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# Episodic Logic: A Situational Logic for Natural Language Processing

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We introduce a new situational logic called *Episodic Logic* (EL). It is Montague inspired and influenced by situation semantics. Its notable features are: first, its expressiveness—it provides an easily computed first order logical form for English, incorporating a DRT-like treatment of indefinites. It covers a wide range of English constructs, including ones involving events, actions, facts, kinds, attitudes, modification and donkey sentences. Second, there is a simple translation from the initial indexical logical form to a nonindexical logical form. Such a transformation is essential because, to be useful for *inference*, a situational logic must be *nonindexical*; i.e., it must not contain atoms whose denotation depends on the utterance context—after all, the “facts” derived by a system from natural language input may have been acquired in very different utterance contexts. Our deindexing algorithm uniformly handles tense, aspect and many temporal PP-adverbials and their interaction, and brings the context information into the logical form, removing context dependency. Finally, the logic has been implemented in a computational system and successfully used in several domains.

## 1 Introduction

Since its introduction by Barwise and Perry (1983), situation semantics has increasingly influenced research in computational linguistics and artificial intelligence (cf., Cooper 1987, Hobbs et al. 1988, Nakashima et al. 1988). One of the most important features of situation semantics is that sentences are viewed as describing *situations* (events, states, eventualities, etc.), where these situations are correlated with *partial*, as opposed to *comp-*

To appear in *Situation Theory and Its Applications*, vol.3.  
Peter Aczel, David Israel, Yasuhiro Katagiri, and Stanley Peters, eds.  
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*lete*, states of affairs. So construed, situations can be used, among other things, as causal antecedents and consequents and as anaphoric referents, which play important roles in AI applications including natural language processing.

**EL**, or *Episodic Logic* (Schubert and Hwang 1989, Hwang 1992), is a first order, situational logic with many extensions designed specifically for natural language processing, although its generality makes it suitable for many AI applications. The adjective *episodic* is intended to suggest that in narrative texts the focus is on *time-bounded* situations (states and events) rather than on “eternal” (or atemporal) ones. Though a situational logic, **EL** differs from mainstream situation semantics, e.g., as developed by Fenstad *et al.* (1987), in several respects. First, **EL** respects Montague’s (1970) central intuition that syntactic structure mirrors semantic structure; thus its syntax is much more “natural language-like” than, say, Fenstad *et al.*’s situation schemata. Second, we map sentences first to a preliminary, *indexical* logical form, and then to a *nonindexical* one, and in this *final* logical form, we depart from situation semantics’ *relational theory of meaning*. In situation semantics, the meaning of a sentence is a relation between an utterance situation and a described situation. However, we contend that a *nonindexical* representation is essential for inference, e.g., in language understanding or question answering. If a system derives its information from different speakers, in different places, at different times, it cannot retain in its logical form indexical atoms whose denotation depends on the utterance context, such as *I* (the speaker), *here*, or *present*, and expect to draw sensible conclusions. That is, the system must either save the relevant features of the utterance context or *deindex*. As an analogy, consider tense logic (cf., Prior 1967, van Benthem 1988). We cannot use two tense logic sentences, say, *pres(alive(John))* and *past(dead(John))*, for inference if they were “collected” at different times (e.g., during John’s lifetime and afterwards respectively)! For *that*, we need an explicit *representation* of the time of utterance. Thus, there is a basic asymmetry with respect to the informational roles of “utterance situation” and “described situation,” which the schema  $u[[SIT \phi]]s$  invites us to overlook. It does us no good to save  $SIT \phi$  and then try to apply a relational theory of meaning to make inferences from it; rather, certain properties of  $u$  need to be brought *into* the representation in the light of which  $\phi$  becomes a determinate assertion about  $s$ .

Two further distinctive features of **EL** are its expressiveness and the manner and ease of the derivation of its logical form from English. It covers constructs involving events, actions, facts, kinds, attitudes, predicate and sentence modifiers, nominalization, and donkey anaphora (the latter via a DRT-like parameter mechanism). The translation from phrase structure to the preliminary logical form (**LF**) is accomplished with simple GPSG-like syntactic and semantic rules; furthermore, the final nonindexi-

cal episodic logical form (**ELF**) is obtained by simple recursive rules applied to the **LF** and context structures called *tense trees*. The novel deindexing algorithm uniformly handles many combinations of tense, aspect and temporal PP-adverbials, and brings the context information into the logical form, removing context dependency.

The logic has been successfully implemented in the **EPILOG** system (Schaeffer et al. 1991), a hybrid inference system combining efficient storage and access mechanisms, forward and backward chaining, and multiple “specialists” for taxonomies, temporal reasoning, sets, strings, etc. This system has been applied to several domains proving **EL**’s practicality: understanding small excerpts from the *Little Red Riding Hood* story (Hwang 1992), as a natural language interface for **TRAINS** planning system at the University of Rochester (Allen and Schubert 1991), and for a message processing application for Boeing Commercial Airplane Reliability and Maintainability Project (Namioka et al. 1992).

In the rest of the paper, we first concisely summarize the syntax and semantics of **EL**, and illustrate it with sample English sentences. Then, we discuss formal semantics, the two-stage derivation of episodic logical form from linguistic form, with emphasis on the second, deindexing stage, how inferences are carried out, and our experience with computer implementation.

## 2 Resources of **EL**: Logical Syntax and Glimpses of Semantics

**EL** is a first order intensional logic with  $\lambda$ -abstraction, nominalization, and various other extensions. Before giving the formal syntax, we indicate its “flavor” with an example below. Additional, less trivial examples are provided in a later section.

- (1) John kicked Pluto
- (2) (past [John kick Pluto])
- (3) ( $\exists e1:[e1 \text{ before Now1}][[\text{John kick Pluto}] ** e1]$ )

Initially, sentence (1) is translated into an unscoped logical form **ULF**,

[John <past kick> Pluto],

where <> and [] indicate unscoped expressions and infix expressions respectively.<sup>1</sup> After scoping of the ‘past’ operator, we get **LF** (2), which is then deindexed to episodic logical form **ELF** (3). As seen in (3), we use

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<sup>1</sup>Infix notation is used for readability, with the last argument wrapped around to the position preceding the predicate. That is, for  $\pi$  a predicate,  $\pi(\alpha)(\beta)$  is written as  $[\beta \pi \alpha]$  in **EL**. In the case of connectives, the conventional way of positioning arguments is observed except that the formula is enclosed in [], e.g., for  $\Phi, \Psi$  formulas,  $\Phi \rightarrow \Psi$  is written as  $[\Phi \rightarrow \Psi]$ . As for the episodic operator ‘\*\*’ to be discussed shortly,  $**(\Phi)(\eta)$  is written as  $[\Phi ** \eta]$  rather than  $[\eta ** \Phi]$ .

restricted quantifiers of form  $(Q\alpha:\Phi\Psi)$ , where  $Q$  is a quantifier,  $\alpha$  is a variable, and restriction  $\Phi$  and matrix  $\Psi$  are formulas. That is,  $(\forall\alpha:\Phi\Psi)$  and  $(\exists\alpha:\Phi\Psi)$  are equivalent to  $(\forall\alpha)[\Phi \rightarrow \Psi]$  and  $(\exists\alpha)[\Phi \wedge \Psi]$ , respectively. In the matrix of (3), ‘\*\*’ is an episodic operator that connects a formula with the episode/situation it describes. Intuitively, for  $\Phi$  a formula and  $\eta$  an episodic term,  $[\Phi ** \eta]$  means “ $\Phi$  characterizes (or, completely describes)  $\eta$ .” We also have a more fundamental episodic operator ‘\*’, where  $[\Phi * \eta]$  means “ $\Phi$  is true in (or, partially describes)  $\eta$ .” Note that  $[\Phi ** \eta]$  implies  $[\Phi * \eta]$ . Whereas the operator ‘\*\*’ is introduced by English sentences as above, ‘\*’ is typically introduced by meaning postulates. For instance,

$$[[\text{John kick Pluto}] ** e1]$$

implies that  $e1$  is a part (in an informational sense) of some episode  $e2$ , coextensive with  $e1$ , such that

$$\begin{aligned} & [[\text{John near Pluto}] * e2], \\ & [(\exists x: [[x \text{ leg}] \wedge [x \text{ part-of John}]] [\text{John move-toward Pluto } x]) * e2], \\ & [[\text{John touch Pluto}] * e2], \end{aligned}$$

etc. Note that ‘\*\*’ and ‘\*’ are modal operators and do not in general allow substitution of a logically equivalent sentence for their sentential argument. For example,  $[[\text{John kick Pluto}] * e1]$  does not entail

$$[[[\text{John kick Pluto}] \wedge [[\text{Mary love Pluto}] \vee \neg [\text{Mary love Pluto}]]] * e1].$$

Mary may not even be a participant in situation  $e1$ .

From a situation semantics perspective, we have roughly the following correspondences:

$$\begin{aligned} [\Phi * s] & \langle - \rangle s \models \Phi \quad (s \text{ supports } \Phi), \\ [\Phi ** s] & \langle - \rangle s \text{ is a minimal situation such that } s \models \Phi \\ & \quad (s \text{ supports only } \Phi, \text{ and supports it as a whole}). \end{aligned}$$

The formal semantics of  $[\Phi * s]$  differs from that of  $s \models \Phi$  in several ways. One difference lies in the denotation of  $\Phi$ , which for us is a sentence intension (a partial function from possible situations to truth values) rather than an infon (a tuple comprised of a relation, the objects related, possibly a location and a polarity). We think that our set-theoretic conception simplifies the semantics of connectives and quantifiers. Another difference, which is more important from the perspective of natural language interpretation, is the two-tiered part-of ordering on situations which underlies our conception of *persistence*. As will be seen in section 4, our basic part-of (subepisode) ordering  $s \preceq s'$  is one that relates a “less informed” situation  $s$  to a “more informed” *coextensive* situation  $s'$ , i.e., one that obtains (or occurs) in the *same spatiotemporal region*. This basic ordering supports full persistence of information. But there is also a generalization  $\sqsubseteq$  of  $\preceq$ , where  $s \sqsubseteq s'$  allows  $s$  to be spatiotemporally as well as informationally subsumed by  $s'$ . Only telic and unlocated (eternal) sentences are guaranteed to have persistent extensions through the  $\sqsubseteq$  ordering.

Most importantly of all, we believe that the notion of complete description (characterization) of a situation, expressed by ‘\*\*’, is crucial for interpreting anaphoric reference to situations and for representing causal relationships among situations.<sup>2</sup> In particular, we claim that an event anaphor like the one in (5) refers to a *minimal* event described in a prior sentence like (4):

- (4) John kicked Pluto  
 (5) *This* prompted Pluto to bite John

In other words, we claim that it would be incorrect to interpret the referent of ‘this’ as simply some event *partially* described by (4). Rather, it is an event *completely* described by (4), i.e., a *minimal* event supporting (4).

To see this, suppose that (4) and (5) truthfully report what happened; an incidental detail was that John yelled “Get lost!” as he kicked Pluto (but this was not what prompted Pluto’s reaction). Now suppose that John takes Pluto’s owner Mary to court over the incident, charging criminal negligence. In his testimony, he asserts

- (4′) I told Pluto to get lost  
 (5′) *This* prompted Pluto to bite me

Is John telling the truth? Surely not. Yet if we were to accept that the anaphor in (5′) can properly refer to an “expanded” version of the situation described in (4′), then John cannot be accused of lying or even distorting the truth. After all, the expanded situation in which John told Pluto to get lost *and* at the same time kicked him truly was the causal antecedent of Pluto’s retaliation. A slightly different way of putting the argument is that if Mary asserts (4), (5) while John asserts (4′), (5′), they cannot both be giving the *same* cause for Pluto’s retaliation, namely, some situation supporting *both* John’s kicking Pluto and his telling Pluto to get lost.<sup>3</sup> Our notion of a sentence (*completely*) characterizing a described situation avoids these potential confusions.  $[[John\ kick\ Pluto] ** e]$  and  $[[John\ tell-to-get-lost\ Pluto] ** e]$  will be inconsistent under any axioma-

<sup>2</sup>Barwise and Perry (1983) used ‘:=’ and ‘in’, analogous to our ‘\*\*’ and ‘\*’ operators, to distinguish *complete* and *partial* descriptions of state of affairs. Roughly,

$$\begin{aligned} [[\tau_n \ \pi \ \tau_1 \ \dots \ \tau_{n-1}] * s] & \ \langle - - \rangle \ \text{in } s: \ \pi, \ \tau_1, \ \dots, \ \tau_n, \ \text{yes} \\ [[\tau_n \ \pi \ \tau_1 \ \dots \ \tau_{n-1}] ** s] & \ \langle - - \rangle \ s := \ \pi, \ \tau_1, \ \dots, \ \tau_n, \ \text{yes} \end{aligned}$$

But in contrast to EL, they used ‘in’ in formulating the *situations described by utterances*; that is, they regarded utterances as *partially* describing a situation. Also, in more recent versions of situation semantics (e.g., Barwise 1989 and Devlin 1991), only ‘⊢’ seems to be in use. An operator that is close to our ‘\*\*’ is Reichenbach’s ‘[\*]’. Like situation semanticists, Reichenbach (1947) viewed a sentence as describing a situation and used the function ‘[\*]’ to map sentences into situation predicates. That is, an EL formula  $[\Phi ** \eta]$  may be written as  $[\Phi]^*(\eta)$  in Reichenbach’s representation.

<sup>3</sup>Of course, it is entirely possible that they both *honestly believe* their version of the story. The point is, the stories are not consistent with each other.

tization of “kicking” and “telling to get lost” which makes them non-synonymous.

As a final point, note that the ‘past’ operator in (2) has been reduced in (3) to  $[e1 \text{ before } Now_1]$ , where  $Now_1$  is a term denoting the utterance time of (1). This reduction, as well as the introduction of an episodic variable, is done in the deindexing stage. We now present a subset of **EL** syntax in BNF form (for a more extensive version, see Hwang 1992). In the following,  $n \geq 1$ , round brackets indicate prefix notation, and square brackets indicate infix notation.

### Basic Logical Syntax

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<sentence> ::=  $\top$  |  $\perp$  | (<1-place-pred> <term>) |  $\forall$ <1-place-pred> |
              (<quantifier> <var> {:<sentence>} <sentence>) |
              (<sentence-op> <sentence>) |
              [<sentence> <episodic-op> <term>] |
              [<sentence>1 <n-place-connective> <sentence>2
              ... <sentence>n]

<term> ::= <var> | <const> | (<1-place-function> <term>) |
              (<pred-nominalization-op> <1-place-pred>) |
              (<sentence-nominalization-op> <sentence>)

<n-place-pred> ::= <n-place-pred-const> |
                  ( $\lambda$ <var> <(n-1)-place-pred>) |
                  (<(n+1)-place-pred> <term>) |
                  (<n-fold-pred-modifier> <1-place-pred>)

<n-place-function> ::= <n-place-function-const> |
                    (<(n+1)-place-function> <term>)

<var> ::= <alphanumeric atom>

<const> ::= <alphanumeric atom> | <numeric const>

<quantifier> ::=  $\forall$  | Most | Few | No |  $\exists$  | The | ...

<sentence-op> ::=  $\neg$  | decl | pres | futr | perf | prog | perhaps | ...
                (adv-e <1-place-pred>) | (adv-f <1-place-pred>) |
                (adv-p <1-place-pred>) | ...

<1-fold-pred-modifier> ::= <1-fold-pred-modifier-const> |
                          (attr <1-place-pred>) |
                          (adv-a <1-place-pred>) | ...

<2-fold-pred-modifier> ::= <2-fold-pred-modifier-const> |
                          (rel <2-place-pred>) | ...

<episodic-op> ::= ** | *

<2-place-connective> ::=  $\wedge$  |  $\vee$  |  $\rightarrow$  |  $\rightarrow_{\langle \text{prob} \rangle \langle \text{var} \rangle_1 \dots \langle \text{var} \rangle_n}$  | because | ...

<prob> ::= <numeric const, with value between 0 and 1>

<1-place-function-const> ::= fst | rst | time-of | - | ...

<2-place-function-const> ::= | (“pairing function”) | + | - |  $\times$  | ...

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<pred-nominalization-op> ::= K | Ka  
 <sentence-nominalization-op> ::= Ke | That | ...

Space limitations prevent detailed explanation, but the following comments should help. According to our syntax, formulas and terms are formed from *one*-place predicates and functions respectively. Yet formulas (2) and (3) shown earlier contain apparent 2-place predicates like *kick* and *before*. This is because we use “curried” predicates and functions, e.g., ((*kick Pluto John*), but apply *flattening* and *infixing* conventions to rewrite these more legibly, e.g., as [*John kick Pluto*].

Sentence operators include: logical ones like negation; indexical ones like **decl** (indicating surface speech acts), **pres**, **past** and **perf** (from English tense and aspect), and **futr** (a futural modal operator); modal operators like **prog** (for progressives); and various operators corresponding to those English adverbials that modify sentence meanings. Such adverbials are translated into operators of form (*adv-δ π*), as in the following.

- (6) (past ((*adv-e in-loc California*) [John see Mary]))  
 “John saw Mary *in California*”
- (7) (past ((*adv-f regular*) [John see Mary]))  
 “John *regularly* saw Mary”
- (8) ((*adv-p probable*) (past [John see Mary]))  
 “John *probably* saw Mary”

**adv-e** and **adv-f** are functions that uniformly map predicates over episodes into sentence modifiers. **adv-p** maps predicates over propositions into sentence modifiers. There are also adverbials that operate on predicates such as “with a hammer,” “toward the car,” and “around the world.” These adverbials are typically translated into operators of form (*adv-a π*), where **adv-a** is a function that uniformly maps predicates over actions (or attributes) into predicate modifiers. The extension operator ‘<sup>v</sup>’ is used in interpreting certain adverbials. It applies its predicate operand to the “current” episode, so that <sup>v</sup>(*during 1992*), for example, is true at episode *s* only if *s* is during 1992.

An *n*-fold predicate modifier is a function that uniformly maps 1-place predicates into *n*-place predicates. 1-fold predicate modifiers such as *plur*, *very*, *former*, *become*, *turn*, etc., map monadic predicates to monadic predicates. 1-fold predicate modifiers may also be formed by applying a function **attr** to an adjectival predicate. For instance, “white wine” is translated into (*K ((attr white) wine)*), where **K** is a kind-forming operator to be explained shortly. 2-fold predicate modifiers map monadic predicates to 2-place predicates. For example, in (*past [Pluto ((rel consider) friendly) John]*), “Pluto considered John friendly,” (*rel consider*) trans-

forms a monadic predicate, “friendly,” into a 2-place predicate, “consider friendly.”<sup>4</sup>

The implication with a probability and a list of controlled variables attached allows for generic conditionals. Discussion of this feature is beyond the scope of this paper, but we should mention that probabilistic inferences can be made in **EL** based on generic conditionals (see Hwang and Schubert 1993).

Various function constants (e.g., **fst**, |, etc.) will be explained later when examples involving them are seen.

A predicate nominalization, such as (*K snow*) or (*K (kick Pluto)*), yields a term denoting an abstract individual; in this case, the kind of stuff, snow, or the kind of thing that kicks Pluto (a generic Pluto-kicker, as it were). (*Ka (kick Pluto)*) similarly forms an abstract individual, but here it is the *action* (or *attribute* or *property*) of kicking Pluto. Thus, we distinguish the abstract kind, ‘Pluto-kickers’, from the abstract property, ‘kicking Pluto’. (And so we should: contrast “Pluto-kickers are a pitiful species” with “The property of kicking Pluto is a pitiful species.”) Sentence nominalization operators likewise form abstract individuals. Both will be illustrated later, but we should note here that we think of the individuals formed by **That** as *propositions*. Such propositions are objects of attitudes, and are *not* situations.

### 3 Illustrations: Donkey Sentences and Other Balky Phenomena

The above sketches of **EL** syntax and the informal remarks on the semantic types of the various operators give a general idea of the resources of **EL**. The following examples illustrate how some of these resources come into play in the representation of anaphora, donkey sentences, attitudes, etc. The reader may occasionally want to look ahead to section 4 (on formal semantics) here. More detailed explanations and further examples may be found in Hwang 1992 and Hwang and Schubert 1993. Note that below we often neglect tense in the logical form translations for the sake of clarity of exposition.

#### Anaphoric Variables

Consider the following two successive sentences and their logical forms.

- (9) Every man shaved  
 (10) (past ( $\forall x: [x \text{ man}] [x \text{ shave}]$ ))  
 (11) ( $\exists e1: [e1 \text{ before Now1}] [(\forall x: [x \text{ man}] [x \text{ shave}]) ** e1]$ )

<sup>4</sup>We could actually treat *consider* itself, rather than its *rel*-transform, as a 2-fold predicate modifier. However, our approach here is intended to acknowledge the semantic relatedness of simple transitive *consider* (as in “John considered the problem”), and the form of *consider* which takes a predicative complement as well as an NP object complement.



- (12) *This* delayed dinner  
 (13) (past (The y: [y dinner] [*This-thing* delay y]))  
 (14) ( $\exists$  e2: [e2 before Now2]  
 (The y: [y dinner] [[e1 delay y] \*\* e2]))

(10) and (13) are preliminary, indexical **LFs**, and (11) and (14) are deindexed **ELFs**. Notice that *This-thing* in (13) has been resolved to e1 in (14), so that e1 now occurs *outside* the scope of its  $\exists$ -quantifier in (11). Semantically, this is handled by conjoining (11) and (14) and widening the scope of  $\exists$ -quantifiers (see section 4). This allows us to avoid skolemization and subsequent deskolemization of existential variables. The importance of episodes in causal relations becomes evident if we replace (12) by “*This* tied up the bathroom and caused an outburst from Mary.”

### Donkey sentences

As indicated, parameters permit a DRT-like treatment of indefinites. Note in (16) the occurrence of the variable  $x$  that appear outside its scope, as a result of resolving *it* in (15). This carrying over of variable bindings beyond their quantifier scope is allowed in **EL** thanks to the parameter mechanism to be discussed shortly.

- (15) If Pedro owns a donkey, he will ride *it* to town tomorrow  
 (16) ( $\exists$ e1 [( $\exists$  x: [x donkey] [Pedro own x]) \*\* e1])  
 $\rightarrow$  ( $\exists$ e2 [[Pedro ride-to-town x] \*\* e2]),  
*neglecting tense and the adverbial*

Notice that, as Schubert and Pelletier (1989) point out, a universal quantifier reading of (15) is not correct. As will become clear in section 4, the semantics of **EL** does not require Pedro ride all the donkeys he owns to town.

As mentioned earlier, our logic also permits representing and reasoning with probabilistic conditionals (a class of generic conditionals). Examples are “A boy who owns a dog usually likes it” or “If a boy owns a dog, he usually likes it.” (See Hwang and Schubert 1993.)

### Attitudes

As mentioned earlier, we think that the objects of attitudes are propositions, not situations. Note the proposition-denoting term headed by **That** below.

- (17) Mary told Jack that John kicked Pluto  
 (18) (past [Mary tell Jack (That (past [John kick Pluto]))])  
 (19) ( $\exists$ e1: [e1 before Now1]  
 [[Mary tell Jack (That  
 ( $\exists$ e2: [e2 before e1] [[John kick Pluto] \*\* e2]))]  
 \*\* e1])

Recall that we take propositions as subsuming possible facts. Possible facts are just consistent propositions—there are self-contradictory propositions (and these may, for instance, be objects of beliefs, etc.), but there are no self-contradictory possible facts.

### NI Perception Statements

We treat NI perception verbs as operators that uniformly map monadic predicates into relational predicates as illustrated below.

- (20) Mary saw John kick Pluto  
 (21) (past [Mary ((rel see) (kick Pluto)) John])  
 (22)  $(\exists e1: [e1 \text{ before Now1} ] [[\text{Mary ((rel see) (kick Pluto)) John}] ** e1])$   
 (23) Pluto smelled something burning  
 (24) (past  $(\exists x [\text{Pluto ((rel smell) } \lambda y(\text{prog [y burn])}) x])$ )  
 (25)  $(\exists e1: [e1 \text{ before Now1} ] [(\exists x [\text{Pluto ((rel smell) } \lambda y(\text{prog [y burn])}) x]) ** e1])$

As explained earlier, **rel** is an operator which transforms a 1-place predicate (e.g., *hear*, *see*, *smell*, etc.) into a function that uniformly maps 1-place predicates (e.g., (*kick Pluto*) and  $\lambda y(\text{prog [y burn]})$  above) into relational predicates that take two arguments (John and Mary and something  $x$  and Pluto, respectively, above). Thus, instead of saying, e.g., what Pluto smelled was a situation in which something was burning (or, what Mary saw was a situation in which John kicked Pluto), which is arguably unnatural, we simply say that the relation “smell burning” (or, “see kick”) held between something and Pluto (or, between John and Mary).<sup>5</sup> Note that from (22), we readily get the following kinds of inferences by meaning postulates (below, **coexten-subep-of** is an object language equivalent of ‘ $\preceq$ ’):

- $(\exists e: [e \text{ coexten-subep-of } e1] [[\text{Mary see John}] ** e])$ ,  
 $(\exists e': [e' \text{ coexten-subep-of } e1] [[\text{John kick Pluto}] ** e'])$ .

This approach to perception sentences predicts that perception verbs are transparent to quantifiers in object position. For instance, there is no reading of “John saw *each person* leave the room” which entails that John saw the event described by “Each person left the room” (though of course it is

<sup>5</sup>One may question our analysis, since (20) may be followed by “Bill saw *it*, too,” suggesting that the object of *saw* must be an individual. True, one may not be able to immediately locate the antecedent of *it* in (22). But we contend this is not a problem since the antecedent of an anaphor is often obtained only after some post processing, as the following examples illustrate.

- (a) Mary bites her fingernails. John does *it*, too.  
 (b) John washed the dishes. Mary didn’t want to do *it*.

In (a) and (b), the antecedents of *it* are *bite one’s fingernails* and *wash the dishes*, respectively, and both of them are kinds of actions which may not be located directly in the first sentence.

*possible* that he witnessed this quantified event, while also observing each individual departure). It may be thought that “John saw everyone in the room clap” provides a counterexample, but we maintain that the ambiguity in this sentence arises from the possibility of interpreting *everyone* as collection-denoting, rather than from opacity of *saw*. This is confirmed by “John saw everyone gather in the hallway.”

### Actions

Actions are distinguished from events or episodes in that they have well-defined *agents*—thus, one may perform an action, but *not* perform an episode or event; likewise, there are “intentional actions,” but not “intentional events.” In **EL**, actions are represented as ‘agent-event’ pairs, so that unlike events, they have well-defined agents.

- (26) a. John stepped on Pluto’s tail  
 b. Pluto thought *it* was intentional
- (27) a. (past (The x: [[x tail]  $\wedge$  [x part-of Pluto]] [John step-on x]))  
 b. (past [Pluto think (That (past [*It* intentional]))])
- (28) a. ( $\exists e_1$ : [ $e_1$  before *Now*<sub>1</sub>]  
 [(The x: [[x tail]  $\wedge$  [x part-of Pluto]] [John step-on x]) \*\*  $e_1$ ])  
 b. ( $\exists e_2$ : [ $e_2$  before *Now*<sub>2</sub>]  
 [[Pluto think (That ( $\exists e_3$ : [ $e_3$  at-or-before  $e_2$ ]  
 [[John |  $e_1$ ] intentional] \*\*  $e_3$ ))]]  
 \*\*  $e_2$ ])

Notice that *It* in (27b) is resolved to the ordered pair [John |  $e_1$ ], namely, John’s action of stepping on Pluto’s tail, in (28b). ‘|’ is a pairing function applicable to individuals and tuples. (As in Prolog, an individual paired with an  $n$ -tuple gives an  $(n + 1)$ -tuple headed by the individual.)

### Kinds of Actions and Events

Our approach here borrows from Carlson (1982) and Chierchia and Turner (1988). For example, “kicking Pluto” is a kind of *action*, and (29) says John likes to do that kind of action. On the other hand, “for Mary to kick Pluto” is a kind of *event*, and (32) asserts that kind of event is rare. (To be more accurate, we should perhaps use **gpres** (generic present) tense below.)

- (29) John likes to kick Pluto  
 (30) (pres [John like (Ka (kick Pluto))])  
 (31) ( $\exists e_1$ : [ $e_1$  at-about *Now*<sub>1</sub>] [[John like (Ka (kick Pluto))] \*\*  $e_1$ ])  
 (32) For Mary to kick Pluto is rare  
 (33) (pres [(Ke [Mary kick Pluto]) rare])  
 (34) ( $\exists e_1$ : [ $e_1$  at-about *Now*<sub>1</sub>] [[[Ke [Mary kick Pluto]) rare] \*\*  $e_1$ ])

Notice that kinds of actions or events are headed by nominalization operators **Ka** and **Ke**, where **Ka** maps 1-place predicates into *kinds of actions*, and **Ke** maps formulas into *kinds of events*. **Ka**- or **Ke**-constructs can be equivalently written as constructs headed by the more fundamental, **K** operator; e.g.,  $(Ke \Phi)$  is equivalent to  $(K \lambda e[\Phi ** e])$ . However, use of **Ka** and **Ke** makes the initial LF translations intuitively clearer, and their computation more direct and simple.

As a final point, we note that infinitives or gerundives often seem to denote *instances*, rather than kinds, of actions or events. For instance, in (35) For Mary to fail the exam was unfortunate,

for Mary to fail the exam evokes to a specific event instance. Such “instance” interpretation may be obtained by meaning postulates. That is, we initially translate (35) into (36) (neglecting tense), treating the infinitival construct as denoting a kind, but we obtain the “instance” reading shown in (37) by applying meaning postulates.

(36)  $[(Ke [Mary \text{ fail Exam3}]) \text{ unfortunate}]$ , or, equivalently,  
 $[(K \lambda e[[Mary \text{ fail Exam3}] ** e]) \text{ unfortunate}]$

(37)  $(\exists e:[e \text{ instance-of } (K \lambda e'[[Mary \text{ fail Exam3}] ** e'])]) [x \text{ unfortunate}]$

Treating nominal infinitives as kinds of actions/events allows us a uniform initial translation of infinitives, whether they are intuitively about kinds or instances. The same phenomenon is found with ordinary kinds as well. Treating bare plurals and mass terms uniformly as kinds facilitates the translation of sentences like “*Apples* are healthful, and Mary eats *them* every day,” “This jar contains *hydrogen*, *which* is the lightest element,” etc., in which there is only a “kind” term, yet an “instance” is evoked (see Pelletier and Schubert 1989).

### Adverbials

As a final example, we show a sentence that involves adverbials. Semantically, adverbials may be classified into two classes: ones that operate on sentences and ones that operate on predicates. Typically, those that modify actions are predicate modifiers, and those that modify episodes are sentential operators. (Propositional adverbials are also regarded as sentence operators.) For example, consider the following sentence, involving three adverbials.

(38) John was walking with Pluto in Disneyland yesterday

(39)  $(\text{past } ((\text{adv-e } (\text{during } \textit{Yesterday})) ((\text{adv-e } (\text{in-loc } \textit{Disneyland})) (\text{prog } [\textit{John } ((\text{adv-a } (\text{with-accomp } \textit{Pluto})) \textit{walk}]))))))$

(40)  $(\exists e1:[e1 \text{ before Now1}]$   
 $[[[e1 \text{ during } (\textit{yesterday-rel-to Now1})] \wedge [e1 \text{ in-loc } \textit{Disneyland}] \wedge$   
 $[[\textit{John} \mid e1] \text{ with-accomp } \textit{Pluto}] \wedge$   
 $(\text{prog } [\textit{John walk}])]$

\*\* e1])

In (38), “in Disneyland” and “yesterday” modify the *episode* described by “John walking,” or, more specifically, its spatial and temporal locations. “With Pluto,” on the other hand, modifies the *action* of John’s walking (by specifying “accompaniment”). As mentioned earlier, episode modifiers are in the form of (*adv-e*  $\pi$ ), where  $\pi$  is a predicate over episodes, and action modifiers take the form (*adv-a*  $\pi$ ), where  $\pi$  is a 1-place predicate over actions/attributes. **prog** is a sentential modal operator that yields the progressive aspect of its operand. By meaning postulates, (40) yields

- (41) a. [(prog [John walk]) \* e1]  
 b. ( $\exists e2$ : [e2 coexten-subep-of e1] [(prog [John walk]) \*\* e2]),

and from (40) and (41), we can get (skolemizing E1/e1 and E2/e2)

- a. [E1 before Now1]  
 b. [[[E1 during (yesterday-rel-to Now1)]  $\wedge$  [E1 at-loc Disneyland]  $\wedge$  [[John | E1] with-accomp Pluto]  $\wedge$  (prog [John walk]) \*\* E1]  
 c. [E1 during (yesterday-rel-to Now1)]  
 d. [E1 at-loc Disneyland]  
 e. [[John | E1] with-accomp Pluto]  
 f. [(prog [John walk]) \* E1]  
 g. [E2 coexten-subep-of E1]  
 h. [(prog [John walk]) \*\* E2]

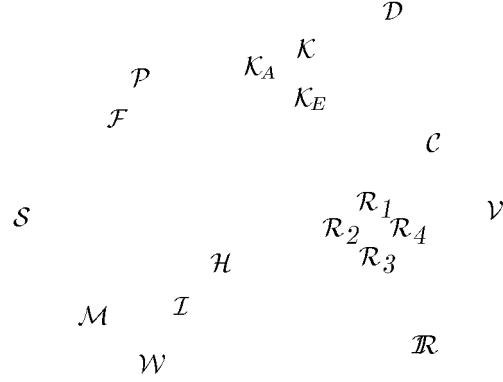
Note that the treatment of adverbials in **EL** views them as providing conjunctive information about the described episode, as in Dowty 1982. Space limitations do not allow us to provide details, but we uniformly handle the interactions between tense and perfect aspect, in conjunction with several kinds of temporal PP-adverbials (see Hwang 1992; Hwang and Schubert 1993).

Some of the constructs yet to be worked out include Wh-questions and the operators *degree*, *-er*, *-est*, and *rank<sub>k</sub>* related to formation of comparison predicates. We believe, however, that **EL** is the most expressive knowledge and semantic representation yet to be brought to bear on the problem of NL understanding.

## 4 Formal Semantics

### 4.1 The Ontology of Basic Individuals

Our ontology consists of a set  $\mathcal{D}$  of *possible individuals*. As shown in Figure 1, possible individuals  $\mathcal{D}$  include *possible situations*  $\mathcal{S}$  and, disjointly from  $\mathcal{S}$ , kinds of individuals  $\mathcal{K}$  (including kinds of properties, kinds of actions  $\mathcal{K}_A$ , and kinds of situations/episodes  $\mathcal{K}_E$ ), propositions  $\mathcal{P}$  (including possible facts  $\mathcal{F}$ ), the real numbers  $\mathcal{R}$  (augmented with  $-\infty$  and  $+\infty$ ), and *1-D* regions  $\mathcal{R}_1$ , *2-D* regions  $\mathcal{R}_2$ , *3-D* regions  $\mathcal{R}_3$ , and *4-D* regions



**Figure 1** Ontology of Basic Individuals

$\mathcal{R}_4$ , containing subsets of  $\mathcal{R}$ ,  $\mathcal{R}^2$ ,  $\mathcal{R}^3$ , and  $\mathcal{R}^4$ , respectively.<sup>6</sup> Situations, i.e., episodes, occupy times and places, or, more generally, occupy spatiotemporal “trajectories” (regions).<sup>7</sup> Among the possible situations are informationally maximal *exhaustive situations*  $\mathcal{H}$ , and among the exhaustive situations are the spatially maximal *possible times*  $\mathcal{I}$ , which in turn include the spatiotemporally maximal *possible worlds*  $\mathcal{W}$  and the spatially maximal, temporally minimal moments of time  $\mathcal{M}$ . The treatment of times (and worlds) as certain kinds of situations is unusual but, we think, quite plausible. Consider, for instance, “This year has been eventful,” suggesting that times, such as *this year*, have episodic content. (We distinguish *clock times* from times in the episodic sense.) Finally, there are collections  $\mathcal{C}$  and  $n$ -tuples (i.e.,  $n$ -vectors,  $n = 2, 3, \dots$ )  $\mathcal{V}$  of all of these.

The metapredicates  $\preceq$  and  $\sqsubseteq$  respectively express *coextensive part of* and (general) *part of* relations between episodes. Thus,  $s \preceq s'$  is a special case of  $s \sqsubseteq s'$ , with the additional stipulation that  $s$  and  $s'$  are coextensive

<sup>6</sup>Examples of object-language functions whose interpretation relies on  $\mathcal{R}$  and  $\mathcal{R}_1$  are **clock-time-of** and **interval**.  $\mathcal{R}_4$  is space-time trajectory that may not be connected. A “trajectory” of an episode is given by a total function,  $Region: \mathcal{S} \rightarrow \mathcal{R}_4$ . The clock time of an episode can then be expressed as the temporal projection of its trajectory, i.e.,

$$Clocktime(s) = \{w \mid \exists x, y, z \text{ such that } \langle w, x, y, z \rangle \in Region(s)\} \in \mathcal{R}_1.$$

<sup>7</sup>It might be thought that the assignment of regions to all situations precludes the “located/unlocated” distinction in situation semantics. However, in situation semantics, it is not situations, but rather the “infons” they support, that are subject to that distinction. Similarly in EL, the *characterizations* of situations (in terms of sentence intensions or corresponding facts or situation types) are distinguishable in terms of their *persistence* properties. Fully persistent or “eternal” characterizations roughly correspond to unlocated infons.

(occupy the same spatial regions and clock-times). Much as in situation semantics, sentences can be true, false or undefined in situations. If  $s \preceq s'$ , any truth value assigned to a sentence at  $s$  is also assigned to it at  $s'$ . This is not in general true for  $s \sqsubseteq s'$ , though it still holds for *unlocated* (or *eternal*) sentences.<sup>8</sup> Thus, if  $s$  is of type  $\Phi$ , then so is  $s'$ , for  $s \preceq s'$ ; but not necessarily so for  $s \sqsubseteq s'$ . (By “ $s$  is of type  $\Phi$ ,” we mean  $[\Phi * s]$ ; for  $[\Phi ** s]$ , we say “ $s$  is *only of type*  $\Phi$ ” or “(situation-type  $s$ ) = (Ke  $\Phi$ ).” If  $s$  and  $s'$  are only of type  $\Phi$ , then  $s \sqsubseteq s'$  implies  $s = s'$ .)

In general, a situation can be part of many worlds, but an exhaustive situation belongs to a unique world (roughly, because it supports not only statements about what *is* the case at that time in that spatial location, but also what *was* and *will be* the case).  $\sqsubseteq$  is regarded as a special case of a transitive, reflexive relation  $Actual \subset \mathcal{D} \times \mathcal{S}$ , determining what individuals are actual with respect to a given situation. Thus, a part of a situation is always actual relative to it. As well, there is a relation  $Nonactual \subset \mathcal{D} \times \mathcal{S}$ , disjoint from  $Actual$ , determining the possible but nonactual individuals involved in a situation. These relations  $\preceq$ ,  $\sqsubseteq$ ,  $Actual$  and  $Nonactual$  play fundamental roles in interpreting EL formulas as will be seen below.

## 4.2 Remarks on Quantifiers, Parameters and Persistence

Before proceeding to the logical semantics, we need to make a little clearer our (slightly unconventional) approach to quantification, logical connectives and persistence.

First, we have a new twist on the semantics of  $\exists$ , making the variable it binds behave *referentially* if it already has a value under the current interpretation  $I$ , and as an ordinary *existential* variable otherwise. In other words, “prior” values of variables *preempt* existential quantifiers (and likewise **The**). More formally, the *parameters* of formula  $\Phi$ , written with an underscore function as  $\underline{\Phi}$ , are a set of exported variables, defined as follows (where  $\mathbf{Q}$  is a non-preemptable quantifier such as  $\forall$ , **Most**, ...):

$$\begin{aligned} \underline{\alpha} &= \emptyset, \text{ for atomic expressions } \alpha; \\ \underline{(\exists \alpha \Phi)} &= \underline{(\text{The } \alpha \Phi)} = \{\alpha\} \cup \underline{\Phi}; \\ \underline{(\exists \alpha: \Phi \Psi)} &= \underline{(\text{The } \alpha: \Phi \Psi)} = \{\alpha\} \cup \underline{\Phi} \cup \underline{\Psi}; \\ \underline{[\lambda \alpha \Phi]} &= \underline{[\Phi * \eta]} = \underline{[\Phi ** \eta]} = \underline{\Phi}; \\ \underline{[\Phi \wedge \Psi]} &= \underline{[\Phi \text{ because } \Psi]} = \underline{\Phi} \cup \underline{\Psi}; \\ \underline{(\neg \Phi)} &= \underline{[\Phi \vee \Psi]} = \underline{[\Phi \rightarrow \Psi]} = \underline{[\Phi \rightarrow_{p, \alpha_1, \alpha_2, \dots, \alpha_n} \Psi]} = \emptyset; \\ \underline{(\mathbf{Q} \alpha \Phi)} &= \underline{(\mathbf{Q} \alpha: \Phi \Psi)} = \emptyset; \\ \underline{(\pi \Pi)} &= \emptyset, \text{ for } \pi \in \{\mathbf{K}, \mathbf{Ka}, \mathbf{Ke}, \dots\}; \end{aligned}$$

<sup>8</sup>Sentences like  $[e1 \text{ before } Now1]$  and  $[[John \text{ kick } Pluto] ** e1]$  are unlocated, i.e., forever true or forever false uniformly everywhere in a world. In contrast, ones like  $[John \text{ kick } Pluto]$  and  $[John \text{ popular}]$  are located, i.e., potentially true at some times and places and false at others. See also footnote 7.

$(\pi \alpha) = \underline{\pi} \cup \underline{\alpha}$ , for *all other nonatomic* expressions of form  $(\pi \alpha)$ .

The last rule applies to various kinds of constructs such as  $\Box\Phi$ ,  $((\text{adv-e } \pi) \Phi)$ ,  $((\text{adv-a } \pi) \Pi)$ ,  $(\text{That } \Phi)$ , etc. Note that negation, implications, non-preemptable quantifiers, and kinds do not allow parameters to be exported beyond their scope. This is intended to account for examples like the following: “John does *not* own a house. \*He rents *it*,” or “Every boy in John’s class has a *girlfriend*. \*He admires *her*.”<sup>9</sup> By defining the *parameters* of a formula as (roughly) its top-level  $\exists$ - (or **The**-) quantified variables, we can then easily implement a DRT-like treatment of anaphora and donkey sentences (cf., Kamp 1981). At the same time, we account for the dual existential/referential character of indefinites (cf., Fodor and Sag 1982).

Another distinctive feature is our conception of “quantified episodes,” i.e., episodes characterized by quantified sentences. The semantics of  $\forall$ , **Most**, **Many**, etc., together with the semantics of ‘\*\*’, leads to a conception of such episodes as the (informational and temporal) *join* of a set of subepisodes of the type quantified over. For instance, in the sentences, “John answered every question that was raised. *That* alone took up half of the lecture,” the question-answering subepisodes together comprise the quantified episode (rather than merely lying within it); that is what makes the second sentence (about the proportion of the lecture taken up) meaningful.

Still, the truth conditions for  $\exists$ ,  $\forall$  and standard connectives do not differ radically from “standard” ones (e.g., as in Fenstad et al. 1987, Barwise 1989 and Devlin 1991). Concerning connectives, one difference is that we unhesitatingly include standard negation, which is unproblematic in our set-theoretic approach.

As already noted, we do not in general assume persistence of positive and negative information from subepisodes to superepisodes, except when these are spatiotemporally coextensive.<sup>10</sup> We call persistence through the

<sup>9</sup>However, this is only a rule of thumb. For instance, for sentences like “Each degree candidate walked to the stage. He took his diploma from the dean and returned to his seat” (Partee, from Roberts 1987), what’s required is that the parameters be exported outside the scope of the universal or that the scope of the universal be widened to cover the second sentence. There are also apparent counterexamples to the non-export of parameters from the scope of negation; e.g., “It’s not that I don’t have a reason. I’m just not telling you what *it* is.” We think that an account in terms of *inferred* entities (e.g., the speaker in the example does have a *reason*) may be possible in such cases.

<sup>10</sup>Previously (e.g., at the STA-3 workshop and in Schubert and Hwang 1989), we treated times as privileged over space, assuming that if certain individuals participate in certain events or relations *at a certain time*, that is sufficient to “locate” the corresponding situation. The existence of tense inflections (but not locative inflections) in many languages also seemed to indicate to us that the temporal dimension is privileged. Moreover, spatial locations of events are often ill-defined, e.g., for sentences like “The star I am looking at in the telescope is slowly moving” or “Dodos became extinct.” In the latter case, although the last dodo may have died in Mauritius, in some sense dodos therewith became extinct *everywhere* on the earth. However, there are some compelling examples suggest-



$\preceq$ -ordering “upward” persistence (or  $\preceq$ -persistence) to distinguish it from “outward” persistence — persistence of positive information when we enlarge the spatial or temporal purview (or both). (Outward persistence of *negative* information is equivalent to inward persistence of positive information.) For example, consider a spatiotemporally bounded situation described (tenselessly) by [*John popular*]. Any expansion of this situation to include more information, without change in spatiotemporal bounds, preserves the truth of [*John popular*]. However, an expansion which stretches the spatial and/or temporal basis may fail to preserve its truth. In other words, viewed over a larger location or time stretch, John may fail to be popular. On the other hand, a *performance* sentence like [*John kick Pluto*] (again tenseless) persists outward (as well as upward).

Here it is important to recall that deindexed logical forms of *tensed* sentences like those seen in (1)-(41) have ‘\*\*’ as top-level operator. Such formulas are syntactically classified as *unlocated* (or *eternal*). We characterize unlocated sentences as having  $\sqsubseteq$ -*persistent* intensions. This amounts to being both outward and inward persistent. If we take performance (telic) sentences to be outward persistent and stative sentences inward persistent (much as in Dowty 1982), it turns out that the negations of performance sentences are inward persistent, and the negations of stative sentences outward persistent.<sup>11</sup> This duality in the persistence properties of performance and stative sentences accounts for many intuitions about the truth of logically compound, quantified, or adverbially modified sentences. Though we cannot elaborate upon this theme here, this is the primary reason for our use of both the  $\preceq$  and the  $\sqsubseteq$  ordering and the related notions of persistence.

### 4.3 The Logical Semantics

We begin by defining certain subclasses of semantic functions in relation to the  $\sqsubseteq$ -ordering, needed to explain what we mean by an interpretation. We next outline the conditions satisfied by an interpretation and by its extension to a valuation function, and then show some sample axioms.

A partial function  $f \in \mathcal{D}^n \rightarrow (\mathcal{S} \rightarrow 2)$ , where  $n \geq 0$ , is  $\preceq$ -*persistent* (“upward” persistent) iff for all  $d_1, \dots, d_n \in \mathcal{D}$  and  $s, s' \in \mathcal{S}$  such that  $s \preceq s'$ ,

$$f(d_1) \cdots (d_n)(s) = f(d_1) \cdots (d_n)(s')$$

---

ing that truth can be dependent on locale in a way quite analogous to its dependence on time; e.g., “John is popular,” “A dozen eggs cost a dollar,” etc. A dozen eggs may cost a dollar in New York, but fifty cents in Ohio. Thus, we now treat spatial locations on a par with temporal ones, amalgamating them into spatiotemporal locations.

<sup>11</sup>This is not to be understood as taking “negative” predicates like *unhappy* or *impolite* as outward persistent. Note that “Mary was *unhappy* last Friday” does not imply “Mary was *unhappy* last week.” However, “*It is not the case that* Mary was happy last Friday” implies “*It is not the case that* Mary was happy last week,” at least if *happy* is understood as *continuously happy*, i.e., inward-persistently.

whenever the LHS is defined. We write  $[\mathcal{G}]$  for the subclass of  $\preceq$ -persistent functions in class  $\mathcal{G}$ .

Similarly we say that a partial function  $f \in \mathcal{D}^n \rightarrow (\mathcal{S} \rightarrow 2)$ , where  $n \geq 0$ , is  $\sqsubseteq$ -persistent (“outward” and “inward” persistent) iff for all  $d_1, \dots, d_n \in \mathcal{D}$  and  $s, s' \in \mathcal{S}$  such that  $s \sqsubseteq s'$ ,

$$f(d_1) \cdots (d_n)(s) = f(d_1) \cdots (d_n)(s')$$

whenever the LHS is defined. We write  $[\mathcal{G}]$  for the subclass of  $\sqsubseteq$ -persistent functions in class  $\mathcal{G}$ . (Note: If we instead had said “ $\dots$  whenever the LHS = 1,” or “ $\dots$  whenever the LHS = 0,” we would have obtained the “outward persistent” or “inward persistent” functions, respectively.)

We now define a partial function  $f \in (\mathcal{D}^m \rightarrow (\mathcal{S} \rightarrow 2)) \rightarrow (\mathcal{D}^n \rightarrow (\mathcal{S} \rightarrow 2))$ , where  $m, n \geq 0$ , as  $\sqsubseteq$ -persistence preserving iff for all  $g \in [\mathcal{D}^m \rightarrow (\mathcal{S} \rightarrow 2)]$ , if  $f(g)$  is defined, then  $f(g) \in [\mathcal{D}^n \rightarrow (\mathcal{S} \rightarrow 2)]$ . We write  $|\mathcal{G}|$  for the subclass of  $\sqsubseteq$ -persistence preserving functions in class  $\mathcal{G}$ .

We are now ready to discuss semantic clauses. An *interpretation*  $I$  is defined so as to assign elements of  $\mathcal{D}$  to all individual constants and to zero or more individual variables, and partial functions of type  $\mathcal{D}^n \rightarrow (\mathcal{S} \rightarrow 2)$  to  $n$ -place predicate constants (where 2 is the set of truth values  $\{0, 1\}$  and  $\mathcal{D}^2 \rightarrow A$  abbreviates  $\mathcal{D} \rightarrow (\mathcal{D} \rightarrow A)$ ,  $\mathcal{D}^3 \rightarrow A$  abbreviates  $\mathcal{D} \rightarrow (\mathcal{D} \rightarrow (\mathcal{D} \rightarrow A))$ , etc.). The set-theoretic types of other atoms are fairly obvious, given this. Note that the interpretation of predicates differs from the usual type in that the situational argument comes *last*, rather than first. It turns out that this allows us to dispense with Montagovian intension and extension operators. The syntactic combination of a predicate or function with a term is of course interpreted as function application in the semantics. By the definition of exhaustive situations, sentential truth values under an interpretation  $I$  are most fully determined at *exhaustive situations*  $h \in \mathcal{H}$ .<sup>12</sup> The following semantic clauses state constraints both on an interpretation  $I$  and a valuation function  $[\![\ ]\!]_I$  ( $[\![\ ]\!]_I$  is an extension of  $I$  to nonatomic expressions). Whenever  $[\![\ ]\!]$  occurs unsubscripted, it is an abbreviation for  $[\![\ ]\!]_I$ .

### Semantic Clauses

1. *Type of atom*  $\alpha$   $I(\alpha)$  is an element of:

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<sup>12</sup>We are allowing for the possibility that even at worlds (and hence times) not all sentences have truth values. Some possible candidates for truth-valueless sentences are sentences with violated presuppositions, vague sentences (admitting “borderline cases”), and paradoxical sentences. However, the arguments for truth-value gaps are not compelling. The first two kinds can be dealt with pragmatically, without resort to truth-value gaps, and for the third, there are several gapless alternatives — fixpoint theories, stable-truth theories, and theories of propositions based on Frege structures (e.g., Turner 1990).

Individual constant:	$\mathcal{D}$
Individual variable:	$\mathcal{D}$ , or is undefined
Function constant:	$\mathcal{D}^n \rightarrow \mathcal{D}$
Sentence constant:	$[\mathcal{S} \rightarrow 2]$
$n$ -place predicate constant:	$[\mathcal{D}^n \rightarrow (\mathcal{S} \rightarrow 2)]$
$n$ -fold predicate modifier:	$[[\mathcal{D} \rightarrow (\mathcal{S} \rightarrow 2)] \rightarrow [\mathcal{D}^n \rightarrow (\mathcal{S} \rightarrow 2)]]$
$attr, adv-a, \dots$ :	$\mathcal{N} \rightarrow  \mathcal{N} \rightarrow \mathcal{N} $
Sentence modifier:	$[[\mathcal{S} \rightarrow 2] \rightarrow [\mathcal{S} \rightarrow 2]]$
$adv-e, adv-f, \dots$ :	$\mathcal{N} \rightarrow  [\mathcal{S} \rightarrow 2] \rightarrow [\mathcal{S} \rightarrow 2]]$
Predicate nominalization operator:	$(\mathcal{D} \rightarrow (\mathcal{S} \rightarrow 2)) \rightarrow \mathcal{K}$
Sentence nominalization operator:	$(\mathcal{S} \rightarrow 2) \rightarrow \mathcal{D}$
$*$ , $**$ :	$[\mathcal{S} \rightarrow 2] \rightarrow [\mathcal{S} \rightarrow (\mathcal{S} \rightarrow 2)]$
$\vee$ :	$[\mathcal{S} \rightarrow (\mathcal{S} \rightarrow 2)] \rightarrow (\mathcal{S} \rightarrow 2)$
	where $\mathcal{N} = [\mathcal{D} \rightarrow (\mathcal{S} \rightarrow 2)]$

2. If  $\alpha$  is an atomic expression, then  $\llbracket \alpha \rrbracket = I(\alpha)$ .
3. If  $\pi, \alpha$  are expressions of type  $\llbracket \pi \rrbracket \in A \rightarrow B$  and  $\llbracket \alpha \rrbracket \in A$  for sets  $A, B$  (derived from the types in clause 1), then  $\llbracket (\pi \alpha) \rrbracket = \llbracket \pi \rrbracket \llbracket \alpha \rrbracket$  (i.e.,  $\llbracket \pi \rrbracket (\llbracket \alpha \rrbracket)$ ).<sup>13</sup>
4. (*Valuation of ‘\*’.*) For  $s \in \mathcal{S}$ ,
  - a.  $\llbracket \Phi * \eta \rrbracket^s = 1$  only if  $Actual(\llbracket \eta \rrbracket, s)$  and  $\llbracket \Phi \rrbracket^{\llbracket \eta \rrbracket} = 1$ ;  
 $= 0$  only if  $Nonactual(\llbracket \eta \rrbracket, s)$  or  $\llbracket \Phi \rrbracket^{\llbracket \eta \rrbracket} \neq 1$ ; and
  - b. for the special case that  $s \in \mathcal{H}$  (i.e.,  $s$  is an exhaustive situation),  
these two conditionals (‘only if’s) become biconditionals (‘iff’s).

*Note:* Thus the modal operator ‘\*’ is a truth operator, i.e., it denotes truth in an (actual) situation. As shown in Clause 1, the “input” formula for ‘\*’ will always be  $\preceq$ -persistent. The previously given set membership requirement for  $I(*)$  ensures that the intension of a sentence of form  $[\Phi * \eta]$  (with the intension of  $\Phi$  upward persistent) is  $\sqsubseteq$ -persistent, i.e., unlocated. This is consistent with the additional requirements on  $\llbracket \Phi * \eta \rrbracket$  inasmuch as the two conditionals can be consistently strengthened to biconditionals, and in that case,  $\sqsubseteq$ -persistence is a *consequence* of these biconditionals. This follows from the basic axioms for *Actual* and *Nonactual*, namely,

$$Actual(d, s) \ \& \ s \sqsubseteq s' \ \supset \ Actual(d, s'),$$

$$Nonactual(d, s) \ \& \ s \sqsubseteq s' \ \supset \ Nonactual(d, s').$$

Next, the semantics of ‘\*\*’ strengthen the conditions for truth.

5. (*Valuation of ‘\*\*’.*) For  $s \in \mathcal{S}$ ,
  - a.  $\llbracket \Phi ** \eta \rrbracket^s = 1$  only if  $\llbracket \Phi * \eta \rrbracket^s = 1$ , and  
there is no  $r \sqsubset \llbracket \eta \rrbracket$  such that  $\llbracket \Phi \rrbracket^r = 1$ ;

<sup>13</sup>This slightly informal statement can be formalized in terms of syntactic types.

= 0 only if  $\llbracket \Phi * \eta \rrbracket^s = 0$ , or  
for some  $r \sqsubset \llbracket \eta \rrbracket$ ,  $\llbracket \Phi \rrbracket^r = 1$ ; and

- b. for the special case that  $s \in \mathcal{H}$  ( $s$  is an exhaustive situation), these two conditionals ('only if's) become biconditionals ('iff's).

*Note:* Again, the  $\sqsubseteq$ -persistence constraint expressed by the set membership requirement is consistent with the further requirements, in that it becomes deducible if the two conditionals are made biconditionals.

6. (*Interpretation of other special functors and constants.*)

We state only three examples.

For  $\pi$  a 1-place predicate,

$$\llbracket \forall \pi \rrbracket^s = \llbracket \pi \rrbracket^{s,s}, \text{ i.e., } \llbracket \pi \rrbracket(s)(s)$$

For all  $d, e \in \mathcal{D}$  and  $h \in \mathcal{H}$ ,

$$\begin{aligned} I(\text{episode})(d)(h) &= 1 \text{ iff } d \in \mathcal{S} \text{ and } \text{Actual}(d, h); \\ &= 0 \text{ iff } d \notin \mathcal{S} \text{ or } \text{Nonactual}(d, h). \end{aligned}$$

$$\begin{aligned} I(\text{during})(d)(e)(h) &= 1 \text{ iff } d, e \in \mathcal{S}, \text{Actual}(d, h), \text{Actual}(e, h), \text{ and} \\ &\quad \text{clock-time}(d) \sqsubseteq \text{clock-time}(e); \\ &= 0 \text{ iff } d \notin \mathcal{S}, \text{ or } e \notin \mathcal{S}, \text{ or} \\ &\quad \text{Nonactual}(d, h), \text{ or } \text{Nonactual}(e, h), \text{ or} \\ &\quad \text{clock-time}(d) \not\sqsubseteq \text{clock-time}(e), \end{aligned}$$

where  $I(\text{episode}) \in [\mathcal{D} \rightarrow (\mathcal{S} \rightarrow 2)]$  and  $I(\text{during}) \in [\mathcal{D}^2 \rightarrow (\mathcal{S} \rightarrow 2)]$ .

Other special functors and constants include  $\top$ ,  $\perp$ , numeric constants, **subep-of**, **coexten-subep-of**, **clock-time-of**, **subset-of**, **actual**, **K**, **Ka**, **Ke**, **That**, and others. The detailed algebraic specifications of kinds, propositions, etc., remains to be completed. An important point about the last 4 functors listed is that, like '\*' and '\*\*', they produce time-independent values.

In the remaining clauses,  $\Phi$  and  $\Psi$  are formulas,  $\alpha$  is a variable,  $\eta$  is a term, and  $s$  is a situation  $\in \mathcal{S}$ . Also, it will be convenient in the semantics of  $\exists$  and **The** to let  $\mathcal{D}_{I(\alpha)}$  denote  $\mathcal{D}$  if  $I(\alpha)$  is undefined, and singleton set  $\{I(\alpha)\}$  otherwise. If  $d \in \mathcal{D}$ ,  $I$  is an interpretation of the atomic symbols of the logic, and  $\alpha$  is a variable,  $I(\alpha:d)$  denotes the interpretation identical with  $I$  except that it interprets  $\alpha$  as  $d$  (regardless of whether or not  $\alpha$  already had a value under  $I$ ). Also, if  $\underline{d}$  is a tuple of  $n$  elements of  $\mathcal{D}$ , and  $\underline{\Phi}$  consists of  $n$  variables, then  $I(\underline{\Phi}:\underline{d})$  denotes the interpretation obtained from  $I$  by setting the denotations of those variables in  $\underline{\Phi}$  which have no prior values to the corresponding individuals in  $\underline{d}$  (e.g., make the assignments in lexicographic order of the variables).

7.  $\llbracket \neg \Phi \rrbracket^s = 1$  iff  $\llbracket \Phi \rrbracket^s = 0$ ;  
= 0 iff  $\llbracket \Phi \rrbracket^s = 1$ .

These conditions are easily shown to entail memberships of  $\llbracket \neg \rrbracket$  in  $[[\mathcal{S} \rightarrow 2] \rightarrow [\mathcal{S} \rightarrow 2]]$ , as assumed in clause 1.

8. Using  $\underline{\sigma}$  for the parameter set  $\Phi \wedge \Psi$  and  $\mathcal{D}^{|\underline{\sigma}|}$  for  $\mathcal{D} \times \mathcal{D} \times \dots \times \mathcal{D}$  ( $n$  times), where  $n = |\underline{\sigma}|$ , the cardinality of set  $\underline{\sigma}$ :

$$\begin{aligned} \llbracket \Phi \wedge \Psi \rrbracket^s &= 1 \text{ iff for some } \underline{d} \in \mathcal{D}^{|\underline{\sigma}|}, \llbracket \Phi \rrbracket_{I(\underline{\sigma}; \underline{d})}^s = \llbracket \Psi \rrbracket_{I(\underline{\sigma}; \underline{d})}^s = 1; \\ &= 0 \text{ iff for all } \underline{d} \in \mathcal{D}^{|\underline{\sigma}|}, \text{ either } \llbracket \Phi \rrbracket_{I(\underline{\sigma}; \underline{d})}^s = 0, \text{ or } \llbracket \Psi \rrbracket_{I(\underline{\sigma}; \underline{d})}^s = 0. \end{aligned}$$

Conjunctive formulas are evaluated as if existential and definite quantifiers at the highest level in  $\Phi$  and  $\Psi$  had wide scope over the entire conjunction, allowing for forward and backward anaphora. Thus, names of existentially quantified variables matter in **EL**. For instance, the conjunction  $[(\exists e [e \text{ before } E1]) \wedge (\exists e [e \text{ after } E1])]$  is unsatisfiable, since there is only one parameter,  $e$ , which is varied “simultaneously” in both conjuncts. On the other hand,  $[(\exists e [e \text{ before } E1]) \wedge (\exists e' [e' \text{ after } E1])]$  has the usual truth conditions ( $e, e'$  assumed to have no “prior” values).

9.  $\llbracket \Phi \vee \Psi \rrbracket^s = 1$  iff  $\llbracket \Phi \rrbracket^s = 1$  or  $\llbracket \Psi \rrbracket^s = 1$ ;  
 $= 0$  iff  $\llbracket \Phi \rrbracket^s = 0$  and  $\llbracket \Psi \rrbracket^s = 0$ .

These conditions are simpler than for conjunction because no special provision needs to be made for anaphoric reference across disjuncts, i.e., we need not “iterate” over values of common parameters, but can instead evaluate the disjuncts independently.<sup>14</sup>

10.  $\llbracket (\exists \alpha: \Phi \Psi) \rrbracket^s = 1$  iff for some  $d \in \mathcal{D}_{I(\alpha)}$ ,  $\llbracket \Phi \wedge \Psi \rrbracket_{I(\alpha; d)}^s = 1$ ;  
 $= 0$  iff for all  $d \in \mathcal{D}_{I(\alpha)}$ ,  $\llbracket \Phi \wedge \Psi \rrbracket_{I(\alpha; d)}^s = 0$ .

Note that if  $I(\alpha)$  is defined, so that the domain of quantification is the singleton  $\mathcal{D}_{I(\alpha)} = \{I(\alpha)\}$ , then the interpretation of the indefinite is in effect referential (i.e., the given interpretation of  $\alpha$  “preempts” the  $\exists$ -quantifier). If  $I(\alpha)$  is undefined, this  $\exists$ -semantics is more or less standard. The referential interpretation is crucial in such embedding contexts as conjunctions (see clause 8) and conditional antecedents (see clause 13), where it allows the interpretation of an indefinite to be “externally” supplied by the embedding construct.

There are well-known difficulties concerning the semantics of quantification, including the problem of intensionality (Montague 1970) and the problem of spatiotemporal (or contextual) reference of nominals (Enç 1981). We do not claim that our semantics of  $\exists$  (and other quantifiers) solves these problems. However, we think that our approach to logical form is sufficiently flexible, and the commitments expressed by clause 10 (and 11 and 12 below) sufficiently weak, to leave open various avenues to their solution. For instance, consider “Mary designed a moon base” or “John resembles a leprechaun,” exemplifying indefinites

<sup>14</sup>Admittedly, there are some potential counterexamples to the assumption of no anaphoric connections across disjuncts, such as “Either John doesn’t have a car or he keeps it hidden,” or “Either John has a license already or he will get it shortly.”

in intensional contexts. We suggest that in these contexts the indefinite noun phrases are rendered in the logical form as predicates, either directly (i.e., *a leprechaun*, when parsed as an NP[pred], is rendered as monadic predicate *leprechaun*), or by abstraction from a quantified NP-translation (i.e.,  $\lambda x(\exists y:[y \text{ leprechaun}] [x = y])$ ). The verbs in these examples are treated as 1-fold predicate modifiers, yielding a 1-place predicate such as (*resemble leprechaun*) from another (in this case, *leprechaun*), and as such their semantics is automatically intensional (cf., the treatment of perception statements in section 3).

Concerning the spatiotemporal reference of nominals, suppose that a sentence like “A baby cried” is assigned an LF like (past ( $\exists x:[x \text{ baby}] [x \text{ cry}]$ )), or, after deindexing, ( $\exists e:[e \text{ before Now1}] [(\exists x:[x \text{ baby}] [x \text{ cry}]) ** e]$ ). Then, according to our semantics, (i) any baby in the world is eligible as the value of  $x$ , and (ii) it must have the “baby” property at the time (more exactly, in the situation  $e$ ) at which it cries. One might well object to (i) on the grounds that we would normally have in mind some contextually limited set of babies as the intended domain of quantification. Our response is that this calls for a refinement of the logical form, rather than of the  $\exists$ -semantics. For instance, we might replace  $[x \text{ baby}]$  by something like ( $\exists e_1:[e_1 \text{ during space-timeframe}_1] [[x \text{ baby}] * e_1]$ ); or perhaps more simply by  $[[x \text{ baby}] \wedge [x \text{ during space-timeframe}_1]]$ , if we view individuals as event-like, with spatiotemporal bounds (as, e.g., in Kratzer 1989). Of course, this shifts the problem to that of determining pragmatically appropriate space-time frames for quantified nominals, but appropriately so, in our view.

One may also object that (ii) does not generalize to other examples, such as “A planet formed” (where the planet-property does not apply until the *end* of the formation event), or “An acorn (I planted) is now an oak” (where the acorn-property no longer applies in the situation described), or “Today’s paper reports an earthquake” (where, similarly, there is no earthquake at the time of the report). We do not know any completely satisfactory solutions to these problems, and are exploring various alternatives involving several seemingly relevant notions: space-time frames (cf., the “reference times” of Hinrichs (1988)); implicit nominal tense (using either sentential tense operators like *past* and *pres* or predicate modifiers like *former*, *current*, and *prospective*); and a construal of individuals as event-like (e.g., the nominal *baby* might ambiguously evoke either the “baby stage” of a person, or the “complete individual,” with “stages” understood as in Carlson 1982).

11.  $\llbracket (\text{The } \alpha: \Phi\Psi) \rrbracket^s$   
 $= 1$  iff  $\llbracket \Phi \rrbracket_{I(\alpha:d)}^s$  is defined for all  $d \in \mathcal{D}_{I(\alpha)}$ ,  
there is a unique  $d \in \mathcal{D}_{I(\alpha)}$  satisfying  $\llbracket \Phi \rrbracket_{I(\alpha:d)}^s = 1$ , and  
 $\llbracket \Phi \wedge \Psi \rrbracket_{I(\alpha:d)}^s = 1$ ;

$= 0$  iff  $\llbracket \Phi \rrbracket_{I(\alpha:d)}^s$  is defined for all  $d \in \mathcal{D}_{I(\alpha)}$ ,  
there is a unique  $d \in \mathcal{D}_{I(\alpha)}$  satisfying  $\llbracket \Phi \rrbracket_{I(\alpha:d)}^s = 1$ , and  
 $\llbracket \Phi \wedge \Psi \rrbracket_{I(\alpha:d)}^s = 0$ .

This leads to a referential reading if  $\alpha$  has a prior value, otherwise, it conforms with Russell's conditions for truth (but if there is no unique individual satisfying the restriction, the formula is truth-valueless).

12.  $\llbracket (\forall \alpha: \Phi \Psi) \rrbracket^s = 1$  iff for all  $d \in \mathcal{D}$ ,  $\llbracket \Phi \rrbracket_{I(\alpha:d)}^s = 0$  or  $\llbracket \Phi \wedge \Psi \rrbracket_{I(\alpha:d)}^s = 1$   
 $= 0$  iff for some  $d \in \mathcal{D}$ ,  $\llbracket \Phi \rrbracket_{I(\alpha:d)}^s = 1$  and  $\llbracket \Phi \wedge \Psi \rrbracket_{I(\alpha:d)}^s = 0$ .

Note that the conditions for truth require the truth value of the restriction  $\Phi$  to be determinate for all individuals in the domain of discourse.

13.  $\llbracket \Phi \rightarrow \Psi \rrbracket^s = 1$  iff  $\llbracket \Phi \rrbracket^s = 0$  or  $\llbracket \Phi \wedge \Psi \rrbracket^s = 1$ ;  
 $= 0$  iff  $\llbracket \Phi \rrbracket^s = 1$  and  $\llbracket \Phi \wedge \Psi \rrbracket^s = 0$ .

Note that through the clause for conjunction, this plausibly handles many nongeneric donkey sentences like the one seen in section 3.

14. For  $\pi$  a formula or  $n$ -place predicative expression ( $n \geq 1$ ),

$$\llbracket \lambda \alpha \pi \rrbracket = \{ \langle d, \llbracket \pi \rrbracket_{I(\alpha:d)} \rangle \mid d \in \mathcal{D}, \llbracket \pi \rrbracket_{I(\alpha:d)} \text{ defined} \}.$$

Note that under any interpretation, this set of pairs is a (partial) function on  $\mathcal{D}$ ; e.g.,  $\llbracket \lambda x [x \text{ dog}] \rrbracket \in \mathcal{D} \rightarrow (\mathcal{S} \rightarrow 2)$  and  $\llbracket \lambda e [\llbracket \text{Pluto yelp} \rrbracket ** e] \rrbracket \in \mathcal{D} \rightarrow (\mathcal{S} \rightarrow 2)$ .

15. For  $\tau_1, \tau_2$  terms,

$$\begin{aligned} \llbracket \tau_1 = \tau_2 \rrbracket^s &= 1 \text{ iff } \llbracket \tau_1 \rrbracket = \llbracket \tau_2 \rrbracket, \text{ with both defined and} \\ &\quad \text{actual or nonactual relative to } s; \\ &= 0 \text{ iff } \llbracket \tau_1 \rrbracket \neq \llbracket \tau_2 \rrbracket, \text{ with both defined and} \\ &\quad \text{actual or nonactual relative to } s. \end{aligned}$$

Primary omissions are the semantics of many quantifiers (such as **Most** and **Few**), some sentential connectives (especially, probabilistic conditionals), and various functors and their algebraic specifications. See Hwang 1992 and Hwang and Schubert 1993 for semantic clauses for some of them. Now we state two persistence theorems and some valid schemas without proof.

#### Persistence Theorems

We distinguish unlocated predicate constants such as  $=$ , *cause-of*, *before*, etc., from located ones such as *walk*, *girl*, *popular*, etc. Intuitively, the unlocated predicates are those that either hold for given arguments everywhere, at all times (in any given world), or nowhere, at no time, whereas the truth of located predicates for given arguments is place and time dependent, at least for some arguments, in some worlds. An *unlocated expression* is defined as an **EL** expression such that any located predicate occurring in it lies within the scope of one or more of  $\{*, **, \mathbf{K}, \mathbf{Ka}, \mathbf{Ke}\}$  (unlocated predicates can occur anywhere in an unlocated formula). Here are the two funda-

mental persistence theorems. Given that a formula  $\Phi$  describes a certain situation, they allow us to infer that it also describes any “enlarged” situation. We assume for simplicity that  $\Phi$  does not contain any occurrences of ‘ $\vee$ ’.

1. (*Upward persistence of formulas.*) If  $\Phi$  is a formula, and  $s, s'$  are situations such that  $s \preceq s'$ , then  $\llbracket \Phi \rrbracket^s = \llbracket \Phi \rrbracket^{s'}$  if the LHS is defined.
2. (*Persistence of unlocated formulas.*) If  $\Phi$  is an unlocated formula, and  $s, s'$  are situations such that  $s \sqsubseteq s'$ , then  $\llbracket \Phi \rrbracket^s = \llbracket \Phi \rrbracket^{s'}$  if the LHS is defined.

### Some Axioms

1.  $[\Phi * \eta] \rightarrow (\exists e: [e \text{ subep-of } \eta] [\Phi ** e])$   
 $\rightarrow (\exists e: [e \text{ coexten-subep-of } \eta] [\Phi ** e]), \text{ for } \Phi \text{ stative}$
2. a.  $(\forall e (\forall e': [e \text{ coexten-subep-of } e'] [\llbracket \Phi * e \rrbracket \rightarrow \llbracket \Phi * e' \rrbracket]))$   
 b.  $(\forall e (\forall e': [e \text{ subep-of } e'] [\llbracket \Phi * e \rrbracket \rightarrow \llbracket \Phi * e' \rrbracket])),$   
 for  $\Phi$  telic or atemporal (unlocated)<sup>15</sup>
3.  $[\Phi ** \eta] \leftrightarrow [\llbracket \Phi * \eta \rrbracket \wedge \neg (\exists e: [e \text{ proper-subep-of } \eta] [\Phi * e])]$
4.  $(\exists x [\Phi * \eta]) \leftrightarrow [(\exists x \Phi) * \eta]$
5.  $[(\exists x \Phi) ** \eta] \rightarrow (\exists e: [\eta \text{ coexten-subep-of } e] (\exists x [\Phi ** e]))$
6.  $[(\neg \Phi) * \eta] \rightarrow \neg [\Phi * \eta]$

## 5 From Linguistic Form to Logical Form

An important advantage of our representation is that it can be directly and uniformly computed from syntactic analyses of input sentences. We conceive of this computation as involving three processing phases (to be interleaved eventually). First, we use a GPSG-style grammar to compute indexical translations with ambiguously scoped quantifiers, connectives and tense operators; second, we scope the unscoped operators; and third, we combine the indexical translation with a *context structure*, and then apply equivalence transformations to the combination, which recursively eliminate the dependence on context, ultimately giving the desired nonindexical translation. We will illustrate the derivation of a logical form for the sentence

(42) John concluded that Pluto was tired.

Here is a GPSG fragment adequate for the above sentence, where each lexical or phrase structure rule is paired with a corresponding semantic rule:<sup>16</sup>

<sup>15</sup>This axiom is really just a statement of outward persistence, and it will be satisfied under any definition of “telic” which entails outward persistence.

<sup>16</sup>In the following rules, the arrows are in “reverse” direction to indicate that the rules express node admissibility conditions. We have combined the ID and LP rules into



- A. NP  $\leftarrow$  *Pluto*; Pluto
- B. NP  $\leftarrow$  *John*; John
- C. A[pred]  $\leftarrow$  *tired*; tired
- D. V[be, past, 3per, sing]  $\leftarrow$  *was*;  $\lambda P \langle \text{past } P \rangle$
- E. V[\_S[that], past]  $\leftarrow$  *concluded*;  $\langle \text{past conclude} \rangle$
- F. AP  $\leftarrow$  A[pred]; A'
- G. VP  $\leftarrow$  V[be] AP[pred]; (V' AP')
- H. VP  $\leftarrow$  V[\_S[that]] S[that]; (V' S')
- I. S  $\leftarrow$  NP VP; [NP' VP']
- J. S[that, tense]  $\leftarrow$  COMPL[that] S[tense]; (That S')
- K. S[tell]  $\leftarrow$  S[full-decl] PUNC[tell]; (decl S')

The initial translation computed for (42) using the above rules is

- (43) (decl [John  $\langle$ past conclude $\rangle$  (That [Pluto  $\langle$ past tired $\rangle$ ]))).

**decl** (for *declarative*) is a speech act operator. As will be seen later, its deindexing rule introduces a surface speech act of type “tell” as well as a token for the utterance. (We assume that utterances of a speaker, or sentences of a text, etc., are ultimately represented in terms of modal *speech act* predications supplied by various deindexing rules.) The second phase consists of “raising” the occurrence of **past** to a permissible sentential level. This has the following unique result, since **decl** and **That** act as “scope traps”:

- (44) (decl (past [John conclude (That (past [Pluto tired]))])).

In the third phase, we combine this with a context structure for the utterance and “deindex” it. We will mainly consider tense-aspect deindexing (other aspects of deindexing, such as anaphoric processing, have not been worked out in detail). This relies on a new type of context component called a *tense tree*.

Tense trees can be viewed as part of the “fine-grained” structure of discourse segments, recording the pragmatic relationships among the clauses and subclauses of a segment. A node of a tense tree may have up to three branches, where leftward branches correspond to *past* tense (going to an earlier episode), straight downward branches to *perfect* aspect (going to an earlier episode or one just ending), and rightward branches to *future* modality (going to a later episode). In addition to tree branches, there may also be (horizontal) *embedding links* from a node to the root of an embedded tense tree. Each node contains a list of (recently introduced) episodes. A tense tree always has exactly one node in focus, and processing of the (indexical) **LF** of a new utterance always begins with the root node in focus and a token for the utterance as the most recently added element of its episode list.

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traditional PSRs, and our features are elements of feature hierarchies rather than feature-value pairs.

As the **LF** is recursively transformed, the tense and aspect operators encountered cause the focus to shift “downward” along existing branches (or new ones if necessary). At the same time, new episode tokens are added to the lists of tokens at the nodes. Eventually, the focus returns to the root. At this point, we have a nonindexical **ELF**, as well as a modified tense tree (with new branches and/or new episode tokens). As the tree is traversed, the lists of episodes at the focal node (and at other “nearby” nodes) provide explicit reference episodes in terms of which *past*, *pres*, *fut*, *perf*, time adverbials, and implicit “orienting” relations are rewritten nonindexically. (“Orienting” relations—a term borrowed from Leech (1987)—are those that exist between successively reported events or situations in a narrative. Typically, the relation is one of temporal precedence or concurrency, depending on aspectual class and other factors.)

The following are *deindexing rules* adequate for deindexing (44), with the **LF** transformation and tree transformation separately stated (see Hwang 1992, for the rest of the rules). **T** denotes the tense tree component of the context.

- Decl:**  $(\text{decl } \Phi)_{\mathbf{T}} \leftrightarrow (\exists e_{\mathbf{T}}: [[e_{\mathbf{T}} \text{ same-time Now}_{\mathbf{T}}] \wedge$   
 $\quad \quad \quad [\text{Last}_{\mathbf{T}} \text{ immediately-precedes } e_{\mathbf{T}}]]$   
 $\quad \quad \quad [[\text{Speaker tell Hearer (That } \Phi \hookrightarrow \circ \mathbf{T})] ** e_{\mathbf{T}}]])$   
*Tree transformation:*  $(\text{decl } \Phi) \cdot \mathbf{T} = \leftarrow (\Phi \cdot (\hookrightarrow \circ \mathbf{T}))$
- Past:**  $(\text{past } \Phi)_{\mathbf{T}} \leftrightarrow (\exists e_{\mathbf{T}}: [[e_{\mathbf{T}} \text{ bef}_{\mathbf{T}} \text{ Emb}_{\mathbf{T}}] \wedge [\text{Last}_{\swarrow \mathbf{T}} \text{ orients } e_{\mathbf{T}}]]$   
 $\quad \quad \quad [\Phi_{\circ \swarrow \mathbf{T}} ** e_{\mathbf{T}}]])$   
*Tree transformation:*  $(\text{past } \Phi) \cdot \mathbf{T} = \uparrow (\Phi \cdot (\circ \swarrow \mathbf{T}))$
- That:**  $(\text{That } \Phi)_{\mathbf{T}} \leftrightarrow (\text{That } \Phi \mapsto \mathbf{T})$   
*Tree transformation:*  $(\text{That } \Phi) \cdot \mathbf{T} = \leftarrow (\Phi \cdot (\mapsto \mathbf{T}))$
- Adv-e:**  $((\text{adv-e } \pi) \Phi)_{\mathbf{T}} \leftrightarrow [\vee \pi_{\mathbf{T}} \wedge \Phi_{\pi} \cdot \mathbf{T}]$   
*Tree transformation:*  $((\text{adv-e } \pi) \Phi) \cdot \mathbf{T} = (\Phi \cdot (\pi \cdot \mathbf{T}))$

Roughly speaking, the first part of the **Decl** rule says that a declaratively uttered sentence (or a declaratively formed and punctuated sentence, in written language) conveys to the hearer that a speech event  $e_{\mathbf{T}}$  has just now occurred (immediately preceded by the last speech event), and this speech event consists of the speaker telling the hearer that the sentence holds. The first part of the **Past** rule says that a past-tensed sentence expresses the existence of an episode  $e_{\mathbf{T}}$  before the “embedding episode” (usually the speech event), where a certain previously introduced episode provides the point of orientation for  $e_{\mathbf{T}}$ , and where the sentence without the tense characterizes  $e_{\mathbf{T}}$ . The first part of the **That** rule introduces no logical structure, but just passes a modified context (with a new embedded tree) “inward” to the embedded sentence. The first part of the **Adv-e** rule asserts that predicate  $\pi$  holds for the episode at which the adverbially modified sentence is evaluated, and that the unmodified sentence is true. In the tree transformations, the dot operator, ‘ $\cdot$ ’, denotes the transformation yielding

a modified tense tree from an indexical formula (its left operand) and an initial tense tree (its right operand).

In these rules, ‘ $e_T$ ’ is assumed to be a new episode variable name uniquely defined for any given  $T$ . (Thus the first two rules above each “create” a new episode token.) ‘ $\circ T$ ’ means “the tense tree which is just like  $T$  except that the new token  $e_T$  has been added to the focal node.” ‘ $\swarrow T$ ’ is  $T$  with the focus displaced to the left (i.e., *past*) daughter, with creation of a new daughter if necessary. ‘ $\downarrow T$ ’ and ‘ $\searrow T$ ’ are defined similarly. ‘ $\hookrightarrow$ ’ and ‘ $\mapsto$ ’ indicate focus shifts to the root of an embedded tree. ‘ $\mapsto$ ’ always adds a *new* embedding link whose destination is a *new* root node, whereas ‘ $\hookrightarrow$ ’ only does so if no embedding link exists at the current focus; otherwise, it causes *re-traversal* of the *last* embedding link added at the current focus.<sup>17</sup> ‘ $\uparrow$ ’ and ‘ $\leftarrow$ ’ indicate focus shifts to a parent node and an embedding node respectively.

$\text{Now}_T$  denotes the speech time for the most recent utterance in  $T$ .  $\text{Emb}_T$  denotes the last-added episode at the node which directly embeds the tree containing the focal node of  $T$ . If there is no embedding node,  $\text{Emb}_T$  denotes what  $\text{Now}_T$  denotes.  $\text{Last}_T$  is the last-stored episode variable at the focus of  $T$ . So, for a succession of simple past-tensed sentences, each episode generated will orient the next one. The **orients** predications can later be used to make (probabilistic or default) *narrative inferences* about the temporal or causal relations between the two episodes.

In the **Past**-rule,  $\text{bef}_T$  is a context-charged predicate that is to be replaced by **before** when the focal node is *not* “past-dominated,” and by **at-or-before** if the focus *is* past-dominated. The following examples illustrate this point.

- (45) Mary *said* that Pluto was asleep.
- (46) Mary *said* that John kicked Pluto.
- (47) John will say that Pluto *kicked* him.

In (45) and (46), the top-level “saying” episodes are *before* the embedding utterance episodes. Also, in (47), the *nonpast*-dominated “kicking” episode is *before* its embedding “saying” episode. But the past-dominated “being

<sup>17</sup>Intuitively, this distinction is motivated by the following kind of contrast:

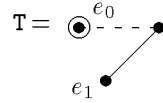
- (A) Mary *finished* the assignment. She *ordered* a pizza.
- (B) Mary *said* that she *finished* the assignment and that she *ordered* a pizza.

In (A), where two episodes are reported successively with the same tense, the first episode orients the second, i.e., the “finishing” event provides the point of *orientation* for the “ordering” episode (in this case, the ordering-episode was probably *right after* the finishing-episode). In (B), the embedded sentences are objects of attitudes, and it is much less clear than in (A) whether they refer to “successive” episodes. Now, the LFs for (A) will have speech act operators  $\text{decl}$ ; since the embedding links in the  $\text{Decl}$  rule are re-traversable, the “finishing” and “ordering” episodes will be stored at the same node in the same embedded tree. But in (B), although the top-level “saying” episodes are stored in the same node, the embedded episodes are stored in different embedded trees and thus will not have any connection between them.

asleep” and “kicking” episodes in (45) and (46) could be either *at the same time as* or *before* their embedding “saying” episodes, depending on the aspectual class of the embedded episode and other factors. In this case, Pluto’s being asleep (which is stative) is likely to be at the *same time as* Mary’s saying, whereas John’s kicking (which is nonstative) is likely to be *before* Mary’s saying.

We now illustrate how deindexing works by tracing the deindexing process for (44), the LF translation of (42). Let us assume (42) was uttered right after the sentence “Pluto was walking slowly,” and that the tense tree component of the context after processing it was like  $\mathbf{T}$  shown below. In  $\mathbf{T}$ , the focus is marked as  $\odot$ , and  $e_0$  and  $e_1$  are, respectively, the utterance event (speech act) and the described event, “Pluto was walking slowly.” We now deindex (44), repeated below, in the context  $\mathbf{T}$ .

(44') (decl (past [John conclude (That (past [Pluto tired]))]))  $\mathbf{T}$



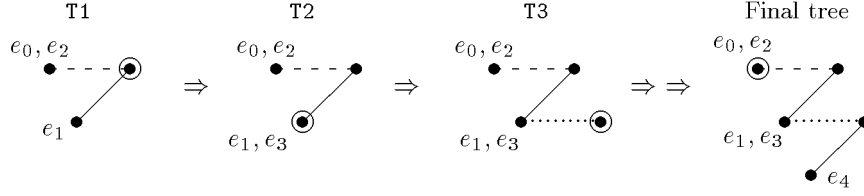
First, we need to deindex the topmost operator ‘decl’. An application of **Decl**-rule to (44') gives us (48). Notice that **Decl** introduces into the formula the new utterance event,  $e_2$ , and transforms the tense tree  $\mathbf{T}$  into  $\mathbf{T}_1$  as shown in Figure 2. In (48), the underlined part is the subformula that still needs to be deindexed (in the modified context  $\mathbf{T}_1$ ).

(48)  $(\exists e_2: [[e_2 \text{ same-time Now}_2] \wedge [e_0 \text{ immediately-precedes } e_2]]$   
 $[[\text{Speaker tell Hearer (That$   
 $\quad \underline{(\text{past [John conclude (That (past [Pluto tired]))})}]_{\mathbf{T}_1}$   
 $\quad ** e_2)]$

Here, **Speaker** and **Hearer** are parameters to be replaced by the speaker and the hearer of the context. Next, the **Past**-rule is applied to (48), resulting in the modified LF (49) and the tense tree  $\mathbf{T}_2$  shown in Figure 2.

(49)  $(\exists e_2: [[e_2 \text{ same-time Now}_2] \wedge [e_0 \text{ immediately-precedes } e_2]]$   
 $[[\text{Speaker tell Hearer (That$   
 $\quad (\exists e_3: [[e_3 \text{ before } e_2] \wedge [e_1 \text{ orients } e_3]]$   
 $\quad \underline{[[\text{John conclude (That (past [Pluto tired]))}]_{\mathbf{T}_2}}$   
 $\quad \quad ** e_3]])]$   
 $\quad ** e_2)]$

Note that **Past** introduces  $e_3$  for John’s “concluding” event, and asserts that it is oriented by  $e_1$ . As previously mentioned, **orients** relations are assumed to have certain “default” consequences, dependent on the aspectual classes of the episodes they relate. Since  $e_1$  (Pluto’s walking slowly) is stative and  $e_3$  (John’s realizing) is nonstative, the inference from [ $e_1$  ori-



**Figure 2** Tense Tree Transformation

ents  $e_3$ ] is that John’s realization was *during* Pluto’s walking slowly, i.e., [ $e_3$  during  $e_1$ ]. (As well, a causal relation, [ $e_1$  cause-of  $e_3$ ], can be tentatively inferred.)

Next, the **That** rule is applied, with the resulting LF (50) and the tense tree **T3**.<sup>18</sup> Note that a new tree has been embedded by the **That**-rule. In **T3**, a *re-traversable* embedding link is indicated with ‘- - -’, and a *non-re-traversable* one is indicated with ‘.....’.

$$(50) \quad (\exists e_2: [[e_2 \text{ same-time Now}_2] \wedge [e_0 \text{ immediately-precedes } e_2]] \\ \quad [[\text{Speaker tell Hearer (That} \\ \quad \quad (\exists e_3: [[e_3 \text{ before } e_2] \wedge [e_1 \text{ orients } e_3]] \\ \quad \quad \quad [[\text{John conclude (That } \underline{\text{(past [Pluto tired])}}]_{\mathbf{T3}}) \\ \quad \quad \quad \quad ** e_3]])] \\ \quad \quad ** e_2])$$

One more application of the **Past**-rule followed by that of the **Pred**-rule to the underlined subformula of (50) completes the deindexing process. The final result is shown in (51), with the final tree structure as shown in Figure 2.

$$(51) \quad (\exists e_2: [[e_2 \text{ same-time Now}_2] \wedge [e_0 \text{ immediately-precedes } e_2]] \\ \quad [[\text{Speaker tell Hearer (That} \\ \quad \quad (\exists e_3: [[e_3 \text{ before } e_2] \wedge [e_1 \text{ orients } e_3]] \\ \quad \quad \quad [[\text{John conclude (That} \\ \quad \quad \quad \quad (\exists e_4: [e_4 \text{ at-or-before } e_3] [[\text{Pluto tired}] ** e_4]])] \\ \quad \quad \quad \quad ** e_3]])] \\ \quad \quad ** e_2])$$

As with the **orients** relation, the **at-or-before** relation is assumed to have certain “default” consequences dependent on the aspectual classes of the episodes it relates. Since  $e_4$  is stative, given its characterization [Pluto tired], the inference from [ $e_4$  at-or-before  $e_3$ ] is that  $e_4$  is coextensive with  $e_3$  (i.e., the same time as John’s realization), in the absence of contrary

<sup>18</sup>We have omitted showing an application of **Pred**-rule here, which simply passes the tree inward to non-atomic expressions (in the above case, the expression headed by *That*).

information. The results of deindexing thus seem to be in complete accord with intuition.

Finally, we briefly indicate how time adverbials such as *yesterday* are deindexed. Simplifying the earlier example (38–40), “John walked yesterday” would lead to  $[[(\text{adv-e (during } Y\text{esterday)}) [\text{John walk}]] ** e1]$  as the relevant part of the logical form, after deindexing of **decl** and **past**. Applying the **Adv-e** rule stated earlier, we obtain

$$[[^V(\text{during } Y\text{esterday})_{\mathbf{T}} \wedge [\text{John walk}]_{\mathbf{T}}] ** e1],$$

assuming  $^V(\text{during } Y\text{esterday}) \cdot \mathbf{T} = \mathbf{T}$ . Further deindexing gives an absolute form of *Yesterday*:

$$[[^V(\text{during (yesterday-rel-to Now2)}) \wedge [\text{John walk}]] ** e1].$$

In view of the meaning of  $^V\pi$ , i.e., “ $\pi$  holds for the episode at which  $^V\pi$  is evaluated,” and since  $^V(\text{during (yesterday-rel-to Now2)})$  is evaluated at  $e1$ , this becomes

$$[[[e1 \text{ during (yesterday-rel-to Now2)}] \wedge [\text{John walk}]] ** e1],$$

i.e., the characterization of the event at issue is that it occurred yesterday and John walked in it.

Readers are referred to Hwang and Schubert 1993 for some grammar fragments for English and for details of our deindexing rules. We should note, however, that we still need substantial expansions in both grammar fragments and deindexing rules. Examples of phenomena we do not yet handle satisfactorily include clausal adverbials and relative clauses, certain forms of sentences involving present perfect, many kinds of generic sentences, constituent questions and wh-nominals, and a variety of more “minor” types of constructions.

## 6 Inference

Since the final **ELF** is nonindexical, it can be used in concert with facts in a knowledge base to work out immediate consequences of new inputs and to answer questions. Our main rules of inference are **RI** (Rule Instantiation) and its inverse **GC** (Goal Chaining). They are generalizations of what are commonly referred to as “forward chaining” and “backward chaining” in AI terminology. In addition, natural deduction is used in goal-driven, i.e., “backward,” inference. We first state **RI** and **GC**.

### Rule Instantiation (RI)

Rule instantiation is heavily used in input-driven inference, i.e., in working out those consequences of (the logical form of) an utterance which people seem to make “automatically.” For instance, in the case of “John kicked Pluto,” this might include inferences that John was near Pluto, that he swung his foot at Pluto and made contact, that Pluto felt pain and reacted somehow, that John wanted this result, etc. **RI** allows arbitrarily many

minor premises to be matched against arbitrarily deeply embedded subformulas of a rule. It subsumes *modus ponens* and *modus tollens*, but can also instantiate probabilistic conditionals. In the unit probability version, with just one minor premise (“fact”), the **RI** rules are:

$$\frac{R^-(\Phi), F^+(\Psi)}{R_\sigma^-(\neg(F_\sigma^+(\perp)))} \quad \frac{R^-(\Phi), F^+(\Psi)}{F_\sigma^+(R_\sigma^-(\top))}$$

where  $\sigma$  unifies  $\Phi, \Psi$ .  $R$  stands for “Rule”, and  $F$  for “Fact”.  $\top$  and  $\perp$  are truth and falsity respectively. The  $+$  and  $-$  signs are intended to indicate positive and negative occurrence of the embedded  $\Phi, \Psi$  formulas being unified.<sup>19</sup> Unification is defined in a way that allows substitution for explicitly quantified, “matchable” variables. A variable in a rule or fact is matchable if it is bound by a positively occurring universal quantifier or negatively occurring existential quantifier. (We could also allow for the quantifier **No**, but we assume that  $(\text{No } \alpha: \Phi \Psi)$  has been replaced by  $(\forall \alpha: \Phi \neg \Psi)$ .) For instance, substitution of  $w$  for  $x$  in a positively embedded subformula  $(\forall x: [x P][x Q])$  yields  $[[w P] \rightarrow [w Q]]$ , and the same substitution in a negatively embedded subformula  $(\exists x: [x P][x Q])$  yields  $[[w P] \wedge [w Q]]$ .

The first rule above is *sound* if  $\Psi$  contains no unmatchable free variables which are bound in  $F$  as a whole. The second rule is sound if  $\Phi$  contains no unmatchable free variables which are bound in  $R$  as a whole. (For soundness proof, see Schubert, in preparation.) So in particular, the first rule is sound if  $F$  contains only constants and top-level universal, hence matchable, variables.

### Goal Chaining (GC)

Goal chaining dominates goal-driven inference, such as might be used in question answering (e.g., about the contents of a story) or in planning (e.g., of speech acts or actions in the world). **GC** is a pair of very general chaining rules, chaining from rule consequents to antecedents is a special case. The following are the **GC** rules in the unit probability case:

$$\frac{R^+(\Phi), ?G^+(\Psi)}{?\neg(R_{\sigma'}^+(\neg(G_{\sigma'}^+(\top))))} \quad \frac{R^+(\Phi), ?G^+(\Psi)}{?G_{\sigma'}^+(\neg(R_{\sigma'}^+(\perp)))}$$

<sup>19</sup>An occurrence of a formula  $\Phi$  within a formula  $F(\Phi)$  is a positive occurrence iff (i)  $F(\Phi) = \Phi$ , or (ii)  $F(\Phi)$  is of one of the forms  $\neg\chi$ ,  $[\chi \rightarrow \psi]$ ,  $[\psi \wedge \psi']$ ,  $[\psi \vee \psi']$ ,  $(\exists \alpha: \psi \psi')$ , or  $(\forall \alpha: \chi \psi)$ , and the occurrence of  $\Phi$  in  $F(\Phi)$  is a positive occurrence of  $\Phi$  in  $\psi$  or  $\psi'$ , or a negative occurrence of  $\Phi$  in  $\chi$ . An occurrence of  $\Phi$  within  $F(\Phi)$  is a negative occurrence iff  $F(\Phi)$  is of one of the forms listed in (ii) above, and the occurrence of  $\Phi$  in  $F(\Phi)$  is a positive occurrence of  $\Phi$  in  $\chi$  or a negative occurrence of  $\Phi$  in  $\psi$  or  $\psi'$ . Note that only subformulas embedded by the “classical” operators  $\neg, \rightarrow, \wedge, \vee, \exists, \forall$  are thus positively or negatively embedded, though the subformulas themselves need not be “classical.” A quantifier is said to occur positively or negatively if it heads a positively or negatively occurring subformula respectively.

where  $\sigma'$  “antiunifies”  $\Phi, \Psi$  (i.e., with positive existentials and negative universals in  $G$  regarded as matchable).  $R$  stands for “Rule”, and  $G$  for “Goal.” The first of the goal chaining rules is *sound* if  $\Psi$  contains no unmatchable (e.g., top-level universal) free variables which are bound in  $G$  as a whole. The second rule is sound if  $\Phi$  contains no unmatchable (e.g., top-level existential) free variables which are bound in  $R$  as a whole.

We now illustrate how some of these inference rules are used. Consider a rule

$$\begin{aligned} & (\forall x: [x \text{ ((attr small) animal)}] \\ & \quad (\forall e_1 [ [ [x \text{ yelp}] ** e_1 ] \rightarrow (\exists e_2: [e_2 \text{ same-time } e_1] \\ & \quad \quad \quad [ [ [x \text{ hungry}] ** e_2 ] \vee [ [x \text{ sick}] ** e_2 ] ] ] ])) \end{aligned}$$

*When a small animal yelps, it is either hungry or sick.*

Note that  $x$  and  $e_1$  are matchable variables. Suppose we want to know *if Pluto was ever sick*. Then the goal can be posed as

$$? (\exists e_3: [e_3 \text{ before } \textit{Now}] [ [Pluto \text{ sick}] ** e_3 ]),$$

where  $e_3$  is a matchable variable. Since the goal has no unmatchable variable, we use the first **GC** rule. Note that the matrix of the goal matches the second disjunct of the consequent of the rule, with substitution  $\langle \textit{Pluto}/x, e_2/e_3 \rangle$ . With the first **GC** rule, we get a new goal

$$\begin{aligned} & ? \neg [ [Pluto \text{ ((attr small) animal)}] \\ & \quad \rightarrow (\forall e_1 [ [ [Pluto \text{ yelp}] ** e_1 ] \\ & \quad \quad \rightarrow (\exists e_2: [e_2 \text{ same-time } e_1] \\ & \quad \quad \quad [ [ [Pluto \text{ hungry}] ** e_2 ] \vee \neg [ [e_2 \text{ before } \textit{Now}] \wedge \top ] ] ] ] ) \end{aligned}$$

which, after simplification and distributing negation becomes

$$\begin{aligned} & ? [ [Pluto \text{ ((attr small) animal)}] \wedge \\ & \quad (\exists e_1 [ [ [Pluto \text{ yelp}] ** e_1 ] \wedge \\ & \quad \quad (\forall e_2: [e_2 \text{ same-time } e_1] \\ & \quad \quad \quad [ [e_2 \text{ before } \textit{Now}] \wedge \neg [ [Pluto \text{ hungry}] ** e_2 ] ] ] ) \end{aligned}$$

Suppose now we have the fact  $[Pluto \text{ dog}]$  in the knowledge base as well as a rule

$$(\forall x: [x \text{ dog}] [x \text{ ((attr small) animal)}]).$$

Then, **RI** will permit instantiation of this rule with  $[Pluto \text{ dog}]$ , leading to immediate success of the subgoal  $? [Pluto \text{ ((attr small) animal)}]$ .<sup>20</sup> Thus, we are left with subgoal

$$\begin{aligned} & ? (\exists e_1 [ [ [Pluto \text{ yelp}] ** e_1 ] \wedge \\ & \quad (\forall e_2: [e_2 \text{ same-time } e_1] \\ & \quad \quad [ [e_2 \text{ before } \textit{Now}] \wedge \neg [ [Pluto \text{ hungry}] ** e_2 ] ] ] ) \end{aligned}$$

<sup>20</sup>This subgoal can also be satisfied by **GC**, i.e.,  $? [Pluto \text{ ((attr small) animal)}]$  will lead to a reduced subgoal  $? [Pluto \text{ dog}]$ , which will be immediately satisfied.



The new goal asks, “Did Pluto yelp sometime in the past, but was not hungry?” This makes sense because one way of proving “Pluto is sick” is to prove that “Pluto is yelping but not hungry.”<sup>21</sup>

The general version of **GC** allows arbitrarily many subsidiary knowledge base facts to be invoked in the process of chaining from the given goal to a subgoal. There is also another class of goal-directed methods that consists of standard natural deduction rules such as proving a conditional by assuming the antecedent and deriving the consequent or proving a universal by proving an arbitrary instance of it.

With the kinds of **EL** inferences described so far, **EPILOG** (the computational system for **EL**) is already making some quite complex inferences and answering questions based on logically represented simple narratives or telegraphic messages. For instance, **EPILOG** makes some rather subtle inferences based on knowledge relevant to a small fragment of the story of *Little Red Riding Hood*. In one version of the story, the wolf would have liked to eat Little Red Riding Hood when he first met her, but dared not do so “on account of woodcutters nearby.” **EPILOG** infers how the wolf might have come to harm if he had tried to eat Little Red Riding Hood at this point (see Hwang and Schubert 1993).

## 7 Concluding Remarks and Future Work

Episodic logic is a very expressive meaning representation whose development has been guided by the interlocking needs of mapping surface form into logical form, allowing for context-dependence, formalizing the semantics, and facilitating inference. It combines ideas from Montague grammar, situation semantics, property theory, DRT, and natural language interpretation as understood in AI, and adds a number of new ideas concerning the semantics of situations, actions, facts, times, quantification and tense and aspect. Besides providing an overview of the representation, we described a systematic way of *deindexing* initially indexical **LFs** using context structures called *tense trees*. The deindexed formulas can be used for inference by methods similar to those familiar in AI. The logic has been tested on realistic (though very small) text samples. The results so far encourage us in our attempt to grapple simultaneously with a wide spectrum of problems in natural language understanding. Future work will be focused on further development of grammar rules and deindexing rules (e.g., for adverbial clauses and relative clauses) and further specification of formal semantics (e.g., for questions and nominalization operators).

<sup>21</sup>The fact  $(\forall e (\forall e_1 (\forall e_2 [[e_2 \text{ same-time } e_1] \rightarrow [[e_2 \text{ before } e] \leftrightarrow [e_1 \text{ before } e]]])))$  would also be needed eventually.

### Acknowledgements

The authors are grateful to James Allen and Philip Harrison for helpful comments on various aspects of EL. Also the University of Alberta Logical Grammar Study Group and the University of Rochester TRAINS Group provided a forum for discussion of the topic, and Stephanie Schaeffer has been the mainstay of the program development effort for EPILOG. The authors also gratefully acknowledge the careful commentary of Ian Pratt and an anonymous referee, which helped improve the paper. This research was supported in part by NSERC Operating Grant A8818, ONR/DARPA research contract no. N00014-82-K-0193, NSF research grant no. IRI-9013160, the Boeing Co. under Purchase Contracts W-278258 and W-288104 and a Killam Memorial Scholarship (CHH).

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