived fluents, as discussed in Section 6.2. The circuit consists of a battery (B), three switches (S1, S2, and S3), a relay (R), and a light (L). A switch can be open or closed, the relay can be activated or not activated, and the light can be lit or not lit. Relay R is activated whenever S1 and S3 are closed. Light L is lit whenever S1 and S2 are closed. Relay R is connected to switch S2, so that when R is activated, S2 is opened.

One behavior of this circuit is as follows. Suppose that initially S1 is open, S2 and S3 are closed, R is not activated, and L is not lit. If we close S1, then R will be activated and S2 will be opened. Because S2 is open, the result will be that light L is not lit.

Now suppose we try to model this behavior using primitive and derived fluents. We use primitive fluents for S1 and S3:

$$Initiates(Close(S1), Closed(S1), t) \tag{6.65}$$
$$Terminates(Open(S1), Closed(S1), t) \tag{6.66}$$
$$Initiates(Close(S3), Closed(S3), t) \tag{6.67}$$
$$Terminates(Open(S3), Closed(S3), t) \tag{6.68}$$

We use derived fluents for R and L:

$$\begin{gathered} HoldsAt(Activated(R), t) \Leftrightarrow \\ HoldsAt(Closed(S1), t) \wedge HoldsAt(Closed(S3), t) \end{gathered} \tag{6.69}$$

$$\begin{gathered} HoldsAt(Lit(L), t) \Leftrightarrow \\ HoldsAt(Closed(S1), t) \wedge HoldsAt(Closed(S2), t) \end{gathered} \tag{6.70}$$

It is not clear what to use for S2, which appears to be both primitive and derived. On the one hand, S2 can be manually opened and closed:

$$Initiates(Close(S2), Closed(S2), t) \tag{6.71}$$

$$Terminates(Open(S2), Closed(S2), t) \tag{6.72}$$

On the other hand, S2 is open whenever R is activated:

$$\neg HoldsAt(Closed(S2), t) \Leftrightarrow HoldsAt(Activated(R), t) \tag{6.73}$$

Unfortunately, if we use all three axioms (6.71), (6.72), and (6.73), then we get inconsistency. To see this, consider the following observations and narrative:

$$\neg HoldsAt(Closed(S1), 0) \tag{6.74}$$

$$HoldsAt(Closed(S2), 0) \tag{6.75}$$

$$HoldsAt(Closed(S3), 0) \tag{6.76}$$

$$\neg HoldsAt(Activated(R), 0) \tag{6.77}$$

$$\neg HoldsAt(Lit(L), 0) \tag{6.78}$$

$$\neg ReleasedAt(f, t) \tag{6.79}$$

$$Happens(Close(S1), 0) \tag{6.80}$$

Proposition 6.4. *Let* $\Sigma = (6.65) \wedge (6.66) \wedge (6.67) \wedge (6.68) \wedge (6.71) \wedge (6.72)$, $\Delta = (6.80)$, $\Omega = U[Close, Open, Activate, Light] \wedge U[Closed, Activated, Lit]$, *and* $\Psi = (6.69) \wedge (6.70) \wedge (6.73)$, *and* $\Gamma = (6.74) \wedge (6.75) \wedge (6.76) \wedge (6.77) \wedge (6.78) \wedge (6.79)$. *Then* $CIRC[\Sigma; Initiates, Terminates, Releases] \wedge CIRC[\Delta; Happens] \wedge \Omega \wedge \Psi \wedge \Gamma \wedge$ DEC *is inconsistent.*

Proof. From $CIRC[\Sigma; Initiates, Terminates, Releases]$ and Theorems 2.1 and 2.2, we have

$$\begin{aligned} &Initiates(e,f,t) \Leftrightarrow \\ &(e = Close(S1) \wedge f = Closed(S1)) \vee \\ \\ &(e = Close(S2) \wedge f = Closed(S2)) \vee \\ &(e = Close(S3) \wedge f = Closed(S3)) \end{aligned} \tag{6.81}$$

$$\begin{aligned} &Terminates(e,f,t) \Leftrightarrow \\ &(e = Open(S1) \wedge f = Closed(S1)) \vee \\ &(e = Open(S2) \wedge f = Closed(S2)) \vee \\ &(e = Open(S3) \wedge f = Closed(S3)) \end{aligned} \tag{6.82}$$

$$\neg Releases(e,f,t). \tag{6.83}$$

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

$$\begin{aligned} &Happens(e, t) \Leftrightarrow \\ &(e = Close(S1) \wedge t = 0) \end{aligned} \tag{6.84}$$

From (6.80) (which follows from (6.84)), (6.65) (which follows from (6.81)), and DEC9, we have $HoldsAt(Closed(S1), 1)$. From this, (6.76), and (6.69), we have $HoldsAt(Activated(R), 1)$. From this and (6.73), we have

$$\neg HoldsAt(Closed(S2), 1) \tag{6.85}$$

Yet, from (6.84) and (6.82), we have $\neg\exists e\,(Happens(e,0) \wedge Terminates(e, Closed(S2), 0))$. From this, (6.75), (6.79), and DEC5, we have $HoldsAt\,(Closed(S2), 1)$, which contradicts (6.85). ■

Thus, it does not work for S2 to be both a primitive and derived fluent.

In order to deal with this circuit, or any commonsense reasoning problem in which indirect effects interact with one another instantaneously, Murray Shanahan enhances the event calculus as follows. First, he adds the following four predicates.

$Started(f,t)$: Fluent f is true at timepoint t, or f is initiated by an event that occurs at t. We say that f is *started* at t.
$Stopped(f,t)$: Fluent f is false at timepoint t, or f is terminated by an event that occurs at t. We say that f is *stopped* at t.
$Initiated(f,t)$: Fluent f is started at timepoint t, and f is not terminated by any event that occurs at t.
$Terminated(f,t)$: Fluent f is stopped at timepoint t, and f is not initiated by any event that occurs at t.

Second, he adds the following axioms.

Axiom CC1.

$$Started(f,t) \Leftrightarrow HoldsAt(f,t) \vee \exists e\,(Happens(e,t) \wedge Initiates(e,f,t))$$

Axiom CC2.

$$Stopped(f,t) \Leftrightarrow \neg HoldsAt(f,t) \vee \exists e\,(Happens(e,t) \wedge Terminates(e,f,t))$$

Axiom CC3.

$$Initiated(f,t) \Leftrightarrow Started(f,t) \wedge \neg\exists e\,(Happens(e,t) \wedge Terminates(e,f,t))$$

Axiom CC4.

$$Terminated(f,t) \Leftrightarrow Stopped(f,t) \wedge \neg\exists e\,(Happens(e,t) \wedge Initiates(e,f,t))$$

We use CC to mean the conjunction of axioms CC1 through CC4. Third, Shanahan introduces a new type of axiom called a causal constraint.

Definition 6.2. If α is an event term, β and $\beta_1, \ldots, \beta_n$ are fluent terms, θ is *Stopped* or *Started*, $\pi_1, \ldots, \pi_n$ are *Initiated* or *Terminated*, and τ is a timepoint term, then

$$\theta(\beta,\tau) \wedge \pi_1(\beta_1,\tau) \wedge \cdots \wedge \pi_n(\beta_n,\tau) \Rightarrow Happens(\alpha,\tau)$$

is a ***causal constraint***.

6.5.1 EXAMPLE: THIELSCHER'S CIRCUIT

We now show how causal constraints can be used to deal properly with Thielscher's circuit. Our axiomatization of the circuit is the same as Shanahan's, except that we use events such as *Close*(*S1*) instead of *Close1*, use fluents such as *Closed*(*S1*) instead of *Switch1*, and have axioms for opening and closing all switches.

We use the observations and narrative just discussed, and we have the following effect axioms:

$$Initiates(Close(s), Closed(s), t) \tag{6.86}$$

$$Terminates(Open(s), Closed(s), t) \tag{6.87}$$

$$Initiates(Activate(r), Activated(r), t) \tag{6.88}$$

$$Initiates(Light(l), Lit(l), t) \tag{6.89}$$

We have the following causal constraints:

$$\begin{aligned} &Stopped(Lit(L), t) \wedge \\ &Initiated(Closed(S1), t) \wedge \\ &Initiated(Closed(S2), t) \Rightarrow \\ &Happens(Light(L), t) \end{aligned} \tag{6.90}$$

$$\begin{aligned} &Started(Closed(S2), t) \wedge \\ &Initiated(Activated(R), t) \Rightarrow \\ &Happens(Open(S2), t) \end{aligned} \tag{6.91}$$

$$\begin{aligned} &Stopped(Activated(R), t) \wedge \\ &Initiated(Closed(S1), t) \wedge \\ &Initiated(Closed(S3), t) \Rightarrow \\ &Happens(Activate(R), t) \end{aligned} \tag{6.92}$$

Given this axiomatization we can show that after switch S1 is closed, light L will not be lit.

Proposition 6.5. *Let* $\Sigma = (6.86) \wedge (6.87) \wedge (6.88) \wedge (6.89)$, $\Delta = (6.80) \wedge (6.90) \wedge (6.91) \wedge (6.92)$, $\Omega = U[Close, Open, Activate, Light] \wedge U[Closed, Activated, Lit]$, *and* $\Gamma = (6.74) \wedge (6.75) \wedge (6.76) \wedge (6.77) \wedge (6.78) \wedge (6.79)$. *Then we have*

$$\begin{aligned} &CIRC[\Sigma; Initiates, Terminates, Releases] \wedge CIRC[\Delta; Happens] \wedge \\ &\Omega \wedge \Gamma \wedge \mathrm{DEC} \wedge \mathrm{CC} \vdash \neg HoldsAt(Lit(L), 1) \end{aligned}$$

Proof. From $CIRC[\Sigma; Initiates, Terminates, Releases]$ and Theorems 2.1 and 2.2, we have

$$\begin{aligned} &Initiates(e, f, t) \Leftrightarrow \\ &\exists s\, (e = Close(s) \wedge f = Closed(s)) \vee \\ &\exists r\, (e = Activate(r) \wedge f = Activated(r)) \vee \\ &\exists l\, (e = Light(l) \wedge f = Lit(l)) \end{aligned} \tag{6.93}$$

$$\begin{aligned} &Terminates(e, f, t) \Leftrightarrow \\ &\exists s\, (e = Open(s) \wedge f = Closed(s)) \end{aligned} \tag{6.94}$$

$$\neg Releases(e, f, t) \tag{6.95}$$

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

$$\begin{aligned}
&Happens(e,t) \Leftrightarrow \\
&(e = Close(S1) \wedge t = 0) \vee \\
&(e = Light(L) \wedge \\
&Stopped(Lit(L),t) \wedge \\
&Initiated(Closed(S1),t) \wedge \\
&Initiated(Closed(S2),t)) \vee \\
&(e = Open(S2) \wedge \\
&Started(Closed(S2),t) \wedge \\
&Initiated(Activated(R),t)) \vee \\
&(e = Activate(R) \wedge \\
&Stopped(Activated(R),t) \wedge \\
&Initiated(Closed(S1),t) \wedge \\
&Initiated(Closed(S3),t))
\end{aligned} \tag{6.96}$$

From (6.77) and CC2, we have

$$Stopped(Activated(R),0) \tag{6.97}$$

From (6.80) (which follows from (6.96)), and (6.86) (which follows from (6.93)), we have $\exists e\,(Happens(e,0) \wedge Initiates(e,Closed(S1),0))$. From this and CC1, we have

$$Started(Closed(S1),0) \tag{6.98}$$

From (6.94) and (6.96), we have $\neg\exists e\,(Happens(e,0) \wedge Terminates(e,Closed(S1),0))$. From this, (6.98), and CC3, we have

$$Initiated(Closed(S1),0) \tag{6.99}$$

From (6.76) and CC1, we have

$$Started(Closed(S3),0) \tag{6.100}$$

From (6.94) and (6.96), we have $\neg\exists e\,(Happens(e,0) \wedge Terminates(e,Closed(S3),0))$. From this, (6.100), and CC3, we have $Initiated(Closed(S3),0)$. From this, (6.97), (6.99), and (6.92) (which follows from (6.96)), we have $Happens(Activate(R),0)$. From this and (6.88) (which follows from (6.93)), we have $\exists e\,(Happens(e,0) \wedge Initiates(e,Activated(R),0))$. From this and CC1, we have

$$Started(Activated(R),0) \tag{6.101}$$

From (6.94), we have $\neg\exists e\,(Happens(e,0) \wedge Terminates(e,Activated(R),0))$. From this, (6.101), and CC3, we have

$$Initiated(Activated(R),0) \tag{6.102}$$

From (6.75) and CC1, we have $Started(Closed(S2),0)$. From this, (6.102), and (6.91) (which follows from (6.96)), we have $Happens(Open(S2),0)$. From this and (6.87) (which follows from (6.94)), we have $\exists e\,(Happens(e,0) \wedge Terminates(e,Closed(S2),0))$. From this and CC3, we have $\neg Initiated(Closed(S2),0)$.

From this and (6.96), we have $\neg Happens(Light(L), 0)$. From this and (6.93), we have $\neg\exists e\ (Happens(e, 0) \wedge Initiates(e, Lit(L), 0))$. From this, (6.78), (6.79), and DEC6, we have $\neg HoldsAt(Lit(L), 1)$. ■

6.6 TRIGGER AXIOMS

There is a further option for representing indirect effects. If the indirect effects are delayed and not instantaneous, then we can represent them using the trigger axioms described in Section 4.1. We can in fact use trigger axioms to represent the behavior of Thielscher's circuit (Figure 6.1). In this case, with the conjunction of axioms DEC the light will light up for two timepoints before going out again; with the conjunction of axioms EC the light will light up for an instant and then go out.

6.6.1 EXAMPLE: THIELSCHER'S CIRCUIT WITH DELAYS

Instead of causal constraints, we use the following trigger axioms:

$$\begin{gathered}\neg HoldsAt(Lit(L), t) \wedge \\ HoldsAt(Closed(S1), t) \wedge \\ HoldsAt(Closed(S2), t) \Rightarrow \\ Happens(Light(L), t)\end{gathered} \tag{6.103}$$

$$\begin{gathered}HoldsAt(Lit(L), t) \wedge \\ (\neg HoldsAt(Closed(S1), t) \vee \neg HoldsAt(Closed(S2), t)) \Rightarrow \\ Happens(Unlight(L), t)\end{gathered} \tag{6.104}$$

$$\begin{gathered}HoldsAt(Closed(S2), t) \wedge \\ HoldsAt(Activated(R), t) \Rightarrow \\ Happens(Open(S2), t)\end{gathered} \tag{6.105}$$

$$\begin{gathered}\neg HoldsAt(Activated(R), t) \wedge \\ HoldsAt(Closed(S1), t) \wedge \\ HoldsAt(Closed(S3), t) \Rightarrow \\ Happens(Activate(R), t)\end{gathered} \tag{6.106}$$

We add the following effect axiom to those already given:

$$Terminates(Unlight(l), Lit(l), t) \tag{6.107}$$

Given the observations and narrative, we can show that the light is lit at timepoint 2 and is not lit at timepoint 4.

Proposition 6.6. *Let* $\Sigma =$ (6.86) $\wedge$ (6.87) $\wedge$ (6.88) $\wedge$ (6.89) $\wedge$ (6.107), $\Delta =$ (6.80) $\wedge$ (6.103) $\wedge$ (6.104) $\wedge$ (6.105) $\wedge$ (6.106), $\Omega = U[Close, Open, Activate, Light] \wedge U[Closed, Activated, Lit]$, *and* $\Gamma =$ (6.74) $\wedge$ (6.75) $\wedge$ (6.76) $\wedge$ (6.77) $\wedge$ (6.78) $\wedge$ (6.79). *Then we have*

$$CIRC[\Sigma; Initiates, Terminates, Releases] \land CIRC[\Delta; Happens] \land$$
$$\Omega \land \Gamma \land \text{DEC} \vdash HoldsAt(Lit(L), 2) \land \neg HoldsAt(Lit(L), 4)$$

Proof. From $CIRC[\Sigma; Initiates, Terminates, Releases]$ and Theorems 2.1 and 2.2, we have

$$\begin{aligned} &Initiates(e, f, t) \Leftrightarrow \\ &\exists s\,(e = Close(s) \land f = Closed(s)) \lor \\ &\exists r\,(e = Activate(r) \land f = Activated(r)) \lor \\ &\exists l\,(e = Light(l) \land f = Lit(l)) \end{aligned} \tag{6.108}$$

$$\begin{aligned} &Terminates(e, f, t) \Leftrightarrow \\ &\exists s\,(e = Open(s) \land f = Closed(s)) \lor \\ &\exists l\,(e = Unlight(l) \land Lit(l)) \end{aligned} \tag{6.109}$$

$$\neg Releases(e, f, t) \tag{6.110}$$

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

$$\begin{aligned} &Happens(e, t) \Leftrightarrow \\ &(e = Close(S1) \land t = 0) \lor (e = Light(L) \land \\ &\neg HoldsAt(Lit(L), t) \land \\ &HoldsAt(Closed(S1), t) \land \\ &HoldsAt(Closed(S2), t)) \lor \\ &(e = Unlight(L) \land \\ &HoldsAt(Lit(L), t) \land \\ &(\neg HoldsAt(Closed(S1), t) \lor \neg HoldsAt(Closed(S2), t))) \lor \\ &(e = Open(S2) \land \\ &HoldsAt(Closed(S2), t) \land \\ &HoldsAt(Activated(R), t)) \lor \\ &(e = Activate(R) \land \\ &\neg HoldsAt(Activated(R), t) \land \\ &HoldsAt(Closed(S1), t) \land \\ &HoldsAt(Closed(S3), t)) \end{aligned} \tag{6.111}$$

First we show that the light goes on. From (6.80) (which follows from (6.111)), (6.86) (which follows from (6.108)), and DEC9 we have

$$HoldsAt(Closed(S1), 1) \tag{6.112}$$

From (6.77) and (6.111), we have $\neg Happens(Open(S2), 0)$. From this and (6.109), we have $\neg\exists e\,(Happens(e, 0) \land Terminates(e, Closed(S2), 0))$. From this, (6.75), (6.79), and DEC5, we have

$$HoldsAt(Closed(S2), 1) \tag{6.113}$$

From (6.74), (6.111), and (6.108), we have $\neg\exists e\,(Happens(e,0) \wedge Initiates(e, Lit(L), 0))$. From this, (6.78), (6.79), and DEC6, we have $\neg HoldsAt(Lit(L), 1)$. From this, (6.112), (6.113), and (6.103) (which follows from (6.111)), we have $Happens(Light(L), 1)$. From this, (6.89) (which follows from (6.108)), and DEC9, we have

$$HoldsAt(Lit(L), 2) \tag{6.114}$$

Second we show that the light goes off again. From (6.74) and (6.111), we have $\neg Happens(Activate(R), 0)$. From this and (6.108), we have $\neg\exists e\,(Happens(e,0) \wedge Initiates(e, Activated(R), 0))$. From this, (6.77), (6.79), and DEC6, we have

$$\neg HoldsAt(Activated(R), 1) \tag{6.115}$$

From (6.111) and (6.109), we have $\neg\exists e\,(Happens(e,0) \wedge Terminates(e, Closed(S3), 0))$. From this, (6.76), (6.79), and DEC5, we have $HoldsAt\,(Closed(S3), 1)$. From this, (6.115), (6.112), and (6.106) (which follows from (6.111)), we have $Happens(Activate(R), 1)$. From this, (6.88) (which follows from (6.108)), and DEC9, we have

$$HoldsAt(Activated(R), 2) \tag{6.116}$$

From (6.115) and (6.111), we have $\neg Happens(Open(S2), 1)$. From this and (6.109), we have $\neg\exists e\,(Happens(e,1) \wedge Terminates(e, Closed(S2), 1))$. From this, (6.113), (6.79), and DEC5, we have

$$HoldsAt(Closed(S2), 2) \tag{6.117}$$

From this, (6.116), and (6.105) (which follows from (6.111)), we have $Happens(Open(S2), 2)$. From this, (6.87) (which follows from (6.109)), and DEC10, we have

$$\neg HoldsAt(Closed(S2), 3) \tag{6.118}$$

From (6.111) and (6.109), we have $\neg\exists e\,(Happens(e,1) \wedge Terminates(e, Closed(S1), 1))$. From this, (6.112), (6.79), and DEC5, we have $HoldsAt\,(Closed(S1), 2)$. From this, (6.117), and (6.111), we have $\neg Happens(Unlight\,(L), 2)$. From this and (6.109), we have $\neg\exists e\,(Happens(e,2) \wedge Terminates\,(e, Lit(L), 2))$. From this, (6.114), (6.79), and DEC5, we have $HoldsAt\,(Lit(L), 3)$. From this, (6.118), and (6.104) (which follows from (6.111)), we have $Happens(Unlight(L), 3)$. From this, (6.107) (which follows from (6.109)), and DEC10, we have $\neg HoldsAt(Lit(L), 4)$. ■

6.6.2 EXAMPLE: SHANAHAN'S CIRCUIT WITH DELAYS

Shanahan showed that if the circuit is modified to that shown in Figure 6.2, then an axiomatization of the circuit using causal constraints as in Section 6.5 produces inconsistency. We can properly represent the behavior of this circuit using trigger axioms. The circuit implements a buzzer that is turned on and off with S1; we ignore the light in this discussion. A moment after S1 is closed, relay R is activated. A moment after R is activated, S2 is open. A moment after S2 is open, R is not activated. A moment after relay R is not activated, S2 is closed. A moment after S2 is closed,

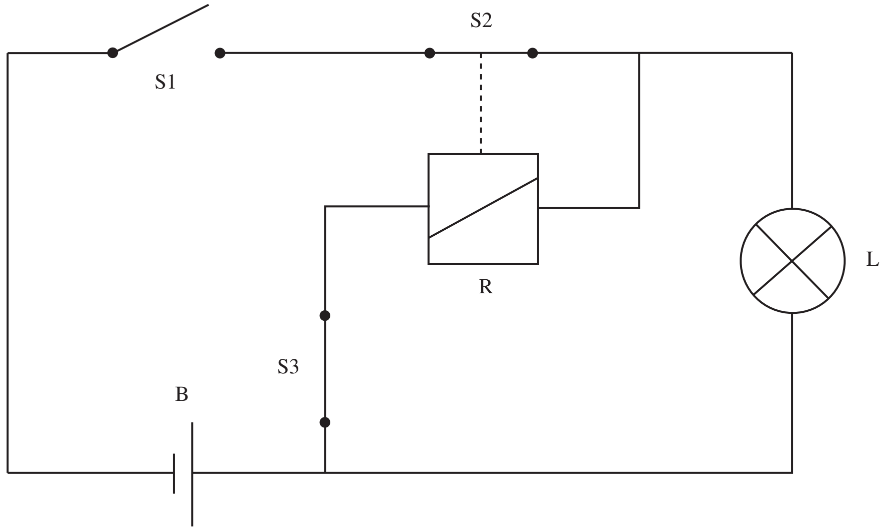

FIGURE 6.2

Shanahan's circuit (Shanahan, 1996b, p. 145).

R is activated again. The cycle repeats. In a real circuit, the result of a relay quickly and repeatedly activating and deactivating is a buzzing sound.

We have the following trigger axioms:

$$\begin{gathered}\neg HoldsAt(Lit(L), t) \wedge \\ HoldsAt(Closed(S1), t) \wedge \\ HoldsAt(Closed(S2), t) \Rightarrow \\ Happens(Light(L), t)\end{gathered} \tag{6.119}$$

$$\begin{gathered}HoldsAt(Lit(L), t) \wedge \\ (\neg HoldsAt(Closed(S1), t) \vee \neg HoldsAt(Closed(S2), t)) \Rightarrow \\ Happens(Unlight(L), t)\end{gathered} \tag{6.120}$$

$$\begin{gathered}HoldsAt(Closed(S2), t) \wedge \\ HoldsAt(Activated(R), t) \Rightarrow \\ Happens(Open(S2), t)\end{gathered} \tag{6.121}$$

$$\begin{gathered}\neg HoldsAt(Activated(R), t) \wedge \\ HoldsAt(Closed(S1), t) \wedge \\ HoldsAt(Closed(S2), t) \wedge \\ HoldsAt(Closed(S3), t) \Rightarrow \\ Happens(Activate(R), t)\end{gathered} \tag{6.122}$$

$$\begin{aligned}&HoldsAt(Activated(R),t) \wedge \\ &(\neg HoldsAt(Closed(S1),t) \vee \\ &\neg HoldsAt(Closed(S2),t) \vee \\ &\neg HoldsAt(Closed(S3),t)) \Rightarrow \\ &Happens(Deactivate(R),t)\end{aligned} \tag{6.123}$$

We add the following effect axiom to those already given:

$$Terminates(Deactivate(r), Activated(r), t) \tag{6.124}$$

We use the observations and narrative as detailed before.

With the conjunction of axioms EC, the circuit buzzes with infinite frequency, whereas with the conjunction of axioms DEC, it buzzes with finite frequency. Using DEC, we can show that R activates at timepoint 1, S2 opens at timepoint 2, and R deactivates at timepoint 3.

Proposition 6.7. *Let* $\Sigma = (6.86) \wedge (6.87) \wedge (6.88) \wedge (6.89) \wedge (6.107) \wedge (6.124)$, $\Delta = (6.80) \wedge (6.119) \wedge (6.120) \wedge (6.121) \wedge (6.122) \wedge (6.123)$, $\Omega = U[Close, Open, Activate, Deactivate, Light, Unlight] \wedge U[Closed, Activated, Lit]$, *and* $\Gamma = (6.74) \wedge (6.75) \wedge (6.76) \wedge (6.77) \wedge (6.78) \wedge (6.79)$. *Then we have*

$$\begin{aligned}&CIRC[\Sigma; Initiates, Terminates, Releases] \wedge CIRC[\Delta; Happens] \wedge \\ &\Omega \wedge \Gamma \wedge \mathrm{DEC} \vdash Happens(Activate(R),1) \wedge \\ &HoldsAt(Activated(R),2) \wedge \\ &Happens(Open(S2),2) \wedge \\ &\neg HoldsAt(Closed(S2),3) \wedge \\ &Happens(Deactivate(R),3) \wedge \\ &\neg HoldsAt(Activated(R),3)\end{aligned}$$

Proof. From $CIRC[\Sigma; Initiates, Terminates, Releases]$ and Theorems 2.1 and 2.2, we have

$$\begin{aligned}&Initiates(e,f,t) \Leftrightarrow \\ &\exists s\,(e = Close(s) \wedge f = Closed(s)) \vee \\ &\exists r\,(e = Activate(r) \wedge f = Activated(r)) \vee \\ &\exists l\,(e = Light(l) \wedge f = Lit(l))\end{aligned} \tag{6.125}$$

$$\begin{aligned}&Terminates(e,f,t) \Leftrightarrow \\ &\exists s\,(e = Open(s) \wedge f = Closed(s)) \vee \\ &\exists l\,(e = Unlight(l) \wedge Lit(l)) \vee \\ &\exists r\,(e = Deactivate(r) \wedge f = Activated(r))\end{aligned} \tag{6.126}$$

$$\neg Releases(e,f,t) \tag{6.127}$$

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

$$\begin{aligned}&Happens(e,t) \Leftrightarrow \\ &(e = Close(S1) \wedge t = 0) \vee \\ &(e = Light(L) \wedge \\ &\neg HoldsAt(Lit(L),t) \wedge\end{aligned} \tag{6.128}$$

$$
\begin{aligned}
&HoldsAt(Closed(S1), t) \land \\
&HoldsAt(Closed(S2), t)) \lor \\
&(e = Unlight(L) \land \\
&HoldsAt(Lit(L), t) \land \\
&(\neg HoldsAt(Closed(S1), t) \lor \\
&\neg HoldsAt(Closed(S2), t))) \lor \\
&(e = Open(S2) \land \\
&HoldsAt(Closed(S2), t) \land \\
&HoldsAt(Activated(R), t)) \lor \\
&(e = Activate(R) \land \\
&\neg HoldsAt(Activated(R), t) \land \\
&HoldsAt(Closed(S1), t) \land \\
&HoldsAt(Closed(S2), t) \land \\
&HoldsAt(Closed(S3), t)) \lor \\
&(e = Deactivate(R) \land \\
&HoldsAt(Activated(R), t) \land \\
&(\neg HoldsAt(Closed(S1), t) \lor \\
&\neg HoldsAt(Closed(S2), t) \lor \\
&\neg HoldsAt(Closed(S3), t)))
\end{aligned}
$$

From (6.80) (which follows from (6.128)), (6.86) (which follows from (6.125)), and DEC9, we have

$$HoldsAt(Closed(S1), 1) \tag{6.129}$$

From (6.74) and (6.128), we have $\neg Happens(Activate(R), 0)$. From this and (6.125), we have $\neg\exists e\,(Happens(e, 0) \land Initiates(e, Activated(R), 0))$. From this, (6.77), (6.79), and DEC6, we have

$$\neg HoldsAt(Activated(R), 1) \tag{6.130}$$

From (6.126), (6.128), and (6.77), we have $\neg\exists e\,(Happens(e, 0) \land Terminates(e, Closed(S2), 0))$. From this, (6.75), (6.79), and DEC5, we have

$$HoldsAt(Closed(S2), 1) \tag{6.131}$$

From (6.128) and (6.126), we have $\neg\exists e\,(Happens(e, 0) \land Terminates\ (e, Closed(S3), 0))$. From this, (6.76), (6.79), and DEC5, we have

$$HoldsAt(Closed(S3), 1) \tag{6.132}$$

From this, (6.130), (6.129), (6.131), and (6.122) (which follows from (6.128)), we have

$$Happens(Activate(R), 1)$$

From this, (6.88) (which follows from (6.125)), and DEC9, we have

$$HoldsAt(Activated(R), 2) \tag{6.133}$$

From (6.130) and (6.128), we have $\neg Happens(Open(S2), 1)$. From this and (6.126), we have $\neg\exists\ e\,(Happens(e, 1) \land Terminates(e, Closed(S2), 1))$. From this, (6.131), (6.79), and DEC5, we have

$$HoldsAt(Closed(S2), 2) \tag{6.134}$$

From this, (6.133), and (6.121) (which follows from (6.128)), we have

$$Happens(Open(S2), 2)$$

From this, (6.87) (which follows from (6.126)), and DEC10, we have

$$\neg HoldsAt(Closed(S2), 3) \tag{6.135}$$

From (6.126) and (6.128), we have $\neg\exists e\,(Happens(e, 1) \wedge Terminates\ (e, Closed\ (S1), 1))$. From this, (6.129), (6.79), and DEC5, we have

$$HoldsAt(Closed(S1), 2) \tag{6.136}$$

From (6.126) and (6.128), we have $\neg\exists e\,(Happens(e, 1) \wedge Terminates\ \ (e, Closed\ (S3), 1))$. From this, (6.132), (6.79), and DEC5, we have $HoldsAt(Closed(S3), 2)$. From this, (6.126), (6.128), (6.136), and (6.134), we have $\neg\exists e\,(Happens(e, 2) \wedge Terminates(Activated(R), 2))$. From this, (6.133), (6.79), and DEC5, we have $HoldsAt(Activated(R), 3)$. From this, (6.135), and (6.123) (which follows from (6.128)), we have

$$Happens(Deactivate(R), 3)$$

From this, (6.124) (which follows from (6.126)), and DEC10, we have $\neg HoldsAt(Activated(R), 3)$. ■

Delayed indirect effects such as the results of dropping an object may be represented using trajectory and antitrajectory axioms, which are described in Chapter 7.

BIBLIOGRAPHIC NOTES

Ramification problem

Minsky (1961) noted something similar to the frame and ramification problems:

> *One problem that has been a great nuisance to us arises in connection with non-mathematical problems in which actions affect the state of some subject domain. … One must then deduce all the consequences of an action in so far as it affects propositions that one is planning to use. (p. 217)*

Green (1969, p. 98) mentions a problem with representing the effects of pushing an object that accidentally hits and moves other objects. Waldinger (1977, pp. 124-129) discusses the difficulty of representing "actions with indirect side effects" (p. 125) using the add lists and delete lists of STRIPS (Fikes & Nilsson, 1971). He gives the examples of pushing a row of boxes to the right by pushing the leftmost box and moving each component of a complex object by moving the object.

Finger (1987) considers ramifications in the context of automating the design of such things as electronic circuits, computer programs, and robot plans. The task is to find a design (similar to a plan) D that achieves a goal specification G given a world model W. He defines a *ramification* as a formula N such that $W \models (D \wedge G) \supset N$ (p. 9) and provides the example that consuming fuel is a ramification of driving an automobile (p. 69). He presents methods for finding ramifications (pp. 92-126) and using them to (1) eliminate inconsistent goals if a ramification is known to be impossible, (2) reduce the search space by providing additional constraints, and (3) provide additional heuristics (pp. 70-71). He defines the *ramification problem* as the problem of having to anticipate and deal with an unbounded set of consequences of a design (p. 16).

Taking their inspiration from Finger, Ginsberg and Smith (1987b, 1988b) define the *ramification problem* as the problem representing all the consequences of an action. They propose an approach to the ramification problem based on state constraints and possible worlds. A *possible world* is defined as a set of logical formulas. The consequences of an action performed in a world S are determined by finding the nearest possible worlds to S in which the direct effects of the action hold. They consider what a household robot would have to reason about and formalize a room in a house with a television set, plant, two ventilation ducts, and other objects. A state constraint represents that the room is stuffy if and only if both ventilation ducts are blocked. When a plant is blocking one duct and a television set is moved on top of the other duct, two nearest possible worlds result: one in which both ducts are blocked and the room is stuffy, and another in which the plant is no longer blocking a duct, the television set is blocking a duct, and the room is not stuffy.

Haas (1987) uses the example of a robot carrying a box and encodes the location of the box (*InRoom*) using a state constraint. Schubert (1990) uses the robot example and encodes "implicit effects" (p. 32) within both state constraints (his axiom A8, p. 33) and explanation closure axioms (his axiom A20, p. 35). The robot examples derive from the robot world model of Fikes and Nilsson (1971) and Fikes, Hart, and Nilsson (1972a) and from the blocks world (Winston, 1970; Winograd, 1972; Sacerdoti, 1977).

In the formulation of the situation calculus of Reiter (1991, 2001) and Pirri and Reiter (1999), a successor state axiom for a fluent specifies the truth value of the fluent in the successor situation $do(\alpha, \sigma)$ that results from performing action α in situation σ. Thus, a successor axiom for a fluent completely specifies how actions affect the fluent. Reiter (1991; 2001, pp. 23-35) presents a method for automatically compiling effect axioms into successor state axioms in order to solve the frame problem. F. Lin and Reiter (1994, sec. 5) and Reiter (2001, pp. 401-402) propose a method for dealing with state constraints in the situation calculus. The method involves making the effects implied by state constraints explicit. Additional effect axioms are derived from state constraints, and then effect axioms are compiled into successor state axioms as usual. They use an example of painting blocks. The action $paint(b, c)$ represents painting block b color c. An effect axiom states that the color of block b in the situation $do(paint(b, c), s)$ is c. A state constraint says that a block has a unique color in a situation. Their method arrives at the indirect effect that a block is no longer red after it is painted yellow. Note that we would not treat this as an indirect effect but would rather simply have the two (direct) effect axioms as follows:

$$Initiates(Paint(b,c), Color(b,c), t)$$

$$HoldsAt(Color(b,c_1),t) \wedge c_1 \neq c_2 \Rightarrow$$
$$Terminates(Paint(b,c_2), Color(b,c_1), t)$$

Similarly, Baral (2003, pp. 233-238) considers the indirect effects resulting from the constraint that an object can be at one location at a time.

Effect axioms

Kakas and Miller (1997a, p. 6) point out that, if effect axioms alone are used to represent indirect effects, then incompletely specified initial situations can lead to unintended models. Suppose that the observations and narrative in the example in Section 6.1 are empty. Then, there are models of the domain description in which the following formulas are true:

$$HoldsAt(Holding(Nathan, Book), 0)$$
$$HoldsAt(InRoom(Nathan, Kitchen), 0)$$
$$HoldsAt(InRoom(Book, LivingRoom), 0)$$

Primitive and derived fluents

The distinction between primitive and derived fluents goes back to STRIPS (Fikes & Nilsson, 1971), which had the notions of a "primitive clause" and a "derived clause" (p. 198). Fahlman (1974, pp. 18-20) distinguishes "primary data" and "secondary data." Kowalski (1979) classifies relations into "primitive" and "derived" (p. 137) in his version of the situation calculus. Lifschitz (1987a) distinguishes "primitive fluents" (p. 45) and fluents "defined in terms of primitive fluents" (p. 44). He writes a state constraint that defines *clear* in terms of the primitive fluent *at* (p. 50):

$$holds(clear\ l, s) \equiv \forall b\ \neg holds(at(b,l), s)$$

Lifschitz (1990b) makes a similar distinction between "frame fluents" and "arbitrary fluents" (p. 370). Shanahan (1999b) discusses the division of fluents into "primitive" and "derived" (p. 141) in the event calculus. State constraints for representing ramifications were introduced into the classical logic event calculus by Shanahan (1995a, pp. 262-264; 1997b, pp. 323-325). The reasons for using state constraints to encode indirect effects rather than effect axioms include "[avoiding] duplication of the same information on the consequent side of several action laws" (Sandewall, 1996, p. 99) and "[ensuring] a modular representation and … dramatically [shortening] an axiomatisation" (Shanahan, 1999b, p. 141). Shanahan (1997b, pp. 123-124) calculates that the number of effect axioms needed to replace a state constraint

$$HoldsAt(\beta_1, t) \wedge \cdots \wedge HoldsAt(\beta_n, t) \Rightarrow HoldsAt(\beta, t)$$

is on the order of $\sum_{i=1}^{n} m_i$, where m_i is the number of effect axioms for β_i. Baral (2003) argues for the use of constraints rather than effect axioms to represent ramifications and uses the example of having to add separate effect axioms for the indirect effects of every type of transportation: "$drive\_to(Y)$, $fly\_to(Y)$, $take\_a\_train\_to(Y)$, $take\_a\_bus\_to(Y)$" (p. 233).

Walking turkey scenario

Baker (1991, pp. 19-21) first described the walking turkey scenario due to Matthew L. Ginsberg: When a turkey that is walking is shot, it is no longer walking. F. Lin (1995) treats the ramification problem in the situation calculus by introducing a predicate $Caused(p, v, s)$, which represents that fluent p is caused to have truth value v in situation v. (A similar proposal is made by McCain and Turner, 1995.) The walking turkey scenario is treated as follows. The direct effect of shooting is specified by the effect axiom (F. Lin, 1995, p. 1989).

$$Caused(dead, true, do(shoot, s))$$

The indirect effect of shooting on walking is specified by the "causal rule" (p. 1990):

$$dead(s) \supset Caused(walking, false, s)$$

The following successor state axiom for *dead* follows from the predicate completion (K. L. Clark, 1978, pp. 303-305) of *Caused* in the conjunction of effect axioms and causal rules (simplified from Lin, 1995, p. 1990):

$$\begin{gathered} walking(do(a, s)) \equiv \\ walking(s) \wedge \neg dead(s) \wedge a \neq shoot \end{gathered}$$

Thus, the following indirect effect of *shoot* is derived (simplified from p. 1990):

$$\neg walking(do(shoot, s))$$

Gustafsson and Doherty (1996) treat indirect effects in the features and fluents framework, which is discussed in Section 16.2. They handle the walking turkey scenario using the "causal constraint" (we would handle this using an effect constraint) (p. 93)

$$\forall t[t]\ \neg alive \ \gg \ \neg walking$$

which gets translated into (p. 93)

$$\begin{gathered} \forall t[(\neg Holds(t, alive) \rightarrow \neg Holds(t, walking)) \wedge \\ (Holds(t-1, alive) \wedge \neg Holds(t, alive) \rightarrow \\ Occlude(t, walking))] \end{gathered}$$

The event calculus analog of Gustafsson and Doherty's treatment of the walking turkey scenario is:

$$\begin{gathered} Terminates(Shoot(a, b), Alive(b), t) \\ Releases(Shoot(a, b), Walking(b), t) \\ \neg HoldsAt(Alive(a), t) \Rightarrow \neg HoldsAt(Walking(a), t). \end{gathered}$$

Effect constraints

Shanahan (1997b, pp. 286-288, 324-325; 1999b, pp. 141-142) devised the effect constraint as a simple way of handling the walking turkey scenario in the event calculus. We need only add the effect constraint:

$$Terminates(e, Alive(a), t) \Rightarrow Terminates(e, Walking(a), t)$$

Fluent calculus

Thielscher (1996, 1997) proposes the following method to deal with indirect effects in the fluent calculus. We are given a set of direct effect descriptions, causal relationships, and state constraints. A causal relationship is an expression such as (Thielscher, 1997, p. 323)

$$sw_1 \texttt{ causes } light \texttt{ if } sw_2$$

The successor state resulting from performing an action α in a state of the world is computed as follows. The direct effects of α are first computed, giving the first intermediate state. Zero or more additional intermediate states are obtained by repeatedly applying causal relationships to intermediate states. Any intermediate state satisfying the state constraints is a successor state. Thus, causal relationships are permitted to interact with one another before a successor state is obtained. A successor state is not guaranteed to exist, and there may be several successor states. Thielscher also proposes a method for automatically compiling state constraints into causal relationships.

Causal constraints

The circuit in Figure 6.1 is taken from Thielscher (1996, p. 19). This circuit is a slight modification of the circuit of Thielscher (1995), which in turn was inspired by Lifschitz's (1990b, pp. 371-372) circuit consisting of two switches and a light. Thielscher's circuit, which is handled by the methods he proposed, led to the introduction of causal constraints into the event calculus by Shanahan (1999b). The event calculus axioms for causal constraints and the axiomatization of Thielscher's circuit are from Shanahan (1999b). Our proof of Proposition 6.5 is based on that of Shanahan (1999b, pp. 143-144). The modified version of Thielscher's circuit (Figure 6.2) is taken from Shanahan (1999b, p. 145), who proves that a formalization of the circuit using causal constraints results in inconsistency. Shanahan (1999b, p. 146) suggests that this circuit could be more properly modeled by taking delays into account.

EXERCISES

6.1 Suppose that in the example in Section 6.5.1, (6.90) is replaced by the state constraint

$$HoldsAt(Lit(L), t) \Leftrightarrow HoldsAt(Closed(S1), t) \wedge HoldsAt(Closed(S2), t)$$

Does the axiomatization still yield the conclusion that the light is off?

6.2 Suppose that in the example in Section 6.5.1, *Initiated* is replaced by *Started* in (6.90), (6.91), and (6.92). Does the axiomatization yield the conclusion that the light is off ?

6.3 Formalize the circuit of Figure 6.1 using effect axioms, effect constraints, and state constraints instead of causal constraints. Discuss the advantages and disadvantages of this axiomatization as compared to that using causal constraints.

6.4 Formalize the following example from Denecker, Dupré, and Belleghem (1998, pp. 4-5): An electronic counter is connected to an input line. The value of the counter is initially zero. The value of the input line is initially false. The value of the input line may fluctuate arbitrarily between false and true. The counter counts how many times the input line changes from false to true. That is, whenever the value of the input line changes from false to true, the value of the counter is incremented by one.

6.5 (Research Problem) Automate the translation of circuit diagrams into event calculus axiomatizations.