EL : A Formal, Yet Natural, Comprehensive Knowledge Representation*

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Abstract

We present *Episodic Logic* (EL), a highly expressive knowledge representation well-adapted to general commonsense reasoning as well as the interpretive and inferential needs of natural language processing. One of the distinctive features of EL is its extremely permissive ontology, which admits situations (episodes, events, states of affairs, etc.), propositions, possible facts, and kinds and collections, and which allows representation of generic sentences. EL is natural language-like in appearance and supports intuitively understandable inferences. At the same time it is both formally analyzable and mechanizable as an efficient inference engine.

Introduction

One of the requirements on knowledge representation is that it should support efficient inference (cf., [Brachman & Levesque, 1985]). Our basic methodological assumption is that this demand on the representation is best met by using a highly expressive logic closely related to natural language itself. The possibility of handling situations, actions, facts, beliefs, attitudes, causes, effects, and general world knowledge simply and directly depends on the expressiveness of the representation. These remarks apply as much to semantic representation of English sentences, as to knowledge representation. In fact, the simplest assumption is that the two are one and the same. On that premise, we have been developing *Episodic Logic* (EL), a highly expressive knowledge and semantic representation well-adapted to commonsense reasoning as well as the interpretive and inferential needs of natural language processing.

EL is a first order, intensional logic that incorporates from situation semantics the idea that sentences describe situations [Barwise & Perry, 1983; Barwise, 1989]. A distinctive feature of the logic, responsible for its name, is the inclusion of *episodic* (situational) variables. (Episodes, as the term is construed in EL, subsume events, states of affairs, circumstances, eventualities, etc.) The adjective "episodic" is intended to emphasize the fact that reasoning about the world and the agents in it often involves inference of the temporal and causal connections among *transient* types (as opposed to *eternal* types) of situations, i.e., occurrences or state changes.

EL is related to natural language through a Montague-style coupling between syntactic form and logical form, allowing the relationship between surface form and logical form to be specified in a modular, transparent way. EL representations derived from English text are natural and close to English surface form. Episodic variables implicit in English sentences and temporal relations between those episodes are automatically introduced into the logical form in the process of deindexing. Very general inference rules, *rule instantiation* and *goal chaining*, have been developed that allow for deductive and probabilistic inferences.

We first describe the ontology of EL, which provides the necessary ingredients for interpreting an expressive representation, and then show how some of the more unusual kinds of objects are represented using these ingredients. After that we briefly discuss how inferences are made in EL.

EL and its Liberal Ontology

A distinctive feature of EL is its very permissive ontology, which supports the interpretation of a wide range of constructs that are expressible in English. EL can represent conjoined predicates by means of λ-abstraction (e.g., *crack longer than 3 inches*); restricted quantifiers (e.g., *most aircrafts manufactured by Boeing*); predicate modifiers (e.g., *severe* damage); perception (e.g., "Mary *heard* the bomb explode"); attitudes and possible facts (e.g., "Mary *believes that* gasoline is heavier than water"); actions (e.g., "John thought *Mary's dropping the glass* was intentional"); opaque contexts (e.g., "John *wants to design a new engine*"); kinds (e.g., "the two kinds of precious metal, *gold* and *platinum*"), etc. We now describe the ontological basis of this wide expressive range of EL.

Model structures for EL are based on an ontology of *possible individuals* $\mathcal{D}$. Like Hobbs [1985], we believe it is better to expand one's ontology to allow more kinds of entities than complicating the logical form. *Possible* individuals include not only real or actual individuals but also imaginary or nonexistent ones (e.g., "*Tomorrow's lecture* has been cancelled" [Hirst, 1991]). As shown in Figure 1, $\mathcal{D}$ includes many unusual types of individuals

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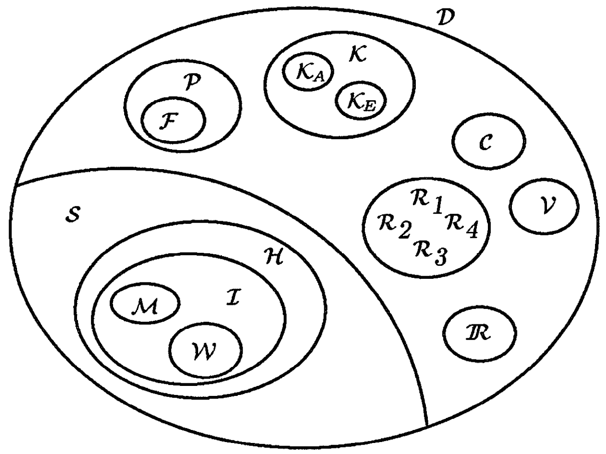

Figure 1: Ontology of Basic Individuals

besides "ordinary" ones. First, unlike situation semantics, EL allows *possible situations* $\mathcal{S}$. These are much like "partial possible worlds," in that predicate symbols are assigned partial extensions (and antiextensions) relative to them. 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 quite plausible. Sentences like "Last week was eventful" suggests that times such as *last week* indeed have episodic content. Note that times in the episodic sense are distinguished from *clock times* (in the metric sense). Also, note that *actions* or *activities* are not included in $\mathcal{S}$, since actions are regarded in EL as events paired with their agents. (More on this later.) In general, a situation can be part of many worlds, but an "exhaustive" situation belongs to a unique world.[1] A transitive, reflexive relation $Actual \subset \mathcal{D} \times \mathcal{S}$ determines what individuals are actual with respect to a given situation. 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.

Disjointly from $\mathcal{S}$, we have not only ordinary individuals of our experience, but also propositions $\mathcal{P}$ (including possible facts $\mathcal{F}$ which we identify with consistent propositions), kinds of individuals $\mathcal{K}$ (including kinds of actions $\mathcal{K}_A$, and kinds of episodes $\mathcal{K}_E$), the real numbers $\mathbb{R}$ (augmented with $-\infty$ and $+\infty$), and *n-D* regions $\mathcal{R}_n$, containing subsets of $\mathbb{R}^n$ ($1 \leq n \leq 4$). Elements of $\mathcal{R}_4$ are space-time trajectories that may not be connected, and whose temporal projection in general is a multi-interval.[2] This allows for repetitive or quantified events in EL.

Finally, there are collections $\mathcal{C}$ and n-vectors (i.e., tuples) $\mathcal{V}$, $n = 2, 3, \ldots$, of all of these. Space limitations prevent further elaboration, but readers are referred to [Hwang, 1992; Hwang & Schubert, To appear] for a more detailed discussion of the EL ontology and semantics.

Some Essential Resources of EL

We now outline some of the essential resources of EL, emphasizing nonstandard ones intended to deal with events, actions, attitudes, facts, kinds, and probabilistic conditionals.

Events and Actions

We discuss events (situations) and actions first. While doing so, we will also indicate the flavor of EL syntax. We then discuss kinds of events and actions, and describe how properties of events and actions are represented. Consider the following sentences and their logical forms.

(1) a. Mary dropped the glass
  b. (past (The x: [x glass] [Mary drop x]))
  c. (∃e1: [e1 before u1] [[Mary drop Glass1] ** e1])

(2) a. John thought *it* was intentional.
  b. (past [John think (**That** (past [*It* intentional]))])
  c. (∃e2: [e2 before u2]
      [[John think (**That** (∃e3: [e3 at-or-before e2]
          [[[Mary | e1] intentional] ** e3]))]
      ** e2])

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

[Mary ⟨past drop⟩ ⟨The glass⟩],

where ⟨ ⟩ indicates unscoped expressions and [ ] indicates infix expressions. (Infix notation is used for readability, with the last argument wrapped around to the position preceding the predicate.) After scoping of the **past** operator and the **The**-determiner, we get LF (1b), which is then deindexed to episodic logical form ELF (1c). As seen in (1c), we use restricted quantifiers of form $(\mathtt{Q}\alpha{:}\Phi\Psi)$, where Q is a quantifier such as $\forall, \exists,$ **The**, **Most**, **Few**, $\ldots$; α is a variable; and restriction Φ and matrix Ψ are formulas. $(\forall\alpha{:}\Phi\Psi)$ and $(\exists\alpha{:}\Phi\Psi)$ are equivalent to $(\forall\alpha)[\Phi \rightarrow \Psi]$ and $(\exists\alpha)[\Phi \wedge \Psi]$, respectively. In (1c), '**' is an episodic, modal operator that connects a formula with the episode/situation it describes. Intuitively, for Φ a formula and η an episodic term, $[\Phi \; {**} \; \eta]$ means "Φ characterizes (or,

[1] Note that if two worlds assign the same truth values to the same unlocated (i.e., eternal) statements, they must be one and the same world. Since exhaustive situations are informationally maximal, any true (or false) unlocated statement in a particular world must be true (or false) in every exhaustive situation that is part of that world. Thus, an exhaustive situation cannot belong to more than one world.

[2] Note that situations occupy such spatiotemporal trajectories, rather than occupying space and time separately. This point is supported by sentences like "It did not snow on the trip from Madison to Chicago" [Cooper, 1985]. As Cooper points out, this sentence "could be true even if it had snowed during the trip on the road between Madison and Chicago and yet had not been snowing at any time at the place where the car was at the time."

completely describes) η."[3] Also notice in (1c) that the past operator is deindexed to the predication [e1 before u1], where u1 denotes the utterance event of sentence (1a). Such temporal deindexing is done by a set of recursive deindexing rules [Hwang & Schubert, 1992; Schubert & Hwang, 1990].

A "characterizing" description of an episode is maximal, or complete, in the sense that it provides *all* the facts that are supported by the episode, except possibly for certain ones entailed by those given. In other words, the episodes so characterized are *minimal* with respect to the characterizing description, in the part-of ordering among situations, i.e., no proper *part* of such an episode supports the same description. We also have a more fundamental episodic operator '*', where [$\Phi * \eta$] means "Φ is true in (or, partially describes) η." '*' is essentially an object-language embedding of the semantic notion of *truth in an episode or situation*. Note that [$\Phi ** \eta$] implies [$\Phi * \eta$]. Thus, for instance, [[Mary drop Glass1] ** e1] implies that e1 is a part (in an informational sense) of some episode e2, coextensive with e1, such that [[Glass1 fall] * e2], [[Mary hold Glass1] * (begin-of e2)], [($\neg$[Mary hold Glass1]) * (end-of e2)], etc. The notion of a complete description (characterization) of a situation using '**' is crucial for representing causal relationships among situations. For instance, if (1a) is followed by "*It* woke up John," "it" refers to an event *completely* described by (1a), i.e., a *minimal*—spatiotemporally as well as informationally—event supporting (1a), not simply some event *partially* described by (1a). (For more detailed argument, see [Hwang & Schubert, In print].) In (2b), That is a proposition-forming (nominalization) operator to be discussed later. In (2a, b), "it" refers to Mary's *action* of dropping the glass, and is resolved in (2c) to [Mary | e1], "the action whose performance by Mary constitutes event e1."[4] '|' is a pairing function (similar to Lisp "cons") applicable to individuals and tuples.

Thus, actions are represented as agent-event pairs in EL. This representation is motivated by the observation that actions are distinguished from events or episodes in that they have well-defined *agents*. That is why it makes sense to talk about "intentional actions," but not "intentional events." It also seems that the criteria for individuating actions are different from those for individuating episodes. For example, it seems that (3) and (4) below may describe the same episode or event (an exchange of a boat for a sum of money), but different actions (a buying versus a selling).

(3) John bought the boat from Mary.
(4) Mary sold the boat to John.

Note, in particular, that the buying in (3) may have been performed *reluctantly* and the selling in (4) *eagerly*, but it would be very odd to say that the *events* described in (3) or (4) were reluctant, or eager, or occurred reluctantly or eagerly. Events simply do not have such properties. If we assume they did, we might end up saying, contradictorily, that an event was both reluctant and eager.[5]

Several event- or situation-based formalisms have been proposed within the AI community also. The first was the situation calculus [McCarthy & Hayes, 1969], which introduces explicit situation-denoting terms and treats some formulas and functions (namely, *situational fluents*) as having situation-dependent values. However, situations are viewed as instantaneous "snapshots" of the universe. (They correspond to $\mathcal{M}$ in our ontology.) As such they cannot serve as models of the events and situations of ordinary experience, which can be temporally extended while having limited spatial extent and factual content, can cause each other, etc. Kowalski and Sergot [1986] developed the event calculus in an effort to avoid the frame problem that exists in the situation calculus. Events in the event calculus are local (rather than global), and initiate or terminate "time periods" (probably best understood as circumstances or states of affairs, since they can be concurrent yet distinct). The main limitation is that (as in a Davidsonian approach) events are associated only with simple subject-verb-object(s) tuples, and not with arbitrarily complex descriptions.

Kinds of Events and Actions. As separate categories from situations and events, there are also *kinds* of events and actions. Below are some sample sentences with their logical forms (with certain simplifications). Ka in (5b) and (6b) is a property forming (nominalization) operator that maps monadic predicate intensions to (reified) types of actions and attributes. Ke in (7b) and (7b) is a sentence nominalization operator, which forms (reified) types of events from sentence intensions.

(5) a. *Skiing is strenuous*
    b. [[(Ka ski) strenuous] ** E1]
(6) a. Mary wants *to paint the wall*
    b. [[Mary want (Ka (paint Wall3))] ** E2]
(7) a. *For John to be late* is rare
    b. [[(Ke [John late]) rare] ** E3]
(8) a. Bill suggested to John that *he call Mary*
    b. [[Bill suggest-to John (Ke [John call Mary])] ** E4]

[3] Our episodic variables are different from Davidsonian [1967] event variables in that they can be "attached" to any formula, whereas Davidsonian ones can be "attached" only to atomic ones. Note that Davidson's method cannot handle sentences with quantifiers or negation. Event variables that are closely related to ours are those of Reichenbach [1947] who, like situation semanticists, viewed a sentence as describing a situation.

[4] Notice the existential variable e1 occurring outside its quantifier scope. This is allowed in EL thanks to the "parameter mechanism," which allows the binding of variables to be carried beyond their quantifier scopes. See [Hwang & Schubert, In print].

[5] Our view appears to resonate with Jacobs' [1987]. Although our conception of actions as agent-event pairs is somewhat different from Jacobs' who regards actions as VIEWs of events, both are based on the intuition that events and actions are different, though closely related.

"Skiing" and "to paint the wall" are *kinds of actions*, while "for John to be late" and "John call Mary" are *kinds of events*.

Properties of Events and Actions. Typically, properties of actions and attributes (manner, purpose, degree, quality, etc.) are introduced through predicate operators; and those of episodes (duration, frequency, spatiotemporal location, etc.) through sentential operators. Consider the following examples.

(9) a. John fixed the engine with Bill yesterday
b. (past (The x: [x engine]
((adv-e (during Yesterday))
[John ((**adv-a** (with-accomp Bill)) (fix x))])))
c. ($\exists$e1:[e1 before u1]
[[$^{\vee}$(during (yesterday-rel-to u1)) $\wedge$
$^{\vee}\lambda e$[[John | e] with-accomp Bill] $\wedge$
[John fix Engine2]]
** e1])

(10) a. Mary bought a brush *to paint the wall*
b. (past (The x: [x wall]
[Mary ((**adv-a** (for-purpose (**Ka** (paint x))))
λz($\exists$y: [y brush] [z buy y]))]))
c. ($\exists$e2:[e2 before u2]
[[$^{\vee}\lambda e$[[Mary | e] for-purpose
(**Ka** (paint Wall3))] $\wedge$
($\exists$y: [y brush] [Mary buy y])]
** e2])

"Yesterday" in (9a) implicitly modifies the *episode* described by "John fix the engine" (its temporal location). "With Bill" in (9a) and "to paint the wall" in (10a), on the other hand, implicitly modify *actions* performed by John and Mary respectively (by specifying their "accompaniment" and "purpose"). As illustrated in the indexical (b)-formulas above, implicit episode modifiers appear as sentential operators of form (**adv-e** π), where π is a predicate over episodes; implicit action modifiers appear as predicate modifiers of form (**adv-a** π), where π is a predicate over actions/attributes. Simple deindexing rules for adverbials (which we omit here; see [Hwang & Schubert, 1993a]) convert the (b)-formulas into the nonindexical **ELF**s shown in (c). Note in (c)-formulas that our treatment of adverbials views them as providing conjunctive information about the described episode (or action), as in Dowty's system [1982]. '$^{\vee}$' is an extension operator that applies its predicate operand to the "current" episode. For example, $^{\vee}$(during 1993) or $^{\vee}\lambda e$[[John | e] with-accomp Bill] is true in situation s iff s occurs during 1993 or the action [John | s] is accompanied by Bill. Notice that the **adv-a** rule introduces the agent-event pair [x | e] into the formula. The following are some relevant meaning postulates.

For π, π' 1-place predicates, η a term, and Φ a formula:
$\Box$ $[^{\vee}\pi \wedge {}^{\vee}\pi'] \leftrightarrow {}^{\vee}\lambda e[[e\ \pi] \wedge [e\ \pi']]$
$\Box$ $[[^{\vee}\pi \wedge \Phi] ** \eta] \leftrightarrow [[[\eta\ \pi] \wedge \Phi] ** \eta]$

Applying the above meaning postulates to (9c) and (10c), we obtain the following (assuming e1, e2 are skolemized to E1, E2).

(9′) d. [E1 during (yesterday-rel-to u1)]
e. [[John | E1] with-accomp Bill]
f. [John fix Engine2] * E1]
g. ($\exists$e3: [e3 coexten-subep-of E1]
[[John fix Engine2] ** e3])

(10′) d. [[Mary | E2] for-purpose (**Ka** (paint Wall3))]
e. [($\exists$y: [y brush] [Mary buy y]) * E2]
f. ($\exists$e4: [e4 coexten-subep-of E2]
[($\exists$y: [y brush] [Mary buy y]) ** e4])

[e coexten-subep-of e'] means that e and e' occupy the same spatiotemporal location and that e is an (informational) part of e'.

Intensions, Attitudes and Possible Facts

We now briefly discuss attitude and intensional verbs.

(11) a. John will *design* the engine
b. (pres (futr [John (design
$\lambda x[x = \langle$The engine$\rangle]$)]))
b′. (pres (futr [John (design
λx(The y:[y engine][$x = y$]))]))

(12) a. Mary *told* John *that the engine gave up*
b. (past (The x: [x engine]
[Mary tell John (**That** (past [x give-up]))]))
c. ($\exists$e1: [e1 before u1]
[[Mary tell John (**That** ($\exists$e2: [e2 before e1]
[[Engine3 give-up] ** e2]))]
** e1])

As shown in (11), intensional verbs are treated as predicate modifiers in **EL**. For objects of intensional verbs, there is generally no presupposition of actual existence — at least not in the "opaque" (*de dicto*) reading. That is, "the engine" in (11), for instance, does not necessarily exist in the world wherein the sentence is evaluated. That is why it is scoped under the intensional verb in (11b′). (We omit the deindexed formula for (11a), but see [Hwang, 1992].) The "transparent" (*de re*) reading can be obtained by choosing wide scope for the unscoped term $\langle$The engine$\rangle$, i.e., just inside the tense operator, but outside the intensional verb.

Objects of attitudes are taken to be (reified) propositions in **EL**. Propositions are formed by a nominalization operator **That** as shown in (12bc). 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. We should remark here that often events and facts are equated, e.g., by Reichenbach [1947]. As Vendler [1967] has pointed out, this is untenable. Most importantly, events take place over a certain time interval, and may cause and be caused by other events. In contrast, facts do not happen or take place. They are abstractions (like propositions) and as such provide explanations, rather than causes. However, they are so closely related to events (e.g., it may be a fact *that an event occurred* or *will occur*) that people often talk of facts as if they were causes. We regard such talk as metonymic, referring to the "events behind the facts."

Kinds and Probabilistic Conditionals

We have seen operators Ka and Ke, forming kinds of actions and events. We now consider a more general kind-forming operator, K, that maps predicates to individuals. It seems that many generic sentences are best translated into formulas involving kinds. Other kinds of generic sentences are more easily represented as probabilistic (generic) conditionals, and we will discuss these after "kind" expressions. First, consider the following sentences.

(13) a. Gold is expensive, but John buys *it* regularly
 b. [(gpres [(K gold) expensive]) ∧
 (pres ((adv-f regular) [John buy *It*]))]
 c. [(∃e1: [[e1 extended-ep] ∧ [u1 during e1]]
 [[(K gold) expensive] ** e1]) ∧
 (∃e2: [e2 at-about u1]
 [[[e2 regular] ∧ (mult [John buy (K gold)])]
 ** e2])]

(14) a. Wasps are pesky and they spoiled our picnic
 b. [(gpres [(K (plur wasp)) (plur pesky)]) ∧
 (past [*They* spoil Picnic1])]

Following Carlson [1982] and Chierchia [1982], we translate mass or abstract nominals like *gold, corrosion, welfare,* etc., and bare plurals like *wasps* into *kinds*. In (13a, b) above, 'it' refers to 'gold' in the first clause and is resolved as (K gold) in (13c). In (13b), adv-f (standing for *f*requency adverbial) is an operator that maps predicates over sequences (i.e., composite episodes) to sentence modifiers, and its deindexing rule introduces the mult operator shown in (13c). For Φ a formula and η a composite episode, [(mult Φ) ** η] reads "every component episode of η is of type Φ." In (14b), plur is an operator that maps predicates applicable to (non-collective) individuals to predicates applicable to collections. That is, (*plur* P) is true of a collection just in case P is true of each member. (plur is similar to Link's [1983] "star" operator.) We omit the deindexed formula for (14a) for space reasons.

Now in (13a), what John buys is apparently quantities of gold, not the "kind" gold. We obtain such "instance" or "realization" interpretations using the following meaning postulates.

For kinds κ and telic, object-level predicates Π:
 $\Box\ [[\tau\ \Pi\ \kappa] \leftrightarrow (\exists x : [x \text{ instance-of } \kappa]\, [\tau\ \Pi\ x])]$
For all monadic predicates π:
 $\Box\ (\forall x\ [[x \text{ instance-of } (\mathrm{K}\ \pi)] \leftrightarrow [x\ \pi]])$

Then, we have the following equivalences.

$$[\text{John buy } (\mathrm{K}\ \text{gold})] \leftrightarrow (\exists x\colon [x \text{ gold}]\,[\text{John buy } x]).$$

Our uniform treatment of mass terms and bare plurals as kinds in EL deals straightforwardly with seemingly problematic sentences like (13a) and (14a), in which kinds and instances appear to co-refer.

Generalizations involving indefinite count singulars (e.g., "*A bicycle* has two wheels") or bare numeral plurals (e.g., "*Two men* can lift a piano") are translated into probabilistic conditionals (i.e., extensionally interpretable generic conditionals), rather than kind-level predications. Such conditionals turn out to be very useful in representing naive physics and causal laws (of the kinds discussed in [Hayes, 1985; Hobbs *et al.*, 1987]) and unreliable knowledge in general, like the following.

(15) a. If one drops an open container containing some liquid, then the container may cease to contain any liquid.
 b. $(\exists x\colon [x \text{ person}]$
 $(\exists e_1\colon [(\exists y\colon [[y \text{ container}] \wedge [y \text{ open}]]$
 $(\exists z\colon [z \text{ liquid}]\,[y \text{ contain } z])) \,**\, e_1]$
 $(\exists e_2\colon [(\text{begin-of } e_2) \text{ during } e_1]$
 $[[x \text{ drop } y] \,**\, e_2])))$
 $\rightarrow_{.3,x,y,e_1,e_2}$
 $(\exists e_3\colon [[e_2 \text{ cause-of } e_3] \wedge [e_3 \text{ right-after } e_2]]$
 $[(\neg(\exists v\colon [v \text{ liquid}]\,[y \text{ contain } v])) \,**\, e_3])$

Here, '.3' attached to the conditional is a lower bound on the *statistical probability*, and $x, y, e1, e2$ are controlled variables.[6] This rule says, roughly, that in at least 30% of the situations in which the antecedent is true, the consequent will also be true.[7] It appears that for many conditional generalizations, a representation in terms of a probabilistic conditional with control over all existentials in the antecedent that occur anaphorically in the consequent leads to intuitively reasonable uncertain inferences. We provide a "first cut" formal semantics in [Hwang, 1992; Hwang & Schubert, To appear].

Inference Rules

The main inference rules in EL are *Rule Instantiation* (RI) and *Goal Chaining* (GC). They are generalizations of "forward chaining" and "backward chaining," in AI terminology.

RI allows arbitrarily many minor premises to be matched against arbitrarily deeply embedded subformulas of a "rule" (an arbitrary formula, though typically a conditional with quantified or controlled variables). As such, it is similar to "nested resolution" [Traugott, 1986], but avoids skolemization. Instead of stating the rule formally (which we have done elsewhere [1993b] & [In print]), we illustrate its use with a simple example.

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[6] As mentioned earlier, the parameter mechanism in EL lets the existential variable bindings be carried beyond their quantifier scope. Different choices of controlled variables lead to different readings. (This addresses the "proportion problem"; cf., [Schubert & Pelletier, 1989].)

[7] If the consequent of the rule said "the container will contain less liquid than before," then the conditional would have a much higher lower bound, say, '.95'.

Suppose we have the following rule (with all episodic variables suppressed for simplicity),

$(\forall x$: [x person]
[[[x healthy] $\wedge$ [[x rich] $\vee$ $(\exists y$:[x has-job y])]]
$\rightarrow$ [x contented]]) ,

For anyone, if he is healthy and is rich or has a job, he is contented

and assume we are given the following facts:

[Joe man] and [Joe has-job Lawyer].

Then RI would trigger on the second fact, matching [Joe has-job Lawyer] to [x has-job y], and thus binding x to *Joe* and y to *Lawyer*. This also particularizes [x person] in the rule to [Joe person], and this would immediately be verified by the "type specialist," with use of [Joe man] and the implicit subsumption relation between *person* and *man*. Substituting truth for both of the matched subformulas and simplifying, RI would then infer

[Joe healthy] $\rightarrow$ [Joe contented],

i.e., Joe is contented provided that he is healthy. Note that the matching process can substitute for either universal variables (provided that the universal quantifier lies in a *positive* environment) or existential variables (provided that the existential quantifier lies in a *negative* environment).[8]

More generally variables controlled by probabilistic conditionals and quantified variables in "facts" may also be bound in the matching process. For instance, suppose that the rule above were slightly reformulated to say "If a person is healthy and either is rich or has a job, then he is *probably* (with lower bound .6 on the probability) contented" (it should not be hard to see how to write this down formally); and suppose [Joe has-job Lawyer] had been replaced by $(\exists z$ [Joe has-job z]), and the additional fact [Joe healthy] given. Then RI would still have applied, and would have yielded conclusion

[Joe contented]$^{.6}$,

i.e., with an epistemic probability of at least 60%, Joe is contented.

While RI is typically used for "spontaneous" (input-driven) inference chaining when new facts are asserted, *goal chaining* (GC) is used for deliberate, goal-directed inference, for instance when answering questions. GC is the exact dual of RI. For example, suppose again that we have the rule and facts given above, and we wish to answer the question, "Is Joe contented?". Then GC would reduce this goal to the subgoal "Is Joe healthy?" in one step. (It would do this either from the original rule and facts, or, if the above result of RI had been asserted into the knowledge base, from the latter.)

In actual use, RI and GC are slightly more subtle than the above examples suggest. First, there are two versions of each rule, whose (sound) use depends on the configuration of quantifiers for matched variables. Second, goal-directed reasoning is supplemented with natural deduction rules, such as that to prove a conditional, we can assume the antecedent and prove the consequent. And finally, there is some limited use of goal-chaining in input-driven inference, so as to verify parts of rules, and some limited use of input-driven inference in goal-directed reasoning, so as to elaborate consequences of assumptions that have been made.

[8] Positive and negative environments correspond respectively to embedding by an even and odd number of negations, implicational antecedents, and universal quantifier restriction clauses. Only subformulas embedded by extensional operators $\neg$, $\wedge$, $\vee$, $\rightarrow$, $\forall$, $\exists$, and generic conditionals may be matched by RI.

Concluding Remarks

EL is a very expressive knowledge representation; its ontology allows for possible situations (events, states, states of affairs, etc.), actions, attitudes and propositions, kinds, and unreliable general knowledge, among other things. As such, EL goes beyond the current state of the art as represented by such works as [Alshawi & van Eijck, 1989; Brachman *et al.*, 1991; Hobbs *et al.*, 1987; Shapiro, 1991; Sowa, 1991]. All features of EL are strongly motivated by corresponding expressive devices found in natural languages — i.e., generalized quantifiers, modifiers, nominalization, etc. As a result, knowledge can be cast in a very natural, understandable form and intuitively obvious inferences can be modelled in a direct, straightforward way.

One of the most important remaining problem is the principled handling of probabilities. The state of the art in probabilistic inference (e.g., [Pearl, 1988; Bacchus, 1990]) is not such as to provide concrete technical tools for a logic as general as EL. Our current techniques consist mainly of probabilistic inference chaining, which is demonstrably sound under certain conditions. As well, the implementation applies a "noncircularity principle" which prevents the same knowledge from being used twice to "boost" the probability of a particular conclusion. Apart from this, independence assumptions are used where there are no known dependencies, and lower probabilities are manipulated in accord with the laws of probability. However, we lack a general theory for *combining evidence* for (or against) a given conclusion. Another remaining problem is inference control. Right now EPILOG terminates forward inference chains when either the probability or the "interestingness" of the inferred formulas becomes too low. We are convinced that "interestingness" is a crucial notion here, and that it must allow for context (salience) and for the inherent interestingness of both objects and predicates, and the interaction between these (e.g., an object should become more interesting if it is found to have interesting properties). We have experimented with such measures, but have not achieved uniformly satisfactory inference behavior.

The kinds of EL formulas we have shown are in principle derivable from surface structure by simple, Montague-like semantic rules paired with phrase structure rules. While developing a grammar and semantic rules that would cover most of English would be a very large undertaking, we have developed GPSG-like grammars to cover story fragments and (more ambitiously) sizable dialogs from the TRAINS domain [Allen & Schubert, 1991]. For some such fragments, as well as rules for mapping indexical LFs into nonindexical ELFs, see [Hwang, 1992; Hwang & Schubert, To appear]. The EPILOG implementation [Schaeffer *et al.*, 1991] of EL has been applied to small excerpts from the *Little Red Riding Hood* story, making complex inferences about causation [Schubert & Hwang, 1989]; and it reasons with telex reports for aircraft mechanical problems in a message processing application for the Boeing Commercial Airplane Reliability and Maintainability Project [Namioka *et al.*, In print; Hwang & Schubert, 1993b].

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