The Situations We Talk about

LENHART K. SCHUBERT
University of Rochester
Rochester, New York 14627-0226
(*schubert@cs.rochester.edu*)

Abstract. I argue in favor of associating situations (events, episodes, eventualities, etc.) with arbitrarily complex sentences, not just atomic predicates, in NL interpretation. In that respect, a Situation Semantics approach to incorporating situations into semantic representations is preferable to a Davidsonian one. However, I will further argue that beyond the notion of truth or falsity of a sentence *in* a situation, as in Situation Semantics, we also need the notion of a sentence *characterizing* a situation, in order to deal adequately with *causal* relations mentioned or implied in NL texts. I propose a way of doing this that essentially reduces complex situations to joins of basic, Davidsonian ones, along with basic situations corresponding to negated predications. The resulting situational logic, called FOL**, captures many of the essential features of both Davidsonian and Situation Semantics approaches to representing the content of sentences describing situations. The proposed semantics supports common intuitions about truth-in-situations, about the existence of situations characterized by sentences, and about persistence of information from parts of situations to the whole. I allow for *temporal* parts of situations as well as concurrent parts, and distinguish persistence properties of telic and atelic sentences. The development of FOL** is part of a continuing effort to fully formalize Episodic Logic, an implemented knowledge representation designed to support language understanding.

1 Introduction: Competing views on the relation between sentences and situations

It is routinely observed in NLP that sentences seem to "evoke" situations (where I use this term comprehensively to cover events, episodes, eventualities, processes, etc.). Much like discourse entities evoked by explicit noun phrases, these evoked situations can be referred to anaphorically, as for instance in (1) and (3) below, and can be modified in various ways, for instance by supplying their duration and location, as in (2) and (4).

1. Molly barked. *This* woke up John.
2. Molly barked for 20 minutes in the yard last night.
3. It's chilly outside. *This* is making the last of the leaves drop from the trees.
4. It has been chilly outside for several weeks.

Thus we need to incorporate situations explicitly into the logical forms of NL sentences. One of the better-known early approaches was that of Hans Reichenbach [16]. For example, he offered the logical form (LF) in (5b) for sentence (5a):

5 a. George VI was crowned.
  b. ∃e. [was-crowned(G)]*e   e = crowning (coronation) of G.

Note the use of the operator '[ ]*' for associating situations[1] with sentences. These sentences were potentially complex, and in that respect Reichenbach anticipated Situation Semantics. Another approach, which proved more influential because of its unproblematic semantics, was that of Donald Davidson [5], as illustrated here.

6 a. George VI was crowned in Westminster Abbey
  b. ∃e. was-crowned(G,e)∧in(e,W)

Here events are simply introduced as additional arguments of event predicates. As is evident in (6b), Davidson also regarded the meaning of adverbial adjuncts as expressible by conjoined predications about the location, time, manner, etc., of the event introduced by the verb.

More recent approaches show the influences of both of these early proposals. For example, Barwise and Perry, in [2] and subsequent writings, suggest meaning representations like the following (where all 3 examples correspond to (6a) and illustrate slightly different notations).

[1] More accurately, Reichenbach had in mind events and facts, whose differences he blurred.

7 a. in e: at W: was-crowned, G; yes

b. e $\models$ <<was-crowned, G, 1>> $\wedge$ <<loc,e,W,1>>

c. e $\models$ was-crowned(G)$\wedge$loc(e,W)

The '$\models$' relation indicates that a situation e *supports* certain facts, and as in the case of Reichenbach's '[ ]*' operator, these facts can be complex. However, while Reichenbach seems to have had in mind that e in $[\phi]*e$ stands *just* for a ϕ-event, no more, no less, Situation Semantics views situations as potentially supporting many other facts besides those explicitly specified. For example, the situation e in (7a) could perfectly well support additional facts (or "infons") such as that there was a bat in the belfry, even if this is not considered part of George VI's coronation. This point is particularly clear in versions of Situation Semantics that employ a more standard syntax and semantics, such as Muskens' very tidy and general formulation [13]. Like Davidson, he treats situations as predicate arguments, but this syntactic similarity is deceptive. For Davidson and his adherents, *was-crowned*(G, e) means that e is the coronation of G; but for Muskens, it means that e is a *partial world* that happens to support the truth of G's being crowned, but may also support arbitrarily many other, possibly quite unrelated, facts.[2]

As an example of a neo-Davidsonian approach, we might mention that of Parsons [15]. The distinctive feature of this approach is the "factoring" of n-ary event predications into a unary predication for the event type and a set of conjoined binary predications specifying the *thematic roles* of the event. For instance, (6a) might be rendered roughly as

8. $\exists$e. $\exists$t. crowning(e) $\wedge$ obj(e,G) $\wedge$ occur(e,t) $\wedge$ past(t) $\wedge$ loc(e,W)

As in Davidson's original approach (as well as in Reichenbach's), e is intended to be a crowning and nothing more. Though various things can be said about it, such as that it involves George VI as its object, it is not a "partial world" supporting miscellaneous positive and negative facts.

Hwang and Schubert (e.g., [17, 8, 9, 18]) have long maintained that logical forms for general NLU must be able to capture both sorts of relationship between sentences and situations – sentences as partial descriptions of situations, and as "characterizing" descriptions of situations. I will reiterate and strengthen the arguments for this view in the next section. Here I briefly introduce the Episodic Logic (EL) notation used in our previous work, in particular the '$**$' and '$*$' operators for connecting sentences with situations (episodes, etc.). (These operators are the only features of EL I will retain for the rest of the paper.) The LF for (6a) would look roughly as follows. (Square brackets indicate sentential infix syntax, with the sentence subject in first place, the predicate second, and additional arguments after the predicate.)

9. ($\exists$e: [e before Now7] ($\exists$x [[G (pasv crown) x]$**$e]$\wedge$[e loc-in W]))

In quantified sentences of form $(Qx\!: \ \phi \ \psi)$, the ϕ-formula is interpreted as a restriction on the domain of quantification, and the ψ-formula is the main, or "matrix" clause. In (9), the quantifier Q is $\exists$, and the restriction and matrix clauses can be viewed as conjoined. (The restriction [e before Now7] captures the past tense information, i.e., that the event e of George VI being crowned is before the time of narration, Now7.) What is noteworthy here is first, that such LFs are easily computed from surface form, keeping the syntax/ semantics interface as simple as possible; and second, that a '$**$' operator is used to connect the main clause with the episode it *characterizes*. Its intended meaning is quite similar to that of Reichenbach's '[ ]*' operator: given $[[G\ (pasv\ crown)\ x]**e]$, e must be the event *of* George VI being crowned, i.e., his coronation. But EL also has another operator, '$*$', which is more akin to the support relation, '$\models$', of Situation Semantics. While the direct LFs of English sentences generally involve only the '$**$' operator, inference often leads to occurrences of the '$*$' operator. For instance, a consequence of (9) via meaning postulates might be

10. ($\exists$y: [y crown] [[x place-upon (head-of G) y]$*$e])

In other words, one of the facts supported by the coronation event is that someone placed a crown on George VI's head.[3] Furthermore there may be many contingent details of this particular coronation all of which are

[2] This is not to say that for Davidson, an event characterized in one way could not also be characterized in many other ways (for instance more or less abstractly, and more or less elaborately); e.g., note his discussion of '*crossing the Channel*' and '*swimming the Channel*', or the various ways of describing a shooting [5]. In his discussion of causes [4], Davidson does move in the direction of admitting a description of a *part* of an event (in particular, part of a causal chain) as a description of the event as a whole (in particular, a complete causal chain). He is motivated by the observation that one can refer to different parts of a causal chain as *the* cause of another event. Whatever the merits of this position may be, it is still very different from saying that we can join arbitrary events to a given event without invalidating the original characterization. Furthermore AI researchers who have followed Davidson's strategy of event-introduction have generally taken a predication $P(e, ...)$ to mean that $P(...)$ describes e as a whole, not just some part of e.

[3] We could eliminate the free occurrence of e in (10) in favor of a Skolem constant replacing e in (9); or else we could simply

supported by e. (Among these details may be aspects of *temporal segments* of the coronation.)

In the next section, I will make the argument for a tighter coupling between sentences and events than is provided by '$*$' (or the *supports* relation '$\models$' of Situation Semantics). A sufficiently tight coupling is provided by '$**$', or by a Davidsonian approach. However, in section 3 I will show that ordinary language makes reference to events more complex than those that can be represented in a Davidsonian framework. This justifies the use of the '$**$' and '$*$' operators, or something like them. In section 4, I will suggest a semantic basis for these operators, in effect showing that both can be explicated in terms of Davidsonian events (along with "negative situations") and their joins in a join semilattice. I will go on to show in section 5 that this semantic basis supports many of the intuitively wanted properties of situations and their descriptions, including the existence of parts of situations characterized by ϕ whenever ϕ partially describes those situations; the "transparency" and truth-like character of the partial description (or support) operator '$*$'; and the persistence of information through the part-of ordering of situations, with different kinds of persistence corresponding to telicity or atelicity of the descriptions employed.

2 Why we need '$**$'

Let me begin by suggesting a few ways of paraphrasing the meaning of '$**$' and '$*$', as a way of fixing intuitions about them:

[G be-crowned]$**$e	e is an episode *of* George VI being crowned; '*George VI is crowned*' *characterizes* e e *as a whole* is of type '*George VI is crowned*'; e is an episode that consists just of George VI being crowned
[G be-crowned]$*$e	e is an episode *in which* George VI is crowned; '*George VI is crowned*' holds (occurs) in e e is (partially) described by George VI being crowned; e is an episode that consists in part of George VI being crowned

Now, it is commonplace in texts (particularly narratives) to find a description of some event or situation e, followed immediately by a description of another event e' that is said or implied to be caused by the first. (The sentence pairs in (1) and (3) illustrate this pattern.) So in the LFs of such causal descriptions, we will need some way of expressing that an event e of type ϕ occurred, and that this caused the subsequent event e'. From a Situation Semantics perspective (and using the $*$-notation), it would seem natural to represent the occurrence of an event e of type ϕ by writing $[\phi * e]$.

However, I maintain that

"e' has a cause e of type ϕ"

cannot be formalized as

"e' has a cause e satisfying $[\phi * e]$".

Rather, the formalization needs to use '$**$' (or some other event characterizing representation, such as a Davidsonian or Reichenbachian one) in place of '$*$'. To recognize the incorrectness of the above formalization, we observe that it can lead to incorrect conclusions in particular instances.

For example, suppose that Mary's waking up was caused by John's singing. Further suppose that John was taking a shower at the time, so it is also correct to say that Mary's waking up was caused by John's simultaneous singing and showering. I.e., though the showering may be causally irrelevant to Mary's waking up, nonetheless the larger, singing-plus-showering event is sufficient to account for Mary's waking up. But John's simultaneous singing and showering is *partially* described by '*John showers*'. In other words, there is an event e (viz., John's simultaneous singing and showering) satisfying

[[John showers]$*e$].

But if it is correct to identify "has a cause e of type ϕ" with "has a cause e satisfying $[\phi * e]$", then we have reached the conclusion that Mary's waking up was caused by John's showering – surely not a valid conclusion

adjoin (10) to (9), relying on the dynamic binding mechanism in EL to "carry forward" values of e that can truthfully bind it in (9) (in effect extending the scope of the quantifier in (9) to include (10)) [9].

under the conditions we have assumed.[4]

This example instantiates a general pattern. Seeing this pattern at a more abstract level should further clarify the nature of the difficulty with using '$*$' in causal descriptions:

(i) We are given events A and E such that

[A cause-of E].

(ii) We consider some arbitrary situation or event B concurrent with A, with some partial description

[ϕ*B].

(iii) Let C be the combination of events A and B. (E.g., the combination of John's singing and showering, above. Instead of his taking a shower, we could have picked any other concurrent situation or event, not necessarily one involving John. While the combination C may not be a "natural" one, it still seems reasonable to assume it exists, in the logical sense.) Then ϕ is also a partial description of C, i.e.,

[ϕ*C].

(iv) In addition, since C includes A as a part, and A caused E, we also have

[C cause-of E].

The reader may not agree that "enlarging" a cause with an arbitrary concurrent situation or event necessarily preserves its status as a cause. But it is sufficient, for the purposes of the generalized refutation I am outlining, that there be some instances where this is reasonable (as in the singing-and-showering example above). I will pursue this point further below.

(v) Hence, if "having a cause C such that [$\phi * C$]" can be understood as "having a cause C of type ϕ", then we have shown that

E has a cause of type ϕ.

But this is in general absurd, since ϕ is a partial description of an arbitrary situation or event that happens to be concurrent with E's actual cause, and need not have any causal relevance to E at all.

For those who are uncomfortable with the idea that events viewed as causes can be augmented with miscellaneous concurrent events without losing their causal status, we can frame a similar argument beginning with conjunctive causes, as in the following examples.

11. The ferry was overloaded and unstable, and this caused it to capsize.
12. John was driving and using his cellular phone, and this caused an accident.

It does not *follow* from (11) that it was the situation of the ferry being overloaded (or that of the ferry being unstable) that caused it to capsize (though these narrower causal claims *might* also be true). Nor does it follow from (12) that John's driving caused the accident in question, or that his using the cellular phone did. Yet, much as before, logical forms for (11) and (12) based on a partial-description connection '$*$' between sentences and the situations they evoke would lead to precisely those consequences. The only assumption this involves is that a situation partially described by '*The ferry was overloaded and unstable*' is also partially described by '*The ferry was overloaded*', and by '*The ferry was unstable*', and similarly for (12).

So '$*$' (or '$\models$' in Situation Semantics) is simply too "unselective" to be able to characterize causes. The truth of $\phi * e$ fails to ensure that e consists *just* of an episode of type ϕ. Instead, it may have parts or aspects of many different types, so in saying that an event e satisfying $\phi * e$ is the cause of e', we are failing to say that it is the "ϕ-part" of e that is causally effective. We need a tighter coupling between sentences and events, and that is what the '$**$' operator provides.

Now in fact a Davidsonian representation also provides a sufficiently tight coupling between sentences and events for characterizing causes. For example, to express that John's singing woke up Mary, we might write (neglecting tense)

[4] Of course it may be the case that if John had not taken a shower he would not have sung and so would not have awakened Mary; in that sense his taking a shower may be a contributing cause in Mary's awakening. But a contributing cause is in general something less than a cause, and in any case he might have sung even if he had not taken a shower. Thus the conclusion that John's taking shower caused Mary to wake up is not deductively valid.

$\exists e. \exists e'. \mathrm{sing}(e,\mathrm{John}) \wedge \text{wake-up}(e',\mathrm{Mary}) \wedge \mathrm{cause}(e,e')$,
where we understand e to be (just) an event of John singing, and e' (just) an event of Mary waking up. In contrast with the case of '$*$'- (or '$\models$'-) based causal descriptions, there is no allowance for e to be something more than an event of John singing, such as an event of John singing and taking a shower. So with respect to causal description, a Davidsonian approach is more nearly adequate than one based on a partial-description relation between sentences and events, as in Situation Semantics. But the limitation of the Davidsonian approach is its inability to describe complex events, as I now argue.

3 Situations described by negative, conjoined and quantified sentences

The observations that led us to posit events in logical forms apply equally to complex descriptions as to simple ones: we can refer anaphorically to them, ascribe properties such as locations and durations to them, and adduce them as causes. Some examples of conjunctively described situations, and reference to such situations as causes, were already seen in the preceding section. The following are some further examples of anaphoric reference to complex situations, including negative, conjoined and quantified situations. (I will use this loose terminology to refer to complex situations characterized respectively by negative, conjoined, or quantified sentences.)

13. There has been no rain for several weeks.
    This has ruined the crops.
14. The evening was warm and windless.
    This brought out the mosquitoes.
15. Kevin is home alone.
    That's a risky situation.
16. Each graduate went to the podium to receive his or her diploma.
    This took half an hour.

Note the adverbial specifying the duration of the no-rain situation in (13), and the anaphoric reference to that situation. (14) and (15) (like the earlier (11) and (12)) describe and subsequently refer to conjunctive situations. Note that '*home alone*' in (15) is equivalent to '*at home while no-one else is at home*' and in that sense specifies a concurrent positive and negative situation. In (16) we have a quantified situation, and anaphoric reference to that situation in the description of its duration. The duration could alternatively have been specified by an initial adverbial such as '*Over the next half hour*'.

(13) and (14) can also be seen as supplying causal relations involving complex causes, since the verbs '*ruined*' and '*brought out*' take an agent or a cause as subject. The following are two examples where a causal relation is explicitly asserted for a negative and a quantified cause.

17. The parachute did not deploy on schedule.
    This caused the loss of the Mars lander.
18. Each superpower menaced the other with its nuclear arsenal.
    This caused an escalating arms race.

Additional clear evidence for the reality and linguistic significance of complex situations is that we can (and do) explicitly refer to them *as* situations/ circumstances/ conditions/ states of affairs, etc. (15) is one example, and the following are two more.

19. It has not rained for several weeks.
    This situation/ circumstance/ condition/ state of affairs has *caused* the crops to fail.
20. *The situation* of her children no longer being at home is disconcerting for Mary.

The notion of "negative" situations (such as in (13), (17), (19) and (20)) deserves further comment. While one can imagine gathering together basic Davidsonian events or situations to form complex situations corresponding to conjunctive or quantified sentences, it is hard to imagine any Davidsonian approach to negative situations. For example, suppose that in (19) we attempt to represent the situation at issue as an episode e (at some locale) such that no rain falls *during* e. But this would not capture the meaning of the causal claim in (19). To say that certain conditions hold *during* e scarcely constrains e at all, merely requiring that it occupy a time and place *during* which the stated conditions obtain. But since many other conditions may obtain at that time and place as well, e could consist of much more than the drought implied by (19), and so cannot adequately serve as the cause anaphorically referred to in (19).

A possible response open to a Davidsonian is to say that negative phrasings like those in (17), (19), (20) imply the existence of corresponding "positive" eventualities, and these are the actual referents of the subsequent referring expressions.[5] For example, (17) implies that the parachute *failed* to deploy, and the deictic pronoun might might refer to this failure; similarly the reference in (19) might be to the implied *dry spell* or *drought* or *lack* of rain; and the reference in (20) might be to the implied *absence* of Mary's children from home. However, such an (essentially pragmatic) account seems hard to defend, since we cannot freely refer deictically to implied entities. For example, the following (a)-examples are infelicitous, in contrast with the (b)-examples (where referents are explicitly introduced):

21 a. He pricked the overinflated balloon with a pin. ??*This* was noisy.
   b. The overinflated balloon burst. *This* was noisy.
22 a. She ate two of the three cookies. ??She left *that cookie* for her brother.
   b. She ate all but one of the cookies. She left *that cookie* for her brother.
23 a. He dreamed all night. ??*This sleep* was not refreshing.
   b. He slept fitfully all night. *This sleep* was not refreshing.
24 a. The sky was cloudless all day at the beach. ?*This* gave Mary a sunburn.
   b. The sun shone all day at the beach. *This* gave Mary a sunburn.

(24a) is perhaps acceptable, but only if we are prepared to view the cloudlessness itself as the (indirect) cause of the sunburn. In other words, it is still the case that the deictic pronoun can refer only to the explicitly mentioned condition (cloudlessness).

A related point is that a Davidsonian approach makes it difficult to give expression to intuitions about the lexical meanings of "absence terms" like the ones employed for the implied positive eventualities in (17), (19) and (20), such as '*fail (to)*', '*dry*', '*empty*, '*lack*', or '*absent*'. For example, it seems natural to say that a situation e of x being absent from y is precisely one of x *not being present* at y. But we cannot express this as

25. $\forall$e,x,y. absent(e,x,y) $\leftrightarrow\neg$present(e,x,y),

since the right-hand side merely says that e is not a situation of x being present at y; this surely doesn't require it to be a situation of x being absent from y. (For instance, it could be a situation of x liking y – which in a Davidsonian framework would presumably be distinguished from a situation of x being present at y, even if both situations occur simultaneously.) But if we omit the "if" direction of the conditional, then we have succeeded in expressing only half of the stated intuition.

Finally, it is sometimes claimed that apparent references to negative or quantified situations are actually references to facts or propositions. I would maintain instead that both simple and complex sentences can evoke situations as well as facts or propositions. It may sometimes be ambiguous whether a reference is to a situation or a fact, but there are predicates that distinguish the two sorts of entities, and can thus be used to test for the two sorts of reference. In particular, situations can persist/ endure/ last/ go on, whereas facts cannot (or if they do, they "persist" forever). On the other hand, facts can be asserted/ denied/ communicated, whereas situations cannot. The following examples illustrate the two kinds of reference, based on the distinguishing predicates, for negative and quantified sentences.

26 a. No rain fell.
   b. This situation endured/ lasted/ persisted/ went on for months.
   c. *This fact lasted for months.
   d. This fact is asserted in today's paper.
   e. *This situation is asserted in today's paper.
27 a. Each superpower menaced the other with its nuclear arsenal
   b. This situation persisted for 4 decades.
   c. *This fact persisted for 4 decades.
   d. This fact is asserted in every history book.

[5]In the context of Davidsonian event theory, the term '*eventuality*' should be understood as an umbrella term covering events, processes, situations, etc., rather than in its ordinary sense of *contingency*, i.e., a *possible* event, outcome, or condition.

e. *This situation is asserted in every history book.[6]

Facts are presumably related closely to true propositions, but I will not attempt develop a theory of facts or propositions here; instead I will focus exclusively on events or situations. However, it is worth mentioning in passing that EL permits both an "event view" and a "propositional view" of causation. They are connected as follows, based on a modal operator *because*:

$\text{cause}(e,e') \wedge (\phi{**}e) \wedge (\psi{**}e') \;\leftrightarrow\; \text{because}(\phi{**}e, \psi{**}e')$.

An example of the corresponding wording in English might be '*John's singing caused Mary to wake up*', *versus* '*Mary woke up because John sang.*

I now show how we can make formal sense of complex situations, where we allow both characterizations (using '$**$') and partial descriptions (using '$*$') of such situations. This leads to a logic that naturally accommodates both Davidsonian events (at the level of atomic fluent predications) and situations of the sort posited in Situation Semantics. Despite the lack of propositions or properties in this logic (at least as first-class entities), the '$*$' operator turns out to have much in common with the '$\models$' relation of Situation Semantics.

4 Formalizing '$*$' and '$**$'

Rather than employing a comprehensive representation for NL logical forms such as EL, I will restrict myself to a minimal extension of first-order logic (FOL) allowing for the '$**$' and '$*$' operators. The syntax will be conventional (without the square-bracketed infix predications of EL). I will call this extension FOL**.

4.1 Syntax of FOL**

Terms in FOL** are individual constants and variables as well as functional terms formed with the 2-place function $\sqcup$ (denoting the situation join). A subsort of the individual constants and variables are the *situational* constants and variables. A functional term contains only situational constants, variables and terms and is likewise a situational term.

Predicate constants have a specified arity and may have the initial argument position designated as situational. (Positions not designated as situational may be filled with any sort of term, general or situational.) Predicates with an initial situational argument are called *fluent* predicates. Note that situations in FOL** are thought of in general as extended in time, and having limited "information content"; in these respects they are more akin to the situations of Situation Semantics than those of McCarthy and Hayes [11]. Still, the latter can be thought of as a special case of the former, and this motivates the "fluent" terminology. Non-fluent predicates are also termed "atemporal", though it should be noted that such predicates can have situational arguments. For instance, we would probably treat $cause(e_1, e_2)$, expressing that situation e_1 causes (caused) situation e_2, as atemporal. Also, the situational/ temporal part-of relations $\sqsubseteq$, $\preceq$ and $\trianglelefteq$ introduced below require situational arguments but are not considered fluents. Technically this means that they will not be used to form "situation abstracts" (see below).

Fluent predicates are further subdivided into *telic* and *atelic* predicates. Telic predicates correspond intuitively to events or occurrences, i.e., the types of situations that have a "built-in" culmination or point of completion; examples are yawning, greeting, dressing, building (something) and so on. Atelic predicates, by contrast, describe "open-ended" situations with no intrinsic point of completion, such as sleeping, walking, being awake, being at a location, being a nonsmoker, etc.[7] Technically, the distinction we are after is that telic predications are "outward persistent", i.e., whatever happens in a temporal segment of a larger episode also happens in the larger episode; whereas atelic predications are "inward persistent" (or homogeneous), i.e., if such a predication characterizes an episode as a whole it also characterizes its temporal segments. As an example, if Mary greeted the audience in the opening of her talk, then she greeted the audience in her talk. This testifies to the telicity of "greet". On the other hand, if Mary was at the microphone for her

[6] I am not claiming, of course, that any predicate applicable to situations is inapplicable to facts, or *vice versa*. For example, one can discuss, recount, ponder, remember, etc., both facts and situations. But the predicates in (26-27) do distinguish facts from situations rather reliably.

[7] It would be more in keeping with traditional usage to classify only sleeping and walking as atelic among these examples, perhaps calling the rest "states". However, lumping these together under a single term serves my purposes here.

talk, then she was at the microphone for the various parts of the talk. This testifies to the atelicity of "be (located) at".[8]

An important observation, which will affect some details of our formal semantics, is that negated fluent predications, whether telic or atelic, behave like atelics. For example, if Mary did not take a sip of water in her talk, then she did not take a sip of water in any part of her talk. So this negated telic shows the same inward persistence that is the defining characteristic of atelics. As well, if Mary was not at the microphone in her talk, then she was not at the microphone in any part of her talk. Again, we have inward persistence. This will motivate making the *anti-extensions* of fluent predicates inward-persistent in the semantics. However, there remains one striking difference between negated telic and atelic predications that we must take into account: if we negate again, we recover a telic and thus outward persistent predication in the first case, and an atelic and thus inward persistent predication in the second. For example, if the claim that Mary didn't take a sip of water halfway through her talk is mistaken, then the claim that she didn't take a sip of water in her talk is also mistaken. I won't attempt to illustrate doubly negated atelics since they are all too susceptible to aspectual coercion; but we surely do not wish to treat double negation as *logically* distinct from the positive form.

Formulas in FOL** are formed as in FOL by applying predicate constants to a suitable number of terms (of the right sort, if the initial argument position is designated as situational), by equating two terms, or by applying connectives $\neg$, $\wedge$, $\vee$, $\rightarrow$, $\leftrightarrow$, or quantifiers $\forall$, $\exists$ to formulas. In addition, where τ, τ_1, τ_2 are situation terms,

$\tau_1 \sqsubseteq \tau_2$, $\tau_1 \preceq \tau_2$, $\tau_1 \trianglelefteq \tau_2$,

are formulas. (Strict versions $\sqsubset$, $\prec$, and $\triangleleft$ may also be used, with the obvious definitions in terms of the non-strict versions and inequality.) Intuitively, the three relations mean respectively that situation (or event) τ_1 is part of situation (or event) τ_2, τ_1 is a concurrent part of τ_2, and τ_1 is a temporal segment of τ_2 (i.e., consists of that part of τ_2 which occupies a subset of the times covered by τ_2).

The final class of formulas involves the notion of a *situation abstract*. A situation abstract is defined exactly like a formula, except that in place of atomic predications, we may use *proper atomic* situation abstracts. The latter are obtained from *fluent* predications by omitting the first argument. For instance, if *loves(E,John,Mary)* is a fluent predication, then

loves(John,Mary)

is a proper atomic situation abstract, and

$\exists$x. $\exists$e. person(e,x)$\wedge$loves(x,Mary), and

$\exists$x. person(x)$\wedge$loves(x,Mary)

are non-atomic situation abstracts. Here '*person*' is also treated as a fluent. Alternatively it might be treated as a unary atemporal predicate; in that case '*person*(x)' in the second formula would not be a proper atomic situation abstract. Note that by definition all formulas are also situation abstracts (though of a "degenerate" sort, if they contain no proper atomic abstracts). A situation abstract is thought of as abstracting over situations satisfying the constraints it imposes with respect to the elided situational arguments. We now add the following types of formulas to our logic, where ϕ is a situation abstract and τ is a situation term:

$(\phi{*}{*}\tau)$, $(\phi{*}\tau)$.

As expected from the earlier discussion, these are read respectively as 'ϕ *characterizes* τ' and 'ϕ *(partially) describes* τ *(or holds or occurs in* τ*)*'. Note that such formulas cannot be converted to proper situation

[8]Since the subject of aspectual verb classes is a subtle one, a couple of comments are in order. First, atelic predicates are often used in a way that implies less than uniform inward persistence. For instance, we might say that Mary was at the microphone in her talk even if she spoke a few words away from the microphone. We might even mean merely that she was at the microphone for some portion of her talk. I take the view that such uses involve tacit down-toning or bounding modifiers of the predicate, such as "mostly" or "for some time". The latter type-shifts the atelic predicate to a telic one [10]. Secondly, it is well-known that in English the aspectual class of a predication depends not only on the predicate but also on the arguments, tense, adverbial adjuncts, and other factors. For instance, '*John yawned*' would normally be understood as specifying just one, terminating yawn, but '*John yawned for an hour*' or '*People yawn when they are tired*' appear to involve indeterminate numbers of yawns. Here again my view is that the corresponding LFs involve operators that interact with telicity. In particular, in '*yawn for an hour*' the duration adverbial forces a repetitive, essentially atelic reading of the verb, and this needs to be made logically explicit with an operator meaning '*repeatedly*' [10]. The second sentence is generic, and its proper LF can be assumed to be a tripartite quantificational structure quantifying over (actual and certain possible) episodes of people being tired [3]. These devices, and others needed for a more adequate treatment of aspectual class, are not available in FOL**.

abstracts, in the sense that the '∗' and '∗∗' operators will "bind" any fluent arguments abstracted in their scope. So in general, we define a proper situation abstract as a situation abstract that contains a proper atomic situation abstract not lying within the scope of a '∗' or '∗∗' operator.

4.2 Models for FOL**

The following formal definition will be followed by explanatory remarks. A *model* for FOL** is a 5-tuple $\mathcal{M}$ = $(\mathcal{D}, (\mathcal{S}it,\sqsubseteq), (\mathcal{T},<), time, \mathcal{I})$,[9] where

- $\mathcal{D}$ is a nonempty set (of individuals, including situations);
- $(\mathcal{S}it,\sqsubseteq)$ is a complete join semilattice with join $\sqcup$ and set join $\bigsqcup$, where $\mathcal{S}it \subset \mathcal{D}$; $\bigsqcup\{s, s'\} = s \sqcup s'$ for all $s, s' \in \mathcal{S}it$; $\bigsqcup\emptyset = \varepsilon$; and $s \sqcup \varepsilon = s$ for all $s \in \mathcal{S}it$;
- $(\mathcal{T},<)$ is a strict linear order (whose elements are regarded as time points);
- *time*: $\mathcal{S}it \rightarrow \mathcal{P}ow(\mathcal{T})$ is a (total) function such that (a) if $s = \bigsqcup S$ then $time(s) = \bigcup\{time(s') | \; s' \in S\}$; (b) $time(s) = \emptyset$ iff $s = \varepsilon$; further conditions on the relation between *time* and situations are stated below.

  We define the derived relations $\preceq$ ("concurrent part of") and $\trianglelefteq$ ("segment of") before proceeding. For $s, s' \in \mathcal{S}it$,

  $s \preceq s'$ iff $s \sqsubseteq s'$ and $time(s) = time(s')$; and

  $s \trianglelefteq s'$ iff and there exists $s'' \in \mathcal{S}it$ such that $time(s'') \cap time(s) = \emptyset$ and $s \sqcup s'' = s'$;

  A further condition on *time* in relation to situations that turns out to be crucial for establishing inward persistence of atelic descriptions is that temporal segmentation of situations is downward-inherited to concurrent parts, in the following sense. Let S be a set of concurrent parts of s (i.e., for each $s' \in S$, $s' \preceq s$) such that $\bigsqcup S = s$, and let $s_1 \trianglelefteq s$. Then there is a function $f : S \rightarrow \mathcal{S}it$ such that $\bigsqcup\{f(s') \mid s' \in S\} = s_1$ and for all $s' \in S$, $f(s') \trianglelefteq s'$ and $f(s') \preceq s_1$ (i.e., $time(f(s')) = time(s_1)$).

- $\mathcal{I}$ (the interpretation) is a pair of functions $(\mathcal{I}^+,\mathcal{I}^-)$ on the individual and predicate constants, where if c is an individual constant, $\mathcal{I}^+(c) = \mathcal{I}^-(c) \in \mathcal{D}$ (and we can also write $\mathcal{I}(c)$ or $c^{\mathcal{I}}$ for $\mathcal{I}^+(c)$ or $\mathcal{I}^-(c)$), and if P is an n-place predicate constant, then $\mathcal{I}^+(P) \subseteq \mathcal{D}^n$ and $\mathcal{I}^-(P) \subseteq \mathcal{D}^n$. In particular, if P is a fluent predicate then $\mathcal{I}^+(P), \mathcal{I}^-(P) \subseteq (\mathcal{S}it - \{\varepsilon\}) \times \mathcal{D}^{n-1}$. In addition we build inward persistence into the anti-extensions of all predicates and the extensions of atelic ones: whenever $(s, d_1, ..., d_{n-1}) \in \mathcal{I}^-(P)$ and $s' \trianglelefteq s$, we also have $(s', d_1, ..., d_{n-1}) \in \mathcal{I}^-(P)$; and if P is atelic then whenever $(s, d_1, ..., d_{n-1}) \in \mathcal{I}^+(P)$ and $s' \trianglelefteq s$, we also have $(s', d_1, ..., d_{n-1}) \in \mathcal{I}^+(P)$. Finally, we stipulate that fluent extensions and anti-extensions do not "collide"; this means that if $(s, d_1, ..., d_n) \in \mathcal{I}^+(P)$ and $(s', d_1, ..., d_n) \in \mathcal{I}^-(P)$ then

  (i) $time(s) \nsubseteq time(s')$; and

  (ii) if P is atelic then $time(s) \cap time(s') = \emptyset$.

A caveat concerning the notation is that the symbols $\sqsubseteq$, $\preceq$, $\trianglelefteq$ and $\sqcup$ are being overloaded (as is routinely done for equality) to do double duty as object-language and metalinguistic symbols.

Note the assumption that we can arbitrarily join situations into larger situations, whether or not they are concurrent. Note also that the concurrent part-of ordering $\preceq$ and the temporal segment-of ordering $\trianglelefteq$ specialize the general part-of ordering $\sqsubseteq$ among situations. These orderings are relevant to the various kinds of persistence we are interested in (upward, outward, and inward). Also, an easily derived consequence from stipulation (a) about *time* is that

if $s \sqsubseteq s'$ then $time(s) \subseteq time(s')$;

i.e., the subset structure of the times at which situations occur (or hold) reflects the part-of structure of those situations. (However, note that we can have $s \sqsubset s'$, yet $time(s) = time(s')$ – in fact, this is the case whenever $s \prec s'$.) Though times play a crucial role in the semantics of FOL**, for instance in assuring the

[9] Strictly, we should speak of models for a specific FOL** *language* based on a particular vocabulary, but this small inaccuracy should cause no confusion

persistence properties established in section 5.5, we make no special provision for talking about times in the object language. (This might be done in later extensions of FOL**.)

The most unusual feature of models as defined above is the use of predicate anti-extensions as well as extensions. This is a feature one would normally find only in partial logics such as Muskens' [13], but FOL** is not partial. Truth and falsity of ordinary formulas (not involving '$*$' or '$**$') will be based on predicate extensions alone. However, anti-extensions are crucial for specifying the semantics of negation in the context of '$*$' and '$**$'. In particular, as will be seen, a negated atomic fluent abstract such as $\neg$*at-home*(*Mary*) characterizes a situation s just in case the anti-extension of the predicate contains the tuple consisting of s followed by the values of the specified arguments. In the example, the negative abstract characterizes s just in case $(s, m) \in \textit{at-home}^{\mathcal{I}^-}$, where m is the denotation of '*Mary*' in the model. Similarly $\neg$*at-home*(*Mary*) (partially) describes s just in case for some $s' \preceq s$, $(s', m) \in \textit{at-home}^{\mathcal{I}^-}$.

Thus, to say that s is a situation of Mary not being at home is in general a much stronger statement (with a semantics determined by anti-extensions) than merely saying that s is not a situation of Mary being at home (whose semantics is determined by extensions). This is what enables us to overcome the problem noted for Davidsonian event semantics, that of not being able to represent negative eventualities on a par with positive ones. For assigning truth values to formulas with outer operator '$*$' or '$**$', the semantics of extensions and anti-extensions gets us off the ground, and we can then generalize to arbitrarily complex event characterizations or descriptions (though as will be seen, we need the mediation of a "situational support" function that provides all sets of situations that can support the truth of a situation characterization or description). The resemblance of FOL** models to those of partial truth theories is explained by the fact that characterization or description of a situation (especially the latter) is essentially a relation of partial truth in a situation; i.e., it is entirely possible that neither a given situation abstract, nor its negation, characterizes or describes a given situation. However, the "collision avoidance" clause in the definition of extensions and anti-extensions ensures that a situation abstract and its negation cannot both characterize (or describe) a situation. This requirement is not automatically satisfied just by making extensions and anti-extensions disjoint, since the persistence of information in the situational part-of orderings can propagate characterization and partial description relations upward, outward, and inward in those orderings.

Finally note that inward and outward persistence are not treated in the semantics as exact duals. Through the definition of an interpretation, we have ensured that atelic as well as negative predications already exhibit inward persistence (homogeneity) in their extensions. By contrast, outward persistence does not show up directly in extensions, but rather shows up only in the context of the '$*$' and '$**$' operators, i.e., in the context of situation descriptions and characterizations. This is why we needed to employ the notion of "collision", which anticipates the persistence properties of descriptions relative to situations.

4.3 Truth in FOL**

Term denotations and truth values of formulas are defined relative to a model $\mathcal{M} = (\mathcal{D}, (\mathcal{S}it, \sqsubseteq), (\mathcal{T}, <), \textit{time}, \mathcal{I})$ and a variable assignment $\mathcal{U}$. Truth for sentences (closed formulas) is then defined by quantifying universally (or existentially) over assignments. Situation variables receive values in $\mathcal{S}it$ under an assignment, while other individual variables receive values in $\mathcal{D}$. As usual, the denotation $c^{\mathcal{M},\mathcal{U}}$ of a constant c is $c^{\mathcal{I}}$, the denotation $x^{\mathcal{M},\mathcal{U}}$ of a variable x is $x^{\mathcal{U}}$, and the denotation $(\sqcup(r_1, r_2))^{\mathcal{M},\mathcal{U}}$ of a term $\sqcup(r_1, r_2)$ (where r_1, r_2 are terms) is $r_1^{\mathcal{M},\mathcal{U}} \sqcup r_2^{\mathcal{M},\mathcal{U}}$.

We first consider truth conditions for formulas other than those with top-level operator '$*$' or '$**$'. In the following P is an n-place predicate, $r_1, ..., r_n$ are terms, x is a variable, and ϕ and ψ are formulas.

T-pred: $\models_{\mathcal{M},\mathcal{U}} \; P(r_1, ..., r_n)$ iff $(r_1^{\mathcal{M},\mathcal{U}}, ..., r_n^{\mathcal{M},\mathcal{U}}) \in P^{\mathcal{I}^+}$;

T=: $\models_{\mathcal{M},\mathcal{U}} \; (r_1 = r_2)$ iff $r_1^{\mathcal{M},\mathcal{U}} = r_2^{\mathcal{M},\mathcal{U}}$;

T$\sqsubseteq$: $\models_{\mathcal{M},\mathcal{U}} \; (r_1 \sqsubseteq r_2)$ iff $r_1^{\mathcal{M},\mathcal{U}} \sqsubseteq r_2^{\mathcal{M},\mathcal{U}}$; and similarly for **T$\preceq$**, **T$\trianglelefteq$**;

T$\neg$: $\models_{\mathcal{M},\mathcal{U}} \; \neg\phi$ iff not $\models_{\mathcal{M},\mathcal{U}} \; \phi$;

T$\wedge$: $\models_{\mathcal{M},\mathcal{U}} \; (\phi \wedge \psi)$ iff $\models_{\mathcal{M},\mathcal{U}} \; \phi$ and $\models_{\mathcal{M},\mathcal{U}} \; \psi$;

Similarly for $\mathbf{T}\vee$, $\mathbf{T}\rightarrow$, $\mathbf{T}\leftrightarrow$;

T$\forall$: $\models_{\mathcal{M},\mathcal{U}} \ (\forall x)\phi$ iff for all $d \in \mathcal{D}$, $\models_{\mathcal{M},\mathcal{U}_{d/x}} \ \phi$; and similarly for $\mathbf{T}\exists$.

The truth conditions for '$*$' and '$**$' are specified in terms of a function $Support^{+}_{\mathcal{M},\mathcal{U}}(\phi, s)$ and its dual $Support^{-}_{\mathcal{M},\mathcal{U}}(\phi, s)$ defined inductively below. Intuitively, $Support^{+}_{\mathcal{M},\mathcal{U}}(\phi, s)$ supplies all possible sets of situations that "support" a situation abstract ϕ in situation s (relative to model $\mathcal{M}$ and assignment $\mathcal{U}$). Roughly speaking, a set of situations supports ϕ in situation s if they are all part of s, and together "verify" a set of basic facts sufficient to support the truth of ϕ in s. The part-of relation between an element of such a support set and s depends on the telicity of the basic fact the element supports. The existence of a support set for ϕ in s verifies the (partial) description relation between ϕ and s. When the join of elements of a support set equals s, this (in addition) verifies the characterization relation between ϕ and s.

For example, consider $\phi = \exists x.\, person(\mathrm{x}) \wedge greet(x, Mary)$, where both conjuncts are proper situation abstracts (i.e., both '*person*' and '*greet*' have an implicit situation argument). A support set for this abstract might be $\{s_1, s_2\}$, where for some individual d, (s_1, d) is in the extension of '*person*' and (s_2, d, m) is in the extension of '*greet*' (where m is the denotation of '*Mary*'); and in addition, $s_1 \preceq s$ and $s_2 \sqsubseteq s$. So in that case, if E denotes s, then $(\phi{*}E)$ is true in the model under consideration. Furthermore, if $s_1 \sqcup s_2 = s$ (i.e., $\{s_1, s_2\}$ is precisely sufficient to support ϕ in s), then $(\phi{**}E)$ is true in the model. Note that we require a '$\preceq$' (concurrent part-of) relation between s_1 and s, since '*person*' is atelic, so that its truth in s requires its truth *everywhere* in s; whereas we merely require a '$\sqsubseteq$' (part-of) relation between s_2 and s, since '*greet*' is telic so that its truth anywhere in s assures its truth in s as a whole.

In the following inductive definition of $Support^{+}_{\mathcal{M},\mathcal{U}}(.,.)$ and $Support^{-}_{\mathcal{M},\mathcal{U}}(.,.)$, ϕ and ψ are situation abstracts, $s \in \mathcal{S}it$, x is a variable, $r_1, ..., r_n$ are terms, and P is an $(n+1)$-place fluent predicate (with an initial situation argument followed by n additional arguments). S is a variable over sets of situations that is understood to be universally quantified.

If ϕ is a formula (i.e., not a proper situation abstract), then

$$Support^{+}_{\mathcal{M},\mathcal{U}}(\phi, s) = \{\emptyset\} \text{ if } \models_{\mathcal{M},\mathcal{U}} \ \phi, \quad = \emptyset \text{ otherwise;}$$

$S \in Support^{+}_{\mathcal{M},\mathcal{U}}(P(r_1, ..., r_n), s)$ iff $S = \{s'\}$ for some $s' \in \mathcal{S}it$ such that s' *rel* s and $(s', r_1^{\mathcal{M},\mathcal{U}}, ..., r_n^{\mathcal{M},\mathcal{U}}) \in P^{\mathcal{I}^{+}}$, where *rel* is $\sqsubseteq$ if P is telic and $\preceq$ if P is atelic;

$S \in Support^{+}_{\mathcal{M},\mathcal{U}}(\neg\phi, s)$ iff $S \in Support^{-}_{\mathcal{M},\mathcal{U}}(\phi, s)$;

$S \in Support^{+}_{\mathcal{M},\mathcal{U}}((\phi \wedge \psi), s)$ iff $S = S' \cup S''$ for some $S' \in Support^{+}_{\mathcal{M},\mathcal{U}}(\phi, s)$ and some $S'' \in Support^{+}_{\mathcal{M},\mathcal{U}}(\psi, s)$;

$S \in Support^{+}_{\mathcal{M},\mathcal{U}}((\phi \vee \psi), s)$ iff $S \in Support^{+}_{\mathcal{M},\mathcal{U}}(\phi, s)$ or $S \in Support^{+}_{\mathcal{M},\mathcal{U}}(\psi, s)$;

(corresponding conditions for $\rightarrow$ and $\leftrightarrow$ are easily filled in);

$S \in Support^{+}_{\mathcal{M},\mathcal{U}}((\forall x)\phi, s)$ iff there exists a function $f : \mathcal{D} \rightarrow \mathcal{P}ow(\mathcal{D})$ such that $S = \bigcup range(f)$ and for each $d \in \mathcal{D}$, $f(d) \in Support^{+}_{\mathcal{M},\mathcal{U}_{d/x}}(\phi, s)$;

$S \in Support^{+}_{\mathcal{M},\mathcal{U}}((\exists x)\phi, s)$ iff for some $d \in \mathcal{D}$, $S \in Support^{+}_{\mathcal{M},\mathcal{U}_{d/x}}(\phi, s)$.

The definition of $Support^{-}_{\mathcal{M},\mathcal{U}}(.,.)$ is very nearly the dual of that of $Support^{+}_{\mathcal{M},\mathcal{U}}(.,.)$, obtained from the clauses for $Support^{+}_{\mathcal{M},\mathcal{U}}(.,.)$ by interchanging $\models$ and $\not\models$, $^{+}$ and $^{-}$, $\wedge$ and $\vee$, and $\exists$ and $\forall$. The only amendment is that *rel* in the second clause (for atomic predications) is simply $\preceq$, since anti-extensions behave like atelic extensions:

$S \in Support^{-}_{\mathcal{M},\mathcal{U}}(P(r_1, ..., r_n), s)$ iff $S = \{s'\}$ for some $s' \in \mathcal{S}it$ such that $s' \preceq s$ and $(s', r_1^{\mathcal{M},\mathcal{U}}, ..., r_n^{\mathcal{M},\mathcal{U}}) \in P^{\mathcal{I}^{-}}$,

We can now complete the truth definition (e is a situation term):

T∗: $\models_{\mathcal{M},\mathcal{U}}\ (\phi{*}e)$ iff $Support^{+}_{\mathcal{M},\mathcal{U}}(\phi, e^{\mathcal{M},\mathcal{U}}) \neq \emptyset$;

T∗∗: $\models_{\mathcal{M},\mathcal{U}}\ (\phi{**}e)$ iff there is an $S \in Support^{+}_{\mathcal{M},\mathcal{U}}(\phi, e^{\mathcal{M},\mathcal{U}})$ such that $e^{\mathcal{M},\mathcal{U}} = \bigsqcup S$.

Note that the definition of $Support^{+}_{\mathcal{M},\mathcal{U}}(\phi, s)$ in the case where ϕ is a formula (and thus not a proper situation abstract) is designed not to "interfere" with the correct selection of support sets for proper situation abstracts. For instance, in the case of a conjunction $(\phi \wedge \psi)$ of a formula ϕ and a proper situation abstract ψ, the support sets will simply be the ones for ψ, as long as ϕ is true. This is because the only support set for ϕ in that case is the empty set (whose union with any support set for ψ is of course that same set). If ϕ is false, then it has no support sets ($Support^{+}_{\mathcal{M},\mathcal{U}}(\phi, s) = \emptyset$), so in that case the conjunction has no support sets either, and $((\phi \wedge\ \psi){*}e)$ will be false regardless of e. This is as it should be, given the truth-like character of the $*$-relation. An easily verified consequence of these stipulations is that a true sentence is considered to (partially) describe any situation, and characterize none, save ε. A false sentence neither describes nor characterizes any situation.

5 Properties of FOL**

We now look at some of the consequences of the preceding semantics for FOL**. First we note a few of the laws that reflect the model-theoretic assumptions made about the situation orderings. Then we state some of the most important relationships between '$*$' and '$**$', laws governing complex formulas within the scopes of '$*$' and '$**$', persistence laws for '$*$' (when we keep the situation abstract argument fixed while replacing the situation argument by one denoting a larger or smaller situation), and finally a set of sound inference rules. The logic seems to deal in a satisfactory way with simple and complex situations. At the level of atomic fluent sentences, the sentence-event connection provided by '$**$' is precisely Davidson's. But '$**$' also provides a coupling between negated atomic sentences and situations, and indeed between arbitrarily complex sentences and situations; and this coupling is tight enough to deal with causal descriptions. Furthermore, the weakened version of the coupling, '$*$', behaves logically very much like the support relation, '$\models$', of Situation Semantics.

5.1 Laws concerning $\sqsubseteq$, $\preceq$, and $\trianglelefteq$

Validity of a formula ϕ, $\models\ \phi$, is defined as usual as truth in all models. The following are some obviously valid formulas, given the truth conditions for $\sqsubseteq$, $\preceq$, and $\trianglelefteq$ and the assumptions about the orderings they represent. Multiple quantifiers of the same type are usually collapsed into a single quantifier with multiple variables.

O1. $\models\ \forall e.(e \sqsubseteq e)$

O2. $\models\ \forall e, e', e''.(e \sqsubseteq e') \wedge (e' \sqsubseteq e'')\ \rightarrow\ (e \sqsubseteq e'')$

O3. $\models\ \forall e, e'.(e \sqsubseteq e') \wedge (e' \sqsubseteq e)\ \rightarrow\ (e = e')$

O4. $\models\ \forall e, e'.(e \sqsubseteq \sqcup(e, e'))$

O5. $\models\ \forall e, e', e''.(e' \sqsubseteq e) \wedge (e'' \sqsubseteq e)\ \rightarrow\ (\sqcup(e', e") \sqsubseteq e)$

O6. $\models\ \forall e, e'.(e \preceq e')\ \ \rightarrow\ (e \sqsubseteq e')$

O7. $\models\ \forall e, e'.(e \trianglelefteq e')\ \ \rightarrow\ (e \sqsubseteq e')$

Idempotency and commutativity of $\sqcup$ follow from **O4** and **O5**, and associativity from **O2-O5**. One law that is not completely obvious is

O8. $\models\ \forall e, e'.(e \trianglelefteq e') \wedge (e \preceq e')\ \rightarrow\ (e = e')$

This is readily proved from the definitions of (metalinguistic) $\trianglelefteq$ and $\preceq$, along with the fact that if $s \neq \varepsilon$, then $time(s) \neq \emptyset$ (in view of the assumptions about ε and $time$).

An intuitively plausible formula whose validity we might want to ensure in a future strengthening of the model theory is

$\forall e, e'.(e \sqsubseteq e') \ \rightarrow \ \exists e''.(e \preceq e'') \wedge (e'' \trianglelefteq e')$.

A final point worth noting is that since we have assumed a minimal element ε in our complete semilattice of situations, we actually have a complete lattice, and so could introduce a meet operator.[10]

5.2 Relationships between '$*$' and '$**$'

Three basic laws connecting '$*$' and '$**$' are the following, where ϕ is a situation abstract.

$$(\mathbf{**\rightarrow*}) \qquad \models \forall e.(\phi{**}e) \ \rightarrow \ (\phi{*}e)$$

$$(\mathbf{*\rightarrow**}) \qquad \models \forall e.(\phi{*}e) \ \rightarrow \ \exists e'.(e' \sqsubseteq e) \wedge (\phi{**}e')$$

$$(\mathbf{*\rightarrow **})_{atel} \ \models \forall e.(\phi_{atel}{*}e) \ \leftrightarrow \ \exists e'.(e' \preceq e) \wedge (\phi_{atel}{**}e')$$

The proof of the first law is immediate from the truth conditions for '$*$' and '$**$'. The second law is more subtle, stating that a (partial) description of a situation always *characterizes* some part of it. For the proof we make use of the following

Lemma 1. (a) If $S \in Support^{+}_{\mathcal{M},\mathcal{U}}(\phi, s)$ then $\bigsqcup S \ \sqsubseteq s$ and for every $s' \in \mathit{Sit}$ such that $\bigsqcup S \sqsubseteq s' \sqsubseteq s$, $S \in Support^{+}_{\mathcal{M},\mathcal{U}}(\phi, s')$. (b) As in (a), with '$^{+}$' replaced by '$^{-}$'.

Lemma 1 can be proved straightforwardly (if somewhat tediously) by simultaneous induction on the complexity of ϕ in (a) and (b), with reference to the definition of support sets. In the inductive argument for negated abstracts, the proof of (a) depends on the induction hypothesis for (b) and vice versa. (Several other lemmas to follow use similar proofs.) The proof of $(\mathbf{*\rightarrow**})$ then essentially starts with the supposition that $\models_{\mathcal{M},\mathcal{U}} \ (\phi{*}e)$ where $e^{\mathcal{U}} = s$ for some arbitrary $s \in \mathit{Sit}$. Then by the lemma there is a positive support set S for (ϕ, s) whose join is part of s, and S is also a positive support set for $(\phi, \bigsqcup S)$. But then $\bigsqcup S$ supplies the value of e' that verifies the consequent in $(\mathbf{*\rightarrow**})$ (relative to the $\mathcal{M}, \mathcal{U}$ under consideration).

In the third law the '*atel*' subscript indicates an *atelic situation abstract*. For such an abstract, every proper atomic situation abstract occurring in it outside the scope of all '$*$' and '$**$' operators either has an atelic predicate or has a telic predicate and lies in a negative environment. A negative environment is one embedded in an odd number of negations, where antecedents of conditional formulas or abstracts count as carrying a negation (and $\leftrightarrow$ is rewritten in terms of $\rightarrow$). For later reference, we similarly define a *telic situation abstract* as one in which every proper atomic situation abstract occurring outside the scope of all '$*$' and '$**$' operators has a telic predicate and lies in a positive environment. Note that not all abstracts are telic or atelic. For instance, $tired(John) \rightarrow yawn(John)$ is neither telic nor atelic, since it involves an atelic predicate in a negative environment and a telic predicate in a positive environment. The proof of $(\mathbf{*\rightarrow **})_{atel}$ depends on the following lemma.

Lemma 2. (a) If ϕ is atelic and $S \in Support^{+}_{\mathcal{M},\mathcal{U}}(\phi, s)$, then for all $s' \in S,\ s' \preceq s$. (b) If the negation of ϕ is atelic (i.e., every proper atomic situation abstract occurring in ϕ outside the scope of all '$*$' and '$**$' operators has an atelic predicate or it has a telic predicate in a positive environment), and $S \in Support^{-}_{\mathcal{M},\mathcal{U}}(\phi, s)$, then for all $s' \in S,\ s' \preceq s$.

The proof is by simultaneous induction for (a) and (b), paying attention to downward inheritance of atelicity to parts of formulas. As basis we consider positive and negated atelic atomic situation abstracts. This involves looking at the positive support definition for positive and negated atelics and negated telics, and the negative support definition for positive and negated atelics and for positive telics. In all cases the $\preceq$ relation applies. For conjunction, disjunction, and quantification telicity is inherited by the constituent abstracts. For negation we again "switch" between the positive and negative support cases (a) and (b).

[10]This well-known fact rests on the ability to take the set join of elements that are common parts of given elements, to obtain their meet – which will exist since at least ε is part of it.

The proof for $(*\!\!\to **)_{atel}$ is then quite obvious in both directions, since all 3 relevant support sets consist of situations concurrent with the denotation of e, by Lemma 2.

5.3 Laws concerning complex formulas within the scope of '$**$'

The behavior of complex formulas within the scope of '$**$' reflects the fact that truth for this characterization operator is based on joins of situations in a support set. I believe that the laws that follow are in keeping with intuitions about what it means to characterize a situation or event. For example, If we characterize a situation with a binary conjunction, then that situation is presumably made up of two parts (which might be concurrent aspects or temporal segments), each characterized by one of the two sentences. That is exactly what we find in $(\wedge)$** below, among other reasonable properties. The first group of laws concerns the movement of various operators out of or into the scope of '$**$'. P is an $(n+1)$-place fluent predicate.

(PRED):** $\models \forall x_1,...,x_n.\forall e.(P(x_1,...,x_n)**e) \ \leftrightarrow\ P(e,x_1,...,x_n)$

$(\neg)$:** $\models \forall e.((\neg\phi)**e) \to \neg(\phi**e)$

$(\wedge)$:** $\models \forall e.((\phi\wedge\psi)**e) \ \to\ \exists e',e''.(\sqcup(e',e'')=e)\wedge(\phi**e')\wedge(\psi**e'')$

$(\wedge)^{**}_{tel}$: $\models \forall e.((\phi_{tel}\wedge\psi_{tel})**e) \ \leftrightarrow\ \exists e',e''.(\sqcup(e',e'')=e)\wedge(\phi_{tel}**e')\wedge(\psi_{tel}**e'')$

$(\wedge)^{**}_{atel}$: $\models \forall e.((\phi_{atel}\wedge\psi_{atel})**e) \ \leftrightarrow\ \exists e',e''.(\sqcup(e',e'')=e)\wedge(e'\preceq e)\wedge(e''\preceq e)\wedge(\phi_{atel}**e')\wedge(\psi_{atel}**e'')$

$(\vee)$:** $\models \forall e.((\phi\vee\psi)**e) \ \leftrightarrow\ (\phi**e)\vee(\psi**e)$

$(\forall)$:** $\models \forall e.((\forall x\,\phi)**e) \ \to\ \forall x.\exists e',e''.(\sqcup(e',e'')=e)\wedge(\phi**e')\wedge((\forall y.(y\neq x)\to\phi_{y/x})**e'')$

$(\exists)$:** $\models \forall e.((\exists x\,\phi)**e) \ \leftrightarrow\ \exists x.(\phi**e)$

$(=)$:** $\models \forall e,x,y.(\phi**e)\wedge x=y \ \to\ (\phi_{y/x}**e)$

(PRED)** shows that characterization at the atomic level is equivalent to a Davidsonian predication. Its validity is obvious from the definition of truth and support for '$**$'. $(\neg)$** is an easy consequence of the following lemma.

Lemma 3. For every situation abstract ϕ and situation s, either $\mathit{Support}^{+}_{\mathcal{M},\mathcal{U}}(\phi,s)=\emptyset$ or $\mathit{Support}^{-}_{\mathcal{M},\mathcal{U}}(\phi,s)=\emptyset$, regardless of $\mathcal{M}$, $\mathcal{U}$.

An inductive basis for proving the lemma is given by the non-collision of predicate extensions and anti-extensions, and the fact that for s' to be in a negative support set relative to s, it must be concurrent with s, and so no tuple in the extension of the predicate can have as its first element a situation that is part of s. The induction step is straightforward.

$(\wedge)$** can be proved from the definition of support for conjunctions (and of course truth of $**$-formulas). A counterexample to the converse direction is obtained by choosing ϕ to be P, an abstract of a unary fluent predicate, and ψ to be $\neg P$, with the denotations of e', e'' temporally non-overlapping and with a join equal to the value of e under some variable assignment. Then with a suitable interpretation of P, the consequent in $(\wedge)$** is verified but the antecedent is false, because its truth requires the supporting situation for $\neg P$ to be concurrent with the denotation of e. However, $(\wedge)^{**}_{tel}$ asserts a biconditional for the case where both ϕ and ψ are telic, and $(\wedge)^{**}_{atel}$ is an analogous law for atelic ϕ and ψ, though it requires the extra condition on the right that e and e' be concurrent with e. The two variants of $(\wedge)$** require lemmas, viz., Lemma 2 and the following related one.

Lemma 4. (a) If ϕ is telic, $S\in\mathit{Support}^{+}_{\mathcal{M},\mathcal{U}}(\phi,s)$, and $s\sqsubseteq s'$ then $S\in\mathit{Support}^{+}_{\mathcal{M},\mathcal{U}}(\phi,s')$. (b) If the negation of ϕ is telic (i.e., every proper atomic situation abstract occurring in ϕ outside the scope of all '$*$' and '$**$' operators has a telic predicate and lies in a negative environment), and $S\in\mathit{Support}^{-}_{\mathcal{M},\mathcal{U}}(\phi,s)$, and $s\sqsubseteq s'$ then $S\in\mathit{Support}^{-}_{\mathcal{M},\mathcal{U}}(\phi,s')$.

The proof (as in Lemma 2) is by simultaneous induction for (a) and (b), again with attention to downward inheritance of telicity to parts of formulas. As basis we consider positive and negated telic atomic situation abstracts. For conjunction, disjunction, and quantification telicity is inherited by the constituent abstracts. For negation we then "switch" between cases (a) and (b).

The proofs of $(\wedge)^{**}_{tel}$ and $(\wedge)^{**}_{atel}$ are then simple. The former uses Lemma 4 for the backward implication, and the latter Lemma 2. $(\vee)^{**}$ is obvious from the definitions. $(\forall)^{**}$ states that a universal characterization of a situation implies that for each element of the domain there is a subsituation supporting the characterization of that element, and another subsituation supporting the characterization of the remaining elements. Since we don't have sets and set joins in the object language, we can't readily break down the universal characterization more uniformly. The proof idea is much as for conjunction. In assuming the truth of the antecedent of $(\forall)^{**}$ for a particular value of e, we are assuming the existence of a function f as specified in the definition of $Support^{+}_{\mathcal{M},\mathcal{U}}((\forall x)\phi, s)$. For any particular value d of x in the consequent, this function supplies the value of both e' (as $\bigsqcup f(d)$) and e'' (as another set join, over the union of sets $f(d')$ for all $d' \neq d$); a variant f' of f which is the same as f except that $f'(d) = \emptyset$ serves to verify the truth of the last conjunct in the consequent of $(\forall)^{**}$. We could again set up special cases for telic and atelic ϕ, but we omit this. $(\exists)^{**}$, a law for existential characterization, indicates the "transparency" of '$**$' to existential quantification. The final law $(=)^{**}$ is particularly noteworthy, showing the transparency of '$**$' with respect to substitution of coreferential terms. This can be shown straightforwardly by induction on the complexity of ϕ, with use of the fact that term denotations are invariant under substitution of coreferential terms (whose proof is as in FOL, since complex FOL** terms, though restricted here to being situational, are interpreted as in FOL). Essentially the induction establishes the rather obvious fact that the definition of (positive and negative) support sets is insensitive to substitution of coreferential terms in any of the situation abstracts mentioned in the definition.

A second group of laws concerns transformations *within* the scope of '$**$'. Negation distribution within the scope of '$**$' turns out to be valid, while the behavior of conjunction and disjunction is non-truth-functional in a way that may at first seem surprising, but which I believe reflects desirable properties of the logic.

$(\neg\neg)^{**}$: $\models \forall e.((\neg\neg\phi){**}e) \leftrightarrow (\phi{**}e)$

$(\neg\wedge)^{**}$: $\models \forall e.((\neg(\phi \wedge \psi)){**}e) \leftrightarrow ((\neg\phi \vee \neg\psi){**}e)$

$(\neg\vee)^{**}$: $\models \forall e.((\neg(\phi \vee \psi)){**}e) \leftrightarrow ((\neg\phi \wedge \neg\psi){**}e)$

$(\neg\forall)^{**}$: $\models \forall e.((\neg(\forall x\, \phi)){**}e) \leftrightarrow ((\exists x\, \neg\phi){**}e)$

$(\neg\exists)^{**}$: $\models \forall e.((\neg(\exists x\, \phi)){**}e) \leftrightarrow ((\forall x\, \neg\phi){**}e)$

$(\phi \wedge \phi)^{**}$: $\models \forall e.(\phi{**}e) \rightarrow ((\phi \wedge \phi){**}e)$ *but not the converse*

$(\phi \vee \phi)^{**}$: $\models \forall e.(\phi{**}e) \leftrightarrow ((\phi \vee \phi){**}e)$

$(\vee\wedge)^{**}$: $\models \forall e.((\phi \vee (\chi \wedge \psi)){**}e) \rightarrow (((\phi \vee \chi) \wedge (\phi \vee \psi)){**}e)$ *but not the converse*

$(\wedge\vee)^{**}$: $\models \forall e.((\phi \wedge (\chi \vee \psi)){**}e) \leftrightarrow (((\phi \wedge \chi) \vee (\phi \wedge \psi)){**}e)$

$(\neg\neg)^{**}$ is obvious from the identity $Support^{+}_{\mathcal{M},\mathcal{U}}(\neg\phi, s) = Support^{-}_{\mathcal{M},\mathcal{U}}(\phi, s)$ and its dual. $(\neg\wedge)^{**}$ is also easily proved from these indentities and the membership conditions for $Support^{-}_{\mathcal{M},\mathcal{U}}(\phi \wedge \psi, s)$ and $Support^{+}_{\mathcal{M},\mathcal{U}}(\neg\phi \vee \neg\psi, s)$; similarly for $(\neg\vee)^{**}$, $(\neg\forall)^{**}$, and $(\neg\exists)^{**}$. The failure of the converse of $(\phi \wedge \phi)^{**}$ may seem surprising – one might expect the embedded conjunction $\phi \wedge \phi$ to be equivalent to ϕ. However, it needs to be kept in mind that ϕ is (in general) a situation abstract, not a formula, and as such makes tacit reference to a situation – and distinct occurrences of ϕ may refer to distinct situations. Consider, for example, a conjunction such as $sneeze(John) \wedge sneeze(John)$. Though this could be a repeated description of the same sneezing event, it could also perfectly well be a description of two distinct such events; the logic as such should not commit us to either one of these possibilities, and so it would be undesirable for the converse of $(\phi \wedge \phi)^{**}$ to hold. The point is perhaps even clearer from an example such as '*Beethoven composed a violin concerto and (he composed) a piano concerto*'; this entails '*Beethoven composed a concerto and (he composed) a concerto*'. We would not want the latter conjunction to be, of necessity, the description of a single composing event.[11] Note that by contrast, ϕ and $\phi \vee \phi$ are indistinguishable in the scope of '$**$', as seen in **($\phi \vee \phi$)**** (again a simple consequence of the definition of *Support*$^+$). A closely related contrast is seen in **($\vee\wedge$)**** and **($\wedge\vee$)****: distribution of '$\vee$' over '$\wedge$' in the scope of '$**$' is not "reversible", unlike distribution of '$\wedge$' over '$\vee$'.

Thus $**$-contexts are quite subtle, in some respects (e.g., **($\vee$)****, **($\exists$)**** and **(=)****) behaving "transparently", and in others (e.g., the failure of the converses of **($\phi \wedge \phi$)**** and **($\vee\wedge$)****) showing an even stronger sensitivity to logical form than classical modal operators. To the extent that '$**$' can be viewed as a reconstruction of Reichenbach's '[ ]*' operator (setting aside Reichenbach's conflation of facts and events), the semantics provided here refutes Davidson's main objection to Reichenbach's proposal [5]. Essentially, Davidson argued that [ ]*-contexts must allow substitution of coreferential singular terms, hence should also allow substitution of logically equivalent sentences, and this leads to indistinguishability of all events. But as seen from the properties of '$**$', a Reichenbach-like operator may perfectly well allow substitution of coreferential singular terms without also allowing substitution of logically equivalent sentences (more precisely, situation abstracts). At the same time, such a theory is compatible with Davidson's conception of events at the level of atomic predication, as seen from **(PRED)****.

5.4 Complex formulas within the scope of '$*$': Truth-likeness and transparency

We now consider complex formulas within the scope of '$*$'. These show the much simpler, more transparent behavior of '$*$' compared to '$**$', as one would expect from a partial truth-like operator.

($\neg$)* $\models \forall e.((\neg\phi)*e) \ \rightarrow \neg(\phi*e)$

($\wedge$)* $\models \forall e.((\phi \wedge \psi)*e) \ \leftrightarrow \ (\phi*e) \wedge (\psi*e)$

($\vee$)* $\models \forall e.((\phi \vee \psi)*e) \ \leftrightarrow \ (\phi*e) \vee (\psi*e)$

($\forall$)* $\models \forall e.((\forall x\, \phi)*e) \ \leftrightarrow \ \forall x.(\phi*e)$

($\exists$)* $\models \forall e.((\exists x\, \phi)*e) \ \leftrightarrow \ \exists x.(\phi*e)$

In addition we could give analogous formulas for $\rightarrow$ and $\leftrightarrow$. Also, many standard manipulations are possible *within* the scope of '$*$', such as the following.

($\neg\wedge$)* $\models \forall e.((\neg(\phi \wedge \psi))*e) \ \leftrightarrow \ ((\neg\phi \vee \neg\psi)*e)$

($\neg\vee$)* $\models \forall e.((\neg(\phi \vee \psi))*e) \ \leftrightarrow \ ((\neg\phi \wedge \neg\psi)*e)$

In fact, bidirectional versions of all the transformations in the scope of '$**$', listed earlier, hold for '$*$', and these (along with others) can be captured by a general "embedded inference rule" (below). **($\neg$)***, like **($\neg$)****, follows from Lemma 3. The laws for $\wedge$, $\vee$, $\forall$ and $\exists$, follow directly from the corresponding support set definitions. The embedded rules (and others like them) are proved by showing that the existence of a support set for one side of the equivalence ensures that one exists for the other side as well. Note that once we have distributed negation in this way, we can apply **($\vee$)*** or **($\wedge$)***; this proves useful below.

5.5 Persistence of information relative to $\sqsubseteq$, $\preceq$ $\trianglelefteq$

Among the most important properties of a situation logic are its persistence properties – as we go from "smaller" to "larger" situations, information is preserved (and expands). The point is that events or situations are limited parts or aspects of the world, and we manipulate these aspects cognitively with great

[11] It turns out that with an additional model-theoretic assumption, the converse of **($\phi \wedge \phi$)****, with ϕ restricted to atelic formulas that can be written as conjunctions of atoms or negated atoms, with no existential quantification, is valid. The additional assumption is the following rather plausible *situation individuation assumption*: If two n-tuples in the extension of a fluent predicate differ only in their (initial) situational element, then the times of those situations are distinct. This applies to both positive and negative extensions. For example, two events of John sneezing, or two episodes of his not being at home, cannot be concurrent yet distinct.

ease, expanding or narrowing our purview at will. In FOL**, we capture not only the "upward" growth of information, but also its "outward" growth to temporally larger episodes, and its "inward preservation" for certain kinds of information, as illustrated earlier. For example, we noted that a greeting uttered at the beginning of a talk is also a greeting uttered in the talk, which may be temporally much larger. In fact, the temporal persistence of information seems to play an important role in NL, finding expression in time adverbials, for example. And it is also important to be aware of inward persistence (homogeneity) of many kinds of information, for instance recognizing that if the library is closed tomorrow, then it will be closed no matter what time I show up tomorrow. The following are the most important persistence properties in FOL**.

(UP) $\models \forall e, e'.(e \preceq e') \wedge (\phi{*}e) \;\rightarrow\; (\phi{*}e')$

(OUT) $\models \forall e, e'.(e \sqsubseteq e') \wedge (\phi{*}e) \;\rightarrow\; \neg((\neg\phi){*}e')$ if ϕ is telic or *strictly atelic* (i.e., both ϕ and $\neg\phi$ are atelic)

(OUT$_{tel}$) $\models \forall e, e'.(e \sqsubseteq e') \wedge (\phi_{tel}{*}e) \;\rightarrow\; (\phi_{tel}{*}e')$

(IN$_{atel}$) $\models \forall e, e'.(e \trianglelefteq e') \wedge (\phi_{atel}{**}e') \;\rightarrow\; (\phi_{atel}{**}e)$

(UP) is the most general persistence property, stating that all types of information persist through the concurrent part-of ordering. One possible proof is by induction and by use of the previous laws for complex formulas in $*$-environments, with a separate induction for negated abstracts, aided by the "embedded" inference rules mentioned above (and again below). A much more direct proof is enabled by the following lemma.

Lemma 5. (a) If $S \in \mathit{Support}^{+}_{\mathcal{M},\mathcal{U}}(\phi, s)$, and $s \preceq s'$, then $S \in \mathit{Support}^{+}_{\mathcal{M},\mathcal{U}}(\phi, s')$. (b) As in (a), with '$^{+}$' replaced by '$^{-}$'.

The proof is again a straightforward simultaneous induction for (a) and (b), using the definition of support sets and the basic properties of the situation orderings.

The **(OUT)** law can also be proved inductively, with a basis that depends on the collision avoidance condition on predicate extensions and anti-extensions in the definition of models. As in the case of **(UP)**, the proof can be carried through using the previously established laws for $*$-environments, or using appropriate semantic lemmas; but we omit further details. The need for the qualification in the statement of **(OUT)** can be appreciated by considering an example of a negated telic in the context of '$*$', such as $((\neg \mathit{lightning}){*}e)$ (i.e., there's no lightning in episode e). Such a negated telic is atelic but not strictly atelic. This is perfectly compatible with $((\neg\neg \mathit{lightning}){*}e')$, i.e., $((\mathit{lightning}){*}e')$ (there's lightning in e') for some larger e' that has e as a temporal segment (which implies that $e \sqsubseteq e'$). **(OUT$_{tel}$)** is an immediate consequence of Lemma 3(a).

(IN$_{atel}$) is a consequence of the following semantic lemma.

Lemma 6. (a) If $S \in \mathit{Support}^{+}_{\mathcal{M},\mathcal{U}}(\phi_{atel}, s)$, $s = \bigsqcup S$, and $s' \trianglelefteq s$, then there exists an $S' \in \mathit{Support}^{+}_{\mathcal{M},\mathcal{U}}(\phi_{atel}, s')$ such that $s' = \bigsqcup S'$. (b) If the negation of ϕ is atelic, $S \in \mathit{Support}^{-}_{\mathcal{M},\mathcal{U}}(\phi_{atel}, s)$, $s = \bigsqcup S$, and $s' \trianglelefteq s$, then there exists an $S' \in \mathit{Support}^{-}_{\mathcal{M},\mathcal{U}}(\phi_{atel}, s')$ such that $s' = \bigsqcup S'$.

The proof as usual is by simultaneous induction. The basis makes use of the assumption in the definition of a model that atelic predications and negated predications that are true for a situation are also true for its temporal segments. The (a)-part of the inductive argument for conjunctive atelic situation abstracts makes use of the inheritance of atelicity to conjuncts, of Lemmas 2(a), 1(a) and 5(a) (in that order), of the downward inheritance of temporal segmentation assumed in the definition of models, and of the commutativity and associativity of situation joins. The (a)-part of the inductive argument for universally quantified abstracts is analogous to that for conjunctive abstracts, and uses the same lemmas. The remaining (a)-cases are straightforward, and the arguments for the (b)-parts are the duals of those for the (a)-parts (with use of Lemmas 2(b), 1(b), and 5(b)).

5.6 Rules of inference

The usual rules of FOL are sound in FOL**. For instance, substitution of equals and ∀-instantiation can be shown to be sound, by a generalization of the usual inductive argument to allow for $*$- and $**$-contexts. I will term the rules in the following group "chaining" rules, since they do not introduce new material, except that ∨-introduction introduces a disjunct and ∀-instantiation can introduce new terms.

- **Chaining rules**
  - Commutativity and associativity rules for ∧, ∨
  - ∧-, →-, and ↔-introduction and elimination
  - ∨-introduction
  - DeMorgan's rules
  - Quantifier negation rules
  - Substitution of equals
  - ∀-distribution, instantiation, and generalization
  - ∃-generalization
  - Modus ponens

We might also use

- **Rules that make assumptions**
  - *Reductio ad absurdum*
  - Assumption of antecedent
  - Assumption of negation of disjunct
  - etc.

and of course there are other possibilities (sequent rules, semantic tableaux, etc.) In any case, the point is just to draw some distinctions, not to make a comprehensive list. The following two rules are particular to FOL** and are sound:

- Embedded weak derivation

$$\frac{\phi{*}\tau, \quad \phi_c \mathrel{|\!\sim} \psi_c}{(\psi{*}\tau)} \qquad (\mathbf{EMB})$$

- Situation consistency

$$\frac{\phi_{c+} \ \vdash \ \Box}{\neg(\phi{*}\tau)} \qquad (\mathbf{CONSIS})$$

In the **EMB** rule, $\phi_c \mathrel{|\!\sim} \psi_c$, read as "$\psi_c$ is *weakly derivable* from ϕ_c", means that ψ_c is derivable from ϕ_c using *chaining rules* only, without recourse to assumption making or logical axioms. The notation ϕ_c indicates uniform conversion of a situational abstract to a formula by filling its implicit argument slots with c. More exactly, ϕ_c denotes a formula obtained from a situation abstract ϕ by adding the initial situational argument c, where c is a situational constant not appearing in any premises, to all proper atomic situation abstracts in ϕ occurring outside the scope of all '$*$' or '$**$' operators in ϕ.

The following are some simple schematic examples of inferences allowed by the **EMB** rule. The first two in effect recast the previous formulas **(¬∧)*** and **(¬∨)*** as rules.

$$\frac{((\neg(\phi \wedge \psi)){*}\tau)}{((\neg\phi \vee \neg\psi){*}\tau)}, \quad \frac{((\neg(\forall x\, \phi)){*}\tau)}{((\exists x\, \neg\phi){*}\tau)}, \quad \frac{((\phi \wedge (\phi \rightarrow \psi)){*}\tau)}{(\psi{*}\tau)}$$

Establishing soundness of **EMB** is basically a matter of showing for each of the chaining rules that the existence of support sets for the premises (cast as situation abstracts, and relativized to some situation) entails existence of support sets for the conclusion (similarly abstracted and relativized to the same situation). For many of the chaining rules this follows directly from the inductive clauses for support sets and the duality between positive and negative support sets. In the case of *modus ponens*, we use the fact that if an abstract is positively supported relative to a situation, then it cannot be negatively supported relative to that situation (see Lemma 3).

The **CONSIS** rule basically says that a situation cannot support inconsistent information. (Thus our notion of situations here is a realistic one – they cannot support inconsistent information any more than ordinary individuals can "support" inconsistent properties.) ϕ_{c+} in **CONSIS** roughly speaking is ϕ with all its tacit situation arguments (in proper atomic abstracts occurring outside the scopes of all '$*$' and '$**$' operators) filled in with distinct new constants, the first such constant being c. (A definition using a systematic way of filling in the new constants is given below, as needed in Lemma 7.)

The reason for the soundness of the rule is that as long as "$\vdash$" is based on sound rules of inference, inconsistent premises have no models, and a corresponding situation abstract has no support sets. To make this argument go through, we use a lemma related to the contrapositive of the soundness claim.

Lemma 7. Given an individual constant c not occurring in a situation abstract ϕ, (a) if $S \in \mathit{Support}^{+}_{\mathcal{M},\mathcal{U}}(\phi, s)$ then $\models_{\mathcal{M}',\mathcal{U}} \phi_{c+}$ for some $\mathcal{M}'$ that differs from $\mathcal{M}$ only in the interpretations of constants occurring in ϕ_{c+} but not ϕ; and (b) if $S \in \mathit{Support}^{-}_{\mathcal{M},\mathcal{U}}(\phi, s)$ then $\models_{\mathcal{M}',\mathcal{U}} \neg\phi_{c+}$ for some $\mathcal{M}'$ that differs from $\mathcal{M}$ only in the interpretations of constants occurring in ϕ_{c+} but not ϕ.

A more precise definition of ϕ_{c+} that facilitates the proof is as follows. Assume that we have some fixed enumeration $c_0, c_1, ...$ of individual situation constants (we refer to i as the *rank* of c_i). Then for a given situation abstract ϕ and a situation constant c that does not occur in ϕ, ϕ_{c+} is the formula obtained from ϕ by inserting initial argument c into the first (leftmost) proper atomic situation abstract occurring in ϕ outside the scopes of all '$*$' and '$**$' operators; and then inserting the lowest-ranked situation constant that outranks c and does not occur in ϕ into the next (second from the left) proper atomic situation abstract occurring in ϕ outside the scopes of all '$*$' and '$**$' operators; and so on, until no further eligible atomic abstracts remain. The inductive proof of the lemma is straightforward, but it is worth mentioning that in the basis for part (b), Lemma 3 can be used; and in the induction step for conjunctions and disjunctions it is useful to note that $(\phi_{c+} \wedge \psi_{c'+})$ is the same as $(\phi \wedge \psi)_{c+}$ if c' is chosen to be the lowest-ranked situation constant that is identical to c or outranks c and does not occur in ϕ_{c+}, and similarly for disjunctions. Models for ϕ_{c+} and $\psi_{c'+}$ can then be combined in the manner required for the induction step.

The proof of the soundness of **(CONSIS)** is then by induction on the number of applications of **(CONSIS)** in the derivation $\phi_{c+} \vdash \Box$, with the basis (0 applications) provided by Lemma 7 and the soundness of the remaining rules of inference.

6 Related work

An earlier discussion of the relation between Davidsonian events and the situations of Situation Semantics is that of Robert Moore [12]. In my view, Moore's essay is best understood as an argument for distinguishing facts from Davidsonian events, based on the contrast between fact modification in sentences like '*Strangely, John sang*', and event modification in sentences like '*John sang strangely*'. As such, the argument seems reasonable; however, unlike Moore, I would not want to take the further step of identifying facts with (actual) situations, for reasons that include the contrasts (26-27) mentioned earlier.

Jerry Hobbs [6] advocates a Davidsonian approach in which any NL-derived predication, such as *loves*(*John, Mary*), is viewed as a shorthand for a predication with an added eventuality argument, conjoined with an existence assertion for that eventuality; e.g., *loves′*(*E,John,Mary*) $\wedge$ *Exist*(*E*). One might make an analogy between the prime $'$ used by Hobbs and the '$**$' operator of FOL**, except that $'$ is not viewed as an operator, but just as part of the name of a predicate related to the unprimed one. Thus there is no general mechanism for introducing eventualities corresponding to complex sentences. In fact, Hobbs *et al.* (in [6, 7] and other later work) attempt to avoid complex sentences (other than conjoined and existentially quantified ones) in LF by viewing all forms of modification (adjective-noun, noun-noun, adverbials, etc.) as adding conjunctive information, interpreting quantified talk as talk about "typical elements" of sets, and treating negation as a relation $not(e_1, e_2)$ between eventualities (that may or may not *Exist*, i.e., be actual).

However, Hobbs' eventualities appear not only in positions where one would expect events (for instance in causal relations, or as arguments of locative predications), but also in positions where one would expect propositions (for instance as objects of belief). I don't think such a conflation of events and propositions is tenable. Just as events and situations need to be distinguished from facts, they also need to be distinguished from propositions (whatever we take the connection between facts and propositions to be). For example, one can state, entertain, and prove propositions but not events; while one can set in motion, observe, and participate in events but not propositions. Propositions, unlike events, can be true or false, while events, unlike propositions, can begin, occur and end. Such incongruities, it seems to me, would ultimately lead to unwanted consequences and contradiction for language-derived information in Hobbs' approach.

In fact, Hobbs' treatment of negation in terms of a relation between eventualities suggests that his eventualities cannot be events at all, in any natural sense. Consider, for instance, a certain event e of *John sprinting*. On any natural conception of such a physical event (even if it is only a "possible" event), e could be characterized in innumerable ways; for instance, it could be characterized more generically as an event of *John running*, or an event of *John moving*. (This is certainly the case in neo-Davidsonian theories that organize event types hierarchically.) But then what is a situation n constrained by Hobbs' relation $not(n, e)$? Is it a situation of *John not sprinting*, or one of *John not running*, or one of *John not moving*? The answer can't be "all of these", since a situation of John not sprinting might well be one where he is running (at a more leisurely pace), and a situation of John not running might well be one where he is moving (e.g., walking). In other words, there is no way to recover, from a *particular event* characterized by a sentence ϕ, the situations characterized by $\neg\phi$. Events just do not carry any particular description "on their sleeves", and so they do not reveal what situations fall under the negated descriptions. This is in contrast with the case of propositions, where the concept of a proposition that is the denial (or complement) of another makes perfect sense.

Robert Wilensky [20] acknowledges the need for quantified and negative situations, but finds fault with the EL approach (as first presented in [17]) and offers an alternative. Concerning the EL representation of sentences such as '*Everyone looked at Mary*', which consists of a universal in the scope of '$**$', Wilensky says that "we cannot explicitly represent the fact that Mary was the patient of any number of looking actions" or relate these individual actions to the overall event. In fact, however, the following holds,

$$(\forall x\phi)**\eta \;\rightarrow\; \forall x.\exists e \sqsubseteq \eta.\, \phi**e,$$

which expresses precisely what Wilensky is looking for. This is a consequence of $(\forall)**$ and has also been valid in every past version of EL, because the semantics of '$**$' has always been defined so that the truth of $(\forall x\phi)**\eta$ guarantees the truth of $(\forall x\phi)$ in the situation denoted by η, and the semantics of universal quantification has always been defined so that the truth of $(\forall x\phi)$ in a situation guarantees the existence of a subsituation characterized by ϕ, for each possible value of x (e.g., see [9]).[12] Wilensky's own proposed LF for quantified sentences essentially corresponds to the right-hand side of the above conditional (*modulo* his use of neo-Davidsonian thematic relations), with an existential quantifier for η and an added predication stating that η is of type *Complex-event*. But this suffers from the same "loose coupling" problem that motivated the introduction of '$**$': it merely says that η has certain subevents, without saying that these subevents comprise *all* of η. Thus the argument of section 2 against loose coupling of events to sentences in causal talk applies to Wilensky's representation.

Wilensky also agrees that "non-events seem to be ... as causally culpable as 'real' events". But again he proposes his own representation of the connection between a negative predication $\neg P(x_1, ..., x_n)$ and the "non-event" it introduces, namely (suppressing thematic roles)

$$\exists n, e.\ \textit{Non-event}(n) \wedge \textit{negated-event}(e, n) \wedge P(e, x_1, ..., x_n).$$

Here $\textit{negated-event}(e, n)$ presumably says much the same as Hobbs' $not(n, e)$, i.e., n is the sort of condition that holds if e doesn't occur. However, the rest of the conjunction asserts that e (the positive event) occurs after all, since Wilensky (unlike Hobbs, judging from the examples he offers) adheres to the conventional view that existential quantification of an event of a specified type with specified participants entails a commitment to the actual occurrence of the event. This problem does not arise in EL or FOL**, despite the existential import of positive event predications. Moreover, even if we take Wilensky's events to be merely possible,

[12] However, our writings on EL have not made this particular consequence explicit.

not necessarily actual, there remains the problem pointed out for Hobbs' proposal, that instances of event types do not reveal the corresponding negative event types.

Finally, Wilensky faults EL for not breaking predications derived from NL sentences into thematic relations (termed *aspectuals* by him). However, it seems to me that the arguments for introducing '$*$' and '$**$' into a logical-form language for NL are entirely independent of whether we subscribe to thematic relations or not. For instance, instead of coding the LF of '*Mary yawned*' as

$\exists$e (yawn(Mary)$**$e),

we could formulate it thematically as

$\exists$e (yawn $\wedge$ experiencer(Mary))$**$e.

(Since *yawn* in this version has just a situation argument, the corresponding situation abstract has no arguments.) Wilensky considers such examples, but places the thematic relations outside the scope of '$**$'. He correctly observes that this leads to an impoverished characterization of the event; but such externalization of thematic relations would be at odds with our strategy of associating events with sentences (or at least with English clauses) as a whole.

7 Concluding remarks

I have argued that LFs for natural language require a way of representing complex situations evoked by complex sentences (as in Situation Semantics), but at the same time these situations must be as tightly linked to sentences as Davidsonian (or Reichenbachian) events, in order to represent causation correctly. I then proposed an extension of FOL called FOL**, containing a situation description operator '$*$' similar to the "supports" relation of Situation Semantics, as well as a situation characterization operator '$**$' that couples events to sentences as tightly as Davidson's approach, but without restriction to atomic predications. FOL** has a well-defined semantics founded on the idea that sets of basic parts of a given situation support a situation abstract relative to that given situation. This idea provides a linkage between Davidsonian event semantics and Situation Semantics, capturing many of the essential features of both.

The semantics of FOL** provides a formal justification for numerous intuitively natural laws and inferences concerning the connections among situations and between sentences and situations. Since FOL** can also capture, in a more satisfactory way than previous approaches, the causal relationships implicit in ordinary language (especially narratives), it should prove useful as a core component of a logical-form language for NLU. Theoretical extensions currently under consideration include strengthening of the temporal syntax and semantics and further work on proof theory, particularly establishment of completeness.

In a sense, FOL** is already a "field-tested" representation, since something quite similar to it is a part of the EL knowledge representation. Over the past 10 years, EL has been used as a logical-form language in various startup applications, including the TRAINS 91-93 interactive transportation planning system [1, 19], a message processing application for airplane repair reports [14], and systems for understanding and answering questions about miscellaneous story fragments (small excerpts from the fairy tale Little Red Riding Hood and from terrorist incident reports). Except for the TRAINS application, this work has made use of the EPILOG system, a full implementation of EL designed to support NLU and input-driven and goal-driven inference for large knowledge bases. For a recent comprehensive overview of both EL and the EPILOG system and applications see [18].

However, I should point out that the semantics of '$*$' and '$**$' assumed (to date) in EL and EPILOG differs from the one developed here. In particular, the EL semantics is intensional, treating the semantic values of sentences (including ones with a top-level '$*$' or '$**$' operator) as partial 0, 1-valued functions on situations; furthermore, the meaning of '$**$' is regarded as derivative from that of '$*$', with predicate intensions supplying partial-description information about situations, rather than characterizing information (as in the present approach). Still, the laws governing '$*$' '$**$' '$\sqcup$', '$\sqsubseteq$', and '$\preceq$' are mostly the same in EL and FOL**. In future work, we intend to adjust the EL semantics so that EL becomes a true syntactic and semantic extension of FOL**. The corresponding adjustments in the EPILOG system should be quite feasible, since the basic laws of EL are represented in EPILOG as axiom schemas (meaning postulates), and these are easily replaced. However, the current study indicates the need for not only some altered and additional basic laws, but also for additional inference rules (**EMB, CONSIS**). Their implementation should significantly improve the inferential adequacy of EPILOG.

Acknowledgements

The paper owes its existence to Jack Minker's instigation (jointly with John McCarthy) and effective planning of the very timely Workshop on Logic-Based AI, LBAI'99. My thanks to David Ahn for his careful reading of the paper, uncovering several slips. Don Perlis, Norm McCain, Jack Minker, and the two anonymous referees offered perceptive and useful comments that have helped to improve the paper.

References

[1] James F. Allen and Lenhart K. Schubert. Language and discourse in the TRAINS project. In A. Ortony, J. Slack, and O. Stock, editors, *Communication from an Artificial Intelligence Perspective*, pages 91–120. Theoretical Springer-Verlag, Heidelberg, 1993.

[2] Jon Barwise and John Perry. *Situations and Attitudes.* MIT Press, Bradford Books, Cambridge, MA, 1983.

[3] Gregory N. Carlson and Francis Jeffry Pelletier. *The Generic Book.* University of Chicago Press, Chicago, 1995.

[4] Donald Davidson. Causal relations. *The J. of Philosophy*, 64:691–703, 1967. Reprinted in Donald Davidson and Gilbert Harman, editors, *The Logic of Grammar*, pp. 246–254. Dickenson Publ., Encino, CA., 1975.

[5] Donald Davidson. The logical form of action sentences. 1967. In Donald Davidson and Gilbert Harman, editors, *The Logic of Grammar*, pp. 235–245. Dickenson Publ., Encino, CA., 1975. (Reprinted from *The Logic of Decision and Action*, Nicholas Rescher, ed., U. of Pittsburg Pr., 1967.).

[6] Jerry R. Hobbs. Ontological promiscuity. In *23rd Ann. Meet. of the Assoc. for Computational Linguistics (COLIG-85)*, pages 61–69, Univ. of Chicago, Chicago, Ill., July 8-12 1985.

[7] Jerry R. Hobbs, William Croft, Todd Davies, Douglas Edwards, and Kenneth Laws. Commonsense metaphysics and lexical semantics. In *24th Ann. Meet. of the Assoc. for Computational Linguistics (COLIG-86)*, pages 231–240, Columbia Univ., New York, NY, July 10-13 1986.

[8] Chung Hee Hwang and Lenhart K. Schubert. Episodic Logic: A comprehensive, natural representation for language understanding. *Minds and Machines*, 3(4):381–419, 1993.

[9] Chung Hee Hwang and Lenhart K. Schubert. Episodic Logic: A situational logic for natural language processing. In Yasuhiro Katagiri Peter Aczel, David Israel and Stanley Peters, editors, *Situation Theory and its Applications*, volume 3, pages 303–338, Stanford, CA, 1993. CSLI.

[10] Chung Hee Hwang and Lenhart K. Schubert. Interpreting tense, aspect and time adverbials: A compositional, unified approach. In Dov M. Gabbay and Hans Jürgen Ohlbach, editors, *Proc., 1st Int'l. Conf. on Temporal Logic*, pages 238–264, Bonn, Germany, July 1994. Springer-Verlag.

[11] John McCarthy and Patrick J. Hayes. Some philosophical problems from the standpoint of artificial intelligence. In B. Meltzer and D. Michie, editors, *Machine Intelligence 4*. Edinburgh University Press, 1969.

[12] Robert C. Moore. Events, situations, and adverbs. In J.P. Martins and E.M. Morgado, editors, *Proc. of the 4th Portugese Conf. on Artificial Intelligence*, Berlin, 1989. Springer-Verlag. Reprinted in R.C. Moore, *Logic and Representation*, CSLI Lecture Notes No. 39, CSLI Publications, 1995.

[13] Reinhard Muskens. *Meaning and Partiality.* CSLI Books, Stanford, CA, 1995.

[14] Aki Namioka, Chung Hee Hwang, and Stephanie Schaeffer. Using the inference tool EPILOG for a message processing application. *Int'l. J. of Expert Systems*, 5(1):55–82, 1992.

[15] Terence Parsons. *Events in the Semantic of English.* MIT Press, Cambridge, MA, 1990.

[16] Hans Reichenbach. *Elements of Symbolic Logic.* Macmillan, New York, NY, 1947.

[17] Lenhart K. Schubert and Chung Hee Hwang. An episodic knowledge representation for narrative texts. In *Proc., 1st Int'l. Conf. on Principles of Knowledge Representation and Reasoning (KR'89)*, pages 444–458, Toronto, Canada, May 15-18, 1989.

[18] Lenhart K. Schubert and Chung Hee Hwang. Episodic Logic meets Little Red Riding Hood: A comprehensive, natural representation for language understanding. In Lucja Iwanska and Stuart C. Shapiro, editors, *Natural Language Processing and Knowledge Representation: Language for Knowledge and Knowledge for Language.* MIT/AAAI Press, to appear, 2000.

[19] David Traum, Lenhart Schubert, Massimo Poesio, Nathaniel Martin, Marc Light, Chung Hee Hwang, Peter Heeman, George Ferguson, and James Allen. Knowledge representation in the TRAINS-93 conversation system. *Int. J. of Expert Sys., special issue on Knowledge Representation and Inference for Natural Language Processing*, 9(1):173–223, 1996.

[20] Robert Wilensky. Sentences, situations, and propositions. In John F. Sowa, editor, *Principles of Semantic Networks: Explorations in the Representation of Knowledge*, pages 191–227 (ch. 6). Morgan Kaufmann, San Mateo, CA, 1991.