TENSE, QUANTIFIERS, AND CONTEXTS

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This paper describes a compositional semantics for temporal expressions as part of the meaning representation language (MRL) of the JANUS system, a natural language understanding and generation system under joint development by BBN Labs and ISI. The analysis is based on a higher-order intensional logic described in detail in Hinrichs (1987a). Temporal expressions of English are translated into this language as quantifiers over times that bind temporal indices on predicates. The semantic evaluation of time-dependent predicates is defined relative to a set of discourse contexts, which, following Reichenbach (1947), include the parameters of speech time and reference time. The resulting context-dependent and multi-indexed interpretation of temporal expressions solves a set of well-known problems that arise when traditional systems of tense logic are applied to natural language semantics. Based on the principle of rule-to-rule translation, the compositional nature of the analysis provides a straightforward and well-defined interface between the parsing component and the semantic-interpretation component of JANUS.

1 INTRODUCTION

JANUS is a natural language understanding and generation system that allows the user to interface with several knowledge bases maintained by the U.S. Navy. The knowledge bases contain, among other things, information about the deployment schedules, locations, and readiness conditions of the ships in the Pacific Fleet.

1. a. Did the admiral deploy the ship?
   b. List all ships as of 4-1-86.
   c. Which C3 ships are now C4?
   d. When will Vincent arrive in Hawaii?
   e. Who was Frederick's previous commander?
   f. Every admiral has to deploy a ship today.

As the sample queries in (1) demonstrate, much of this information is highly time-dependent: ships change locations in accordance with their deployment schedules. They can incur equipment failures or undergo personnel changes. Such events, in turn, can affect the ships' readiness ratings, which are expressed by codes such as C3 or C4. Much of the information that the JANUS user is trying to access is time-dependent in that an appropriate answer can be given only if the time of the query and/or the time of the events in question are taken into account. It is, therefore, imperative that at the level of semantic representation of the natural language input an adequate analysis can be provided for those linguistic expressions that carry time information: for example, tenses, temporal adverbials, and temporal adjectives.

The rest of this paper is organized as follows: In Section 2, I will sketch the basic ideas of the framework of logical semantics, or more specifically, of Montague Grammar, the framework that I will use for my analysis. Section 2 also gives a brief overview of the conceptual modularity of the JANUS system, which demonstrates how Montague Grammar as a linguistic theory can be applied in natural-language processing research. In sections 3–8, I will address the subject matter of temporal semantics itself. My own analysis of temporal semantics is very much a response to the kinds of analyses that have been provided in classical tense logic. Section 3, therefore, provides a brief overview of analyses of the latter type. In Section 4, I will review some well-known problems that arise when one applies classical tense logics to the semantics of natural language. In Section 5, I will show how a logic with multiple indices that is based on Reichenbach's analysis of English tense can overcome most of the problems that standard tense logic cannot. While this richer logic will solve most of our problems, the issue of tense and noun-phrase (NP)

quantification does require additional refinements of the analysis. Section 6 will show how giving narrow scope to tense quantifiers enables us to provide adequate scope relations with respect to NP quantifiers. In addition, I will show how a contextual analysis of nouns and noun phrases lets us account for the kind of temporal phenomena that were first discussed in Enc 1981, 1986. In Section 7, I argue that the context-dependent feature of the analysis does not add extra complexity to my treatment of time-dependent expressions, but is needed for purposes of discourse understanding in general. Finally, I will demonstrate in Section 8 how the narrow scope of tense also leads to a compositional syntax and semantics of tensed sentences in English.

2 THE SEMANTIC FRAMEWORK

The semantic theory that I have adopted in my research is that of truth-conditional semantics. More specifically, I have adopted the framework of Montague Grammar, a version of truth-conditional semantics that has been developed by the logician Richard Montague (cf. Montague 1973).[1] Montague Grammar shares the fundamental assumption of all truth-conditional theories of meaning, namely that natural language semantics has to relate in a systematic fashion linguistic expressions such as words, phrases, and sentences to nonlinguistic, real-world objects, events, and states of affairs. In particular, a semantic theory has to provide a rigorous definition of the truth conditions for the sentences of a language. The emphasis in Montague Grammar lies on the descriptive aspect of language use. Sentences say something true or false about the world. For a speaker to know the meaning of a sentence amounts to knowing what state of affairs has to obtain in the world, in order for the sentence to be true.

In a Montague Grammar the meanings of sentences, phrases, and words are interpreted relative to a model that assigns meanings of the appropriate type to such linguistic entities. In his papers Montague develops various instantiations of his theory. The one that is most commonly used by linguists is the one that Montague (1973) uses in his paper "The Proper Treatment of Quantification in Ordinary English" (commonly abbreviated as **PTQ**). In that paper Montague associates meanings with linguistic expressions in an indirect fashion. As shown in Figure 1, syntactic expressions of English are first translated into a language of higher-order intensional logic, which in turn is interpreted model-theoretically. This indirect method of semantic interpretation obeys Frege's Principle of Compositionality, which says that the meaning of a complex phrase is a function of two things: (1) the meanings of its constituent parts, and (2) the way in which these parts are syntactically combined. Formally speaking, the meaning of a complex expression is the homomorphic image of its syntactic composition. In more practical
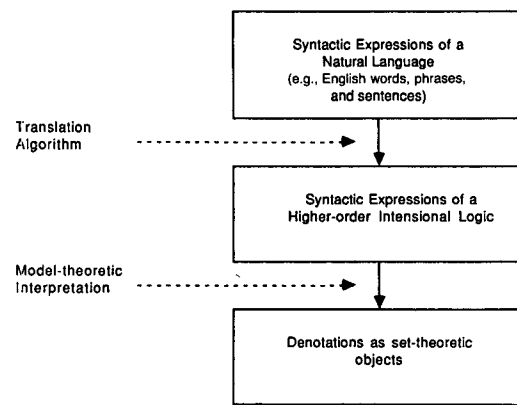

Figure 1. Montague Grammar—Syntax and Semantics.

terms, a translation procedure from English into intensional logic that is based on Frege's Principle has to specify two things: (1) for each lexical item, the procedure has to specify a translation into the appropriate type of the logic, and (2) for each syntactic rule, the procedure has to specify how the translations of the input constituents combine in the translation for the output constituent of the syntactic rule.

Montague Grammar provides a simple and elegant interface between the syntactic and semantic components of a grammar. Since each syntactic operation is mirrored by a semantic operation, semantic interpretation is in a sense syntax-driven. Moreover, syntactic analysis and semantic interpretation can proceed in parallel: while a sentence or phrase is being parsed in accordance with the syntactic rules, its logical form can be computed by the translation rules. This inherent parallelism is one of the features that makes Montague Grammar an attractive theory for natural language processing. Everything else being equal, a system in which syntax and semantics can operate in parallel is computationally more efficient than one in which they have to operate sequentially.

Another attractive feature is the strict modularity between syntax and semantics. Modularity is not only good practice in software engineering, it is particularly important in building natural language interfaces. If one wants to extend the coverage of the grammar of a given system, one wants to do so in an incremental fashion and without having to modify the control structure between major components. Montague Grammar allows one to upscale a system in this way: in order to extend the coverage of the grammar, one simply writes additional syntactic rules and translation rules that cover the new data.

Apart from these methodological considerations, it turns out that the same three components (syntax, translation, and model-theoretic interpretation) that are of importance in Montague's theory form an integral part in the functional components of natural language interface systems such as JANUS.[2] Figure 2 shows that
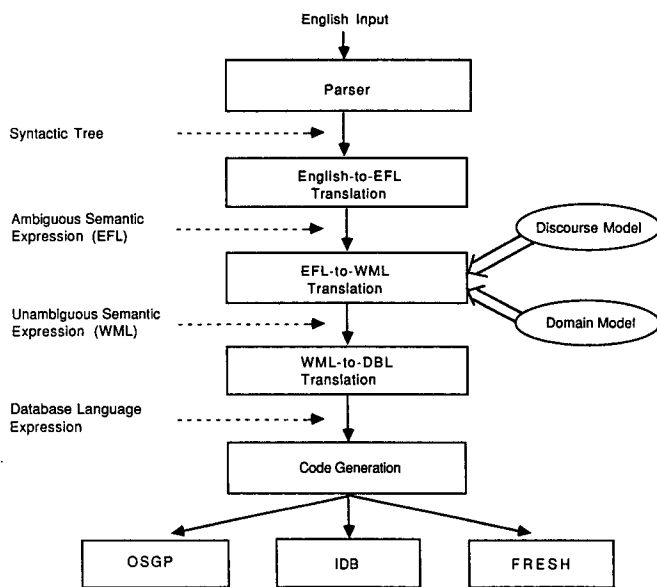
Figure 2. Components of JANUS.

the English input is fed into the syntactic parser of JANUS, which yields as output a parse tree, which in turn forms the input to the translation component. The translation component generates some logical expression that represents the meaning of the English input. This logical expression is then evaluated with respect to the database, which one can take to be a proxy for a partial model of the real world, in the case of JANUS a model of the objects and states of affairs pertaining to the Pacific Fleet.

The translation component of JANUS is somewhat more elaborate than the one Montague 1973 formulates. At the first level of translation, every lexical item of English is translated into some logical expression of an English-oriented formal language called **EFL**. At the EFL level, no attention is given to the context that may contribute to the interpretation of the English input. Neither is any attempt made at the EFL level to disambiguate lexical meanings. Lexical disambiguation is provided by a domain model, which, among other things, captures all the information about lexical meanings known to the system.[3]

Apart from domain knowledge, the system keeps track of those aspects of a user's question-answer session that are relevant for determining the reference of context-dependent queries such as (2).

2. a. Question: Where were the carriers yesterday?
   b. Answer: In the Indian Ocean.
   c. Question: How long have they been there?

The discourse model contains parameters such as the time at which the question-answer session is taking place. This parameter is necessary to calculate the referent of deictic time adverbials such as *yesterday* in (2a). In addition, the discourse model keeps track of

locations such as the Indian Ocean and referents of noun phrases such as *the carriers* in order to interpret locational adverbs such as *there* and anaphoric pronouns such as *they* in (2c).

Input from the domain model and the discourse model leads to translation to a **world-model language** (WML), which in turn is translated into expressions of the query language of the appropriate knowledge base: a database IDB, an expert system FRESH, or a display knowledge base OSGP. In this paper I will for the most part concentrate on the level of syntax to EFL translation, although the context-dependent aspects of my treatment of temporal semantics will lead to some discussion of the discourse model of JANUS in sections 6 and 7 below.

3 APPLYING CLASSICAL TENSE LOGIC TO NATURAL LANGUAGE SEMANTICS

With this much of an introduction, let me now turn to the topic of temporal semantics itself. My own analysis is very much a response to the kinds of analyses that have been provided in classical tense logic. When I refer to classical tense logic, I mean the kinds of logics that originate in the work of the logician Arthur Prior (cf. Prior 1967) and that have subsequently been applied to natural language semantics (cf. Montague 1973 and Mott 1973).

In classical tense logic time-dependency of information enters into the definition of the notion of a **proposition**. Propositions are defined as functions from a set of times (TI) to the set of truth values (T—"true") and (F—"false"). Declarative sentences of natural language are taken to express propositions. The sentence *It is raining* can be taken to be that proposition that yields the value true for those times at which it is raining, and false for those at which it is not.

Tense operators can be defined in such a logic as in (3) and (4). Formula 3 defines a past operator P, which, applied to a proposition p, yields the value true for some time t if p is true at some time t' prior to t. Likewise, (4) defines a Y operator, where Y is mnemonic for *yesterday*, with the expected truth conditions: Yp is true at t if p is true at some time t' that falls within the day prior to the day in which t falls.

3. $[P\ p]_t = T$ iff $[p]_{t'} = T$ for some time $t' < t$.

4. $[Y\ p]_t = T$ iff $[p]_{t'} = T$ for some time $t' \subseteq [DAY\ (t) - 1]$.

All of this sounds rather plausible. However, it turns out that if one tries to apply tense operators such as P and Y in natural-language semantics, a set of well-known problems arises.[4]

4. Inadequacies of Classical Tense Logic

4.1 Interaction of Tense and Time Adverbials

The first such problem, which I pointed out in Hinrichs 1981 and which was independently noted in Dowty 1982, concerns the interaction between tense and time adverbials. If for Sentence 5, one interprets the past tense in (5) by the P operator and the adverbial *yesterday* by the Y operator, then one of the two operators has to have scope over the other.

5. Vincent left yesterday.

6. P [Y [leave' (Vincent')]]

7. Y [P [leave' (Vincent')]]

However, neither the formula in (6), nor the one in (7) gives adequate truth conditions for (5). The truth conditions imposed by (6) are inadequate, since the sentence in (5) would, for example, count as true when uttered on January 15, 1988, if the ship Vincent left not on January 14, 1988, but instead on May 23, 1986. This is because the P operator can shift the temporal evaluation of the proposition *Y [leave' (Vincent')]* from the speech time to any past time (t''), for example to some time (t'') on May 24, 1986. In this case the Y operator will, in turn, shift evaluation to t' within the day prior to t'', i.e., to some time on May 23, 1986. Hence the proposition *leave' (Vincent')* will be evaluated with respect to that day, instead of the day prior to the speech time.

Formula 7 can assign wrong truth conditions as well. Here the Y operator shifts evaluation to some time within the day prior to the speech time. But the P operator, in turn, shifts evaluation to some time prior to that, but necessarily not within the same day.

4.2 Interaction of Tense and Negation

Similar problems arise when one uses standard tense logic for sentences in which tense interacts with sentence negation as in (8). As was first pointed out in Partee 1973, one can assign the past-tense operator (P) either narrow scope with respect to negation as in (9), or wide scope as in (10).

8. Vincent did not leave.

9. ¬ [P [leave' (Vincent')]]

10. P [¬ [leave' (Vincent')]]

However, neither the formula in (9), nor the one in (10) assigns adequate truth conditions to (8). Formula 9 says that there exists no time in the past at which the proposition is true, clearly not capturing the meaning of (8). Formula 10 makes (8) true if at any time in the past Vincent did not leave. Given that ships participate in events other than arrivals at some point during their existence, (10) will be trivially satisfied, but does not capture adequately the truth conditions of (8).

4.3 Tense and Quantified Noun Phrases

The third type of inadequacy of standard tense logic has to do with the interaction of tense and quantified NPs and was first pointed out in Enc 1981, 1986. Enc points out that Priorean tense operators fail to capture certain readings of sentences such as (11).

11. Every admiral was (once) a cadet.

12. ∀ x [admiral' (x) → P [cadet' (x)]]

13. P [∀ x [admiral' (x) → cadet' (x)]]

Since P is a propositional operator, it can take scope over the consequent of the material implication in (12). Formula 12 represents the reading that everyone who is an admiral now was a cadet at some time in the past. The second reading in (13), where P has scope over the entire formula, assigns the somewhat absurd truth conditions that at some time in the past every admiral was simultaneously a cadet. However, as Enc observes correctly, with propositional tense operators we cannot obtain the perfectly natural reading that everyone who is an admiral now or who was an admiral at some time in the past was a cadet at some time prior to being an admiral.

4.4 Temporal Anaphora

There is a fourth problem that arises when one uses tense operators of standard tense logic for the semantic interpretation of pieces of discourse or of single sentences that describe multiple events.

14. Vincent was hit by a harpoon, was abandoned by its crew, and sank.

The most natural interpretation of (14) is one in which the events are understood to have happened in the same temporal order as they are sequenced in the sentence. However, if one uses a Priorean P operator to interpret each occurrence of the past tense in (14), one arrives at an interpretation, which incorrectly allows for any temporal ordering.

5 A Tense Logic with Multiple Indices

It turns out that most of the problems that we have just discussed can be solved if one recognizes more than one parameter of temporal evaluation. In the models given to tense logics such as the ones first developed by Prior, one standardly evaluates propositions with respect to a single time that we may call the event time, the time at which an event happens or at which a state of affairs obtains. The point of speech is taken to be a special case of this parameter.

An alternative to models with only one temporal parameter was given in Reichenbach 1947. Reichenbach argues for distinguishing between three parameters, which he calls **speech time, event time,** and **reference time.** The meaning of the first two parameters should be self-explanatory. It is the third parameter, reference

time, that requires explanation. Reichenbach conceives of reference time as the temporal perspective from which an event is viewed, as opposed to the event time, the time at which the event occurs. Reference time can be either implicit in the discourse context or explicitly specified by temporal adverbials such as *yesterday*. For each individual tense, reference time is temporally ordered with respect to the other two parameters. Reference time plays a crucial role in Reichenbach's account of the distinction between the simple past and the present perfect in English. In both cases event time precedes speech time. But while for the simple past, the event time is viewed from a perspective in the past, the event is viewed from the perspective of the present in the case of the present perfect.

As first shown in Aqvist 1976 and Guenthner 1979, Reichenbach's analysis can be formalized in a tense logic in which tense operators are evaluated with respect to multiple indices. For example, a Reichenbachean past operator (P) can be defined as in (15).

15. $[P \ p]_{ts,tr,te} = T$ iff $[p]_{ts,tr,t'}$ for some time t' such that $t' < ts$ and $t' \subseteq tr$.

The parameters of evaluation in (15), *ts*, *tr*, and *te*, stand for speech time, reference time, and event time, respectively. The operator P shifts evaluation of the event time te to some time (t') in the past such that t' falls within some reference time tr. Note that contrary to Reichenbach's original account of the past tense, the parameters of reference time and speech time are not directly ordered in (15), but only indirectly by virtue of the temporal ordering between event time t' and the speech time ts. This weaker ordering between tr and ts is motivated by sentences such as (16), in which the reference time denoted by the adverbial *today* contains the speech time ts.

16. Vincent arrived today.

In the intended models of interpretation for the P operator in (15), times are taken to be time intervals. Since (15) requires that the event time t' be located prior to ts and be contained in tr, (15) imposes as a restriction on tr that a subinterval of tr be ordered prior to ts. In order for (16) to be true, the subinterval of tr that lies in the past has to be a proper subinterval of tr, whereas for (17) all of tr has to precede ts.

17. Vincent left yesterday.

Given Reichenbach's parameters, the definition of the Y operator, given earlier in (5), can be modified as in (18).

18. $[Y \ p]_{ts,tr,te} = T$ iff $[p]_{ts,DAY(ts)-1,te} = T$.

Unlike the P operator in (15), Y in (18) does not shift te; instead, it operates on tr and shifts that parameter to day prior to ts.

With the redefined operators P and Y, one can now give adequate truth conditions for sentences involving tense and time adverbials. The logical form for (17), for example, can be evaluated as in (19): Y specifies the reference time to be the day prior to the speech time, and the P operator, in turn, correctly locates the event time as being within that reference time.

19. $[Y \ [\ P \ [\ leave' \ (Vincent') \ ] \ ] \ ]_{ts,tr,te} = T$ iff
$[\ P \ [leave' \ (Vincent') \ ]_{ts,[DAY(ts)-1],t} = T$ iff
$[\ leave' \ (Vincent') \ ]_{ts,[DAY(ts)-1],t'} = T$
for some $t' < t$ and $t' \subseteq [DAY \ (ts)-1]$.

The P and Y operators, defined in (15) and (18) above, differ from the operators found in Aqvist, Guenthner, and Dowty in that in my analysis all three of Reichenbach's parameters are taken to be separate for purposes of evaluation, while Aqvist, Guenthner, and Dowty define operators that are evaluated with respect to two parameters only. This is because Dowty considers the speech time as a special case of the reference time, while Aqvist and Guenthner consider speech time to be a special case of the event time.

As I have argued elsewhere (cf. Hinrichs 1981, 1986) and as was noted independently in Dowty 1982, the need for tense operators with three separate parameters arises in the context of sentences such as (20).

20. Vincent rescued a ship yesterday which is now in Hawaii.

As first noted in Kamp 1971, the interpretation of *now* requires that the speech point of the utterance be carried along at every stage of evaluating sentences such as (20), whose logical form can be represented as in (21).

21. Y [P [∃x [ship' (x) & rescue' (Vincent', x) & NOW [be-in' (x,Hawaii')]]]]

In the evaluation of (21), the Y operator, as defined in (18), fixes the reference time as the day prior to ts, while the P operator from (15) shifts the event time to some time within that reference time. NOW, the third temporal operator in (21), appears in the scope of the Y and the P operator. NOW, which can be defined as in (22), can be interpreted correctly in the context of (20), only if the speech time is kept as a separate index and held constant even though reference time and event time have been changed by the P and Y operators.

22. $[NOW \ p]_{ts,tr,te} = T$ iff $[p]_{ts,tr',te} = T$ for $ts \subseteq tr'$.

Using temporal operators with multiple indices of evaluation, one can also account correctly for the interaction of tenses and negation. In the evaluation of (23) shown in (24), the past operator locates the event time t' prior to speech time and within some reference time tr, which in the case of (23) has to be taken to be contextually specified.

23. Vincent did not leave.

24. $[\ \neg \ [\ P \ [\ leave' \ (Vincent') \ ]]]_{ts,tr,te} = T$ iff
$[\ P \ [\ leave' \ (Vincent') \ ]]_{ts,tr,te} = F$ iff

[leave' (Vincent')]$_{ts,tr,t'}$ = F for all times t'
such that t' < ts and t' $\subseteq$ tr.

Sentence 23 is true according to Formula 24 if there is no time within tr at which the untensed proposition *leave' (Vincent')* is true.

It turns out that a multi-indexed tense logic provides the basis for an adequate account of tense in discourse. By associating event times with respect to temporally ordered reference times, as sketched in (26), one can indirectly induce an ordering among the events themselves. Moreover, by updating such reference times after each event description, one can order multiple events as described in (25) in the appropriate way. The relations < and $\subseteq$ in (26) are meant to stand for **temporal precedence** and **temporal inclusion**, respectively.

25. Vincent [was hit by a harpoon]$_{e1}$, [was abandoned by its crew]$_{e2}$, and [sank]$_{e3}$.

26. tr1   <   tr2   <   tr3
     UI   UI   UI
     te1   te2   te3

In order to induce the correct temporal orderings among events and states of affairs in a given discourse, reference times have to be updated appropriately during discourse processing. Formula 26 shows the simplest case of such updating. A new reference time is introduced after processing each event so that the temporal order of the events becomes isomorphic to the order in which the events are introduced. However, for more complicated pieces of discourse the conditions under which new reference times are introduced can be far more complex. The aspectual properties of the events in question, event-subevent relations, causal connections obtaining among events and states of affairs, as well as the overall structure of the discourse itself are among the conditioning factors. It will not be possible to give a detailed account of these issues here; for a more thorough discussion of how to interpret temporal structures in discourse on the basis of a multi-indexed tense logic, I refer the reader to Hinrichs 1981, 1986 and Partee 1984.

Let us consider next two alternative logical representations for Sentence 27 in such a multi-indexed logic.

27. Vincent left yesterday.

28. [Y [P [leave' (Vincent')]]]$_{ts,tr,te}$

29. $\exists$ t' [t' < ts & tr = [DAY (ts) − 1]
    & t' $\subseteq$ tr & leave' (Vincent') (t')]

The formula in (28) we have already discussed. In (28) past tense is translated into a propositional operator whose semantics is implicit in the truth conditions imposed with respect to the model-theory. In (29) the past tense leads to existential quantification over times. The existential quantifier binds variables which appear as extra argument positions on predicates. Thus, *leave'*,

which is ordinarily a one-place predicate, turns into a two-place predicate that takes individuals and times as its arguments. The variables ts and tr occur as free variables in (29) and, as stated earlier, stand for the Reichenbachean speech time and reference time, respectively.

Although the two formulas in (28) and (29) are logically equivalent in the sense that both are true under the same set of models, I will adopt the style of logical representation in (29) for the remainder of this paper. This is because in the context of the JANUS system it is important to explicitly quantify over times, since in the database times are explicitly entered as dates, time stamps, etc. In order to be able to access them, it is important to incorporate time information explicitly at the level of logical form.

A second reason for preferring the style of representation in (29) over the one in (28) concerns the interaction between tenses and quantified NPs. Since formulas such as (29) explicitly quantify over times, scope relations with respect to quantification over individuals become completely transparent.

6 TENSE AND QUANTIFIED NOUN PHRASES

Using the style of representation exemplified by formula (29), let me then return to the issue of tense and quantification, which is still unresolved. Consider once again the types of examples that, as Enc points out, cannot be handled in a tense logic that gives temporal operators scope over entire propositions.

30. Every admiral graduated from Annapolis.

31. $\forall$ x [admiral' (x) $\rightarrow$ P [graduate-from'
    (x,Annapolis')]]

32. P [$\forall$x [admiral' (x) $\rightarrow$ graduate-from'
    (x,Annapolis')]]

If tense operators such as P have propositional scope, P can either scope over an entire formula, as in (32), or over the consequent of the material implication, as in (31). Now, as we saw earlier, neither formula captures the reading that all present or past admirals graduated from the Naval Academy in Annapolis prior to their being admirals.

Enc 1981 provides an interesting solution to the problem posed by examples such as (30). Her solution is based on two assumptions: 1. Semantically, tenses should have scope only over verb meanings, but not over any larger elements in a sentence, and 2. verb meanings as well as noun meanings are indexical in the sense that their interpretations depend on the context of the utterance in the same way that demonstrative pronouns such as *that* and anaphoric pronouns such as *she* and *they* do.

As shown in Formula 33, which represents the translation for (30) in my analysis, I adopt Enc's first

assumption and assign tense scope only over the main verb of the sentence.

33. $\forall$ x [$\exists$t [admiral$'$ (x) (t) & R (x) (t)] $\rightarrow$
$\exists$ t$'$ [t$'$ < ts & t$'$ $\subseteq$ tr &
graduate-from$'$ (Annapolis$'$) (x) (t$'$)]]

In accordance with the Reichenbachean analysis of tense outlined in the previous section, the past tense of sentence (30) contributes to (33) the existential quantification over times t$'$ that precede the speech point ts and are contained in some contextually specified reference time tr. Following Enc, tense is thus given scope only over the predicate that corresponds to the main verb. However, I do not follow Enc in her second assumption, namely, her treatment of nouns and verbs as indexicals. It is characteristic of true indexicals such as *I, there,* or *you* that their denotation is completely determined by a certain aspect of the context of the utterance. *I* refers to the speaker, *you* to the addressee(s), *there* to some contextually salient location, etc. In contrast to such indexical expressions, the (temporal) evaluation of nouns and verbs does not always depend on a single contextual parameter. In the case of complex nouns such as *former admiral, last readiness rating,* or *previous nautical position,* temporal evaluation has to be shifted twice: first from the speech point to some contextually salient reference point and then in turn to some second time relative to which the nouns *admiral, readiness rating,* and *nautical positions* themselves are evaluated. In order to accommodate complex temporal evaluations of nouns and verbs, their corresponding predicates in logical form, such as *admiral$'$* and *graduate-from$'$* in (36), carry a time-denoting argument position as part of their function-argument structure. Since the temporal evaluation of such predicates can be shifted freely, their interpretation differs crucially from that of true indexicals whose interpretation can be completely determined with respect to a single contextual parameter.

Even though I do not follow Enc in treating nouns and verbs as indexical expressions, I do recognize that the interpretation of noun phrases such as *every admiral* in (30) is in part dependent on the context in which the sentence is used. Speakers asserting (30) are not likely to make the claim that every admiral who ever served in the navy of any country that has naval forces graduated from the Naval Academy in Annapolis. Typically, (30) will be used to make a claim about a much restricted set of admirals, say all the admirals in the U.S. Navy or all admirals in the Pacific Fleet. Exactly which set of admirals a speaker focuses on will depend on the discourse context in which the sentence is used. This phenomenon of restricted quantification of noun phrases is certainly not restricted to the interpretation of *every admiral* in (30), but applies to quantified noun phrases in general, as Stalnaker (1973), who cites examples such as (34), was among the first to point out.

34. Everyone is having a good time.

In (34) the interpretation of *everyone* typically does not involve the set of all individuals currently alive, but rather the set of all individuals in a given context; for example, everyone at a certain party, at a certain location, and at a given time.

In order to accommodate this contextual aspect of the interpretation of noun phrases in my analysis, I introduce into the translation of quantified NPs a predicate (R), which is meant to range over properties that are salient in a given context and which serve to narrow down the reference of the noun phrase in question. Let me illustrate the context-dependent evaluation of quantified NPs by once again focusing on Sentence 30 and its translation in (33).

30. Every admiral graduated from Annapolis.

33. $\forall$ x [$\exists$t [admiral$'$ (x) (t) & R (x) (t)] $\rightarrow$
$\exists$ t$'$ [t$'$ < ts & t$'$ $\subseteq$ tr &
graduate-from$'$ (Annapolis$'$) (x) (t$'$)]]

Imagine that (30) is uttered in a context in which all current admirals in the Pacific Fleet are under discussion. In that context, R could be instantiated as in (35), i.e., as the intension of the set of individuals (x) who are in the Pacific Fleet at a time which equals the speech time ts.

35. λ t λ y [be-in$'$ (Pac-Fleet$'$) (y) (t) & t = ts]

Substituting (35) for R in (33), we arrive at the formula in (36).

36. $\forall$ x [$\exists$t [admiral$'$ (x) (t) & be-in$'$ (Pac-Fleet$'$) (x) (t)
& t = ts] $\rightarrow$ [$\exists$ t$'$ [t$'$ < ts & t$'$ $\subseteq$ tr &
graduate-from$'$ (Annapolis$'$) (x) (t$'$)]]

In a context in which all present or past admirals in the Pacific Fleet are under discussion, a reading that, as we pointed out in Section 4.3, one cannot capture using Priorean tense operators, we can capture by instantiating R as in (37), where $\leq$ stands for the relation *temporally preceding or equal to.*

37. λ t λ y [be-in$'$ (Pac-Fleet$'$) (y) (t) & t $\leq$ ts]

Notice that the contextual variable R serves double duty in my analysis. This double role derives from the fact that R is a two-place predicate with individuals and time intervals as its two arguments. The argument ranging over individuals serves to restrict the denotation of the noun that R is associated with; for example, it restricts the denotation of *admiral* in (33). The argument of R that ranges over time intervals, on the other hand, serves to restrict the time interval at which the associated noun denotation is evaluated; for example, if R is instantiated by (35) or (37), temporal evaluation of the associated predicate *admiral* in (33) is restricted to the speech point or to time intervals prior to or including the speech point.

Temporal evaluation of the verbal predicates is, thus,

kept separate from the temporal evaluation of predicates corresponding to other constituents in the sentence. As first pointed out by Enc, this strategy makes it possible to account for sentences such as (38) and (39), whose translations require that the predicates *secretary* and *fugitive* be evaluated relative to a time that is distinct from the evaluation time of the predicate corresponding to the verb.[5]

38. Oliver North's secretary testified before the committee.

39. Every fugitive is now in jail.

In contrast to an analysis that interprets the past tense in terms of a Priorean P operator, the narrow-scope analysis of tense also avoids the dilemma of inducing a simultaneity reading for Sentence 30, if P has scope over the entire formula, as in the Translation 40 of (30).

30. Every admiral graduated from Annapolis.

40. P [∀ x [admiral' (x) →
     graduate-from' (Annapolis') (x)]]

The reading in (40) is factually implausible for two reasons: 1. It imposes simultaneity as part of the truth conditions and requires that all admirals graduated at the same time, and 2. since the P operator forces temporal evaluation of all predicates in its scope at the same index, in the case of (40) it requires that every admiral graduated from Annapolis as an admiral, and not, as is actually the case, subsequent to graduation from the Naval Academy.

Notice that the formula in (33), which represents the translation of (30) in my analysis, avoids both problems associated with (40).

33. ∀ x [∃ t [admiral' (x) (t) & R (x) (t)] →
     ∃ t' [t' < ts & t' ⊆ tr &
     graduate-from' (Annapolis') (x) (t')]]

Since temporal evaluation of the predicates *admiral'* and *graduate-from'* are kept separate, the first problem does not arise. Since the predicates are existentially quantified over independently, (33), in contrast to (40), also avoids having to assign a simultaneity reading to (30).

As I have outlined in this section, my treatment of tense and quantification is based on two basic assumptions: 1. Verbal predicates and nominal predicates both have an argument position that ranges over time intervals; however, evaluations of verbal and nominal predicates are independent of one another. The evaluation of verbal predicates is governed by quantification over time intervals that involve Reichenbach's parameters of speech time, event time, and reference time. 2. The denotation of quantified NPs is restricted by the predicate R, which ranges over properties that are salient in the context of utterance. In conjunction with the narrow-scope analysis of tense, it is this context dependent

feature of my analysis that makes it more flexible than a wide-scope analysis of tense.

One of the counterarguments that one may raise against this context-dependent aspect of my analysis of temporal semantics concerns the fact that tracking the salience of objects and their properties in natural-language discourse is a notoriously difficult problem. However, I will argue in the next section that whatever mechanisms are needed to track saliency, such mechanisms are independently motivated by semantic and pragmatic phenomena that go beyond the phenomenon of temporal interpretation.

7 EVALUATING TIME-DEPENDENT PREDICATES IN CONTEXT

Objects and certain of their properties can receive or maintain salience in a discourse in any number of ways. The notions of **focus** (Sidner 1983), of **common ground** (Stalnaker 1973), and of **mutual knowledge** (Clark and Marshall 1981) are certainly cases in point. In this section I will concentrate on two such mechanisms that play a role in the context-dependent interpretation of time-dependent predicates. In each case I will argue that the mechanism is needed for purposes other than temporal interpretation and, therefore, does not add complexity to my analysis of temporal semantics.

The first such mechanism concerns the way in which objects and their properties can become salient in the discourse context by virtue of the goals that the discourse participants are trying to accomplish over the course of a given interaction. Consider a user of the JANUS system whose goal it is to deploy a set of ships. As part of achieving this goal, the user interacts with JANUS by asserting (41a) and then by querying (41b), whose translation is given by the formula in (42).

41. a. I need to deploy a ship immediately for a search-and-rescue mission.
    b. Which ships are in the Indian Ocean?

42. QUERY [^λx [x ∈ POW [λ y ∃ t' [ship' (y) (t')
     & R (y) (t')]] & ∃ t [t = ts & t ⊆ tr &
     in' (Indian-Ocean') (x) (t)]]]

Following Scha 1983, I base the semantics of questions on speech-act operators, such as QUERY, which take the intensional meaning of the question as an argument. The ^ symbol in (42) stands for the intension operator as defined in Montague 1973. POW stands for the **power-set operation**, which I use for the interpretation of plural nouns.[6] POW in (42) is used to form the set of those objects that at some time t have the property of being a ship.[7] For the technical details concerning the semantics of the QUERY operator I refer the reader to Scha 1983. For the purposes of this paper, it should suffice that QUERY has the effect of consulting the underlying knowledge bases of the system as to which members of the power set of ships, if any, have the property of being in the Indian Ocean at the time of the query.

The point that I want to concentrate on with respect to the formula in (42) concerns the instantiation of the context-dependent predicate (R) that is associated with the translation of the noun phrase *which ships*. Given that the system recognizes the user's goal to be that of immediate ship deployment for a search-and-rescue mission, ships with a current readiness rating of C3 or better are salient in the context, since only such ships are deployable. By instantiating R appropriately, the formula in (42) turns into (43).

43. QUERY [ˆ λ x [× ∈ POW [λ y ∃ t' [ship' (y) (t')
     & readiness-rating' (y) (t') ≥ C3 & t' = ts]] &
     ∃ t [t = ts & t ⊆ tr & in' (Indian-Ocean') (x) (t)]]]]

The instantiation of R in (42) follows from recognizing the user's plan as that of immediate ship deployment. The importance of plan recognition for designing question-answering systems that generate cooperative responses was emphasized in Allen/Perrault 1980, Allen 1983, and Pollack 1986. In the context of Example 41, if it turned out that two ships, Frederick and Vincent, are in the Indian Ocean, but both ships are rated C4, then a cooperative response would be (44), instead of merely listing the ship names.

41. a. I need to deploy a ship immediately for a search-
        and-rescue mission.
    b. Which ships are in the Indian Ocean?

44. Frederick and Vincent, but they are rated C4 and
     cannot be deployed.

Recognizing the user's intention, which in the given context leads to the recognition of the current readiness rating of ships as a salient property, will make such a response possible. It, therefore, turns out that tracking properties that are salient in context is needed not only for evaluating predicates in the approach to temporal semantics that I have developed in this paper, but constitutes a task that is independently needed for the purposes of generating cooperative responses in question-answering.

The issue of plan recognition in discourse demonstrates that objects and their properties can become salient implicitly in discourse, that is, without explicit linguistic reference. However, salience of objects and properties can, of course, also be achieved at any point within a discourse by virtue of the previous linguistic context. Consider a sequence of user-system interactions as in (45).

45. a. Query: Did every admiral deploy a ship yester-
                 day?
    b. Answer: Yes.
    c. Query: Which ships will arrive in Hawaii?

The person who asks the follow-up query (45c) to the system's affirmative answer to the initial query (45a) is not interested in being informed about all ships that at some time in the future will arrive in Hawaii. Instead,

the user is interested in a much more restricted set of ships that will arrive there, namely, the ones that were deployed by some admiral the day before. The noun *ship* in the final query in (45) has to be interpreted relative to the discourse context, and the temporal evaluation of the predicate is determined with respect to that context, rather by the tense of the sentence, in this case, the future. It turns out that a detailed proposal for how to construct such a mechanism does, in fact, already exist in the literature. Webber (1978, 1983) in her work on the interpretation of pronouns in discourse, has developed a framework that constructs during the interpretation of a discourse a context that consists of a set of what she calls discourse entities. These discourse entities then become available as objects that pronouns can refer to. One of the examples that Webber discusses is the interpretation of the pronoun *they* in (47) in the context of sentence (46).

46. Every admiral deployed a ship yesterday.

47. They arrived.

Clearly, *they* refers to the set of ships deployed by some admiral.[8] In order to derive the appropriate discourse entity for the interpretation of *they*, Webber suggests the rule schema such as (48). Formula 48, which is a slightly simplified version of Webber's original rule schema, says that for any formula that meets the structural description (SD), a discourse entity identified by the ID formula is to be constructed.

48. SD: ∀ y_1 · · · y_k ∃ x [P → Q]
     ID: λ x ∃ y_1 · · · y_k [P & Q]

Instantiated for Sentence 49 and its translation (50), the rule produces the expression in (51).

49. Every admiral deployed a ship yesterday.

50. ∀ x ∃ y,t,t',t'' [admiral' (x) (t) & R_1 (x) (t) →
     ship' (y) (t') & R_2 (y) (t') & tr = [DAY(ts) − 1]
     & t'' < ts & t'' ⊆ tr & deploy' (y) (x) (t'')]

51. λ y ∃ x,t,t',t'' [ship' (y) (t) & R_2 (y) (t)
     & admiral' (x) (t') & R_1 (x) (t') & tr = [DAY(ts) − 1]
     & t'' < ts & t'' ⊆ tr & deploy' (y) (x) (t'')]

Formula 50 imposes as truth conditions for (49) that each member of a contextually specified set of admirals deployed some contextually salient ship at some time t' within the day prior to the given speech time ts. Contextual salience enters into the translation in (50) since the predicates *ship'* and *admiral'* are associated with distinct occurrences of the contextual variable R. Which ships and which admirals are salient will, once again, depend on the particular context. In a context in which activities within the Pacific Fleet on the day prior to the speech time are at issue, R1 and R2 in (50) will be instantiated in such a way that the denotations of *ship'* and *admiral'* are restricted to ships and admirals from that particular fleet. Formula 51, the output of Rule

Schema 48 applied to (50), further restricts which ships are salient, namely, the set of ships contextually specified by R1, which, in addition, were deployed on the previous day by one of the admirals in question. The discourse entity with the description, in turn, becomes available for the interpretation of the pronoun *they* in a follow-up sentence such as (47).

It turns out that the method of constructing discourse entities is not only relevant to the interpretation of pronouns, but also to the contextual interpretation of nouns and noun phrases that I am concerned with here. In particular, the discourse entity with the description in (51) can serve not only for interpreting pronouns, but also for instantiating R for the interpretation of the noun *ship* in (45c) in the context of (45a).[9]

45. a. Query: Did every admiral deploy a ship yester-
                 day?
    b. Answer: Yes.
    c. Query: Which ships will arrive in Hawaii?

Since the discourse entity in (51), which ranges over a set of ships, is described in terms of the property of having been deployed by some admiral the day prior to the day of the speech point, that property can be taken to be salient in the discourse context. If one substitutes R in Translation 52 of (45c) by this contextually salient property, the temporal evaluation of the predicate *ship'* in resulting Formula 53 is no longer governed by the existential quantifier t for the future tense, but rather by the quantifier t' introduced by the contextually salient property. As a consequence of this instantiation of R, the set of ships under consideration is restricted in the appropriate way.

52.   QUERY [˄λ z [z ∈ POW [λ y ∃ t' [ship' (y) (t')
      & R(y) (t')]] & ∃ t [t > ts & t ⊆ tr
      & arrive' (Hawaii') (z) (t)]]]

53.   QUERY [˄λ z [z ∈ POW[λ y ∃ t' [ship' (y) (t')
      & ∃ x, t'', t''' [admiral' (x) (t'') & R₁ (x) (t'')
      & tr = [DAY(ts) − 1] & t''' ⊆ tr
      & deploy' (y) (x) (t''')]]] & ∃ t [t > ts
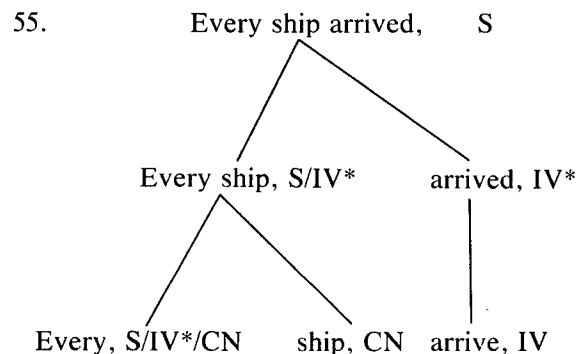   & t ⊆ tr' & arrive' (Hawaii') (z) (t)]]]

The mechanism for deriving contextually salient properties that are introduced through the previous linguistic discourse may strike the reader as rather complicated in detail. However, the point that I made earlier in this section with respect to tracking saliency as a side effect of plan recognition applies to the tracking of properties introduced by the linguistic context as well: tracking such properties is important not only for temporal evaluation, but is independently motivated by other discourse phenomena such as anaphoric reference, as Webber (1978, 1983) has convincingly shown.

8 A COMPOSITIONAL SYNTAX AND SEMANTICS OF TENSE

In the previous sections I have focused on the semantic and pragmatic aspects of my analysis of temporal expressions, which concern in particular the features of narrow-scope assignment and of context-dependent interpretation of quantified NPs. In this section I will concentrate on matters of syntax and will demonstrate how the narrow-scope analysis makes it possible to construct a straightforward compositional syntax and semantics of tense in the framework of Montague Grammar, the linguistic theory on which my analysis is based.

Syntactically, tenses in English appear as inflectional morphemes on verbs. In the notation of categorial grammar, we may assign a syntactic tree as in (55) to Sentence 54. The infinitival form of the verb *arrive* of Category IV is combined with the past-tense morpheme *-ed* to form a tensed intrasensitive verb IV*. Morphosyntactically, tenses are therefore items that apply to individual words.

54. Every ship arrived.

55.

```
        Every ship arrived,     S
                /\
               /  \
              /    \
             /      \
      Every ship, S/IV*      arrived, IV*
            /\                    |
           /  \                   |
          /    \                  |
         /      \                 ·
   Every, S/IV*/CN   ship, CN   arrive, IV
```

Since I assign tense narrow scope in the semantics and let temporal quantifiers bind only the temporal index associated with the main verb, I arrive at an analysis of tense whose syntactic domain coincides with its semantic domain. Compared to analyses in which tense is assigned wide scope over formulas that correspond to entire sentences (Montague 1973) or over entire verb phrases (Bach 1980), the narrow-scope analysis, which I have developed in this paper, has the advantage of leading to a straightforward compositional syntax and semantics of tense. In the syntax the tense morpheme turns an untensed verb into its tensed counterpart, while the corresponding translation rule existentially quantifies over the time index of the predicate that translated the untensed verb.

56.   If a ∈ $P^{IV/\!^\frown NP}$ and then F_1 (a) ∈ $P^{IV^*/\!^\frown NP}$, where
      F_1 = a-ed.

57.   If a ∈ $P^{IV/\!^\frown NP}$ and a translates into a', then F_1 (a)
      translates into λ S₁ · · · Sₙ λ x [∃ t' [t' < ts
      & t' ⊆ tr & a' (S₁) · · · (Sₙ) (x) (t')]].

Rule Schema 56 ranges over untensed intrasensitive verbs (IV), transitive verbs (IV/NP), ditransitive verbs (IV/NP/NP), etc. The notation IV/^{n}NP thus stands for an IV followed by n slashed NPs. The corresponding translation schema in (57) denotes a function from the type of meanings associated with object NPs, if any, to functions from individuals to truth values. Although these rule schemata are rather technical, their meaning should become clear when one considers a concrete example. Consider once again Example 54, whose syntax has been given in (53).

54. Every ship arrived.

The translation of the entire sentence can be built up in a compositional fashion as in (57), which mirrors the syntactic composition of (53).

58. *arrived* translates as:

λ x [$\exists$ t' [t' < ts & t' $\subseteq$ tr & arrive' (x) (t')]]

every translates as:

λ P λ Q $\forall$ x [$\exists$ t [P (x) (t) & R (x) (t)] $\rightarrow$ Q (x)]

every ship translates as:

λ Q $\forall$ x [$\exists$ t [ship' (x) (t) & R(x) (t)] $\rightarrow$ Q(x)]

Every ship arrived translates as:

1. λ Q $\forall$ x [$\exists$ t [ship' (x) (t) & R(x) (t)] $\rightarrow$ Q (x)]
   (λ y [$\exists$ t' [t' < ts & t' $\subseteq$ tr & arrive' (y) (t')]])
2. $\forall$ x [$\exists$ t [ship' (x) (t) & R (x) (t)] $\rightarrow$
   λ y [$\exists$ t' [t' < ts & t' $\subseteq$ tr & arrive' (y) (t')]] (x)]
3. $\forall$ x [$\exists$ t [ship' (x) (t) & R (x) (t)] $\rightarrow$ $\exists$ t' [t' < ts & t' $\subseteq$ tr & arrive' (x) (t')]]

The phrase *every ship* is formed by supplying the predicate *ship'* as an argument to the translation of *every*. Notice that R is introduced by the translation of the quantifier *every*. The translation of the entire sentence is formed by supplying the translation of the tensed verb *arrived*, which is produced by the translation rule in (57), to the translation of the subject NP. The reduced translation results from two steps of lambda reduction.

9 Conclusion

In this paper I have argued that a logical semantics for temporal expressions can provide adequate representations for natural-language input to an interface such as JANUS. The temporal logic is based on Reichenbach's models for the semantics of English tense and uses multiple indices for semantic interpretation. This multi-indexed logic overcomes the kinds of problems that arise when systems of tense logics are used that rely on just one index of evaluation.

I have demonstrated how giving narrow scope to tense quantifiers enables us to provide adequate scope relations with respect to NP quantifiers and to interpret such NPs relative to a given discourse context. I have argued that the context-dependent feature of the analy-

sis does not add extra complexity to my treatment of time-dependent expressions, but is needed for purposes of discourse understanding in general. Finally, I have demonstrated how the narrow scope of tense results in a fully compositional syntax and semantics of tensed sentences in English.

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NOTES

1. For a detailed introduction to Montague's theory, see Dowty, Wall, and Peters 1981.

2. The components shown in the diagram are based on the architecture of the PHLIQUA system described in Scha 1983.

3. For details on how the domain model functions in the overall system see Ayuso, Shaked, and Weischedel 1987.

4. In fairness to Prior, it has to be pointed out that he designed his temporal modal logics as purely formal systems and did not design them with idea of applying them to natural language. However, Priorean tense logic has, nonetheless, been applied to natural language semantics. It is those studies that are subject to the criticisms presented in sections 4.1-4.4.

5. Recall that Fawn Hall, North's secretary, testified before the committee when she was no longer North's secretary. The example is due to an editorial in the *Boston Globe*.

6. The reader may prefer some other approach to the semantics of plurals or questions, say the lattice-theoretic approach to plurality developed in Link 1983 or the analysis of questions found in Groenendijk/Stokhof 1982 over the approach based on power sets and the QUERY operator, respectively. These approaches are also consistent with the point that I want to concentrate on with respect to the formula in (42)—that is, the instantiation of the context-dependent predicate (R).

7. Note that it follows from the narrow-scope analysis of tense developed in Section 4 that the time at which the set of objects x are ships need not be the same as the time at which that set of objects is in the Indian Ocean. This aspect of (42) may strike the reader as counterintuitive. Notice, however, that (42) represents the first level of translation (the EFL level of Figure 2 with no input from the domain model). It will be part of the domain knowledge, however, that there are two kinds of properties: a. properties such as being an admiral, which can hold of an individual for certain subperiods; and b. properties such as being a ship, which hold of an entity throughout its existence. It is on the basis of such domain knowledge that at lower levels of translation the two evaluation times at issue in (42) can, in fact, be equated.

8. What is interesting about the example in its own right is that syntactically there is no plural noun phrase in the preceding discourse that could serve as the referent for the plural pronoun *they*.

9. I am indebted to Bonnie Webber for pointing out to me that the discourse entity evoked by (45a) can be used to restrict the interpretation of the noun phrase *which ships* in (45c), only if the answer to (45a) is affirmative. Thus, whether a discourse entity can serve as a restrictor for the interpretation of subsequent NP's is in part a function of the type of sentence that evokes the discourse entity. If the expression that evokes a discourse entity occurs in a declarative sentence, the discourse entity will automatically be available as a potential restrictor for the interpretation of subsequent NPs. However, if the discourse entity is evoked within an interrogative sentence and the existence of the entity is not already presupposed by the question, the discourse entity is licensed as a potential restrictor, only if the question has an affirmative answer.