Synopsis of previous lectures and plan for today

- we have seen arguments to the effect that tense and aspect are intimately related to planning and causality
- we have also argued that semantics must be computational in order to account for language comprehension and production
- it follows that we need a computational formalism for planning and causality
- the cognitive reality of these computations is taken very seriously:
  - we are currently investigating their neural correlates using EEGs
  - neurally conditioned aberrations in these computations are taken to underlie deviant use of tense and aspect, e.g. in ADHD
- running example: ‘Max fell. John pushed him.’

Introducing the event calculus

- we have seen arguments to the effect that tense and aspect are intimately related to planning and causality
- we have also argued that semantics must be computational in order to account for language comprehension and production
- it follows that we need a computational formalism for planning and causality
- this is furnished by the *event calculus*, a theory of *causation* developed by Kowalski and extended by Shanahan to apply to robotics
- *event* calculus: ontology of the system does justice to the various kinds of events used in natural language (and cognition generally)
- event *calculus*: the system allows us to compute complete event structures from given events and knowledge of causal relations among events – as a consequence, it can compute discourse structures

What the event calculus is not: ‘neo-Davidsonianism’

- verbs denote events – following Davidson, interpretation of (action) verb has event variable:
- ‘Reichenbach’s proposal is that ordinary action sentences have, in effect, an existential quantifier binding the action-variable. When we were tempted into thinking a sentence like ‘Brutus kissed Caesar’ describes a single event we were misled: it does not describe any event at all. But if ‘Brutus kissed Caesar’ is true, then there is an event that makes it true. (This unrecognized element of generality in action sentences is, I think, of the utmost importance in understanding the relation between actions and desires.)’
- natural language is mapped unto event language via $V \mapsto V(e)$
- event language has temporal/aspectual predicates: $Cul(e,t)$, $Hold(e,t)$, and predicates for thematic roles: $Ag(e,x)$, $Obj(e,x)$

Criticism of ‘neo-Davidsonianism’

- ‘Mary drew a circle’ becomes
- $\exists e, x, t(circle(x) \wedge draw(e) \wedge Ag(e, m) \wedge Obj(e, x) \wedge \underline{Cul(e, t)} \wedge t < now)$
- ‘Mary was drawing a circle’ becomes
- $\exists e, x, t(circle(x) \wedge draw(e) \wedge Ag(e, m) \wedge Obj(e, x) \wedge \underline{Hold(e, t)} \wedge t < now)$
- this relies on intuitive understanding of the temporal/aspectual predicates
- $Cul(e, t)$ means that e is terminated at t; $Hold(e, t)$ means that e is still going on
- to make a distinction one needs e.g. $Cul(e, t) \rightarrow \neg Hold(e, t)$
- even more importantly: what is the x in $circle(x)$? x must depend on t and on e, but how?!

Event calculus: ontology

- event variable in neo-Davidsonianism ranges over event *tokens* ('lightning On March 15 2006, 8.25pm'), not types ('lightning')
- there are good reasons for having both event types and tokens; e.g. nominalization yields event types
- neo-Davidsonianism also conflates kinds of events, e.g. those corresponding to perfect and to imperfect nominals
- distinction in the event calculus between
  - action/event types: e, e' ... (for example 'break', 'ignite') [perhaps a further distinction between actions and events is necessary]
  - implicitly time-varying properties or *fluents*: f, f' ... (for example 'being broken', 'walking'), possibly with parameters (e.g. for the subject of 'walking')
- event types (or tokens?) cause changes in time-varying properties

Reminder: what causality has to do with planning

- earlier claim: verb tenses have to do with planning, verb semantics reflects goal-directed event structuring
- how to get from causality to planning:
  - a *goal* is a desired state of affairs (fluent), or desired event type, at a particular time
  - a *plan* is a sequence of actions (together with the times at which these actions have to be executed) which achieves some goal
- ideally, a plan can be computed on the basis of
  - knowledge of properties of, and occurrences of events in the world
  - causal knowledge about effects of actions under preconditions
- computation proceeds by regression from the goal: to achieve the goal (say a desired state), see what action(s) bring(s) this state about, what the preconditions for the actions are and so on

Event calculus: auxiliary ontology

Caution: logic!!!

- individual objects ('John') – although many individuals will be modelled as fluents, not as objects
- instants of time, interpreted as 'real numbers' – technically variables for time take values in a 'real-closed field'
- this choice does not reflect an ontological commitment to a particular structure of time (e.g. a continuum of *points*): there are many structures satisfying the axioms for real-closed fields, in some of these all 'reals' are computable, and hence approximable
- various other real quantities for e.g. position, velocity, degree of some quality (such as state of completion of a house in the process of being built) [with the same proviso as for time]

Another avenue to the event calculus: the perfective/imperfective dichotomy and nominalization

'Il y a d'autres intuitions de base qui ont été évacuées par la logique, ainsi la distinction essentielle entre *parfait* et *imparfait*, distinction rendu en français par le choix des temps, ...' (Girard)

- once we have explained how the ontology of the event calculus relates to natural language, we will see it embodies the fundamental distinction between perfective and imperfective aspect:
- event types correspond to perfective aspect (cf. Passé Simple, also perfect nominals); fluents correspond to imperfective aspect (cf. Imparfait, also imperfect nominals)
- this distinction was absent in the event axiomatizations that we studied so far (e.g. Walker)
- Davidsonian approaches also cannot capture this distinction because of the single quantifier $\exists e(\ldots)$

More on event types and fluents

- event types are like *nouns* – they can be used in pointing: ‘Look, lightning!’
- fluents can be viewed as *descriptions* of event types – in this case for instance a description of the paths that the light takes (from cloud to church steeple and old oak tree etc.)
- another example (to be used later): *fall* as event type and the corresponding fluent describing the trajectory of the falling object
- note there is a distinction between an event type (e.g. ‘lightning’) and an event token (‘lightning at a particular time and place’ – the latter can be represented by (the Gödel number of) a formula *Happens*(e, t_0)
- in fact event types and fluents are terms which can be seen as codes for formulas via *reification* (also called Gödelization):

More on event types and fluents

- start with a formula $\varphi(\overline{x}, t)$ and form the set $\{t \mid \varphi(\overline{x}, t)\}$ (depending on $\overline{x}$) – one may think of this set as the fluent $f(\overline{x})$ (which thus contains an implicit temporal parameter)
- therefore fluents come with the <u>truth predicate</u> *HoldsAt*$(f(\overline{x}), s)$, intuitively meaning $s \in \{t \mid \varphi(\overline{x}, t)\}$, i.e. $\varphi(\overline{x}, s)$
- event types $e(\overline{x})$ can be constructed as (the Gödel number of) a formula $\exists t \varphi(\overline{x}, t)$ (i.e. abstracting away from time)
- this is why event types and fluents are suitable for representing perfect and imperfect nominalization, respectively

Event calculus: primitive predicates for instantaneous change

- predicates and functions such as $+, \times, <$ over the reals
- event calculus predicates for *instantaneous* change

1. *Initially*(f) (‘fluent f holds at the beginning of the discourse’)
2. *Happens*(e, t) (‘event type e has a token at t’)
3. *Initiates*(e, f, t) (‘the causal effect of event type e at time t is the fluent f’)
4. *Terminates*(e, f, t) (‘the causal effect of event type e at time t is the negation of the fluent f’)
5. *Clipped*(s, f, t) (roughly, ‘an event type terminating f has a token between times s and t’)
6. *HoldsAt*(f, t) (a truth predicate – see below)

Event calculus: nature of the computations

- typical computation in robotics: goal can be certain location (say in office building) and action to be performed at that location; plan is sequence of actions to get you there, which can be obtained by backward chaining (i.e. logic programming)
- this requires a world model (including a map of the building, and initial position), a repertoire of activities and actions (e.g. 'follow wall', 'go through door') and of possible observations (e.g. 'door open/closed')
- on the basis of the world model a plan is computed, which may have to be recomputed in mid-course when the world model must be updated due to new observations (e.g. a closed door which was expected to be open)
- a plan may consist of continuous activities ('traverse distance x') and (almost) instantaneous actions ('observe distance to wall'), such that the latter take place during the former

Planning in cognition: executive function

- the nature of the computations facing robots and humans is the same – although the event calculus comes from robotics, it can therefore be applied to human cognition
- ‘executive function’ umbrella term for processes responsible for higher-level action control that are necessary for maintaining a goal and achieving it in possibly adverse circumstances
- another characterization: executive function is ‘the’ cognitive capacity which allows one to maintain a goal and to initiate and inhibit physical and mental actions appropriate to achieving that goal
- executive function comprises maintaining a goal, planning, inhibition, coordination and control of action sequences
- claim: several components of executive function involved in comprehension and production of tense
- failures of executive function can show up in deviant verb tenses (ADHD, schizophrenia)

From executive function to verb tenses via planning

- executive function comprises *maintaining a goal*, *planning*, inhibition, coordination and control of action sequences
- in *The proper treatment of events* the construction of event structures from discourses, using tense and aspect, is viewed as a planning problem
- verb tenses are represented as *goals* in the same sense as goals are used in planning
- in both comprehension and production, the goal is to introduce the event corresponding to the tensed VP into the event structure
- goal has to components:

1. location of event in time
2. meshing it with other events

From executive function to verb tenses via planning

- example: comprehending the mini-discourse

  'Max fell. John pushed him.'

- goals in this case:
- '`update discourse with past event` e_1 `=` ***`fall(m)`*** `and fit` e_1 `in context`'
- '`update discourse with past event` e_2 `=` ***`push(j,m)`*** `and fit` e_2 `in context`'
- planning must determine the event structure; here it tries to determine the order of e_1, e_2
- to determine the order of e_1, e_2, the planning system recruits causal knowledge as well as the principle that causes precede effects

From executive function to verb tenses via planning

- compare this with, say, planning the steps which lead to a pile of pancakes – e.g. causal knowledge dictates that one must pour oil in the frying-pan before putting in the batter
- applied to the case at hand, the planning system scans declarative memory for causal connections between e_1 and e_2 and finds (roughly) 'e_2 causes e_1'
- this fixes the temporal order of e_1 and e_2
- neurophysiological prediction for language comprehension:
  - re-planning must lead to characteristic EEG signal: 'Max fell. John pushed him, or rather what was left of him, over the edge.' – order of e_1 and e_2 can now be different
  - currently tested at F.C. Donders Centre for Neuroimaging Nijmegen (with Hagoort, Baggio)

Production: deviant verb tenses and ADHD

- patients with ADHD have difficulty keeping goals in working memory
- recall the goal corresponding to a verb tense consists of two components
  1. location of event in time
  2. meshing it with other events
- if someone has trouble maintaining a goal in working memory, this may lead to a simplification of the goal
- in the case of verb tenses most likely simplification to ‘ location of event in time’ (never mind the meshing with other events)
- in the case of the simple past tense, this could lead to a decrease in context-setting verbal material – compare
- ♯‘John arrived late.’
- ‘The workshop dinner was held in ‘la Rive’. John arrived late.’

Example: narration in schizophrenia

(J. Wrobel, Language and schizophrenia)

- executive function comprises maintaining a goal, planning, inhibition, *coordination and control* of action sequences

Q. Which of your relatives is still alive?

A. One of my uncles is alive in France. He died already in some kind of car accident.

- evidence of unstable 'now' – corresponds to not knowing where one is in action sequence
- related to 'goal-directed serial alternation task': starting from the number 101, do the following until one reaches 54

  1. subtract 7
  2. add either 1,2 or 3

Axioms for the event calculus, instantaneous change only

Assume given a set of axioms for the reals with $+, \times, <$ ('axioms for real-closed fields'). Axioms specific to the event calculus (EC) are (all variables universally quantified):

Axiom' 1 $\mathit{Initially}(f) \ \wedge \ \neg \mathit{Clipped}(0, f, t) \rightarrow \mathit{HoldsAt}(f, t)$

Axiom' 2 $\mathit{Happens}(e, t) \wedge \mathit{Initiates}(e, f, t) \wedge \ t < t^{'} \ \wedge \neg \mathit{Clipped}(t, f, t^{'}) \rightarrow \mathit{HoldsAt}(f, t^{'})$

Axiom' 3 $\mathit{Happens}(e, s) \ \wedge \ t < s < t^{'} \wedge \ \mathit{Terminates}(e, f, s) \ \rightarrow \mathit{Clipped}(t, f, t^{'})$

General models for EC are just structures for the many-sorted language of EC which satisfy the axioms, but . . .

- without axioms for *HoldsAt* there is no connection between fluents and time
- even with axioms for *HoldsAt*, there are many unintended models

HoldsAt as a truth predicate.

- binary truth predicate $T(\bullet, \bullet)$ satisfies

$$\mathcal{M} \models \varphi(a) \iff \mathcal{M} \models T('\varphi(x)', a)$$

- *HoldsAt* is like $T(\bullet, \bullet)$, but the second argument always stands for time
- we *need* it because in the event calculus formulas may also occur as objects, in particular fluents
- ever since Gödel 1931: coding formulas as terms
- in our case we made a formula $\varphi(t)$ act as a term (function or set) $\{s \mid \varphi(s)\}$, which which can be viewed as a fluent
- *HoldsAt* establishes a correspondence between fluents and sets of instants via

$$\mathcal{M} \models \varphi(t) \iff \mathcal{M} \models \mathit{HoldsAt}(\{s \mid \varphi(s)\}, t)$$

Additional axioms for HoldsAt of the following type

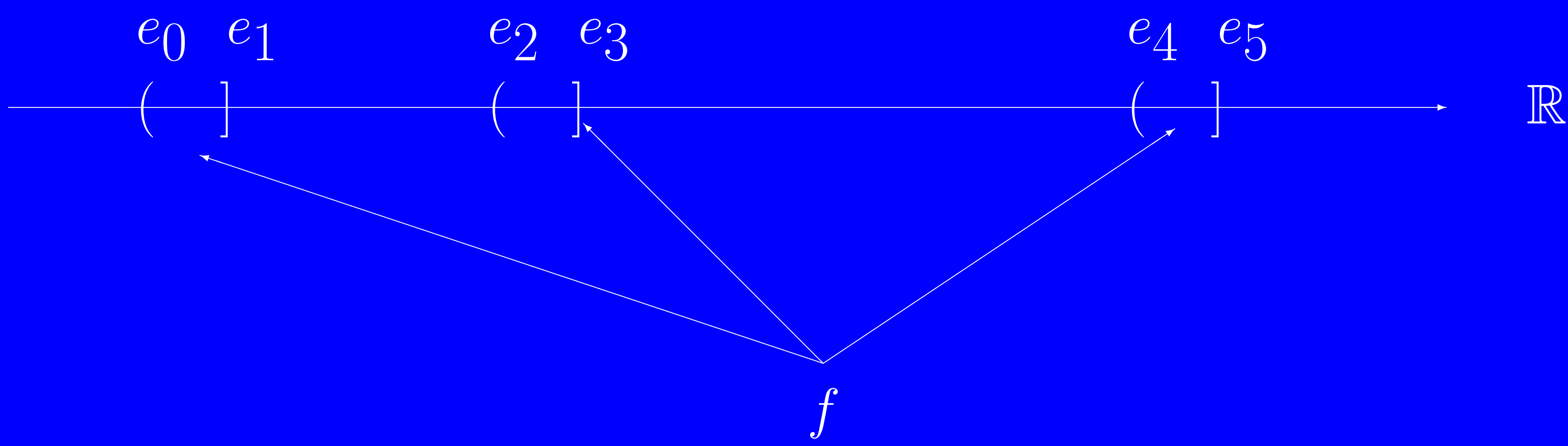
Assume $\psi(t), \psi_1(t), \psi_2(t) \ldots$ are formulas of a first order language, and $'\psi', \ldots$ their codes.

Axiom' 4 $HoldsAt('\psi_1 ', t) \wedge HoldsAt('\psi_2 ', t) \rightarrow HoldsAt('\psi_1 \wedge \psi_2 ', t)$

Axiom' 5 $\neg HoldsAt('\psi', t) \rightarrow HoldsAt('\neg\psi', t)$

Etc.

Typical models of the event calculus: instantaneous change



- intuitively, fluents are represented by intervals because of inertia
- left-open because fluent f does not hold at the moment it is initiated
- there cannot be *both* a last moment at which f does not hold and a first moment at which f holds – if ‘hold’ is two-valued
- best to assume last moment at which f does hold

More on the structure of time assumed by the event calculus

Caution: logic!!

- the variable t is assumed to range over the reals – does this mean we have to assume the uncountable continuum as the 'true' structure of time?
- no: we are always considering *computations* over *cognitive* time – it is sufficient if the results are consistent with 'real time'
- in particular, using the reals does not take a stand on the question whether time 'really' consists of instants or on the contrary of (temporally extended) events only
- in fact, a consequence of inertia is that event types and fluents correspond to finite sets of intervals (with computable end points), which is consistent with the assumption that events are basic
- since the end points are computable, they can be approximated – one need not assume infinite precision (and no uncountable set of reals)

Event calculus: states and scenarios

- tenses will be represented as *goals*
- a *goal* is of the form ?*Happens*$(e, t), t < now, \ldots$ or ?*HoldsAt*$(f, t), t < now, \ldots$ for given f, e – the $\ldots$ indicate ‘ .. and fit e into context’
- which is short for: ‘can we update the discourse model with e, f, t so that *Happens*$(e, t), t < now \ldots$ [*HoldsAt*$(f, t), t < now, \ldots$]?’
- it is checked whether a given goal can be satisfied by applying axioms of EC and the *scenario*:
- the *scenario* describes the cognitive representation of agent and environment in the language of event calculus
- a scenario must be a theory (a finite set of sentences) of a specific syntactic form to be plausible as memory structure – basically Horn clauses with negations allowed in the antecedent
- syntactic form of scenario defined in two steps

Scenarios: formalizing world knowledge

Definition 1 *A state $S(t)$ at time t is a conjunction of literals involving only*

1. *literals of the form $(\neg)$HoldsAt(f, t)*
2. *equalities between fluent terms, and between event terms*
3. *equations and inequalities involving real numbers*

Definition 2 *[First version] A* scenario *is a conjunction of statements of the form*

1. *Initially(f),*
2. *$\forall t(S(t) \longrightarrow$ Initiates$(e, f, t))$,*
3. *$\forall t(S(t) \longrightarrow$ Terminates$(e, f, t))$,*
4. *$\forall t, s(S(t, s) \wedge$ Happens$(e_0, s) \longrightarrow$ Happens$(e, t))$,*

where the $S(t), \ldots$ are states in the sense of definition 1.

Main point: restriction to atomic formulas in consequent.

Max fell. John pushed him.

Recall the goals involved in comprehending this discourse

1. '`update discourse with past event` e_1 `=` ***fall(m)*** `and fit` e_1 `in context`'
2. '`update discourse with past event` e_2 `=` ***push(j,m)*** `and fit` e_2 `in context`'

Reformulated in the language of the event calculus

1. ?*Happens*(e_1, t), $t < now$, *Happens*(e', t') [...]
2. ?*Happens*(e_2, s), $s < now$, *Happens*(e'', t'') [...]

Here, e' and e'' are *variables* for event types in the context – which have to be found by substitution (more precisely, *unification*)

Max fell. John pushed him.

1. ?*Happens*(e_1, t), $t < now$, *Happens*(e', t') [. . .]
2. ?*Happens*(e_2, s), $s < now$, *Happens*(e'', t'') [. . .]

- the two goals have to be satisfied, preferably so that $e'' = e_1$ and $s < t''$ – if 'Max fell' is the first sentence of the discourse, we may disregard e' for the moment
- the event type *fall(m)* corresponds to a fluent f describing the physical process of *falling*, which has the following [simplified!] scenario

1. *HoldsAt*$(f, t) \rightarrow$ *Happens*(e_1, t)
2. *Initiates*(e_2, f, s)

Max fell. John pushed him.

- 'John pushed him' represented by the indefinite goal $?Happens(e_2, s)$, $s < now$, $Happens(e'', t'')$
- by applying 1 and putting $e'' = e_1 =$ *fall(m)*, the second goal is reduced to
- $?Happens(e_2, s)$, $s < now$, $Happens(e_1, t'')$, $HoldsAt(f, t'')$
- by applying the axiom

  $Happens(e, t) \wedge Initiates(e, f, t) \wedge \ t < t' \ \wedge \neg Clipped(t, f, t')$
  $\rightarrow HoldsAt(f, t')$

  the goal is further reduced to
- $?Happens(e_2, s)$, $s < now$, $Happens(e_1, t'')$, $Happens(e, t)$, $Initiates(e, f, t)$, $t < t''$, $\neg Clipped(t, f, t'')$
- using 2 and putting $e = e_2 =$ *push(j,m)* , $s = t$, we reduce this goal to $?Happens(e_2, s)$, $s < now$, $Happens(e_1, t'')$, $s < t''$, $\neg Clipped(s, f, t'')$

Max fell. John pushed him.

- last reached goal in computation ?*Happens*(e_2, s), $s < now$, *Happens*(e_1, t''), $s < t''$, $\neg$*Clipped*(s, f, t'')
- this is a definite goal which almost says that *push* precedes *fall* – except for the formula $\neg$*Clipped*(s, f, t'') which expresses that f has not been terminated between s and t''
- if f were terminated between s and t'' we have a situation as in

  Max fell. John pushed him a second time and Max fell all the way to the bottom of the pit.
- since we have no information to this effect, we assume $\neg$*Clipped*(s, f, t'') – this is *closed world reasoning*
- the final goal is ?*Happens*(e_2, s), $s < now$, *Happens*(e_1, t''), $s < t''$
- which is the instruction to update the discourse model with past events e_1 and e_2 such that e_2 precedes e_1

Replanning

'Max fell. John pushed him, or rather what was left of him, over the edge.'

- one prominent interpretation is now that $e_2 =$ *push* comes after $e_1 =$ *fall* – this can be viewed as the result of a computation
- in fact a re-computation, since after the first 'him' one may have computed that e_2 precedes e_1
- the phrase 'or rather what was left of him' suggests Max is now *dead*, so the goal corresponding to the second sentence is something like
- ?*Happens*(e_2, s), $s < now$, *HoldsAt*(*dead(m)*,s), *Happens*(e'', t'') $[\ldots]$
- it seems reasonable to assume that at the start of *falling* (the fluent f), Max is still *alive*
- this can be formalized as *HoldsAt*(*alive(m)*,t) $\rightarrow$ *Initiates*(*start*, f, t)

Replanning, c'td

- reducing the goal using EC we get something like ($e_2 =$ *push*, $e_1 =$ *fall*)
- the goal ?*Happens*(e_2, s), $s < now$, *HoldsAt*(*dead(m)*,s), *HoldsAt*(*alive(m)*,t''), *Happens*(e_1, t'')
- a meaning postulate ('integrity constraint') on *alive* and *dead* is necessary to enforce
- *HoldsAt*(*dead(m)*,s) $\wedge$ *HoldsAt*(*alive(m)*,t'') $\rightarrow t'' < s$
- it follows that we must have that $e_1 =$ *fall* precedes $e_2 =$ *push*

Exercise

Consider a room in which there are two lights and two switches, each serving one light. We have the following event types and fluents:

1. $a_1 =$ *switch*$_1$ *on*
2. $a_2 =$ *switch*$_1$ *off*
3. $e_1 =$ *switch*$_2$ *on*
4. $e_2 =$ *switch*$_2$ *off*
5. $f_1 =$ *light*$_1$ *on*
6. $f_2 =$ *light*$_2$ *on*

At time 5 light 1 is switched on, at time 10 it is switched off. Light 2 is on initially. Write a scenario for this setup. Can you describe uniquely the light situation at times t for $0 \leq t \leq 15$?

The frame problem (McCarthy), or the robot's dilemma (Dennett)

- intuitively: events might also occur at other times (e.g. *switch*$_1$ *off* at $t = 6$, but also collision with an asteroid at $t = 7$)
- intuitively: events might have causal effects not mentioned in the scenario, e.g. *Terminates*(a_1, f_2, t)
- formally: the scenario allows a great many models which are not intended
- formally: in classical logic, nothing interesting follows from axioms plus scenario, because these premisses allow too many models
- the robot's dilemma is therefore that it is impossible to decide what to do, since there are so many possibilities to take account of

First solution: restricting the set of models by employing the completion of the scenario

- we want to say that the *only* occurrences of events are: at time 5 light 1 is switched on, at time 10 it is switched off
- formally the completion of *Happens* is defined by

$$\forall e, t(\mathit{Happens}(e,t) \leftrightarrow (t = 5 \wedge e = a_1) \vee (t = 10 \wedge = a_2))$$

- similarly the completion of *Initially* is defined as

$$\forall f(\mathit{Initially}(f) \leftrightarrow f = f_2)$$

- now redo the exercise
- does anything change if we do not specify anything about light 2?
- we will have to further restrict the class of models by using the completion of the axioms (i.e. *HoldsAt*)

The frame problem and nonmonotonic inference

- classical definition of validity
  $\varphi_1 \dots \varphi_n \models \psi$ iff for *all* models $\mathcal{M}$: if $\mathcal{M} \models \varphi_1 \wedge \dots \wedge \varphi_n$, then $\mathcal{M} \models \psi$
- useless for reasoning about goals, plans and actions
- reasoning with the completion
  $\varphi_1 \dots \varphi_n \mid\approx \psi$ iff $comp(\varphi_1 \wedge \dots \wedge \varphi_n) \models \psi$
- is nonmonotonic

$$Happens(a_1, 5), Happens(a_2, 10) \mid\approx \neg Happens(a_2, 7)$$

$$Happens(a_1, 5), Happens(a_2, 7), Happens(a_2, 10) \mid\not\approx \neg Happens(a_2, 7)$$

Event calculus: primitive predicates (full version)

- predicates and functions such as $+, \times, <$ over the reals
- event calculus predicates for instantaneous change: *Initially*(f), *Happens*(e, t), *Initiates*(e, f, t), *Terminates*(e, f, t), *Clipped*(s, f, t), *HoldsAt*(f, t)
- event calculus predicates for *continuous* change
  1. *Releases*(e, f, t) ('event type e has the effect of freeing f from the law of inertia')
  2. *Trajectory*(f_1, t, f_2, d) ('if f_1 holds between t and $t+d$, then f_2 will hold at $t + d$')
- *Clipped*(s, f, t) gets extended meaning: 'an event type *releasing* or terminating f has a token between times s and t'

Causation and continuous change

- axioms for instantaneous change formalize principle of *inertia*: after the cause has stopped acting, the caused state does not change
- this principle is not valid for continuous causation: think of gravity acting on a falling object
- *Releases*(e, f, t) stipulates that when e happens, f is no longer subject to the principle of inertia
- example of continuous change: crossing the street
  HoldsAt(*distance*(x), t) $\rightarrow$ *Trajectory*(*crossing*,t,*distance*$(x+d)$,d)

Axioms for the event calculus (full version)

Assume given a set of axioms for the reals with $+, \times, <$ ('axioms for real-closed fields').

Axioms specific to the event calculus are (all variables universally quantified):

Axiom 1 $\mathit{Initially}(f) \rightarrow \mathit{HoldsAt}(f, 0)$

Axiom 2 $\mathit{HoldsAt}(f, r) \wedge r < t \wedge \neg\exists s < r \mathit{HoldsAt}(f, s) \wedge \neg \mathit{Clipped}(r, f, t) \rightarrow \mathit{HoldsAt}(f, t)$

Axiom 3 $\mathit{Happens}(e, t) \wedge \mathit{Initiates}(e, f, t) \wedge t < t' \wedge \neg \mathit{Clipped}(t, f, t') \rightarrow \mathit{HoldsAt}(f, t')$

Axiom 4 $\mathit{Happens}(e, t) \wedge \mathit{Initiates}(e, f_1, t) \wedge t < t' \wedge t' = t + d \wedge \mathit{Trajectory}(f_1, t, f_2, d) \wedge \neg \mathit{Clipped}(t, f_1, t') \rightarrow \mathit{HoldsAt}(f_2, t')$

Axiom 5 $\mathit{Happens}(e, s) \wedge t < s < t' \wedge (\mathit{Terminates}(e, f, s) \vee \mathit{Releases}(e, f, s)) \rightarrow \mathit{Clipped}(t, f, t')$

Scenarios (full version)

Definition 3 *A* scenario *is a conjunction of statements of the form*

1. *Initially*(f),
2. $\forall t(S(t) \longrightarrow$ *Initiates*$(e, f, t))$,
3. $\forall t(S(t) \longrightarrow$ *Terminates*$(e, f, t))$,
4. $\forall t(S(t) \longrightarrow$ *Releases*$(e, f, t))$,
5. $\forall t, s(S(t, s) \wedge$ *Happens*$(e_0, s) \longrightarrow$ *Happens*$(e, t))$,
6. $S(f_1, f_2, t, d) \longrightarrow$ *Trajectory*(f_1, t, f_2, d),

where the $S(t), \ldots$ *are states in the sense of definition 1.*

Example: lexical entry for the accomplishment 'cross the street' (roughly)

1. *Happens*(*start*,t_0)
2. *HoldsAt*(*crossing*, *now*)
3. *Initially*(*one–side*)
4. *Initially*(*distance*(0))
5. *HoldsAt*(*distance*(m), t) $\wedge$ *HoldsAt*(*crossing*, t)$\rightarrow$ *Happens*(*reach*, t)
6. *Initiates*(*start*, *crossing*, t)
7. *Releases*(*start*, *distance*(0), t)
8. *Initiates*(*reach*, *other–side*, t)
9. *Terminates*(*reach*, *crossing*, t)
10. *HoldsAt*(*distance*(x), t) $\rightarrow$ *Trajectory*(*crossing*,t,*distance*($x+d$),d)
11. *HoldsAt*(*distance*(x_1),t) $\wedge$ *HoldsAt*(*distance*(x_2), t) $\rightarrow x_1 = x_2$.

Plans contained in a lexical entry

- consider the goal ?*HoldsAt*(*other–side*,t), $t \geq$ *now*
- want to *derive* plan for achievement of this goal
- do this by backward chaining (i.e. logic programming) using axioms of the event calculus and the scenario
- e.g. by axiom 3 *reach* event must have occurred,
- by scenario 5 this can only be if *distance* m has been covered
- by axiom 4 this distance can be covered only if the activity *crossing* persists for sufficiently long, *etc*.
- compare this semantic representation with set theoretic representation, such as (?)$\{(a, b) \mid cross(a, b)\}$, $s=$ 'the street'
- which cannot capture the semantic contribution of the 'incremental theme' (Dowty); even more relevant in examples such as 'draw a circle', where the Davidsonian analysis fails

Event calculus: model of the above

- Above scenario represents present progressive 'John is crossing the street'
- Comes with goal ?*Happens*(*reach*,t), $t \geq$ *now*.
- Goal can (only) be achieved in *minimal model* of scenario, defined by the *completion* of the axioms plus scenario.
- E.g.

$$\textit{Happens}(e, t)$$

$$\updownarrow$$

$$(e = \textit{start} \wedge t = t_0) \vee (e = \textit{reach} \wedge \textit{HoldsAt}(\textit{distance}(m), t) \wedge \textit{HoldsAt}(\textit{crossing}, t))$$

Exercise on continuous change

Suppose we want to show that a bucket of height 10 units, into which water flows continuously, will ultimately overflow. This can be formalised by assuming fluents *filling*, a fluent function *height*(x) (where $x \in I\!N$), and events *overflow*, *tap–on*, *tap–off* which are connected by axioms such as the following (this list is not exhaustive!)

1. *Initially*(*height*(0))
2. *Happens*(*tap–on*,5)
3. *Initiates*(*tap–on*,*filling*,t)
4. *Terminates*(*overflow*,*filling*,t)
5. *HoldsAt*(*height*(10),t)$\wedge$*HoldsAt*(*filling*,t) $\rightarrow$*Happens*(*overflow*,t)
6. *Releases*(*tap–on*,*height*$(0), t$).

Complete the specification under the assumption that after d units of time the water level has also increased d units; this gives a *scenario*.