Introducing the event calculus

- what distinguishes this approach to semantics: comparison with standard model theoretic semantics
- cognitive semantics as usually conceived
- psycholinguistic approaches to semantics
- event calculus: a fusion between these approaches

Non-cognitive formal approaches to natural language semantics

"I distinguish two topics: first, the description of possible languages or grammars as abstract semantic systems whereby symbols are associated with aspects of the world; and second, the description of the psychological and sociological facts whereby a particular one of these abstract semantic systems is the one used by a person or a population. Only confusion comes of mixing these two topics. . . . Semantics without truth conditions is not semantics." (David Lewis)

Characteristic features

- necessary and sufficient truth conditions (Lewis), possible worlds semantics (Montague, Dowty, ...),
- semantic representations are sets in classical *models* $(D; R, \ldots; f, \ldots; a, \ldots)$, or possible world structures, i.e. families of such models related by an accessibility relation
- models often viewed as 'general metaphysics', general description of how the world is
- 'sense relations' modelled by entailment: deeper analysis of lexicography
- hence uses logical techniques
- example: (branching) tense logic for modelling the future tense

Tense logic

- modal logic with operators P ('in the past'), F ('in the future'), $H = \neg P \neg$ ('always in the past'), $G = \neg F \neg$ ('always in the future')
- interpreted on *tense structure* $(T, <, V)$, where $<$ is at least antisymmetric and transitive, and each proposition letter q is interpreted as subset $V(q)$ of T
- for $t \in T$, $(T, <, V) \models \ Pq[t]$ iff $\exists s < t(s \in V(q))$ and $(T, <, V) \models Fq[t]$ iff $\exists s > t(s \in V(q))$
- axioms e.g. $q \rightarrow GPq$, $q \rightarrow HFq$ (minimal tense logic); $PPq \rightarrow Pq$
- unicity of the past: $Pq \rightarrow H(Pq \vee q \vee Fq)$ – still allows branching future
- tries to explain tenses purely temporally–but we have seen that richer structure is involved

Cognitively inspired approaches to semantics: ‘Languages of the mind’

”Conceptual Semantics . . . is concerned most directly with the form of the internal mental representations that constitute conceptual structure and with the formal relations between this level and other levels of representation. . . . Conceptual Semantics is thus a prerequisite to [truth conditional] semantics: the first thing one must know about an English sentence is its translation into conceptual structure. Its truth conditions should then follow from its conceptual structure plus rules of inference, which are stated as well in terms of conceptual structure.” (Ray Jackendoff)

Characteristic features

- semantic representations are *mental* entities – what is their 'most general' theory?
- criticism of traditional formal approaches to semantics
  - takes dim view of set theoretic models and truth conditions
  - prototypes
  - role of analogy/metaphor . . .
- tries to anchor semantics in 'conceptual structure'
- 'componential analysis in terms of supposed primitives of conceptual structure/language of the mind: EVENT, PATH, STATE, GOAL, CAUSE ...

(1) a. $[_S[_{NP}$ John$][_{VP}$ ran $[_{PP}$ into $[_{NP}$ the room$]]]]$

b. $[_{Event}$ GO $([_{Thing}$ JOHN$],[_{Path}$ TO $([_{Place}$ IN $([_{Thing}$ ROOM$])])])]$

- but why do cognitive linguists reject formal/logical methods?

Psychologists' views on semantics

- emphasis on *algorithms*–e.g. 'sets of possible worlds' irrelevant because non-computable
- e.g. meaning of an expression is *algorithm* which tests whether object falls under the expression (Miller and Johnson-Laird, *Language and Perception*)
- psychologists' aim is to understand issues like language comprehension and production, in quantitative terms (e.g reaction times, error rates)
- psychologists are very fond of network architectures such as spreading activation nets
- compare Marr's three levels of inquiry/division of labour
  - information processing task
  - algorithm
  - neural implementation

Event calculus: a language for mental representations

- human processing of temporal notions is in terms of goals/plans/actions
- this also requires a theory of causality and change, which comes in two forms
  - instantaneous change
  - continuous change

Event calculus, and what it talks about

- actions and events: e, . . . ('break')
- time–varying properties or *fluents*: f, . . . ('being broken'), possibly with parameters
- individuals ('John')
- instants of time, interpreted as real numbers
- various other real quantities (e.g. position, velocity)
- a *goal* is a desired state of affairs
- a *plan* is a sequence of actions which achieves some goal

Event calculus: primitive predicates ...

- predicates such as $<$ over the reals
- instantaneous change

1. *Initially*(f)
2. *Happens*(e, t)
3. *Initiates*(e, f, t)
4. *Terminates*(e, f, t)
5. *Clipped*(s, f, t)
6. *HoldsAt*(f, t)

- continuous change

1. *Releases*(e, f, t)
2. *Trajectory*$(f_1, t, f_2(x), d)$

. . . but what do they mean?

- compare primitives of conceptual structure: EVENT, PATH, STATE, GOAL, CAUSE ... of conceptual semantics – how do these get their meaning?
- hypothesis: *meaning* of an expression:= 'the' algorithm which allows us to compute 'the' denotation of that expression
- i.e. meaning is *not* just set in a model
- cf. Frege on *Sinn* and *Bedeutung*, but here with psychological emphasis

Axioms for the event calculus, instantaneous change only

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

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

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

Axioms for the event calculus, full version

Axiom 1 *Initially*$(f) \rightarrow HoldsAt(f, 0)$

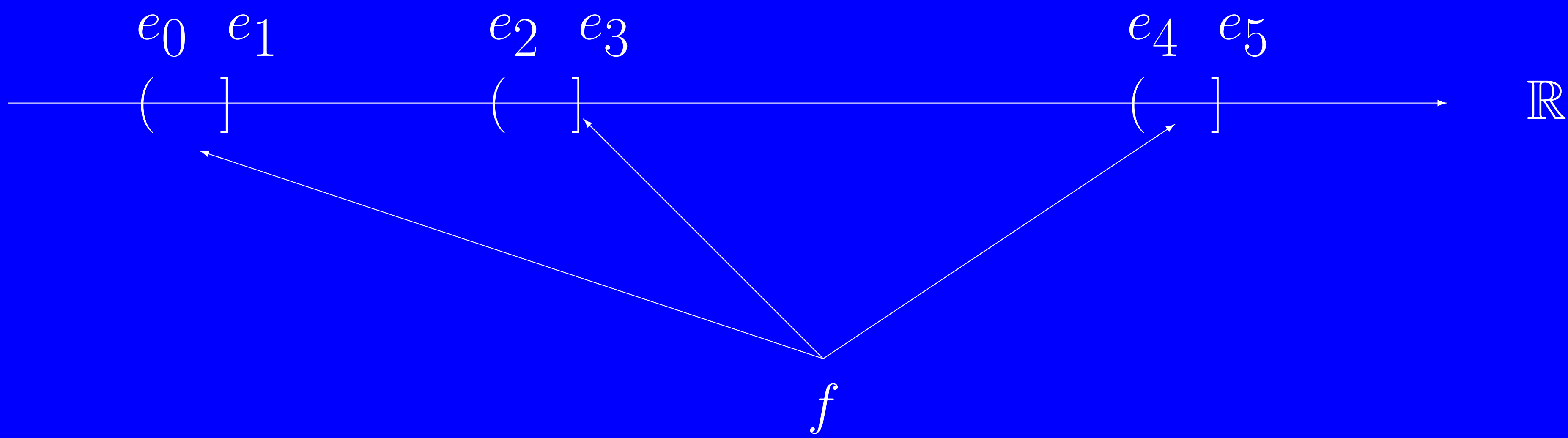
Axiom 2 *HoldsAt*$(f, r) \wedge r < t \wedge \neg\exists s < r HoldsAt(f, s) \wedge$ $\neg$*Clipped*$(r, f, t) \rightarrow$ *HoldsAt*(f, t)

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

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

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

Typical models of the event calculus



- left-open because fluent f does not hold at the moment it is initiated
- a version of Zeno's paradox: there cannot be *both* a last moment at which f does not hold and a first moment at which f holds
- best to assume last moment at which f does not hold

Event calculus: states and scenarios

- *goal* of the form ?*HoldsAt*(f, t) or ?*Happens*(e, t)
- *scenario* describes cognitive representation of agent and environment in language of event calculus
- scenario must be theory of specific syntactic form to be plausible as memory structure
- syntactic form of scenario defined in two steps

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)*, for* t *fixed and possibly different* f*,*
2. *equalities between fluent terms, and between event terms*
3. *equations and inequalities involving real numbers*

Definition 2 *A* scenario *is a conjunction of statements of the form*

1. Initially(f),

2. $\forall t(S(t) \rightarrow$ *Initiates*$(e, f, t))$,

3. $\forall t(S(t) \rightarrow$ *Terminates*$(e, f, t))$,

4. $\forall t(S(t) \rightarrow$ *Releases*$(e, f, t))$,

5. $\forall t, s(S(t, s) \wedge Happens(e_0, s) \rightarrow$ *Happens*$(e, t))$,

6. $S(f_1, f_2, t, d) \rightarrow Trajectory(f_1, t, f_2, d)$,

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

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. Can you describe uniquely the light situation at times t for $0 \leq t \leq 15$?

The frame problem

- intuitively: events might also occur at other times (e.g. *switch*$_1$ *off*, but also collision with an asteroid at $t = 7$)
- formally: nothing interesting follows from axioms plus scenario, because these premisses allow too many models

Economizing on models: the completion

- we want to say that the *only* 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

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

- now redo the exercise
- does anything change if we do not specify anything about light 2?

Nonmonotonic inference

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

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

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

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
- *Releases*(e, f, t) stipulates that when e happens, f is no longer subject to the principle of inertia
- example: crossing the street
  HoldsAt(*distance*(x), t) $\rightarrow$ *Trajectory*(*crossing*,t,*distance*$(x+d)$,d)

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 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 (?)

$$\{(a,b) \mid cross(a,b)\},\ s = \text{`the street'}$$

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.

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

$$\updownarrow$$

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

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 $scenario$.