Interpreting Tense, Aspect and Time Adverbials: A Compositional, Unified Approach*

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Abstract

We extend our theory of English tense, aspect and time adverbials [Hwang and Schubert, 1992, 1993] to deal with a wider range of time adverbials, including many adverbials of frequency, cardinality, duration, and time span, and adverbials of temporal relation involving subordinating conjunctions such as *after, since,* and *until*. Our theory is fully formal in that it derives indexical (quasi-)logical forms from syntactic-semantic rule pairs of a formal grammar, and nonindexical logical forms via deindexing rules in the form of equivalences and equations. The grammar allows for complex sentences and the semantic rules and deindexing rules are easy to implement computationally, producing formulas in Episodic Logic.

1 Introduction: A Compositional Alternative to Reichenbach

Researchers concerned with higher-level discourse structure, e.g., Webber [1988], Passonneau [1988] and Song and Cohen [1991], have almost invariably relied on some Reichenbach [1947]-like conception of tense. The syntactic part of this conception is that there are nine tenses in English, namely *simple* past, present and future tense, past, present and future *perfect* tense, and *posterior* past, present and future tense (plus progressive variants). The semantic part of the conception is that each tense specifies temporal relations among exactly three times particular to a tensed clause, namely the event time (E), the reference time (R) and the speech time (S). On this conception, information in discourse is a matter of "extracting" one of the nine Reichenbachian tenses from each sentence, asserting the appropriate relations among E, R and S, and appropriately relating these times to previously introduced times, taking account of discourse structure cues implicit in tense shifts. While there is much that is right and insightful about Reichenbach's conception, the lumping together of tense and aspect is out of step with modern syntax and semantics, providing an unsatisfactory basis for a compositional account of intra- and intersentential temporal relations.

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In particular, we think that the uniform use of E, R, S triples rests on a very dubious basis: first, appeal is made to the intuition that in tensed perfects, there is an implicit reference time involved besides the time of speech and the time of the described event. Then, this extra reference time is also imported into the *simple* tenses, even though for these there is no analogous intuition about the presence of such a reference time. Then some systematic role is sought for these reference times, and different researchers find different uses for them. Often, the "reference time" for a simple past sentence is claimed to be the time of the event introduced by the *previous* sentence, which intuitively tends to be closely aligned with the new event time. But this glosses over the fact that people have quite different intuitions about perfect reference times and these past reference times. More importantly, it glosses over the fact that the *same* "event reference" relations that are felt to exist intersententially for simple pasts like "John picked up the phone. He called Mary" also exist for past perfects like "John had picked up the phone. He had called Mary." In both cases, the "calling" event is felt to be right after the picking up of the phone. But if the time of the "previously reported event" is to be treated as a "reference time" in simple pasts, it ought to be treated as a "reference time" in past perfects as well — in other words, past perfects should have *two* reference times (the perfect reference time and previous event reference time) besides the time of speech and event time! So by the same reasoning, should we then not have two extra reference times for simple tenses, as well?

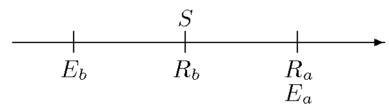
We think not — rather, we think that the presence of the extra reference time in tensed perfects is due to the presence of the extra *perf* operator (in addition to the *past* operator). More generally, we contend that English past, present, future and perfect are separate morphemes making separate contributions to syntactic structure and meaning. (Note that perfect *have*, like most verbs, can occur untensed; e.g., "She is likely to have left by now.") The corresponding operators *past, pres, futr,* and *perf* contribute separately and uniformly to the meanings of their operands, i.e., formulas at the level of logical form. Thus, for instance, the temporal relations implicit in "John will have left" are obtained not by extracting a "future perfect" and asserting relations among E, R and S, but rather by successively taking account of the meanings of the nested *pres, futr* and *perf* operators in the logical form of the sentence. As it happens, each of those operators implicitly introduces exactly one *episode*, yielding a Reichenbach-like result in this case. (But note: a simple present sentence like "John is tired" would introduce only *one* episode concurrent with the speech time, not two, as in Reichenbach's analysis.) Even more importantly for present purposes, each of *pres, past, futr* and *perf* is treated uniformly in deindexing and context change.[1]

Equally importantly, the clausal structure of sentences (or their logical forms) is not in general "flat," with a single level of constituents and features, but may contain multiple levels of embedding. This substructure can give rise to arbitrarily complex relations among the contributions made by the parts, such

[1] Well, almost uniformly; we think there are two variants of *perf* in English. There may also be *generic* variants of *pres* and *past*.

as temporal and discourse relations among subordinate clausal constituents and events or states of affairs they evoke. It is therefore essential that these intra-sentential relations be systematically brought to light and integrated with larger-scale discourse structures. Consider, for instance, the following passage.

(1) John will find this note when he gets home.
(2) He *will think*$_{(a)}$ Mary *has left*$_{(b)}$.



Reichenbach's analysis of (2) gives us $E_b < S, R_b < R_a, E_a$, where $t_1 < t_2$ means t_1 is before t_2, as shown above. That is, John will think that Mary's leaving took place some time before the speaker uttered sentence (2). This is incorrect; it is not even likely that John would know about the utterance of (2). In actuality, (2) only implies that John will think Mary's leaving took place some time before the time of his thinking, i.e., $S < R_a, E_a$ and $E_b < R_b, R_a$. Reichenbach's system fails to take into account the local context created by syntactic embedding. Attempts have been made to refine Reichenbach's theory (e.g., [Hornstein, 1977; Smith, 1978]), but we think these have generally not gone far enough in rebuilding the foundations.

We have developed a uniform, compositional approach to interpretation in which a parse tree leads directly (in rule-by-rule fashion) to a preliminary, *indexical* logical form (`LF`), and this `LF` is *deindexed* by processing it in the current *context* (a well-defined structure). The relevant context structures are called *tense trees*. Deindexing simultaneously transforms the `LF` and the context: context-dependent constituents of the `LF`, such as operators *past, pres* and *perf* and adverbs like *today* or *earlier*, are replaced by explicit relations among quantified *episodes*; (anaphora are also deindexed, but this is not discussed here); and new structural components and episode tokens (and other information) are added to the context. This dual transformation is accomplished by simple recursive equivalences and equalities. More specifically, they drive the generation and traversal of *tense trees* in deindexing. Our treatment of various kinds of time adverbials is fully compatible and integrated with the treatment of tense and aspect.

We describe tense trees in section 2 and tense-aspect deindexing rules in section 3. We then discuss our compositional approach to the interpretation of temporal adverbials in section 4, and an extension of our system that accommodates aspectual class shifts and the interaction between multiple temporal adverbials in section 5. Concluding remarks are in section 6.

2 Tense Trees

Tense trees provide that part of a discourse context structure which is needed to interpret (and deindex) temporal operators and modifiers within the logical form of English sentences. They differ from simple lists of Reichenbachian indices in that they organize episode tokens (for described episodes and the utterances themselves) in a way that *echoes the hierarchy of temporal and modal operators* of the sentences and clauses from which the tokens arose. Tense trees for successive sentences are "overlaid" in such a way that related episode tokens typically end up as adjacent elements of lists at tree nodes. For instance, tense trees allow the reference times/episodes of the perfect to be automatically identified. The traversal of trees and the addition of new tokens is simply and fully determined by the logical forms of the sentences being interpreted.

The major advantage of tense trees is that they allow simple, systematic interpretation (by deindexing) of tense, aspect, and time adverbials in texts consisting of arbitrarily complex sentences, and involving implicit temporal reference across clause and sentence boundaries. This includes certain relations implicit in the ordering of clauses and sentences. As has been frequently observed, for a sequence of sentences within the same discourse segment, the temporal reference of a sentence is almost invariably connected to that of the previous sentence in some fashion. Typically, the relation is one of temporal precedence or concurrency, depending on the *aspectual class* or *aktionsart* involved (cf., "John closed his suitcase; He walked to the door" *versus* "John opened the door; Mary was sleeping"). However, in "Mary got in her Ferrari. She bought it with her own money," the usual temporal precedence is reversed (based on world knowledge). Also, other discourse relations could be implied, such as *cause-of, explains, elaborates,* etc. Whatever the relation may be, finding the right pair of episodes involved in such relations is of crucial importance for discourse understanding. Echoing Leech [1987], we use the predicate constant `orients`, which subsumes all such relations. Note that the `orients` predications can later be used to make probabilistic or default inferences about the temporal or causal relations between the two episodes, based on their aspectual class and other information. We now describe tense trees more precisely.

The form of a tense tree is illustrated in Figure 1. As an aid to intuition, the nodes in Figure 1 are annotated with simple sentences whose indexical `LF`s would lead to those nodes in the course of deindexing. A tense tree node may have up to three branches—a leftward *past* branch, a downward *perfect* branch, and a rightward *future* branch. Each node contains a stack-like list of recently introduced episode tokens (which we will often refer to simply as episodes). In addition to the three branches, the tree may have (horizontal) *embedding links* to the roots of embedded tense trees. There are two kinds of these embedding links, both illustrated in Figure 1. One kind, indicated by dashed lines (with the label `mod-sub`), is created by subordinating constructions such as VPs with *that*-complement clauses. The other kind, indicated by dotted lines (and labelled `utt`), is derived from the surface speech act (e.g., telling, asking or requesting) implicit in the mood of a sentence.[2] On our view, the utterances of a speaker (or sentences of a text, etc.) are ultimately to be represented in terms of modal predications expressing these surface speech acts, such as [`Speaker` tell `Hearer` (That Φ)] or [`Speaker` ask `Hearer` (Whether Φ)]. `Speaker` and `Hearer` are indexical constants to be replaced by the speaker(s) and the hearer(s) of the utterance context. The two kinds of embedding links

[2] There is also a third kind of link (labelled `sub`), as will be shown in section 4.

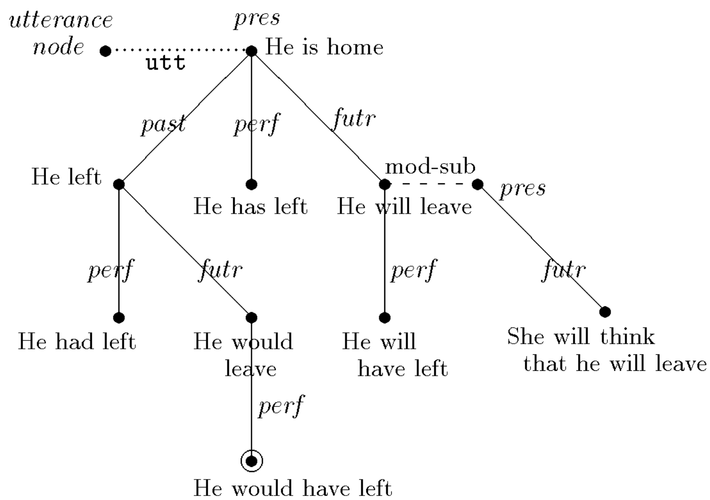


Figure 1. A Tense Tree

require slightly different tree traversal techniques as will be seen later.

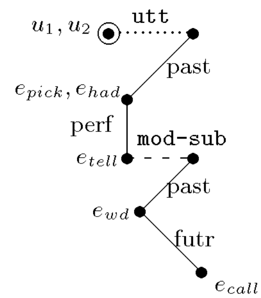
A set of trees connected by embedding links is called a *tense tree structure* (though we often refer loosely to tense tree structures as tense trees). At any time, exactly one node of the tense tree structure for a discourse is in focus, and the focal node is indicated by ⦿. Note that the "tense tree" in Figure 1 is in fact a tense tree structure, with the lowest node in focus. By default, an episode added to the right end of a list at a node is "oriented" by the episode which was previously rightmost. For episodes stored at different nodes, we can read off their temporal relations from the tree roughly as follows. At any given moment, for a pair of episodes e and e' that are rightmost at nodes n and n', respectively, where n' is a daughter of n, if the branch connecting the two nodes is a past branch, [e' before e][3]; if it is a perfect branch, [e' impinges-on e] (as we explain later in sections 3, this yields entailments [e' before e] if e' is bounded and [e' extends-to e] if e' is unbounded,[4] respectively illustrated by "John has left" and "John has been busy"); if it is a future branch, [e' after e]; and if it is an embedding link, [e' at-about e]. These orienting relations and temporal relations are not extracted *post hoc*, but rather are automatically asserted in the course of deindexing using the rules shown later.

As a preliminary example, consider the following passage and a tense tree annotated with episodes derived from it by our deindexing rules:

[3] Or, sometimes, *same-time* (cf., "John noticed that Mary *looked* pale" *vs.* "Mary realized that someone *broke* her vase"). This is not decided in an *ad hoc* manner, but as a result of systematically interpreting the context-charged relation $bef_{\mathbf{T}}$. More on this later.

[4] Technically, *boundedness* is defined for formulas, rather than episodes. However, we can also speak of bounded (or unbounded) episodes, namely those whose characterizing formulas are bounded (or unbounded).

(3) John picked up the phone.
(4) He had told Mary that he would call her.



u_1 and u_2 at the root node are utterance episodes for sentences (3) and (4) respectively. Intuitively, the temporal content of sentence (4) is that the event of John's *telling*, e_{tell}, took place *before* some time e_{had}, which is at the same time as the event of John's *picking* up the phone, e_{pick}; and the event of John's *calling*, e_{call}, is located *after* some time e_{wd}, which is the at the same time as the (past perfect) event of John's *telling*, e_{tell}. For the most part, this information can be read off directly from the tree: [e_{pick} orients e_{had}], [e_{tell} before e_{had}] and [e_{call} after e_{wd}]. In addition, the deindexing rules yield [e_{wd} same-time e_{tell}]. From this, one may infer [e_{tell} before e_{pick}] and [e_{call} after e_{tell}], assuming that the `orients` relation defaults to *same-time* here.

How does [e_{pick} orients e_{had}] default to [e_{pick} same-time e_{had}]? One of the most important features of our account is that the tendency of past perfect "reference time" to align itself with a previously introduced past event is just an instance of a general tendency of atelic episodes to align themselves with their orienting episode. This is the same tendency noted previously for "John opened the door. Mary was sleeping." In the present tense tree, e_{had} is an episode evoked by the past tense operator which is part of the meaning of *had* in (4). It is an *atelic* episode, since this past operator logically operates on a sentence of form (perf Φ), and such a sentence describes a *state* in which Φ has occurred—in this instance, a state in which John has told Mary that he will call her. It is this atelicity of e_{had} which (by default) leads to a *same-time* interpretation of `orients`.

We remarked that the relation [e_{wd} same-time e_{tell}] is obtained directly from the deindexing rules. We leave it to the reader to verify this in detail (see `Past` and `Futr` rules stated in section 3). We note only that e_{wd} is evoked by the past tense component of *would* in (4), and denotes a (possible) *state* in which John *will* call Mary. Its atelicity, and the fact that the subordinate clause in (4) is "past-dominated,"[5] causes [e_{wd} bef$_{\mathtt{T}}$ e_{tell}] to be deindexed to [e_{wd} same-time e_{tell}].

[5]A node is *past-dominated* if there is a *past* branch in its ancestry (where embedding links also count as ancestry links).

3 Deindexing with Tense Trees

We now discuss show how tense trees are modified as discourse is processed, in particular, how episode tokens are stored at appropriate nodes of the tense tree, and how context-independent, "deindexed" *episodic logical forms* (ELFs), with orients and temporal ordering relations incorporated into them, are obtained. The processing of the (indexical) LF of a new utterance always begins with the root node of the current tense tree (structure) in focus. The processing of the top-level operator immediately pushes a token for the surface speech act onto the episode list of the root node. A typical indexical LF (derivation of indexical LFs is discussed in section 4) looks like:

(*decl* (*past* (¬ [Mary answer]))) "*Mary did not answer.*"

(*decl* stands for *declarative*; its deindexing rule introduces the surface speech act of type "tell"). As mentioned earlier, our deindexing mechanism is a compositional one in which operators *past, futr, perf,* ¬*, That, decl,* etc., contribute separately to the meaning of their operands. As the LF is recursively transformed, the tense and aspect and modal operators encountered, *past, perf* and *futr*, in particular, cause the focus to shift "downward" along existing branches (or new ones if necessary). That is, processing a *past* operator shifts the current focus down to the left, creating a new branch if necessary. The resulting tense tree is symbolized as $\swarrow$T. Similarly *perf* shifts straight down, and *futr* shifts down to the right, with respective results $\downarrow$T and $\searrow$T. *pres* maintains the current focus. Certain operators embed new trees at the current node, written $\mapsto$T (e.g., *That*), or shift focus to an existing embedded tree, written $\hookrightarrow$T (e.g., *decl*). Focus shifts to a parent or embedding node are symbolized as $\uparrow$T and $\leftarrow$T respectively. As a final tree operation, $\circ$T denotes storage of episode token $e_{\mathtt{T}}$ (a new episode symbol not yet used in T) at the current focus, as rightmost element of its episode list. As each node comes into focus, its episode list and the lists at certain nodes on the same tree path provide explicit reference episodes in terms of which *past, pres, futr, perf,* time adverbials, and implicit "orienting" relations are rewritten nonindexically. Eventually the focus returns to the root, and at this point, we have a deindexed ELF, as well as a modified tense tree.

Before we proceed with deindexing rules, we need to mention some basic features of EL, our semantic representation. In EL we take it that utterances characterize situations or episodes, and central to EL are the two episodic operators "*" and "**". Roughly, $[\Phi * \eta]$ means that Φ is true in episode η (or, Φ describes η), and $[\Phi ** \eta]$ means that Φ, and only Φ, is true in episode η (or, Φ characterizes η).[6] As mentioned, each of the deindexing rules for tense-aspect operators introduces an episode into the logical form and predicates that the episode is *characterized* ("**") by the operand (after recursive deindexing). (Use of "*" will be seen later when deindexing of adverbials is discussed.) The

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[6] Like "situations", "episodes" is a generic term that may stand for events, states, processes, eventualities, etc. Operators similar to our episodic ones are the "support" relation ($\eta \models \Phi$) in situation semantics [Barwise, 1989] and the eventuality "type" condition (η: $\boxed{\Phi}$) in DRT [Kamp and Reyle, 1993].

square-bracketed, infixed form is the preferred sentence syntax in **EL**. In general, $[\tau_n \ \pi \ \tau_1 \ldots \tau_{n-1}]$ is an equivalent way of writing $(\pi \ \tau_1 \ldots \tau_n)$, which is in turn equivalent to $(\ldots((\pi \ \tau_1)\tau_2) \ldots \tau_n)$. Also used in **EL** are restricted quantifiers of form $(Q\alpha{:}\, \Phi\, \Psi)$, where Q is a quantifier, α is a variable, and restriction Φ and matrix Ψ are formulas. For details of syntax and semantics of **EL**, see [Hwang, 1992; Hwang and Schubert, 1993]. We now show some of the basic deindexing rules.[7]

$\texttt{Decl:}$ $(\text{decl } \Phi)_{\mathrm{T}} \leftrightarrow (\exists e_{\mathrm{T}}{:}[[e_{\mathrm{T}} \text{ same-time } \texttt{Now}_{\mathrm{T}}] \wedge [\texttt{Last}_{\mathrm{T}} \text{ immediately-precedes } e_{\mathrm{T}}]]$
$[[\texttt{Speaker} \text{ tell } \texttt{Hearer} \ (\text{That } \Phi_{\hookrightarrow \circ \mathrm{T}})] \ ** \ e_{\mathrm{T}}])$

Tree transformation: $(\text{decl } \Phi) \bullet \mathtt{T} = \leftarrow \ (\Phi \bullet (\hookrightarrow \circ \mathtt{T}))$

$\texttt{Pres:}$ $(\text{pres } \Phi)_{\mathrm{T}} \leftrightarrow (\exists e_{\mathrm{T}}{:}[[e_{\mathrm{T}} \text{ at-about } \texttt{Emb}_{\mathrm{T}}] \wedge [\texttt{Last}_{\mathrm{T}} \text{ orients } e_{\mathrm{T}}]] \ [\Phi_{\circ \mathrm{T}} \ ** \ e_{\mathrm{T}}])$

Tree transformation: $(\text{pres } \Phi) \bullet \mathtt{T} = (\Phi \bullet (\circ \mathtt{T}))$

$\texttt{Past:}$ $(\text{past } \Phi)_{\mathrm{T}} \leftrightarrow \exists e_{\mathrm{T}}{:}[[e_{\mathrm{T}} \text{ bef}_{\mathrm{T}} \ \texttt{Emb}_{\mathrm{T}}] \wedge [\texttt{Last}_{\swarrow \mathrm{T}} \text{ orients } e_{\mathrm{T}}]] \ [\Phi_{\circ \swarrow \mathrm{T}} \ ** \ e_{\mathrm{T}}])$

Tree transformation: $(\text{past } \Phi) \bullet \mathtt{T} = \uparrow (\Phi \bullet (\circ \swarrow \mathtt{T}))$

$\texttt{Futr:}$ $(\text{futr } \Phi)_{\mathrm{T}} \leftrightarrow (\exists e_{\mathrm{T}}{:}[[e_{\mathrm{T}} \text{ after } \texttt{Emb}_{\mathrm{T}}] \wedge [\texttt{Last}_{\searrow \mathrm{T}} \text{ orients } e_{\mathrm{T}}]] \ [\Phi_{\circ \searrow \mathrm{T}} \ ** \ e_{\mathrm{T}}])$

Tree transformation: $(\text{futr } \Phi) \bullet \mathtt{T} = \uparrow (\Phi \bullet (\circ \searrow \mathtt{T}))$

$\texttt{Perf:}$ $(\text{perf } \Phi)_{\mathrm{T}} \leftrightarrow (\exists e_{\mathrm{T}}{:}[[e_{\mathrm{T}} \text{ impinges-on } \texttt{Last}_{\mathrm{T}}] \wedge [\texttt{Last}_{\downarrow \mathrm{T}} \text{ orients } e_{\mathrm{T}}]] \ [\Phi_{\circ \downarrow \mathrm{T}} \ ** \ e_{\mathrm{T}}])$

Tree transformation: $(\text{perf } \Phi) \bullet \mathtt{T} = \uparrow (\Phi \bullet (\circ \downarrow \mathtt{T}))$

$\texttt{That:}$ $(\text{That } \Phi)_{\mathrm{T}} \leftrightarrow (\text{That } \Phi_{\mapsto \mathrm{T}})$

Tree transformation: $(\text{That } \Phi) \bullet \mathtt{T} = \leftarrow \ (\Phi \bullet (\mapsto \mathtt{T}))$

As mentioned earlier, `Speaker` and `Hearer` in the `Decl`-rule are to be replaced by the speaker(s) and the hearer(s) of the utterance. Note that each equivalence pushes the dependence on context one level deeper into the **LF**, thus deindexing the top-level operator. The symbols $\texttt{Now}_{\mathrm{T}}$, $\texttt{Last}_{\mathrm{T}}$ and $\texttt{Emb}_{\mathrm{T}}$ refer respectively to the speech time for the most recent utterance in `T`, the last-stored episode at the current focal node, and the last-stored episode at the current embedding node. When no such stored episodes exist for $\texttt{Last}_{\mathrm{T}}$, certain other episodes may be substituted for $\texttt{Last}_{\mathrm{T}}$; and within certain subtrees, $\texttt{Emb}_{\mathrm{T}}$ is interpreted as the embedding node of the "superordinate tree" (see section 4.3). As already mentioned, bef_{T} in the `Past`-rule will be replaced by either *before* or *same-time*, depending on the aspectual class of its first argument and on whether the focal node of `T` is past-dominated. In the `Perf`-rule, $\texttt{Last}_{\mathrm{T}}$ becomes the analogue of the Reichenbachian reference time for the perfect. The *impinges-on* relation confines its first argument e_{T} (the situation or event described by the sentential operand of *perf*) to the temporal region preceding the second argument. As in the case of `orients`, its more specific import depends on the aspectual types of its arguments. If e_{T} is a state or process, *impinges-on* implicates that it persists to the reference time/episode, i.e., $[e_{\mathrm{T}} \text{ extends-to } \texttt{Last}_{\mathrm{T}}]$. If e_{T} is an event (e.g., an accomplishment), *impinges-on* entails that it occurred sometime

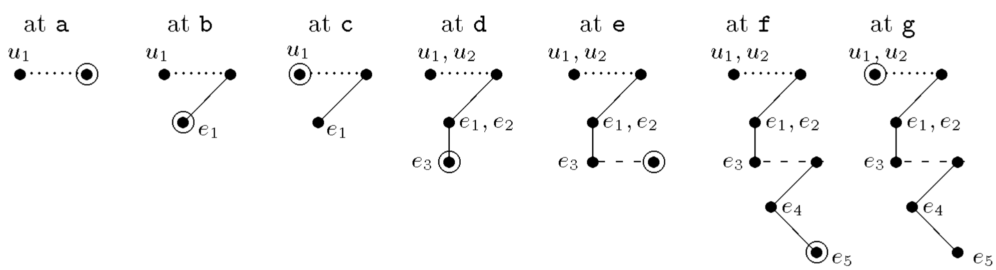
[7]See [Hwang, 1992] for the rest of our deindexing rules. Some of the omitted ones are: `Fpres` ("futural present," as in "John has a meeting tomorrow"), `Prog` (progressive aspect), `Pred` (predication), `K`, `K1`, `Ka` and `Ke` ("kinds"), those for deindexing various operators such as *negation*, etc. Deindexing rules for adverbials are in section 4.

before the reference time/episode, i.e., [e_T before $\texttt{Last}_T$], and implicates that its main effects persist to the reference time.

To see the deindexing mechanism at work, let us consider sentences (3) and (4) again. The LFs before deindexing are shown in (3a,4a) below (where the labelled arrows mark points we will refer to); the final, context-independent ELFs are in (3b,4b). The transformation from (a)'s to (b)'s and the corresponding tense tree transformations are done with the deindexing rules shown earlier. Anaphoric processing is presupposed here. The snapshots of the tense tree while processing (3a) and (4a) with a null initial context, at points ↑a –↑g, are shown below the formulas.

(3) John picked up the phone.
  a. (decl ↑a (past ↑b [John pick-up Phone])) ↑c
  b. (∃ u1:[u1 same-time *Now1*]
    [[*Speaker* tell *Hearer* (That
      (∃ e1:[e1 before u1] [[John pick-up Phone] ** e1]))]
    ** u1])

(4) He had told Mary that he would call her.
  a. (decl (past (perf ↑d [John tell Mary (That ↑e (past (futr ↑f [John call Mary]))))]))) ↑g
  b. (∃ u2:[[u2 same-time *Now2*] ∧ [u1 immediately-precedes u2]]
    [[*Speaker* tell *Hearer* (That
      (∃ e2:[[e2 before u2] ∧ [e1 *orients* e2]]
        [(∃ e3:[e3 impinges-on e2]
          [[John tell Mary (That
            (∃ e4:[e4 same-time e3]
              [(∃ e5:[e5 after e4] [[John call Mary] ** e5])
              ** e4]))]
          ** e3])
        ** e2]))]
    ** u2])



What is important here is, first, that Reichenbach-like relations are introduced compositionally. In addition, the recursive rules take correct account of embedding. For instance, the embedded "past-future" in (4) is correctly interpreted as future relativized to John's (past) telling time. But beyond that, episodes evoked by successive sentences, or by embedded clauses within the same sentence, are correctly connected to each other. In particular, note that the orienting relation between John's picking up the phone, e1, and the reference time e2 for the telling event is automatically incorporated into the deindexed formula (4b). Thus we have established inter-clausal connections automatically, which in other approaches require heuristic discourse processing. This was a primary motivation for tense trees.

The `orients` relation is essentially an indicator that there could be a more specific discourse relation between the argument episodes. As mentioned, it can usually be particularized to one or more temporal, causal, or other "standard" discourse relations. Existing proposals for getting these discourse relations right appear to be of two kinds. The first uses the aspectual classes of the predicates involved to decide on discourse relations, especially temporal ones, e.g., [Partee, 1984; Dowty, 1986; Hinrichs, 1986]. The second approach emphasizes inference based on world knowledge, e.g., [Lascarides and Asher, 1993]. Our approach fully combines the use of aspectual class information and world knowledge. For example, in "Mary got in her Ferrari. She bought it with her own money," the successively reported "achievements" are by default in chronological order. Here, however, this default interpretation of `orients` is reversed by world knowledge: one owns things *after* buying them, rather than before. But sometimes world knowledge is mute on the connection. For instance, in "John raised his arm. A great gust of wind shook the trees," there seems to be no world knowledge supporting temporal adjacency or a causal connection. Yet we tend to infer both, perhaps attributing magical powers to John (precisely because of the lack of support for a causal connection by world knowledge). So in this case default conclusions based on `orients` seem decisive. In particular, we would assume that if e and e' are achievements or accomplishments, where e is the performance of a volitional action and e' is not, then [e orients e'] suggests [e right-before e'] and (less firmly) [e cause-of e'].[8]

The tense tree mechanism, and particularly the way in which it automatically supplies orienting relations, is well suited for longer narratives, including ones with tense shifts. For example, in (5) below (from [Allen, 1987] with slight simplification), even though {b–d} would normally be considered a subsegment of the main discourse {a, e}, both the temporal relations *within* each segment and the relations *between* segments (i.e., that the substory temporally precedes the main one) are automatically captured by our rules. For instance, e_1, e_{10} and e_{11} are recognized as successive episodes, both preceded at some time in the past by e_3, e_5, e_7, and e_9, in that order.

(5) a. Jack and Sue went$_{\{e_1\}}$ to a hardware store
b. as someone had$_{\{e_2\}}$ stolen$_{\{e_3\}}$ their lawnmower.
c. Sue had$_{\{e_4\}}$ seen$_{\{e_5\}}$ a man take it and had$_{\{e_6\}}$ chased$_{\{e_7\}}$ him down the street,
d. but he had$_{\{e_8\}}$ driven$_{\{e_9\}}$ away in a truck.
e. After looking$_{\{e_{10}\}}$ in the store, they realized$_{\{e_{11}\}}$ that they couldn't afford a new one.

[8] Our approach to plausible inference in EL in general, and to such default inferences in particular, is probabilistic.

That is not to say that our tense tree mechanism obviates the need for larger-scale discourse structures. For example, many subnarratives introduced by a past perfect sentence may continue in simple past. That is, if *past* is followed by *past*, the latter could be either a continuation of the current perspective and segment (see 6a,b below), or a perspective shift with opening of a new segment (see 6b,c), or closing of the current segment, with resumption of the previous perspective (see 6c,d).

(6) a. Mary found that her favorite vase was broken.
b. She was upset.
c. She bought it at a special antique auction,
d. and she was afraid she wouldn't be able to find anything that beautiful again.

Only plausible inference can resolve these ambiguities. This inference process will interact with resolution of anaphora and introduction of new individuals, identification of spatial and temporal frames, the presence of modal/cognition/perception verbs, and most of all will depend on world knowledge. See [Hwang and Schubert, 1992] for our approaches to this general difficulty.

4 Syntax and Semantics of Time Adverbials

We have shown that tense and aspect can be analyzed compositionally in a way that accounts not only for their more obvious effects on sentence meaning but also, via tense trees, for their cumulative effect on context and the temporal relations implicit in such contexts. We now move on to temporal adverbials.

Previous theoretical work on temporal adverbials has mostly concentrated on adverbials specifying temporal locations (e.g., "yesterday"), durations (e.g., "for a month") and time spans (e.g., "in three hours"). It appears that interest in the first kind of adverbial originated from the desire to correct the erroneous analyses provided by Priorean tense logics (see [Prior, 1967; van Benthem, 1988]), in particular, their treatment of the interaction between time adverbials and tense (see, for example, [Dowty, 1982; Hinrichs, 1988]). The second and third kinds of adverbials were often considered in connection with the aspectual classes of the VPs or sentences those adverbials modify (e.g., durative adverbials may modify only atelic sentences, whereas adverbials of time span may modify only accomplishment sentences). However, other kinds of temporal adverbials have received little attention, including ones specifying *repetition*:

The engineer shut down the motor *twice* yesterday.
The engine *frequently* broke down.
The operator checked the level of oil *every half hour*.
The inspector visits the lab *every Monday*.

On our analysis, these sentences describe complex events, consisting of a sequence of subevents of specified types, and the given adverbials modify the structure of these complex events: the cardinality of component events ("twice"), the frequency or distribution pattern of component events ("frequently," "regularly," "every hour," etc.), and the temporal location of cyclic events that occur synchronously with other recurrent time frames or events ("every Monday" or "every time the alarm went off").

Other issues that are rarely addressed are the interactions between multiple temporal adverbials, and various kinds of aspectual class shift due to aspectual class constraints on the use of adverbials (occurring singly or jointly with others). The following sentences illustrate these issues.

John ran *for half an hour every morning for a month.*
John stepped out of his office *for fifteen minutes.*
Mary is going to Boston *for three days.*
Mary won the competition *for four years.*
John saw Mary *twice in two years.*

Our aim in this section is to provide a uniform analysis for a wide range of temporal adverbials. Our approach is compositional in that the lexicon supplies meanings at the word level (or possibly at the morpheme level, e.g., for '-ly' adverbs), and the meanings of adverbials are computed from the lexical entries by our GPSG-like grammar rules. The grammar rules take care of aspectual compatibility of adverbials with the VPs they modify. The resulting indexical `LF` is then deindexed by a set of recursive rules. The resultant `ELF` is formally interpretable and lends itself to effective inference. We now show logical form representations of temporal adverbials, in both indexical and deindexed form, and how to obtain them from the surface structure, together with a brief discussion of semantics.

4.1 The Basic Mechanism

We first discuss the basic interpretive mechanism, using *yesterday* as an example, and then generalize to other types of temporal adverbials. As indicated in the following fragment of a GPSG-like sentence grammar, we treat all adverbial adjuncts as VP-adjuncts at the level of syntax. (Aspectual feature agreement is assumed, but not discussed till section 5.)

NP $\leftarrow$ *Mary*; Mary
V[1bar, past] $\leftarrow$ *left*; <past leave>
VP $\leftarrow$ V[1bar]; V$'$
VP $\leftarrow$ VP ADVL[post-VP]; (ADVL$'$ VP$'$)
S $\leftarrow$ NP VP; [NP$'$ VP$'$]

However, despite this surface syntax, the semantic rule (ADVL$'$ VP$'$), specifying functional application of the ADVL-translation to the VP-translation, may lead to either predicate modification or sentence modification at the level of immediate logical form. In particular, manner adverbials (e.g., *with a brush, hastily,* etc.) are uniformly interpreted as predicate modifiers at the level of immediate `LF`, while temporal (and locative) adverbials are all interpreted as sentence modifiers. How such sentence-modifier interpretations are formed from VP adjuncts is easily seen from rules such as the following:

NP[def-time] $\leftarrow$ *yesterday*; *Yesterday*
PP[post-VP] $\leftarrow$ NP[def-time]; (during NP′)
ADVL $\leftarrow$ PP[e-mod, post-VP]; λPλx((adv-e PP′) [x P]).

(`adv-e` stands for 'episode-modifying adverbial'.[9]) From these rules it is clear that the logical translation of *yesterday*, as an adverbial adjunct, is

λPλx((adv-e (during *Yesterday*)) [x P]).

In the interpretation of a sentence such as "Mary left yesterday," this λ-abstract would be applied to predicate `leave` (initially paired with unscoped tense operator `past`), yielding

λx((adv-e (during *Yesterday*)) [x <past leave>]),

and this in turn would be applied to term `Mary` (translating the NP *Mary*), yielding

((adv-e (during *Yesterday*)) [Mary <past leave>]).

Here, (during *Yesterday*) is a 1-place predicate (the result of applying the 2-place predicate `during` to the indexical constant *Yesterday*, allowable in the "curried function" semantics of `EL`). `adv-e` maps this 1-place predicate into a *sentence* modifier; i.e., (adv-e (during *Yesterday*)) denotes a function from sentence meanings to sentence meanings. In the present case, the operand is the sentence [Mary <past leave>].

The above indexical `LF` is obtained quite directly as a byproduct of parsing, and is subsequently further processed — first, by scoping of ambiguously scoped quantifiers, logical connectives, and tense operators, and then by applying deindexing rules, which introduce explicit episodic variables into the LF, and temporally relate these based on tense operators, temporal adverbials, and tense trees. Tense operators are generally assumed to take wide scope over adverbials in the same clause. Thus, after scoping, we get

(past ((adv-e (during *Yesterday*)) [Mary leave])).

Since the deindexing rules "work their way inward" on a given indexical `LF`, starting with the outermost operator, the past tense operator in the sentence under consideration will already have been deindexed when the `adv-e` construct is encountered. In fact we will have

($\exists e_1$: [e_1 before u_1]
[((adv-e (during *Yesterday*)) [Mary leave])$_{\mathtt{T}}$ ** e_1]),

where, u_1 denotes the utterance event for the sentence concerned, and `T` denotes the current tense tree. At this point the following deindexing rule for `adv-e` is brought to bear:

For π a monadic predicate, and Φ a formula,
`adv-e`: ((adv-e π) Φ)$_{\mathtt{T}} \leftrightarrow [^{\vee}\pi_{\mathtt{T}} \wedge \Phi_{\pi\cdot\mathtt{T}}]$
Tree transformation: ((adv-e π) Φ) $\cdot$ `T` = $\Phi \cdot (\pi \cdot \mathtt{T})$

[9] Certain feature principles are assumed in the grammar — namely, certain versions of the head feature principle, the control agreement principle, and the subcategorization principle. Notice that in our system, features are treated as trees; e.g., the subtree rooted by feature `mod-vp` has daughters `pre-vp` and `post-vp`, and the subtree rooted by feature `e-mod` has daughters `temp-loc`, `dur`, `time-span`, `freq`, `card`, `cyc-time`, etc., where `temp-loc` in turn has daughters `def-time`, `indef-time`, etc.

This rule essentially splits the formula into a conjunction of two subformulas: one for the adverbial itself, the other for the sentence modified by the adverbial, much as in Dowty's system [1982]. Now the expression $^{\vee}\pi_{\mathtt{T}}$ on the RHS of the deindexing rule for **adv-e** is a sentential formula (formed from predicate $\pi_{\mathtt{T}}$) which can be read as "$\pi_{\mathtt{T}}$ *is true of the current episode* (*i.e., the one at which* $^{\vee}\pi_{\mathtt{T}}$ *is evaluated*)." In view of this, the combination $[[^{\vee}\pi_{\mathtt{T}} \wedge \Phi_{\pi\cdot\mathtt{T}}] ** \eta]$ is equivalent to $[[[\eta\ \pi_{\mathtt{T}}] \wedge \Phi_{\pi\cdot\mathtt{T}}] ** \eta]$. Note that $\pi_{\mathtt{T}}$ is now predicated directly of episode η. In the example above, we obtain

$(\exists e_1 \colon [e_1 \text{ before } u_1]$
$\quad [[[e_1 \text{ during } \mathit{Yesterday}_{\mathtt{T}}] \wedge [\text{Mary leave}]] ** e_1]),$

and this leaves only $\mathit{Yesterday}_{\mathtt{T}}$ to be deindexed to a specific day (that is, $(\mathit{yesterday\text{-}rel\text{-}to}\ u_1)$).

To make the semantics of '$^{\vee}$', '$*$' and '$**$' a little more precise, we mention two clauses from the truth-conditional semantics of **EL**:

1. For Φ a formula, and η a term,
   $[\![\Phi * \eta]\!]^s = 1$ only if $\mathit{Actual}([\![\eta]\!], s)$ and $[\![\Phi]\!]^{[\![\eta]\!]} = 1$;
   $\quad = 0$ only if $\mathit{Nonactual}([\![\eta]\!], s)$ or $[\![\Phi]\!]^{[\![\eta]\!]} \neq 1$,
   where these conditionals become biconditionals (iffs) and "$\neq 1$" becomes "$= 0$" for s an *exhaustive* (informationally maximal) situation.
2. For $s \in \mathcal{S}$, and π a predicate over situations,
   $[\![^{\vee}\pi]\!]^s = [\![\pi]\!]^{s,s}$, i.e., $[\![\pi]\!](s)(s)$,
   where $\mathcal{S}$ is the set of possible situations.

Also, a few relevant axioms are (for π, π' 1-place predicates, η a term, and Φ a formula):

$\Box\ [\Phi ** \eta] \leftrightarrow [[\Phi * \eta] \wedge \neg(\exists e \colon [e \text{ proper-subep-of } \eta]\,[\Phi * e])]$
$\Box\ [^{\vee}\pi \wedge {}^{\vee}\pi'] \leftrightarrow {}^{\vee}\lambda e[[e\ \pi] \wedge [e\ \pi']]$
$\Box\ [[^{\vee}\pi \wedge \Phi] ** \eta] \leftrightarrow [[[\eta\ \pi] \wedge \Phi] ** \eta]$

4.2 Adverbials of Duration, Time-span, and Repetition

Like adverbials of temporal location, durative adverbials are also translated as (**adv-e** π). For instance, "John slept for two hours" becomes (with tense neglected)

((adv-e (lasts-for (**K** ((num 2) (plur hour))))) [John sleep]).

Like **during**, **lasts-for** is a 2-place predicate. Here it has been applied to a term (**K**...), leaving a 1-place predicate.[10] Just as in the case of (during *Yesterday*), the deindexed LF will contain a predication stating that the episode characterized by *John sleeping* lasts for two hours. Time-span adverbials (as in "John ran the race *in two hours*") are treated in much the same way, using predicate **in-span-of**.

[10] The details of (**K**...), denoting the abstract kind of quantity, two hours, need not concern us here.

The translation of cardinal and frequency adverbials involves the sentence-modifying construct (**adv-f** π). π is a predicate which applies to a *collection* of temporally separated episodes. It may describe the cardinality of the episodes or their frequency (i.e., their relative density), periodicity or distribution pattern. So, for instance, we have

((adv-f ((num 2) (plur episode))) [John see Movie])

for "John saw the movie twice," and

((adv-f ((attr frequent) (plur episode))) [John call Mary])

for "John called Mary frequently." (**num** is an operator that maps numbers into predicate modifiers, and **plur** ('*plural*') is a function that maps predicates applicable to individuals into predicates applicable to collections. **attr** ('*attributive*') is an operator that maps predicates into predicate modifiers.) Table 1 shows lexical rules and PP and ADVL rules handling large classes of frequency adverbials, including periodic ones such as *every two hours* and synchronized cyclic ones such as *every spring*.

The deindexing rule for **adv-f** is as follows:

For π a monadic predicate, and Φ a formula,
adv-f: $((\text{adv-f } \pi)\ \Phi)_{\mathtt{T}} \leftrightarrow [{}^{\vee}\pi_{\mathtt{T}} \wedge (\text{mult } \Phi_{\pi \cdot \mathtt{T}})]$
Tree transformation: $((\text{adv-e } \pi)\ \Phi) \cdot \mathtt{T} = \Phi \cdot (\pi \cdot \mathtt{T})$

As illustrated in Table 1, π could take various forms. **mult** on the RHS side of the rule is a function that transforms sentence intensions, and is defined as follows.

For η an episode, and Φ a formula,

$$\Box\ [(\text{mult } \Phi) ** \eta] \leftrightarrow [[\eta \text{ (plur episode)}] \wedge (\forall e{:}[e \text{ member-of } \eta]\ [[\Phi ** e] \wedge \neg (\exists e' [[e' \neq e] \wedge [e' \text{ member-of } \eta] \wedge [e' \text{ overlaps } e]])])]$$

Sentences (7)–(9) below illustrate the rules stated in Table 1. The (a)-parts are the English sentences, the (b)-parts their immediate indexical **LF**s, and the (c)-parts the deindexed **ELF**s. (7c) says that "some time before the utterance event, there was a 2 month-long (multi-component) episode, that consists three episodes of type 'John date Mary'." (8c) reads as "there was a 10 day-long episode that consists of periodically occurring subepisodes of type 'John take medicine', where the period was 4 hours." (9c) is understood as "at the generic present there is a collection of episodes of type 'Mary swim', such that during each Saturday within the time spanned by the collection,[11] there is such an episode."

(7) a. Mary visited Paris *three times in two months*.
b. (past ((adv-e (in-span-of (**K** ((num 2) (plur month)))))
((adv-f ((num 3) (plur episode))) [Mary visit Paris])))

[11] This constraint on the Saturdays under consideration is assumed to be added by the deindexing process for time- or event-denoting nominals, but has been omitted from (9c).

Table 1: GPSG Fragment

`% VP Adjunct Rules`

ADVL $\leftarrow$ PP[e-mod, post-VP] ; λPλx((adv-e PP$'$) [x P])
ADVL $\leftarrow$ ADV[e-mod, mod-VP] ; λPλx(ADV$'$ [x P])
VP $\leftarrow$ VP ADVL[mod-vp] ; (ADVL$'$, VP$'$)

`% Temporal ADV, PP Rules`

NP[def-time] $\leftarrow$ *yesterday* ; *Yesterday*
PP[post-VP] $\leftarrow$ NP[def-time] ; (during NP$'$)
e.g., yesterday$'$ = λPλx((adv-e (during *Yesterday*)) [x P])

N[time-unit, plur] $\leftarrow$ *hours*; (plur hour)
ADJ[number, plur] $\leftarrow$ *two*; (num 2)
N[1bar, time-length] $\leftarrow$ ADJ[number] N[time-unit] ; (ADJ$'$ N$'$)
NP $\leftarrow$ N[1bar, time-length] ; (`K` N$'$)
P[dur] $\leftarrow$ *for* ; lasts-for
P[span] $\leftarrow$ *in* ; in-span-of
PP[e-mod, post-VP] $\leftarrow$ P NP[time-length] ; (P$'$ NP$'$)
e.g., for two hours$'$ = λPλx((adv-e (lasts-for (`K` ((num 2) (plur hour))))) [x P])
e.g., in two hours$'$ = λPλx((adv-e (in-span-of (`K` ((num 2) (plur hour))))) [x P])

ADV[card, post-VP] $\leftarrow$ *twice*; (adv-f ((num 2) (plur episode)))
ADV[freq, mod-VP] $\leftarrow$ *frequently*; (adv-f ((attr frequent) (plur episode)))
ADV[freq, mod-VP] $\leftarrow$ *periodically*; (adv-f ((attr periodic) (plur episode)))
ADV[freq, post-VP] $\leftarrow$ Det[every] N[1bar, time-length] ;
(adv-f λs[[s ((attr periodic) (plur episode))] $\wedge$ [(period-of s) = (`K` N$'$)]])
e.g., twice$'$ = λPλx((adv-f ((num 2) (plur episode))) [x P])
e.g., frequently$'$ = λPλx((adv-f ((attr frequent) (plur episode))) [x P])
e.g., every two hours$'$ = λPλx((adv-f λs[[s ((attr periodic) (plur episode))] $\wedge$
[(period-of s) = (`K` ((num 2) (plur hour)))]]) [x P])

N[indef-time] $\leftarrow$ *spring*; spring
NP[cyc-time] $\leftarrow$ Det[every] N[1bar, indef-time] ; <Det$'$ N$'$>
PP[post-VP] $\leftarrow$ NP[cyc-time] ; (during NP$'$)
ADV $\leftarrow$ PP[cyc-time, post-VP] ; (adv-f λs($\exists e$ [[e member-of s] $\wedge$ [e PP$'$]]))
e.g., every spring$'$ = λPλx((adv-f λs($\exists e$ [[e member-of s] $\wedge$ [e during <$\forall$ spring>]]))
[x P])

c. $(\exists\, e_2\!: [e_2 \text{ before } u_2]$
$[[[e_2 \text{ in-span-of } (\mathtt{K}\,((\text{num } 2)\,(\text{plur month})))] \wedge [e_2\ ((\text{num } 3)\,(\text{plur episode}))] \wedge$
$(\text{mult } [\text{Mary visit Paris}])] \;{*}{*}\; e_2])$

(8) a. John took medicine *every four hours for ten days.*

b. $(\text{past } ((\text{adv-e } (\text{lasts-for } (\mathtt{K}\,((\text{num } 10)\,(\text{plur day})))))$
$((\text{adv-f } \lambda s\, [[s\ ((\text{attr periodic})\ (\text{plur episode}))] \wedge$
$[(\text{period-of } s) = (\mathtt{K}\,((\text{num } 4)\,(\text{plur hour})))]])$
$[\text{John take } (\mathtt{K} \text{ medicine})])))$

c. $(\exists\, e_4\!: [e_4 \text{ before } u_4]$
$[[[e_4 \text{ lasts-for } (\mathtt{K}\,((\text{num } 10)\,(\text{plur day})))] \wedge [e_4\ ((\text{attr periodic})\,(\text{plur episode}))] \wedge$
$[(\text{period-of } e_4) = (\mathtt{K}\,((\text{num } 4)\,(\text{plur hour})))] \wedge (\text{mult } [\text{John take } (\mathtt{K} \text{ medicine})])]$
${*}{*}\; e_4])$

(9) a. Mary swims *every Saturday.*

b. $(\text{gpres } ((\text{adv-f } \lambda s (\forall d\!: [d \text{ Saturday}]\ (\exists e\, [[e \text{ member-of } s] \wedge [e \text{ during } d]])))$
$[\text{Mary swim}]))$

c. $(\exists e_5\!: [e_5 \text{ gen-at } u_5]$
$[[(\forall d\!: [d \text{ Saturday}](\exists e\, [[e \text{ member-of } e_5] \wedge [e \text{ during } d]])) \wedge$
$(\text{mult } [\text{Mary swim}])] \;{*}{*}\; e_5])$

We have a tentative account of adverbials such as *consecutively* and *alternately*, but cannot elaborate within the present space limitations. We also set aside certain well-known problems involving temporal adverbials in perfect sentences, such as the inadmissibility of *"John has left yesterday" (for a possible approach, see [Schubert and Hwang, 1990]), and now move on to clausal adverbials.

4.3 SINCE, UNTIL and AFTER: Clausal Adverbials

Since and *until* provide a time "frame" which the episode described by the main clause spans (at least if that main clause is atelic). More specifically, *since* and *until* connect an episode characterized by the main clause to a time indicated by the subordinate clause (or PP) such that the latter specifies the beginning and the end point the episode respectively. For instance, in

"Mary has been taking care of John's dog *since* he went off to college,"[12]

the since-clause specifies that the episode of Mary's taking care of John's dog started at the time John went off to college, and in

"Mary kept silent *until* John had had his say,"

the until-clause specifies the (earliest) time of John's *having* had his say as the end point of Mary's episode of being silent.[13] On the other hand, *before* and *after* do not provide a time frame but simply specify the temporal ordering between the episodes described by the main and subordinate clauses. In this subsection, we discuss the treatment of adverbial clauses headed by connectives

[12]Despite this example and a later one, we do not consider progressives in detail here. Progressives involve syntactic complications as well as appeal to a reference time at the semantics/discourse level, where that reference time is constrained to be within the progressive episode. (It can be "picked" from the tense tree much like other reference times.)

[13]Thus, it is strongly implied that Mary was no longer silent as soon as John finished speaking. However, such an implicature of until-clauses is cancellable as the following example illustrates: "Mary was fine at least until I left."

like *since*, *until* and *after*, which can also serve as temporal prepositions. We do not discuss *while* and *when*, which are not derived from prepositions (but a similar treatment is possible). We also omit discussion of *before*, which requires a slightly more complicated treatment as it can be used hypothetically (even in the past tense), as in "The police arrived before the burglars could run away."

Here are lexical and phrase structure rules we use.

P[since] ← *since*; since
P[until] ← *until*; until
P[after] ← *after*; after
PCONJ[_S[fin]] ← P[pc-temp];
$\lambda S \lambda e$[e P′ <The-earliest λt(sub ((adv-e (at-time t)) S))>]
ADVL[post-VP] ← PCONJ[pc-temp] S[fin];
$\lambda P \lambda x$((adv-e (PCONJ′ S′)) [x P])

In the PCONJ rule, feature `pc-temp` ("p-to-conj") is to distinguish CONJ-convertible temporal prepositions from the rest of the temporal prepositions such as *at, for,* etc. The semantic part of the PCONJ rule essentially analyses a phrase of form "since/until/after **S**" as equivalent to "since/until/after the (earliest) time at which **S**." Note that this is a relative-clause analysis of the implicit temporal reference. Thus if the episode corresponding to the main clause is **e**, the adverbial will assert that "**e** is since/until/after the earliest time at which **S** is true." `sub` ("`sub`ordinate") is a sentence operator which is semantically trivial (i.e., an identity operator) but forms a scope island. It is intended to be used for explicit relative clauses as well as in the present case. It also functions as a cue for the deindexer to embed a new tree for the subordinate adverbial clause, as will be seen shortly. `The-earliest` is a definite quantifier much like `The`, except that it strongly (but defeasibly) implicates "earliest."

We regard the entailments of the relational predicate *since* as dependent on the aspectual category of the first argument. For an atelic first argument (as in "The company has thrived since Mary took over"), *since* means "starting at the (earliest) time at which ..." For a telic first argument (as in "John has graduated since you last saw him"), *since* means "after." One might ask how this could account for the implicatures of a sentence like

"Mary has visited John three times since he moved to California."

Here it seems that Mary has visited John three times *only*. We think that the answer lies in the implicatures of cardinal modifiers and of the *impinges* relation we use in the analysis of the perfect. Note that "Mary visited John three times *after* he moved to California" also implicates that he visited her three times *only*. The additional implicature in the present perfect version (due to "impingement" of the three-and-only-three visits on the present reference time) is that the result state of the three-and-only-three visits — viz., that three-and-only-three visits took place — still obtains at present.

A well-known property of *since* is that it requires the main clause to be a perfect sentence. Semantically, though, it appears that since-clauses operate not on the perfect VP or sentence as a whole but rather on "the underlying nonperfect VP" (in Kamp and Reyle's [1993] phrase). In our compositional rule-by-rule approach, we can ensure the right semantics by having since-adverbials combine with phrases of category VP[-en] (a VP headed by a past participle). The underlying VP[-en] is usually atelic (e.g., it would be odd in most contexts to say "Mary bought a book since last December"), but does not have to be as was seen above. In contrast, until-adverbials are normally used with atelic VPs (more exactly, "unbounded" ones — see section 5).

I plan to stay here *until* tomorrow/*until* you return.
*I plan to finish the paper *until* tomorrow/*until* you return.
I plan to finish the paper *by* tomorrow/*by the time* you return.

We now refine the VP rule shown in Table 1 to reflect these properties of *since* and *until*. (*Before* and *after* do not require special rules.)

VP ← VP[-en] ADVL[since]; (ADVL′ VP′)
VP ← VP[unbounded] ADVL[until]; (ADVL′ VP′)

For deindexing of adverbial clauses, we assume that the `sub` operator triggers creation of an embedded subtree, much as in the case of that-clauses. Note that there is a slight difference between adverbial clauses and that-clauses. That-clauses signal modal subordination, and the "anchoring" time for them is that of the embedding VP (usually, an attitude VP). As *since*, *until* and *after* signal non-modal subordination, we take the anchoring time for the tense of the subordinate clause to be the same as the anchoring time for the superordinate clause. For instance, in "John arrived after Mary had waited for an hour," the anchoring time for the subordinate clause is the speech time, rather than the arrival-time, and this allows the perfect to be oriented by the arrival-time (as intuitively required). Thus, we use a slightly different kind of embedding link, '= = =', with the label `sub`, which interprets the embedding node ($\mathtt{Emb}_{\mathtt{T}}$) as the "next-highest" embedding node (typically, the "utterance node" at the main tense tree), rather than the immediate embedding node. We now show the relevant deindexing rule.

For Φ a formula,
`sub`: $(\mathrm{sub}\ \Phi)_{\mathtt{T}} \leftrightarrow \Phi_{\Rightarrow\mathtt{T}}$
Tree transformation: $(\mathrm{sub}\ \Phi) \bullet \mathtt{T} = \leftarrow(\Phi \bullet \Rightarrow\mathtt{T})$

'⇒' indicates: build a new tree, embed it at the current focal node with a double link (i.e., a `sub` link), and move the focus to the root node of the newly embedded tree. Note that the deindexing rule peels off the (semantic) identity operator `sub` from the logical form. We now illustrate the deindexing mechanism using sentence (10) below which we have seen already.

(10) *Mary has been taking care of John's dog since he went off to college.*

With the rules introduced earlier, the adverbial clause "since he [John] went off to college" is translated into

λPλx((adv-e λe[e since <The-earliest
λt(sub ((adv-e (at-time t)) [John <past go-college>]))>]) [x p]).

This applies to the nonperfect VP "been taking care of John's dog," yielding

```
λx((adv-e λe[e since <The-earliest
        λt(sub ((adv-e (at-time t)) [John <past go-college>]))>])
                (prog [x take-care-of Dog])).
```

Applying the perfect auxiliary "has" (λPλx<pres (perf [x P])>) to this and then incorporating the rest of the sentence (i.e., the subject and the punctuation) and scoping the unscoped operators, we get the following indexical logical form for the entire sentence.

```
(decl (pres (perf
        ((adv-e λe(The-earliest t:(sub (past ((adv-e (at-time t)) [John go-college]))))
                                        [e since t]))
    (prog [Mary take-care-of Dog])))))
```

Deindexing is straightforward, and the resultant deindexed **EL** formula shown below can be easily verified.

```
(∃ u1:[u1 same-time Now1]
   [[Speaker tell Hearer (That
     (∃ e1:[[e1 at-about u1] ∧ [e9 orients e1]]
       [(∃ e2:[[e2 impinges-on e1] ∧ [e10 orients e2]]
          [[∨λe(The-earliest t1: (∃ e3:[[e3 before u1] ∧ [e11 orients e3]]
                                     [[∨(at-time t1) ∧ [John go-college]] ** e3])
                                 [e since t1]) ∧
           (prog [Mary take-care-of Dog])]
          ** e2])
       ** e1]))]
    ** u1])
```

Since we did not provide a context for (10), the deindexer introduces dummy episodes $(e9, e10, e11)$ as orienting episodes. These episodes could be resolved against appropriate episodes later if more information becomes available. Finally, by meaning postulates, we get the following logical form.

```
(∃ u1:[u1 same-time Now1]
   [[Speaker tell Hearer (That
     (∃ e1:[[e1 at-about u1] ∧ [e9 orients e1]]
        [(∃ e2:[[e2 impinges-on e1] ∧ [e10 orients e2]]
           [[(The-earliest t1: (∃ e3:[[e3 before u1] ∧ [e11 orients e3]]
                                  [[[e3 at-time t1] ∧ [John go-college]] ** e3])
                            [e2 since t1]) ∧
            (prog [Mary take-care-of Dog])]
           ** e2])
        ** e1]))]
    ** u1])
```

This formula says that there is a perfect episode $e1$ which lies at the end of episode $e2$ (Mary's taking care of John's dog); and $e2$ is "since" the earliest time

t at which an event $e3$ of John's going off to college occurred. Note that [e2 impinges-on e1] implies [e2 extends-to e1] (so that $e1$ is at the end of $e2$), as the underlying formula (*prog* [*Mary take-care-of Dog*]) is unbounded.

Below are more sample sentences and their logical forms, followed by some remarks. (For brevity, we omit some orienting relations in the deindexed formulas, and use simplified translations for some irrelevant complex expressions.)

```
(11) a. John has moved to California since Mary met him last.
     b. (decl (pres (perf ((adv-e λe(The-earliest t1:(sub (past ((adv-e (at-time t1))
                                                          [Mary meet-last John])))
                                                  [e since t1])) [John move-to-CA]))))
     c. (∃u1:[u1 same-time Now1]
          [[Speaker tell Hearer (That
            (∃e1:[e1 at-about u1]
              [(∃e2:[e2 impinges-on e1]
                 [[(The-earliest t1:(∃e3:[e3 before u1] [[[e3 at-time t1] ∧
                                         [Mary meet-last John]] ** e3])
                                  [e2 since t1]) ∧
                   [John move-to-CA]] ** e2])
               ** e1]))]
          ** u1])
(12) a. Mary has visited John three times since he moved to California.
     b. (decl (pres (perf ((adv-e λe(The-earliest t1: (sub (past ((adv-e (at-time t1))
                                                           [John move-to-CA])))
                                                   [e since t1]))
                 ((adv-f ((num 3) (plur episode))) (mult [Mary visit John]))))))
     c. (∃u1:[u1 same-time Now1]
           [[Speaker tell Hearer (That
             (∃e1:[e1 at-about u1]
               [(∃e2:[e2 impinges-on e1]
                  [[(The-earliest t1:(∃e3:[e3 before u1] [[[e3 at-time t1] ∧
                                          [John move-to-CA]] ** e3])
                                   [e2 since t1]) ∧
                    [e2 ((num 3) (plur episode))] ∧ (mult [Mary visit John])] ** e2])
                ** e1]))]
           ** u1])
(13) a. Mary had been fine until she had eaten the cake.
     b. (decl (past (perf ((adv-e λe(The-earliest t1:(sub (past ((adv-e (at-time t1))
                                                          (perf [Mary eat Cake]))))
                                                  [e until t1]))) [Mary fine]))))
     c. (∃u1:[u1 same-time Now1]
          [[Speaker tell Hearer (That
            (∃e1:[[e1 before u1] ∧ [e9 orients e1]]
              [(∃e2:[[e2 impinges-on e1] ∧ [e10 orients e1]]
                 [[(The-earliest t1:(∃e3:[[e3 before u1] ∧ [e11 orients e3]]
                                       [[[e3 at-time t1] ∧
                                         (∃e4:[[e4 impinges-on e3] ∧ [e12 orients e4]]
                                             [[Mary eat Cake] ** e4])] ** e3])
                                  [e2 until t1]) ∧
```

```
                [Mary fine]] ** e2])
             ** e1]))]
         ** u1])
```

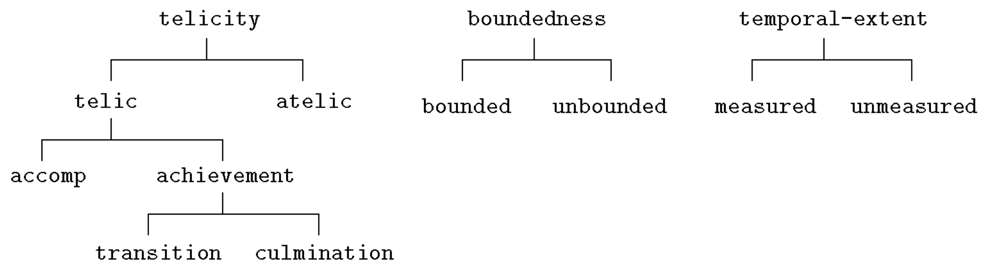
(14) a. John arrived after Mary had left.

```
b. (decl (past ((adv-e λe(The-earliest t1: (sub (past ((adv-e (at-time t1))
                                                      (perf [Mary leave]))))
                                           [e after t1])) [John arrive]))))
c. (∃ u1:[u1 same-time Now1]
      [[Speaker tell Hearer (That (∃ e1:[e1 before u1]
          [[(The-earliest t1:(∃ e2:[e2 before u1] [[[e2 at-time t1] ∧
                                (∃ e3:[[e3 impinges-on e2] ∧ [e11 orients e3]]
                                    [[Mary leave] ** e3])] ** e2])
                         [e1 after t1]) ∧
             [John arrive]] ** e1]))]
       ** u1])
```

Formula (11b) says that e2 (the event of John's moving) is "since" t, i.e., the time at which Mary met him last, and "impinges-on" $e1$, i.e., the present time. Since the characterization of $e2$, [John move-to-CA], is *transition*, the context-charged relation [e2 impinges-on e1] implies that the *result state* of $e2$ holds until the time of $e1$. Thus, we can infer that John moved to California some time after Mary met him last and that he is still living in California. Note that the main clause in (12) describes a complex episode whose temporal extent is a multi-interval (that is, the actual times at which the component episodes take place may not be consecutive). And it is this multi-interval that lies in the time frame provided by the since-clause and the present. Formula (13b) says that the episode of Mary's being fine, e1, lasted until the earliest such time at which the cake-eating event can be described as perfect (i.e., the moment she finished eating the cake). Thus, it is strongly implicated that the end points of the cake-eating event and the being-fine state were concurrent and that quite likely Mary was no longer fine right after the eating event. Note that the definite quantifier `The-earliest` makes possible this interpretation. Notice next the orienting relation [e10 orients e2] in (13b). Since an adverbial clause is deindexed with respect to a *new* embedded tree, there is no orienting episode for $e2$ which would serve as a reference time for the perfect. Thus, the deindexer supplies an unidentified episode ($e10$ in this case) for the orienting relation. During the subsequent "ampliative" inference stage, this $e10$ is then identified with $e1$. Note that we do *not* force the reference time of a subordinate perfect clause uniformly to be identical with the event time of the main clause, in view of sentences like "Mary arrived two hours after John had left." We omit discussion of example (14).

5 Temporal Adverbials & Aspectual Class Shifts

So far, we have assumed aspectual category agreement between temporal adverbials and VPs they modify. We now discuss our aspectual class system and our approach to apparent aspectual class mismatch between VPs and adverbials, based on certain aspectual class transformations. We make use of three aspectual class feature hierarchies, `telicity`, `boundedness` and `temporal-extent` as below:



Untensed sentences may be telic or atelic, depending on the type of the predicate (e.g., achievement/accomplishment versus state/process predicates) and on the object and subject (e.g., count versus mass).[14] Sentences or predicates describing achievements or accomplishments are assigned the feature `telic`, while those describing states or processes are assigned the feature `atelic`. Examples of accomplishment VPs are *write a book* and *blink*; transition predicates are *step out, turn off, go to, become, wake up,* etc.; and culmination VPs are *reach the top, win the race,* etc. Intuitively, a formula is `bounded` if the episode it characterizes terminates in a distinctive result state (result states are formally defined in [Hwang, 1992].) That is, episodes with a bounded characterization have a definite end point (in virtue of their characterization), while ones with an unbounded characterization do not. By a co-occurrence restriction, telic formulas are bounded. Atelic formulas are *by default* unbounded. Some atelic episodes are bounded such as an episode of John's being ill, at the end of which he is *not* ill. For instance, *was ill* in "John was ill when I saw him last week" is unbounded as the sentence does not entail that John was not ill right after the described episode. However, when we say "John was ill twice last year," we are talking about bounded "ill" episodes. The `temporal-extent` feature has to do with whether a VP contains a durative adverbial (e.g., *for-* or *throughout-*) or an adverbial of time-span (e.g., *in-*), i.e., whether the temporal extent of an episode is indicated in its characterization. to the persistence of a formula. (E.g., unmeasured atelic formulas are inward persistent (modulo granularity) in general, while telic ones are outward persistent.) See [Hwang, 1992] for further discussion.

As has been discussed by many authors (e.g., in [Moens and Steedman, 1988; Mourelatos, 1981; Vendler, 1967]), VPs and temporal adverbials may not arbitrarily combine. Normally, durative adverbials combine with atelic VPs; cardinal and frequency adverbials with bounded VPs; and adverbials of time-span with

[14] Every tensed English sentence, e.g., "Mary left before John arrived," in combination with a *context*, is considered `factual`, where `factual` features are ascribed to atemporal (or, unlocated) sentences whose truth value does not change over space and time. We neglect the `factual` feature in this paper.

telic VPs. Thus, for instance,

> Mary studied *for an hour.*
> *Mary finished the homework *for a second.*
> Mary called John *twice* | *repeatedly* | *every five minutes.*
> Mary wrote the paper *in two weeks.*

Note, however, that we also say

> Mary sneezed *for five minutes.*
> Mary stepped out of her office *for five minutes.*
> Mary was ill *twice* | *repeatedly* | *every two months.*

The latter group of sentences show that VPs often acquire an interpretation derived from their original, primitive meaning. More specifically, when cardinal, frequency or cyclic adverbials are applied to telic VPs, usually iteration is implied, as in the first sentence. However, in the case of the second sentence, which involves a transition verb, the preferred reading is one in which the adverbial specifies the duration of the resultant episode, i.e., "the *result state* of Mary's stepping out of her office" (i.e., her being *outside* of her office). When cardinal or frequency adverbials (i.e., "bounded" adverbials) are applied to unbounded-atelic VPs, those VPs are interpreted as bounded-atelic. Thus, the third sentence above means that the kind of episode in which Mary becomes ill and then ceases to be ill occurred twice, repeatedly, etc.

To be able to accommodate such phenomena, the syntactic parts of our grammar use `telicity` and `boundedness` as head features. The semantic parts introduce, as needed, operators for aspectual class transformation such as *result-state*, *iter* (iteration), *temporarily* (bounded), etc. (In place of *iter*, we may sometimes use a habitual operator, *H*.)

Adverbials of temporal location like *yesterday* or *last week* may combine with either bounded or unbounded formulas: with bounded ones, these imply a *sometime during* reading; with unbounded ones, by default, a *throughout* reading if they are `unmeasured`, and a *sometime during* reading if they are `measured`. For instance, in "John left last month," the "leaving" episode took place *sometime during* last month, but in case of "Mary was ill for two weeks last month," Mary's "ill" episode is considered to be *sometime during* last month. Synchronized cyclic adverbials like *every spring* or *every time I saw Mary* may combine with either bounded or unbounded and either measured or unmeasured formulas.

Secondly, an application of certain temporal adverbials often induces shifts in the aspectual classes of the resultant VPs. Frequency adverbials and synchronized cyclic ones yield atelic, unmeasured VPs, while while durative adverbials always yield measured VPs. Thus,

> John {{*was ill twice*} *in three years*}.
> ?John {{*was ill twice*} *for three years*}.
> John {{*was frequently ill*} *for three years*}.
> ?John {{*was frequently ill*} *in three years*}.
> John {{*worked for five hours*} *three times*} last week.

We now rewrite the VP adjunct rules introduced earlier to accommodate the interaction between VPs and adverbials and possible shifts in aspectual classes.[15] We also show VP rules that perform aspectual class shifts. Keep in mind that aspectual class features, **telicity**, **bounded**, and **temporal-extent**, are head features, and so are shared between mother and daughter VPs except when explicitly overridden.

$$\begin{array}{l}
\mathrm{VP[measured]} \leftarrow \mathrm{VP[atelic, unmeasured]\ ADVL[dur]}\,;\ (\mathrm{ADVL'\ VP'}) \\
\mathrm{VP[measured]} \leftarrow \mathrm{VP[telic,unmeasured]\ ADVL[span]}\,;\ (\mathrm{ADVL'\ VP'}) \\
\mathrm{VP[accomplishment]} \leftarrow \mathrm{VP[bounded]\ ADVL[card]}\,;\ (\mathrm{ADVL'\ VP'}) \\
\mathrm{VP[atelic, unmeasured]} \leftarrow \mathrm{VP[bounded]\ ADVL[freq]}\,;\ (\mathrm{ADVL'\ VP'}) \\
\mathrm{VP[atelic, unmeasured]} \leftarrow \mathrm{VP\ \ ADVL[cyc\text{-}time]}\,;\ (\mathrm{ADVL'\ VP'})
\end{array}$$

$$\begin{array}{l}
\mathrm{VP[bounded]} \leftarrow \mathrm{VP[atelic]}\,;\ (\mathrm{temporarily\ VP'}) \\
\mathrm{VP[atelic, unmeasured]} \leftarrow \mathrm{VP[bounded]}\,;\ (\mathrm{iter\ VP'}) \\
\mathrm{VP[atelic, unmeasured]} \leftarrow \mathrm{VP[transition]}\,;\ (\mathrm{result\text{-}state\ VP'})
\end{array}$$

These rules allow transitions in aspectual class and VP-adverbial combinations somewhat too liberally. We assume, however, that undesirable transitions and combinations may be ruled out on semantic grounds. We now show some additional sentences and their initial translations (with speech acts neglected) to illustrate some of the above rules.

(15) a. Mary was ill twice in December
b. (past ((adv-e (during (in-time *December*)))
((adv-f ((num 2) (plur episode))) [Mary (*bounded* ill)])))

(16) a. Mary received an award for three years
b. (past ((adv-e (lasts-for (K ((num 3) (plur year)))))
[Mary (*iter* $\lambda x(\exists y{:}\,[y$ award$]\,[x$ receive $y]))$]))

6 Concluding Remarks

We have shown that tense and aspect can be analyzed compositionally in a way that accounts not only for their more obvious effects on sentence meaning but also, via tense trees, for their cumulative effect on context and the temporal relations implicit in such contexts. Our scheme is easy to implement, and has been successfully used in the TRAINS interactive planning advisor at Rochester [Allen and Schubert, 1991].

Much theoretical work has been done on temporal adverbials (e.g., [Dowty, 1982; Hinrichs, 1988; Kamp and Reyle, 1993; Mittwoch, 1988; Moltmann, 1991; Richards and Heny, 1982]). There is also some computationally oriented work. Moens and Steedman[1988], among others, discussed the interaction of adverbials and aspectual categories. Our work goes further, in terms of (1) the scope of syntactic coverage, (2) interaction of adverbials with each other and with tense and aspect, (3) systematic (and compositional) transduction from syntax

[15] Similar kinds of shift in aspectual classes have previously been discussed in the literature; e.g., in [Steedman, 1982; Moens and Steedman, 1988; Smith, 1991].

to logical form (with logical-form deindexing), (4) formal interpretability of the resulting logical forms, and (5) demonstrable use of the resulting logical forms for inference.

Remaining work includes analysis of participial and infinitival adverbials and adverbials involving implicit anaphoric referents. Consider, e.g., "John came back *in ten minutes*" and "*After three years*, John proposed to Mary." These adverbials involve an implicit reference episode. Such implicit referents may often be identified from our tense trees, but at other times require inference. Another important remaining issue is handling of event nominals; e.g., "Mary is angry about the accident. The other driver had been drinking", where the event nominal *accident* serves as reference episode for the subsequent perfect. The interaction between event nominals and frequency adjectives (along the lines of [Stump, 1981]) also calls for further investigation.

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