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Abstract

In this paper, we present an account of the semantics of the English temporal prepositions and some related temporal adverbials. This account aims to describe how these expressions function in English sentences, and in particular how they contribute to the truth-conditions of the sentences in which they occur. Our account will be couched at a sufficiently formal level to enable us to define a procedure for assessing the validity of a range of arguments couched in everyday temporal English.

We develop a temporal representation language, TL, into which English sentences involving temporal prepositions can be naturally translated. Our goal is to tailor the representation language so as to fit as closely as possible the expressive resources provided by temporal constructions in English. In particular, we show how many restrictions on use of multiple preposition phrases are explained naturally by the semantics we give for these phrases, and the structure of the formal language we translate them into. This close match, we claim, justifies a program of work in which TL will be extended so as to permit a more refined and comprehensive account of the semantics of English temporal expressions than has been undertaken so far.

1 Introduction

Temporal prepositions, together with other temporal adverbials, serve to describe the temporal location and distribution of states and events, for example:

(1) Gunner visited Ridley *one Monday in January*

(2) Gunner and Ridley met *when Ridley started work with MI5 in January*

(3) Gunner had been working as a Soviet spy *since before 1988*

(4) Gunner shot Ridley *on Saturday at 5 o'clock.*

In this paper, we present an account of the semantics of the English temporal prepositions and some related temporal adverbials. This account aims to describe how these expressions function in English sentences, and in particular how they contribute to the truth-conditions of the sentences in which they occur. Our account will be couched at a sufficiently formal level to enable us to define a procedure for assessing the validity of a range of arguments couched in everyday temporal English.

Even very cursory reflection shows how intricate English temporal adverbials can be. It is well known that the choice of preposition depends somewhat irregularly on the prepositional object: thus an event may occur *at* 2 o' clock, *on* Monday, *at* the weekend or *in* January. Less obviously, perhaps, temporal adverbials cannot be arbitrarily combined in the same sentence. Thus, sentences (5)–(7) are incomprehensible:

(5) * Gunner had visited Ridley *since Monday one January*

(6) * Gunner was not spying for the Soviets *until 1988 until 1988*

(7) * Gunner shot Ridley *by Saturday at 5 o'clock.*

The contrast between the allowable combinations of adverbials in sentences (1)–(4), which perform useful temporal quantification, and the meaningless combinations in sentences (5)–(7) raises the question of just which states of affairs English temporal adverbials express, and how, exactly, they express them. These are the questions we shall address in this paper. We shall develop a temporal representation language, TL, into which English sentences involving temporal prepositions can be naturally translated. Our goal is to tailor the representation language so as to fit as closely as possible the expressive resources provided by temporal constructions in English. In particular, we show how many restrictions on use of multiple preposition phrases, exemplified by sentences (5)–(7), are explained naturally by the semantics we give for these phrases, and the structure of the formal language we translate them into. This close match, we claim, justifies a program of work in which TL will be extended so as to permit a more refined and comprehensive account of the semantics of English temporal expressions than has been undertaken so far.

The topic of this paper is closely related to several extensively studied areas in the semantics of natural language, especially the topics of verb-tense and -aspect[1], and of temporal anaphora[2]. However, we have tried as far as possible to skirt these topics, because they have been treated elsewhere in greater detail than we could hope to match here. The lack of any adequate treatment of tense and aspect represents a considerable limitation of this paper, but one which we believe is justified in view of the complexities of our subject matter. Various authors within the fields of formal semantics and artificial intelligence have offered accounts of temporal prepositions within larger systems.[3] However, these highly precise accounts do not include sufficient detail to account for the phenomena involving multiple temporal preposition-phrases discussed below. In addition to these formal accounts, other, more descriptive accounts of temporal prepositions have been given, concentrating on the cognitive (non-truth-conditional) aspects of temporal prepositions or on fine details of English usage.[4] However, these accounts are couched in a form which does not immediately lend itself to computer implementation. In this paper, we adopt a relatively formal approach; but we have done so in a way which, we believe, is more sensitive to the subtleties of English usage. Our detailed semantic proposals are gathered together in the technical appendices to this paper, so as to permit relatively easy incorporation into existing natural language processing systems.

Any temporal representation language must legislate to some extent on issues in temporal ontology, and there is currently some debate within the AI community as to how best to do this. Should a representation language, for example, distinguish between states and events, or perhaps between states, events, and processes? Should states and events be seen as things which happen at points or over intervals? Should restrictions be imposed on the sets of points and intervals at which events occur and states hold? And if we do distinguish between states, events and perhaps other categories, how do we determine which of these a given English sentence reports?[5] We do not propose to resolve this debate here. However, the close fit between our proposed representation language, namely TL, and temporal prepositions in English make TL, and therefore the ontological decisions it incorporates, a useful framework for temporal representation in AI.

The ability to translate fragments of natural language into formal languages for which provably sound and complete inference procedures are available is of considerable practical importance.[6] Like most temporal logics, TL is decidable.[7] In fact, TL can be layered naturally into a series of languages of increasing complexity, able to handle increasingly large fragments of English, but for which the decision procedure is increasingly slow. Thus, in developing a representation language closely tailored to temporal constructions in natural language, we propose to exploit the expressive limitations of fragments of temporal English in automated reasoning systems with natural language input. However, in this paper, we shall not dwell on the logical aspects of TL, since it will be dealt with in some detail elsewhere.

The plan of the paper is as follows. We begin with a review of the syntax of English temporal preposition-phrases. We then present a temporal logic by means of which we can capture the truth-conditions of English sentences involving temporal prepositions. In the remaining sections, we show how (syntactically analysed) English sentences can be mapped to formulae of our temporal logic.

2 Basic syntax

Our aim in this section is to review the structure of temporal preposition-phrases in English, and to establish a compact way of representing just those aspects of phrase-structure relevant to our semantic enterprise. Although not everything in this section is uncontroversial, most of it will be familiar to readers versed in formal semantics. We warn the reader at this stage that our account in this section is

[1] See, for example, Dowty [10], Parsons [26], Lascarides [18] and Mittwoch [24].

[2] See, for example, Dowty [11], Hinrichs [15], Lascarides and Asher [19] and ter Meulen [23].

[3] See, for example, Richards *et al.* [33], Alshawi [3].

[4] See, for example, Lakoff [17], Rice [32] and Quirk *et al.* [30].

[5] See, for example, Herweg [14], Allen and Hayes [2], Verkuyl [35] and Krifka [16].

[6] For example, Fantechi *et al.* [12] address the problem of automatically generating computer code from natural language specification; and Crouch and Pullman [8] describe a natural language front-end for a planning program.

[7] For a useful survey of systems of temporal logic, see Gabbay *et al.* [13].

somewhat simplified, in order to keep the formal apparatus introduced in later sections manageable.[8]

We say that a $\bar{\bar{\mathrm{P}}}$ (*P-double-bar* or *preposition-phrase*) consists of a *specifier* followed by a $\bar{\mathrm{P}}$ (*P-bar*); and a $\bar{\mathrm{P}}$ consists in turn of a P (*preposition*) followed by a *complement*. (Actually, the term *specifier* is somewhat controversial in this context; however, nothing of importance to the rest of the paper hinges on this issue.) The preposition P is said to be the *head* of the $\bar{\bar{\mathrm{P}}}$ containing it. The specifier and complement may belong to a number of grammatical categories, or may be missing altogether. The following examples illustrate some of the possibilities (the preposition-phrases are italicized):

(8) Gunner shot Ridley *at 5 o'clock* (missing specifier + *at* + noun-phrase complement)

(9) Gunner shot Ridley *after Ridley had sat down in the drawing room* (missing specifier + *after* + sentence complement)

(10) Gunner waited by the French windows *until after Ridley had sat down in the drawing room* (missing specifier + *until* + preposition-phrase complement)

(11) Gunner and Ridley had met *before* (missing specifier + *before* + missing complement)

(12) Gunner fired the shots *5 minutes after Ridley sat down* (noun-phrase specifier + *after* + sentence complement)

(13) Gunner and Ridley had been acquainted *ever since Ridley started work at MI5* (adverb specifier + *since* + sentence complement).

Of course, allowing prepositions to take complements of various categories abolishes the traditional grammatical distinction between prepositions and their cognate adverbs and subordinating conjunctions. But this strategy is now generally accepted, and needs no further defence.

The following phrase-structure rules allow the parsing of the above sentences.

(14) $\bar{\mathrm{X}} \to \bar{\mathrm{X}}, \bar{\bar{\mathrm{P}}}$ where X is either V or N

(15) $\bar{\bar{\mathrm{P}}} \to \mathrm{X}, \bar{\mathrm{P}}$ where X is $\bar{\bar{\mathrm{N}}}$, ADV or missing

(16) $\bar{\mathrm{P}} \to \mathrm{P}, \mathrm{X}$, where X is $\bar{\bar{\mathrm{N}}}$, S, $\bar{\bar{\mathrm{P}}}$ or missing.

As an example, figure 1 shows the phrase structure which these rules assign to sentence (8). (The lambda-expressions and items enclosed in angle-brackets will be explained later.) In this example, rule (14) is applied with X set to V, rule (15) with X set to 'missing' and rule (16) with X set to $\bar{\bar{\mathrm{N}}}$. Note that the missing specifier is represented in figure 1 with the label {MISSING}: this is merely for later notational convenience, and should not be interpreted as making any syntactic or psycholinguistic claim.

When several temporal prepositions occur in a sentence, structural ambiguities arise. Consider, for example,

(17) Ridley worked in his laboratory until 5 o' clock on Wednesday.

Here, the preposition-phrase *on Wednesday* may attach to either the verb-phrase *worked in his laboratory until 5 o'clock*, or simply to the noun-phrase *5 o'clock*. The two phrase-structures are shown in figures 2 and 3. (Again the lambda-expressions etc. will be explained later.)

We need a more compact way of representing phrase-structure than the trees of figures 1–3: one that highlights just those structural aspects relevant to the semantics of temporal adverbials. Consider again sentence (8). We can view the preposition *at* as acting to combine the components *Gunner shot Ridley* and *5 o'clock*. Letting $\langle$Gunner shoot Ridley$\rangle$ and $\langle$5 o' clock$\rangle$ stand for these components, we we take (8) to exhibit the *sentence-structure*:

(18) $\mathbf{at}(\langle$5 o' clock$\rangle, \langle$Gunner shoot Ridley$\rangle)$.

[8] For a very approachable introduction to the syntax assumed in this paper, see Radford [31]. For a more thorough account of the syntax of preposition phrases, see van Riemsdijk [34].

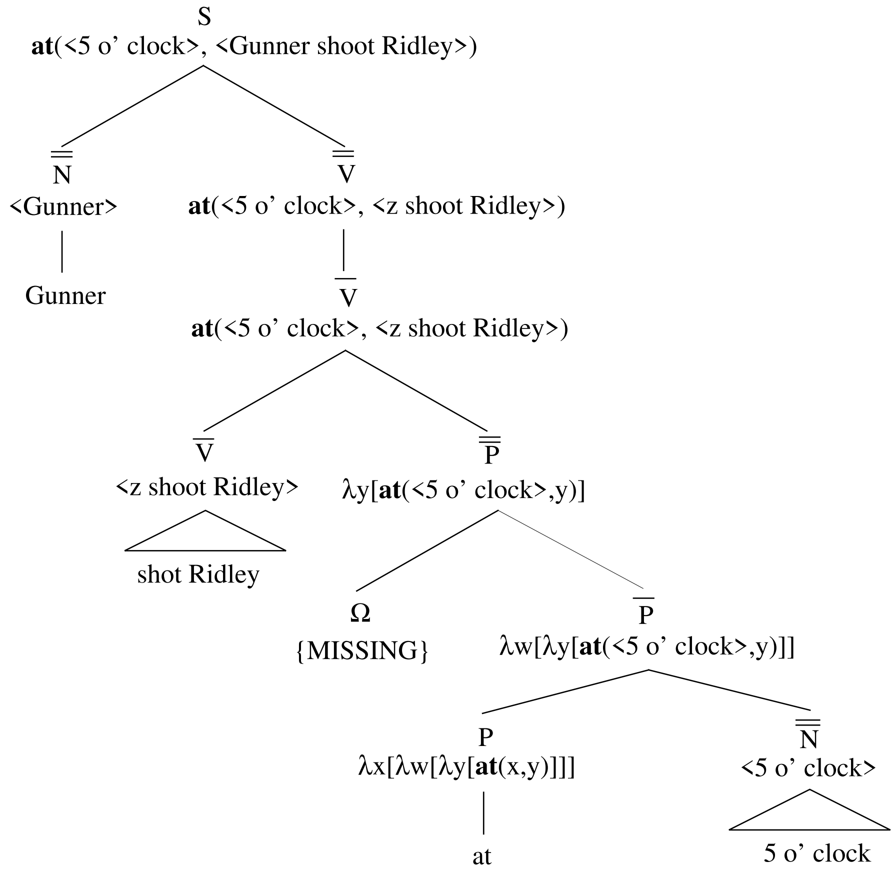

Figure 1: The computation of a sentence-structure for a sentence involving a temporal preposition phrase: *Gunner shot Ridley at 5 o' clock.* (For notational simplicity, the contribution of the subject of the sentence has been given an informal treatment.)

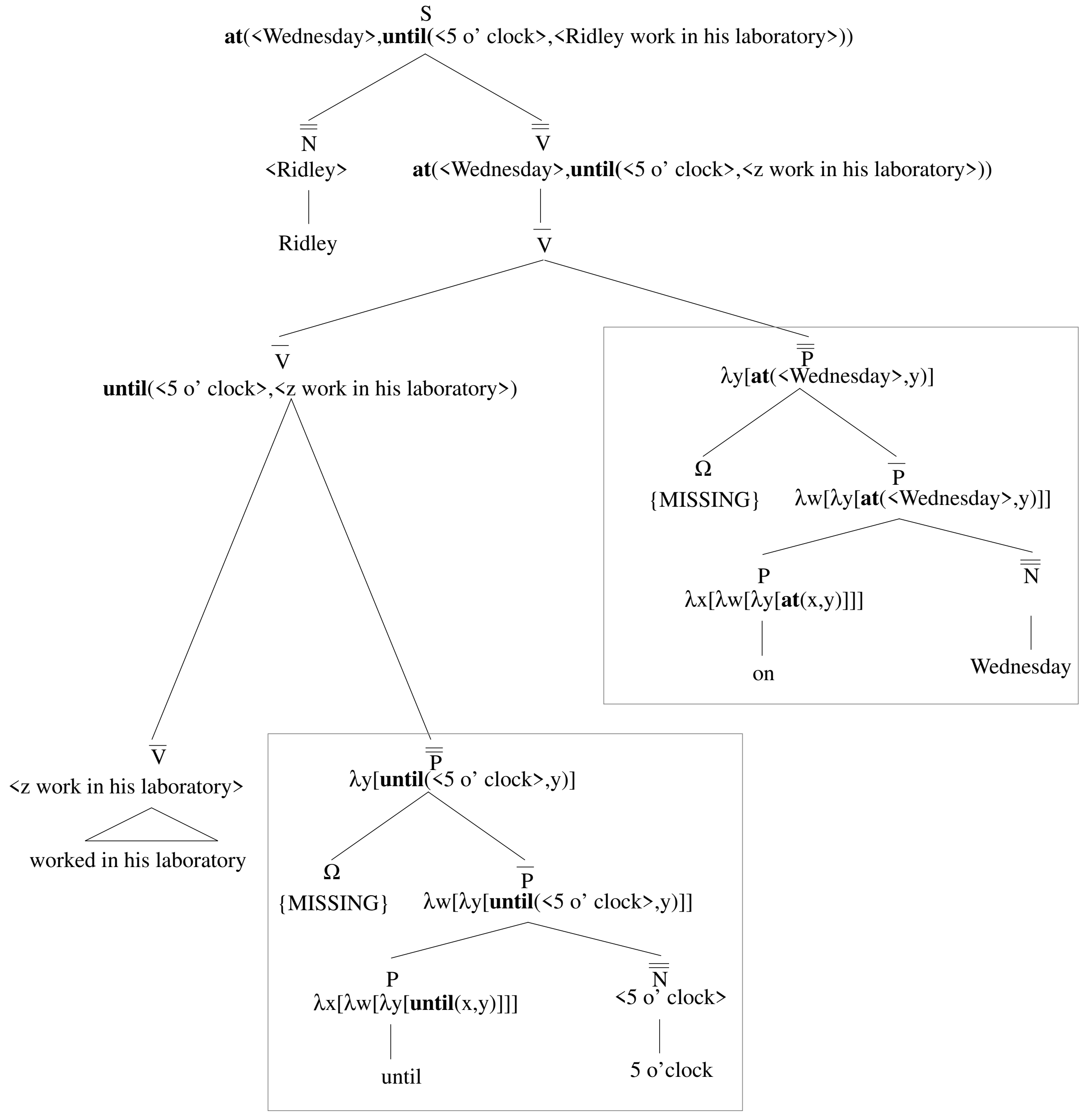

Figure 2: The computation of a right-inserted sentence-structure for a sentence involving two temporal preposition phrases: *Ridley worked in his laboratory until 5 o' clock on Wednesday*

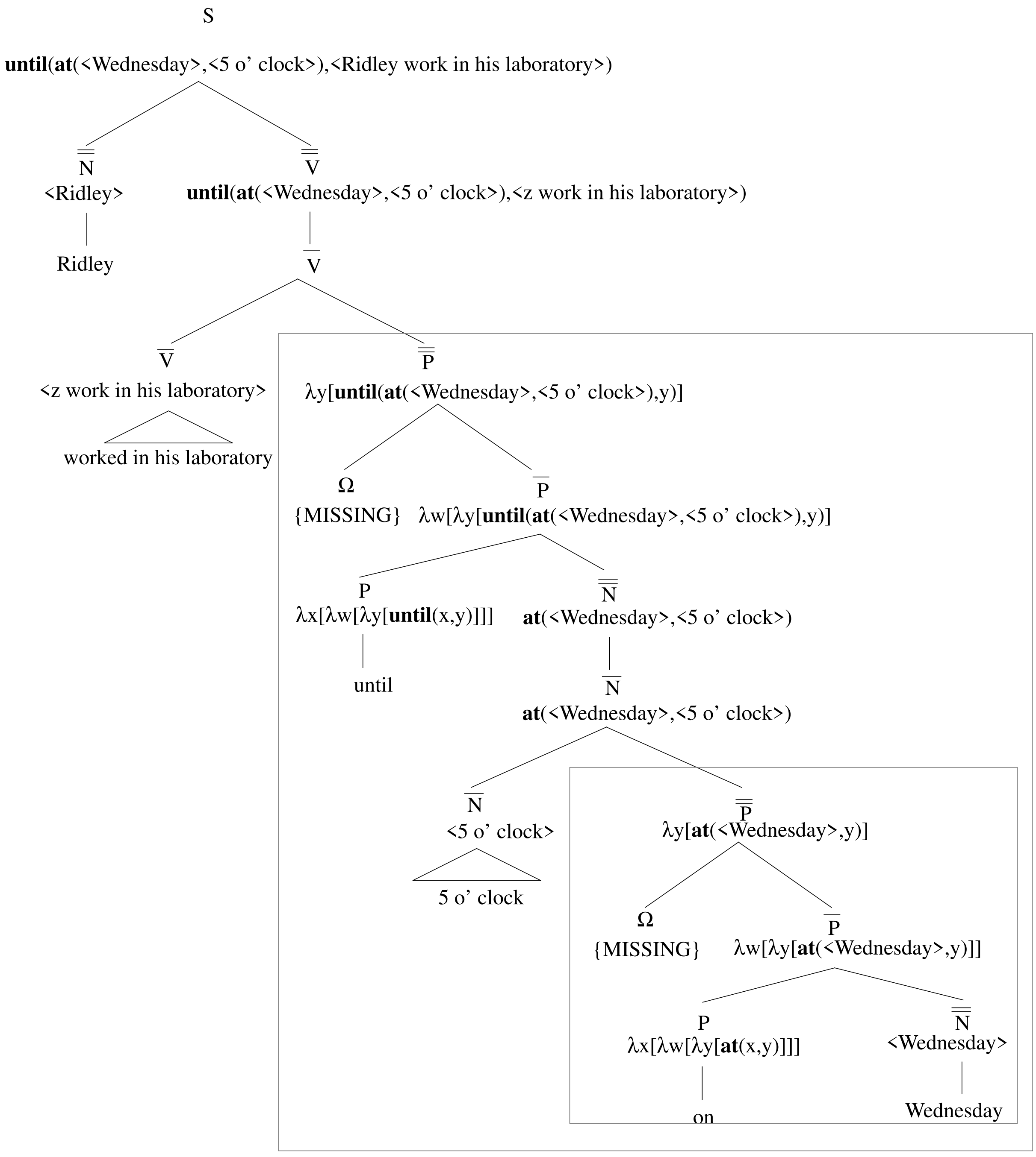

Figure 3: The computation of a left-inserted sentence-structure for a sentence involving two temporal preposition phrases: *Ridley worked in his laboratory until 5 o' clock on Wednesday*

Here, **at** represents the contribution made by the preposition *at* to the sentence-structure. We call such operators, which combine simpler sentence-structures into more complex ones, *functors*. This functor has two arguments, the first corresponding to the complement of the *at*-phrase, the second, to the simple sentence which the *at*-phrase modifies. The reader will notice that we have, for simplicity, suppressed all information concerning verb-tense and -aspect in sentence-structures. In this paper, we avoid the issue of the semantics of verb-tense and aspect as far as possible.[9]

The notation illustrated in sentence-structure (18) can be used to represent more compactly the two phrase-structures for sentence (17) depicted in figures 2 and 3. In the phrase structure of figure 2, we have two preposition-phrases modifying the main verb-phrase. Taking the prepositions *until* and *on* to correspond to functors in the same way as *at*, this suggests the sentence-structure:

(19) $\mathbf{at}(\langle\text{Wednesday}\rangle, \mathbf{until}(\langle\text{5 o' clock}\rangle, \langle\text{Ridley work in his laboratory}\rangle))$.

(The reason for taking the functor to be **at** rather than **on** will be explained later.) In the phrase structure of figure 3, on the other hand, we have one preposition-phrase (headed by *until*) modifying the main verb-phrase; but the complement of *until* is itself modified by a second preposition-phrase. And this arrangement suggests the sentence-structure:

(20) $\mathbf{until}(\mathbf{at}(\langle\text{Wednesday}\rangle, \langle\text{5:00}\rangle), \langle\text{Ridley work in his laboratory}\rangle)$.

We will come to the significance of this ambiguity in section 5. For the present, our concern is merely with establishing a compact representation of phrase-structure.

So much for the general intuitions behind the notion of a sentence-structure: now for the formal account. Sentence-structures can be automatically generated from their corresponding sentences by augmenting the phrase-structure rules with lambda-expressions in the familiar way. Thus, we change rules (14), (15) and (16) to:

(21) $\bar{\mathrm{X}}\sharp f(a) \to \bar{\mathrm{X}}\sharp a, \bar{\bar{\mathrm{P}}}\sharp\lambda x[f(x)]$ where X is either V or N

(22) $\bar{\bar{\mathrm{P}}}\sharp f(a) \to \mathrm{X}\sharp a, \bar{\mathrm{P}}\sharp\lambda x[f(x)]$ where X is $\bar{\bar{\mathrm{N}}}$, ADV or missing.

(23) $\bar{\mathrm{P}}\sharp f(a) \to \mathrm{P}\sharp\lambda x[f(x)], \mathrm{X}\sharp a$, where X is $\bar{\bar{\mathrm{N}}}$, S or missing.

The expressions after the $\sharp$-sign represent the structure of the phrase in question, and show how the structures of complex phrases can be derived, via function application, from those of their immediate constituents. For example, rule (21) says: a $\bar{\mathrm{V}}$ with structure a and a $\bar{\bar{\mathrm{P}}}$ with structure $\lambda x[f(x)]$ make up a $\bar{\mathrm{V}}$ with structure $f(a)$. We need to explain how the symbols after the $\sharp$-signs are to be interpreted in the cases where X is missing. Let us suppose that a missing category produces the 'dummy' structure Ω. We then say that Ω may combine with an expression of the form $\lambda w[f]$, where w does not occur in f, and that the result is simply the expression f. By assigning structures to the prepositions *at*, *on* and *until* as follows:

(24) at $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{at}(x, y)]]]$

(25) on $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{on}(x, y)]]]$

(26) until $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{until}(x, y)]]]$,

the rules (21)–(23) generate the sentence structure (18) from sentence (8), and generate sentence-structures (19) and (20) from sentence (13). The derivations are shown in figures 1, 2 and 3.

The reader may notice that, in the derivations of sentence-structures in figures 1, 2 and 3, we have permitted ourselves a measure of informality when combining the subject of the sentence with the prepositionally qualified verb-phrase, since, technically, the semantic contribution of the verb-phrase should be a lambda-expression. The basic problem is that we wish to regard the preposition phrase as operating on an underlying sentence when, syntactically, it attaches to a $\bar{\mathrm{V}}$. Thus, formally, the assignment to the preposition *at* should be, not (24), but maybe

[9] See, for example, Parsons [26], Lascarides [18] and Mittwoch [24].

(27) at $\sharp$ $\lambda x[\lambda w[\lambda y[\lambda z[\mathbf{at}(x, y(z))]]]]$.

Thus, the $\bar{\bar{\mathrm{V}}}$ in figure 1 would be associated with the lambda-expression $\lambda z[\mathbf{at}(\langle 5 \text{ o' clock}\rangle, \langle z \text{ shoot Ridley}\rangle)]$, and the subject would then be taken to contribute a second-order property to produce the form (18). However, this detail adds nothing relevant to the semantics of temporal prepositions; and for our purposes, we can treat the y and z as a single variable.

The following terminology will be useful: in the sentence structure (19) we say that the functor **until** is *right-inserted* within the functor **at**, because the former modifies the latter's second (right-hand) argument; in the sentence structure (20) we say that the functor **at** is *left-inserted* within the functor **until**, because the former modifies the latter's first (left hand) argument. The reader will have realized that sentence-structures are merely projections of phrase-structure which highlight those features relevant to the semantics of temporal prepositions.

Lambda-expressions are a familiar device in formal semantics. For our purposes, their main function is to stop the arguments corresponding to specifiers and complements (including those cases where one of these components is missing) from getting mixed up, since the syntax rules require the specifier to combine first, the complement second, and the modified verb-phrase third. Furthermore, if we insist that an expression of the form $\lambda w[f]$, where f does not contain any free instances of w, can combine *only* with the dummy structure Ω, the assignments (24)–(26) state that *at*, *on* and *until* cannot take specifiers. This is correct to a first approximation:

(28) * Ridley died 10 minutes at 5 o' clock.

Of course, accommodating a wider range of linguistic constructions than considered in this paper would require a more complicated treatment. But for our purposes, we can take the assignments (24)–(26) to specify the important syntactic features of the relevant temporal prepositions.

Additional facets of prepositional behaviour can be specified by placing restrictions—either semantic or syntactic—on the structures that are allowed to combine with the variables. For examples of semantic restrictions, note that the temporal preposition *on* can take only days or day-parts as complements, whereas *at* (to a first approximation) can take only clock times and weekends; *until*, by contrast, can be completed by almost any temporal entity. For examples of syntactic restrictions, note that *on* and *at* must take noun-phrase complements, whereas *until* may take either a noun-phrase, sentence or preposition-phrase complement (a missing complement is not allowed, however). These facets of prepositional behaviour can be specified by suitably decorating the assignments (24)–(26):

(29) at $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{at}(x, y)]]$ / $\{x : \{\text{very short interval, weekend, religious festival}\}\}$ / $\{x : \{\bar{\bar{\mathrm{N}}}\}\}$.

(30) on $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{at}(x, y)]]$ / $\{x : \{\text{day, day-part}\}\}$ / $\{x : \{\bar{\bar{\mathrm{N}}}\}\}$.

(31) until $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{until}(x, y)]]$ / $\{\ \}$ / $\{x : \{\bar{\bar{\mathrm{N}}}, \mathrm{S}, \bar{\bar{\mathrm{P}}}\}\}$.

Appendix A contains a listing of assignments in the style of (29)–(31) for all the commonly encountered temporal prepositions in English. Some prepositions have several entries, corresponding to different semantic functions or to different possible combinations of specifiers and complements. In addition, some prepositions are assigned surprising functors, for example, the assignment of **at** to *on* in rule (30). Of course, a fully adequate specification of these prepositions (especially with regard to the semantic restrictions) would be far more detailed than the assignments of appendix A. To take just one example, the assignments in appendix A make *when*, *while* and *as* interchangeable, which is incorrect. However, little would be gained by trying to do justice to all the intricacies of English prepositions here. We still have plenty to do in establishing the general framework.

We consider next a minor technical complication. The preposition *after*, like the prepositions *before*, *into* and *ago*, can take a noun-phrase specifier denoting a duration:

(32) Gunner fired the shots *5 minutes after Ridley had entered the drawing room.*

We shall call these four prepositions *specifier offset prepositions*, since they function so as to locate one event with respect to another by means of an offset given in the specifier. Specifier offset prepositions, but no other temporal prepositions, can head preposition-phrases that are themselves complements of other temporal preposition-phrases, thus:

(33) Gunner waited until *5 minutes after Ridley had entered the drawing room*

(34) Gunner waited until *after 5 o' clock*

(35) * Gunner waited until *by 5 o' clock.*

This dual role of specifier offset prepositions causes difficulties. In sentence (32), we want the structure of the italicized preposition-phrase to be a lambda-expression that operates on the verb-phrase *fired the shots*. In sentence (33), by contrast, we want the structure of the italicized preposition-phrase to be a an object (picking out a time) on which the lambda-expression corresponding to the preposition *until* operates.

For our purposes, we require a convenient (rather than theoretically justified) solution; so we proceed as follows. We assign to the preposition *after* a structure with just two lambda-operators: one to combine with the specifier and the other to combine with the complement:

(36) after $\sharp$ $\lambda x[\lambda w[\mathbf{after}_1(x, w)]]$ / $\{w : \{\text{free-floating}\}\}$ / $\{x : \{\bar{\bar{\mathrm{N}}}, \mathrm{S}\}, w : \{\bar{\bar{\mathrm{N}}}\}\}$.

(The functor in (36) is called $\mathbf{after}_1$ to differentiate between other uses of *after*. The use of the term *free-floating* to classify durative expression will be explained in section 3.) This assignment causes any $\bar{\bar{\mathrm{P}}}$ headed by *after* to be given a structure of the form $\mathbf{after}_1(a, b)$ — i.e. a structure which does not begin with a lambda-operator. The generation of a sentence-structure for sentence (33) then proceeds unproblematically to give the result

(37) $\mathbf{until}(\mathbf{after}_1(\langle\text{Ridley enter the drawing room}\rangle, \langle\text{5 mins}\rangle), \langle\text{Gunner wait}\rangle)$.

The process is illustrated in figure 4.

In order to deal with sentence (32), we add to our phrase-structure rules a modified version of rule (21):

(38) $\bar{\mathrm{V}}\sharp\mathbf{at}(b, a) \rightarrow \bar{\mathrm{V}}\sharp b, \bar{\bar{\mathrm{P}}}\sharp a$ where $\bar{\bar{\mathrm{P}}}$ is headed by a specifier offset preposition,

which inserts an extra **at**-operator into the sentence-structure when a specifier offset preposition heads a verb-phrase adjunct. With this phrase-structure rule and the structure assignment in (36), sentence (32) generates the sentence-structure:

(39) $\mathbf{at}(\mathbf{after}_1(\langle\text{Ridley enter the drawing room}\rangle, \langle\text{5 mins}\rangle), \langle\text{Gunner fire the shots}\rangle)$.

Thus, it is as if we are interpreting sentence (32) as saying *Gunner fired the shots* at *5 minutes after Ridley entered the drawing room*. The derivation is illustrated in figure 5. As we shall see, assigning sentence-structures in this way to sentences involving specifier offset prepositions simplifies the account of their semantics.[10]

As a final illustration of our approach, consider *ago*. We take *ago* to be a specifier offset preposition having no complement, but an obligatory specifier, which must be a noun-phrase denoting a duration. This behaviour is forced by the following assignment:

(40) ago $\sharp$ $\lambda x[\lambda w[\mathbf{ago}(w)]]$ / $\{w : \{\text{free-floating}\}\}$ / $\{w : \{\bar{\bar{\mathrm{N}}}\}\}$.

The sentence

(41) Gunner visited Ridley three years ago

is then unproblematically assigned the structure

(42) $\mathbf{at}(\mathbf{ago}(\langle\text{three years}\rangle), \langle\text{Gunner visited Ridley}\rangle)$,

[10] There are additional uses of *after* which we do not discuss here, e.g. *After three years with MI5.*

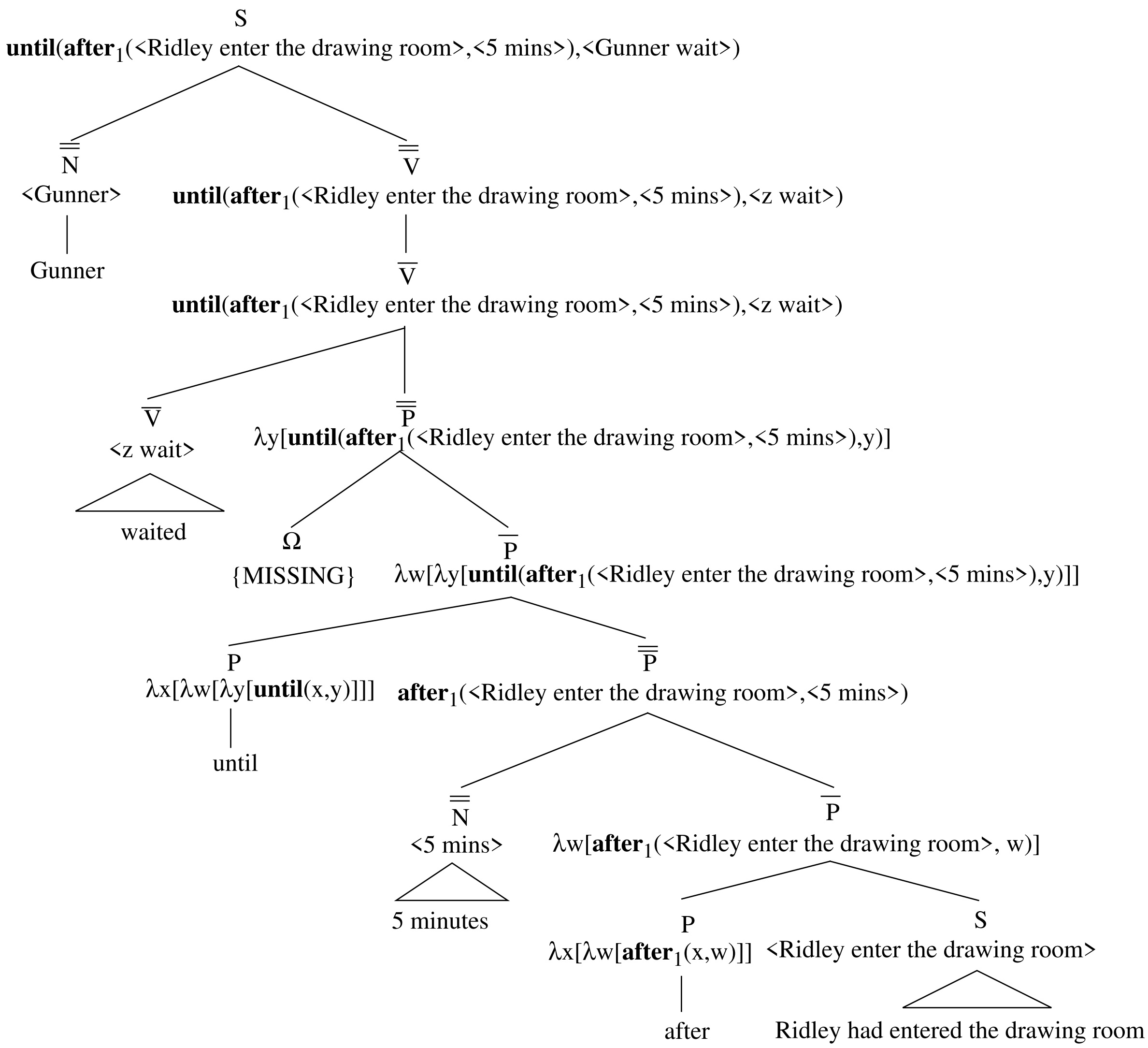

Figure 4: The computation of a sentence-structure for a sentence involving a specifier offset preposition used as a complement to a preposition: *Gunner waited until 5 minutes after Ridley had entered the drawing room.*

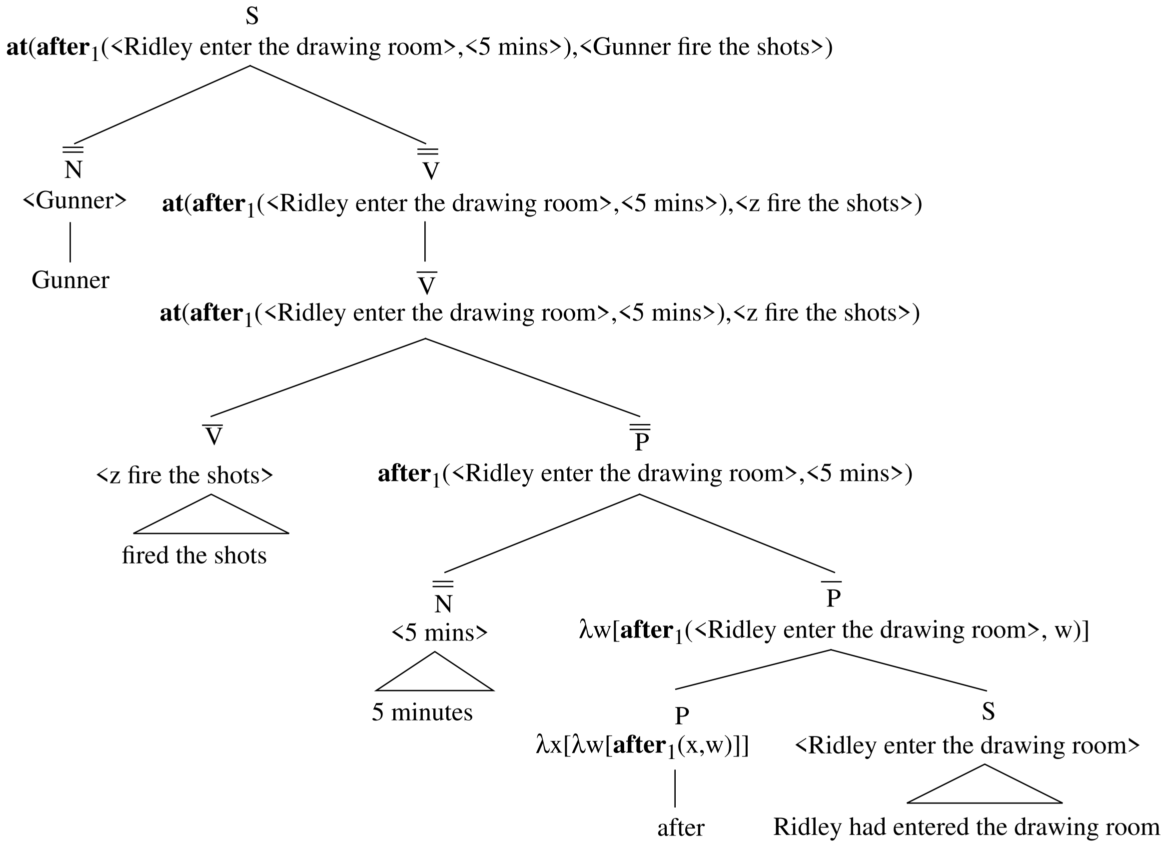

Figure 5: The computation of a sentence-structure for a sentence involving a specifier offset preposition used as an adjunct to a verb-phrase: *Gunner fired the shots 5 minutes after Ridley had entered the drawing room.*

while sentences such as

(43) * Gunner visited Ridley ago three years

(44) * Gunner visited Ridley Monday ago

fail to be parsed.[11]

So far, we have spoken about sentence-structures for sentences involving temporal preposition-phrases. But what of sentences involving other temporal adverbials we shall be concerned with? What of, for example:

(45) Gunner visited Ridley one Monday

(46) Gunner visited Ridley every Monday ?

The determiners *one* and *every* belong to a larger class of quantifying expressions in English which lie beyond the scope of this paper. Our purpose in considering them at all is merely to increase the range of interesting examples we can cover. Accordingly, we simply propose that these sentences be taken to have the structures

(47) $\mathbf{one}(\langle\text{Monday}\rangle, \langle\text{Gunner visited Ridley}\rangle)$

(48) $\mathbf{every}(\langle\text{Monday}\rangle, \langle\text{Gunner visited Ridley}\rangle)$,

respectively. Thus, we take the determiners *one* and *every* to correspond to functors **one** and **every** respectively. These functors take two arguments: the first corresponding to a noun-phrase, the second to the modified sentence. We shall not pause to describe the generation of such sentence-structures by means of augmented syntax rules.

Mention of determiners raises the issue of the role of these expressions in the noun-phrase complements and specifiers of prepositional phrases. For example, one can say

(49) Gunner secretly took photographs during the meeting

(50) Gunner secretly took photographs during a meeting

(51) Gunner secretly took photographs during every meeting.

However, the use of determiners within preposition-phrases is more complicated than these examples suggest. For example, we have:

(52) Gunner visited Ridley at the weekend

(53) ? Gunner visited Ridley at a weekend.

Or again, we have

(54) Gunner has visited Ridley since Monday

(55) * Gunner has visited Ridley since a/one/every Monday

In this paper, we will not investigate the interactions between determiners and temporal prepositions. All the noun-phrases we shall be concerned with will be calendrical terms such as *Monday*, *24th January*, *3 o' clock*, which have no (written) determiners, or are durational terms such as *3 hours*, *5 minutes* with numerical quantifiers. We hope the reader will agree that the material covered below is sufficiently complicated to justify this simplification.

[11] In fact, *ago*—and indeed all the specifier offset prepositions—enjoy a wider variety of specifiers than just durations. Thus, phrases such as *three Mondays ago*, *two pages ago*, occasionally crop up. This paper offers no account of these complications.

In this section, we have introduced sentence-structures—simple projections of phrase structure designed to highlight those aspects relevant to the semantics of temporal adverbials. In effect, sentence-structures are intermediate representations between phrase-structure trees and the logical formulae we shall eventually produce to give the truth-conditions of sentences.[12] We have explained in this section how sentence-structures can be computed for English sentences involving temporal prepositions. Our task in the following sections is to show how these sentence-structures can in turn be mapped to formulae expressing the truth-conditions of the original English sentences.

3 A temporal representation language

In this section, we introduce a formal language, TL, capable of expressing the truth-conditions of English sentences involving temporal prepositions and some related adverbials. In subsequent sections, we shall show how these truth-conditions can be automatically generated from the corresponding sentence structures.

Consider the sentence

(56) Gunner shot Ridley one Monday.

This sentence contains three temporally significant components: (i) the tense and aspect of the verb, (ii) the temporal adverbial *one Monday*, and (iii) the underlying tenseless sentence, *Gunner shoot Ridley.* The verb-tense and -aspect help to locate the general segment of time under discussion; we shall call this segment of time the *interval of interest.* We have little to say in this paper about how the interval of interest is determined, and we shall simply denote it by I_0. Most examples will be in the simple past, in which case I_0 will be some interval entirely in the past, usually (though not always) bounded below by the time of reference, if there is one. The temporal adverbial *one Monday* functions as an existential quantifier, helping to locate the reported event more precisely in time. Since we need to quantify over Mondays, we shall employ an *event-atom* $\langle$Monday$\rangle$, which we take to be true at all and only those intervals which coincide exactly with Mondays (starting at 00:00 hours and ending at 24:00 hours). Event-atoms are basic building-blocks of our representation language, and correspond to (for us) unanalysed components of sentence-structures. Finally, the underlying tenseless sentence describes the type of event or state located in time by the other two components. Here too, we employ an event-atom $\langle$Gunner shoot Ridley$\rangle$, which we take to be true at all and only those intervals over which Gunner shoots Ridley (starting when the shooting begins and finishing when the shooting ends). For simplicity, we model time using the real line, and we assume events to occur over closed intervals of the real line. (Thus, we allow point-events). We denote the set of all such intervals by Ω, and the set of event-atoms by E.

For the present, let us take an *interpretation* M for formulae of our language to be a function mapping E to the power set of Ω. Intuitively, if e is an event-atom, $M(e)$ is the set of intervals I in Ω such that an event of type e occurs at I, according to M. The temporal modal operator $\diamond$ we then define as follows. Let e be an event-atom and ϕ a formula of TL.

(57) $M \models_I \diamond(e)$ if there exists a $J \subseteq I$ such that $J \in M(e)$

(58) $M \models_I \diamond(e, \phi)$ if there exists a $J \subseteq I$, $J \in M(e)$ and $M \models_J \phi$.

With these technical resources at our disposal, we can write down the truth-conditions for Sentence (56). This sentence states that, sometime in the interval of interest, there is a Monday such that, sometime within that Monday, Gunner shoots Ridley. That is:

(59) $\diamond(\langle\text{Monday}\rangle, \diamond(\langle\text{Gunner shoot Ridley}\rangle))$.

[12] Such intermediate representations are quite standard in implemented systems of formal semantics for natural language. See, for example, Alshawi [3].

Formula (59) is the translation into TL of the sentence (56), and thus, once the interval of interest is specified, gives its truth-conditions. (We take it as read, in giving the semantics of English sentences, that the formulae into which we translate them are supposed to be true at the interval of interest, I_0.)[13]

Note that the event-atom ⟨Monday⟩, which arises from the prepositional complement, and the event-atom
⟨Gunner shoot Ridley⟩, which arises from the underlying tenseless sentence, are treated entirely on a par: they are both true or false at a given interval. Sometimes, we will refer to event-atoms corresponding to prepositional complements as *temporal restrictions*, because they serve to restrict the kinds of intervals over which quantification ranges. But this term will be used only informally: officially, event-atoms just receive truth-values at intervals.

Now consider the sentences:

(60) Gunner visited Ridley every Monday.

(61) Gunner visited Ridley on Monday.

Sentence (60) states that, for every Monday in the interval of interest, sometime within that Monday, Gunner visits Ridley. Sentence (61), by contrast, can be taken to assert that there is a unique Monday in the interval of interest, and that, sometime within that Monday, Gunner visits Ridley.[14] We can formalize these truth-conditions by introducing two further operators into TL:

(62) $M \models_I \Box(e, \phi)$ if, for all $J \subseteq I$ such that $J \in M(e)$, $M \models_J \phi$.

(63) $M \models_I \bullet(e, \phi)$ if (i) there is a unique $J \subseteq I$ such that $M \models_J e$ and (ii) there is a $J \in \Omega$ such that $J \subseteq I$, $J \in M(e)$ and $M \models_J \phi$.

The truth-conditions of (60) and (61) are then, respectively:

(64) $\Box(\langle\text{Monday}\rangle, \diamond(\langle\text{Gunner visit Ridley}\rangle))$.

(65) $\bullet(\langle\text{Monday}\rangle, \diamond(\langle\text{Gunner visit Ridley}\rangle))$.

Finally, consider the sentences

(66) Gunner had telephoned Ridley by Monday

(67) Gunner has returned to the scene of the crime since Saturday

By analogy with sentence (61), we can take sentence (66) to assert that there is a unique Monday in the interval of interest, and that, sometime within the interval of interest, but before that Monday, Gunner telephones Ridley.[15] Likewise, we can take sentence (67) to assert that there is a unique Saturday in the interval of interest, and that, sometime within the interval of interest, but after that Saturday, Gunner visits the scene of the crime.

We can formalize these truth-conditions by introducing two further operators into TL. First, some notation for relations between intervals. Let I, J and K be intervals in Ω. We say that $\text{lgp}(I, K, J)$ iff $J \subseteq I$ and $\text{start}(I) = \text{start}(K)$ and $\text{start}(J) = \text{end}(K)$. Similarly, we say that $\text{rgp}(I, K, J)$ iff $J \subseteq I$ and $\text{end}(J) = \text{start}(K)$ and $\text{end}(I) = \text{end}(K)$. The two relationships are depicted in figure 6 (lgp and rgp stand for *left group* and *right group* respectively). Then we write:

(68) $M \models_I \bullet\!\!\rightarrow (e, \phi)$ if (i) there is a unique $J \subseteq I$ such that $J \in M(e)$ and (ii) there are $J, K \subseteq I$ such that $\text{lgp}(I, K, J)$, $J \in M(e)$ and $M \models_K \phi$.

[13] Quantifying over intervals in the predicate calculus is an established way of representing of temporal knowledge (e.g. Allen [1]).

[14] This claim is not entirely proper, since it is plausible to take the existence of a unique Monday in the interval of interest to be *presupposed* rather than asserted. However, in order to simplify TL, we shall take a small liberty here and ignore the difference. We will return to this matter below.

[15] Similar remarks to those in footnote 14 concerning the distinction between truth-conditions and presuppositions apply here. Moreover, we shall not discuss whether sentence (66) is true if Gunner telephoned Ridley *on* Monday. English tends to be rather unclear on this point. We legislate below (arbitrarily) in the negative.

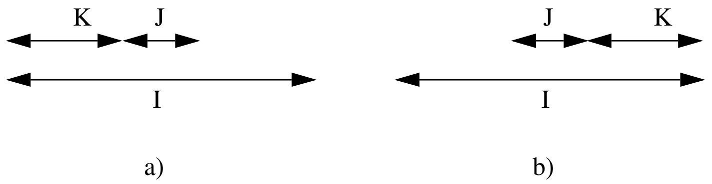

Figure 6: The temporal relations: a) $\mathrm{lgp}(I, J, K)$ and b) $\mathrm{rgp}(I, J, K)$.

(69) $M \models_I \leftarrow\!\!\bullet(e, \phi)$ if (i) there there is a unique $J \subseteq I$ such that $J \in M(e)$ and (ii) there are $J, K \subseteq I$ such that $\mathrm{rgp}(I, K, J)$, $J \in M(e)$ and $M \models_K \phi$.

The truth-conditions of (66) and (67) are then, respectively:

(70) $\bullet\!\!\rightarrow (\langle\text{Monday}\rangle, \diamond(\langle\text{Gunner telephone Ridley}\rangle))$

(71) $\leftarrow\!\!\bullet(\langle\text{Saturday}\rangle, \diamond(\langle\text{Gunner return to the scene of the crime}\rangle))$.

Prepositions with sentential components can be given truth-conditions in TL in exactly the same way as those with noun-phrase complements. Thus:

(72) Gunner telephoned Ridley before *Ridley resigned from MI5*

(73) Gunner has returned to the scene of the crime since *Ridley was killed*

are assigned the truth-conditions:

(74) $\bullet\!\!\rightarrow (\langle\text{Ridley resign from MI5}\rangle, \diamond(\langle\text{Gunner telephone Ridley}\rangle))$ [16]

(75) $\leftarrow\!\!\bullet(\langle\text{Ridley be killed}\rangle, \diamond(\langle\text{Gunner return to the scene of the crime}\rangle))$.

In other words, the event-atoms $\langle$Ridley resign from MI5$\rangle$ and $\langle$Ridley be killed$\rangle$, derived from the sentential prepositional complements in sentences (72) and (73), are treated in the same way as the event-atoms $\langle$Monday$\rangle$ and $\langle$Saturday$\rangle$, derived from the noun-phrase prepositional complements in sentences (66) and (67): both are made true or false at intervals.

At this point, we have already encountered the principal features of our formal language, TL. These are: (i) event-atoms, which are evaluated with respect to intervals, and which correspond to the content-bearing components of sentences and (ii) temporal modal operators, which form complex formulae out of simpler ones, and which correspond to English temporal prepositions and related adverbial constructions. The specifications of the temporal operators given above have been simplified somewhat for ease of exposition; the official definitions are given in appendix B.

We draw readers' attention to one feature of these temporal operators which will figure prominently in the ensuing discussion. In the semantics for the operators $\diamond$, $\Box$, $\bullet$, $\bullet\!\!\rightarrow$ and $\leftarrow\!\!\bullet$, given in in (57), (62), (63), (68) and (69), all the quantification is restricted to sub-intervals of the current interval of evaluation. In terms of most systems of temporal logic, this feature is unusual. However, it is a feature that seems to pervade temporal constructions in English, as we shall see when we come to examine sentences containing several temporal adverbials. Thus, the fact that the operators in TL quantify over sub-intervals of the current interval of evaluation is a central feature of the temporal representation system we propose.

We will return to this central feature presently, when we come to consider sentences involving multiple temporal adverbials. Before doing so, however, a few complications must be dealt with. These

[16] In section 5, we will give a more general (but more complicated) treatment of sentences involving *before* and *after* than that adopted in this section.

complications concern: (i) clock times, (ii) events versus states, (iii) free-floating temporal restrictions, (iv) anaphora and indexicality and (v) negation and presupposition.
(i) Clock times: In addition to days of the week, months, years and other calendrical items, temporal prepositions often take clock-times as arguments, for example:

(76) Gunner forged Ridley's suicide note at ten o'clock.

Suppose that Gunner forges such a note, starting at time t_1 and finishing at time t_2, insofar as it is possible to say exactly when an event begins and ends. Then (76), on any reasonable interpretation, must be taken to say that the whole of the interval $[t_1, t_2]$ is near to 10:00. Thus, if t_1 = 7:30, (76) is false—no matter how close to 10:00 Gunner finished. And (76) is of course likewise false if t_2 lies too long after 10:00. It follows that there is a limit to how long the time period $[t_1, t_2]$—and hence the suicide note Gunner forged in it—can be.[17] Accordingly, we propose to give the truth-conditions of (76) as

(77) $\bullet(\langle 10{:}00\rangle, \diamond(\langle \text{Gunner forged the suicide note}\rangle))$

where the predicate $\langle 10{:}00\rangle$ is taken to be true at an interval $[10{:}00 - \varepsilon,\ 10{:}00 + \varepsilon]$ centred on ten o'clock, in which ε is some small, contextually determined quantity. Notice that (77) does not require that Gunner be in the middle of forging the note at 10:00—he could finish just before or start just afterwards. This is in accordance with linguistic intuition. In the sequel, we shall take clock-times in English to pick out intervals with a contextually determined duration.[18]
(ii) States and events: All the examples encountered so far report the occurrence of an *event* — that of Gunner's visiting Ridley, his shooting him, his returning to the scene of the crime. Accordingly, we represented the meaning of the underlying tenseless sentence using event-atoms true at those intervals over which the event occurs. By contrast, the sentence

(78) Ridley worked in his laboratory until 5 o'clock

reports the holding, until 5 o'clock, of the *state* of Ridley's working in his laboratory, where a state is something that is true at all times throughout some interval. Theories of temporal representation disagree as to what to do here. *We* adopt the following policy. We employ a *state-atom* $\langle$Ridley work in his laboratory$\rangle$, which we take to be true or false at time-*points*. To say that a state-atom holds throughout an interval is just to say that it holds at all points in that interval. If we identify a time point t with the instantaneous interval $[t, t]$, and if we introduce the special atom point, true at all and only such point-intervals, then we can write the truth-conditions of sentence (78) as:

(79) $\bullet\!\!\rightarrow (\langle 5{:}00\rangle, \Box(\text{point}, \langle \text{Ridley work in his laboratory}\rangle))$.

Thus, events are true at closed intervals (which may be point-intervals); states are only true at point-intervals. This means that we must extend the notion of an interpretation M. Let S be the set of state atoms. Then we take an interpretation M to be a function from $E \cup S$ to the power set of Ω, with the property that, for any $s \in S$, $M(s)$ is a set of point-intervals. For technical reasons concerning theorem-proving in TL, we adopt the following assumptions regarding the interpretations of event- and state-atoms. If events of the atomic type e are true at intervals I_1 and I_2, then I_1 and I_2 do not overlap. Furthermore, if an event of type e is true at a point-interval (something we do not rule-out), then there are intervals either side of that point in which e does not occur. (This prohibits certain pathological situations, such as an event's occurring at, say, the rational points on the time axis.) Finally, the set of points at which a state s holds can be expressed as the union of a finite set of closed intervals. These

[17] Admittedly, we can say things like: "The QE II will sail to New York at 3 o'clock'. But we can probably best take this to be simply elliptical for the more correct: "The QE II will set sail for New York at 3 o'clock'.

[18] To say that the context *determines* ε is perhaps misleading, since it is plausible to claim that this quantity, and, therefore, the truth-conditions of (76), are inherently vague (hence *in*determinate). Notice the policy we adopt to deal with this vagueness: we map sentence (76) into, in effect, a parametrized collection of formulae (77), with parameter ε, each instance of which has completely determinate truth-conditions. The vagueness is located entirely in the conversational dynamics which govern the allowable settings of the parameter in different contexts. A discussion of these dynamics, however, is more general than the subject of temporal adverbials, and would take us beyond the scope of the present paper. For a classic (if rather general) discussion of these issues, see Lewis [20] .

assumptions about temporal ontology should constitute no undue restriction for most of the states and events that normally get talked about. Certainly, similar assumptions are common in formal theories of temporal reasoning in AI.[19]

Although we have distinguished event- and state-atoms in terms of restriction on the sets of intervals at which those atoms can be true, a simple and well-known linguistic test can be used to distinguish underlying tenseless sentences that report events from those that report states. Event-reporting tenseless sentences combine with *in*-adverbials, but not *for*-adverbials; state-reporting tenseless sentences, by contrast, combine with *for*-adverbials, but not *in*-adverbials:

(80) Ridley solved the equation in 10 minutes

(81) * Ridley solved the equation for 10 minutes

(82) Ridley worked in his laboratory for 4 hours

(83) * Ridley worked in his laboratory in 4 hours.

An explanation of why this test works will be given in section 4.

It is common in semantics to distinguish more than just two aspectual classes of tenseless sentence. Most writers, following Vendler, distinguish between *states*, *events*, *achievements* and *processes*, though the precise meanings of these terms tend to vary and are sometimes hard to pin down. Our treatment of aspectual class differs from that normally found in the literature in two ways. First, we distinguish only between events and states, understood in the sense explained above. Second, we speak of the aspectual class only of (the meanings of) tenseless sentences *containing no temporal adverbials*. Thus, for example, while $\langle$Gunner shoot Ridley$\rangle$ is an event-atom and $\langle$Ridley work in his laboratory$\rangle$ a state-atom, the tenseless sentences *Gunner shoot Ridley after 5 o clock* and *Ridley work in his laboratory for 5 hours* will not be assigned any aspectual class, since no such assignment is required by the semantic account that follows.

In simply speaking of events and states, understood in our somewhat non-standard way, we do not claim that further aspectual-class distinctions are unnecessary. Likewise, in declining to assign aspectual classes to tenseless sentences containing adverbials, we are not committed to the conclusion that such assignments are unnecessary. However, we claim that, by supposing *merely* that the meanings of atomic tenseless sentences (i.e. those containing no temporal adverbials) can be assigned to one or the other of our two aspectual classes, many well-known phenomena concerning combinations of temporal adverbials in sentences can be elegantly explained. If further, orthogonal, aspectual-class distinctions must be drawn to account for phenomena not considered here (indeed, we believe they must), we have no objection.

One further disclaimer is in order at this point. As has been noted by many authors, the aspectual class of a tenseless sentence is somewhat flexible and context-dependent. For example, the tenseless sentence *Gunner photographed the documents* would normally be taken as reporting an event—something that is true over a specific interval, but not over subintervals of thereof—as suggested by the sentence:

(84) Gunner photographed the documents in five minutes.

However, the same tenseless sentence can also report a state, true throughout an interval, for example in:

(85) Gunner photographed the documents for five minutes.

Clearly, there has been a shift in meaning in the tenseless sentence—roughly, the suspension of the requirement that the documents be *completely* photographed—to accommodate the different preposition phrases. This phenomenon of aspectual class coercion applies to our distinction between events and states just as much to any other treatment of aspectual class; we have nothing to add to what has already been said on this topic.[20]

[19] For example, in Allen [1].

[20] See, e.g. Moens and Steedman [25] for a fuller discussion of aspectual class coercion.

We mention one additional complication here. Truth-conditions (79) have it that Ridley is working in his laboratory at every instant of the interval in question. But what does this mean? If Ridley takes a 5-minute tea-break, is he working in his laboratory during these instants? What if he goes to the toilet? Or scratches his head? Or blinks? It seems that, if sentences such as (78) are to be true at all, we must allow interruptions. Does this not mean that the truth-conditions (79) have been falsified?

Not necessarily. Our proposal is that we take the state-atom ⟨Ridley work in his laboratory⟩ to be true at time points that occur during negligible interruptions to what we happily think of as episodes of Ridley's working in his laboratory. On this view, whether a state-atom is true at a point depends on what is happening at neighbouring points. How big may an interruption become before it ceases to be negligible in this way? Well, it depends on how strict we want to be. For the sentence

(86) Gunner had been spying for the Soviets since 1987,

a month's holiday may be negligible; for the sentence (78), on the other hand, a five-minute tea-break may not be. But we do not need to specify here how the requisite degree of strictness is set. All that matters here is that we can locate the varying degrees of strictness in varying interpretations of the underlying temporal predicates, whilst maintaining a simple and uniform logic framework.[21]

(iii) Free-floating temporal restrictions: Consider the sentence

(87) Gunner broke the code within 10 minutes

On one reading of this sentence, it is true just in case the interval of interest includes some 10-minute-long interval which itself includes an interval at which Gunner broke the code. Helping ourselves to the atom ⟨10 minutes⟩, which we take to be true at all intervals of duration 10 minutes, we can write these truth-conditions as follows:

(88) $\diamond(\langle\text{10 minutes}\rangle, \diamond(\langle\text{Gunner break the code}\rangle))$.

A similar treatment is possible for

(89) Ridley worked in his laboratory for 4 hours.

On one reading of this sentence, it is true just in case the interval of interest includes some 4-hour-long interval throughout which Ridley works in his laboratory. Given our decision to treat state-atoms as being true at points, we can write these truth-conditions as:

(90) $\diamond(\langle\text{4 hours}\rangle, \Box(\text{point}, \langle\text{Ridley work in his laboratory}\rangle))$.

The point to note here is that the temporal restrictions ⟨10 minutes⟩ and ⟨4 hours⟩ apply to all intervals of the requisite duration regardless of when those intervals start. In particular, any period, no matter how small, contains the starting points of infinitely many intervals at which ⟨10 minutes⟩ and ⟨4 hours⟩ are true. In this respect, these atoms contrast with event-atoms such as ⟨Monday⟩, ⟨January⟩ and ⟨6 o clock⟩, which all have the property that the intervals satisfying them start at specific times. Thus, each Monday begins at 00:00 hours that day; likewise, each January begins at 00:00 hours on the first of that month. We shall call atoms such as ⟨10 minutes⟩ *free-floating atoms*.

As we saw in section 2, the prepositions *before* and *after* are frequently used with noun-phrase specifiers. These specifiers motivate a minor extension to our logic. Consider the sentences:

(91) Ridley entered the drawing room *5 minutes* before Gunner fired the shots

(92) Gunner returned to the scene of the crime *4 hours* after Ridley was killed.

[21] Our approach to the state/event distinction follows that proposed by Herweg [14], in taking states to hold at time points and events to occur over (non-instantaneous) time intervals. An alternative scheme, proposed by Allen [1], takes states to hold at all sub-intervals of any interval at which they hold. That is, if ϕ is a state, it satisfies the condition: if $\models_I \phi$ and $J \subset I$ then $\models_J \phi$. One disadvantage of Allen's scheme is that, if a state holds at two overlapping intervals, we want to infer that it holds at their union, an inference which is automatically licensed on our point-based approach, but which requires a special axiom within Allen's approach. However, both schemes would be perfectly workable for our purposes, and both have their advantages and disadvantages. We regard our choice merely as a technical convenience.

Sentences (91) and (92) function in the same way as the *at*-sentence (76), except that the temporal location is specified using an event together with an offset. Consequently, we extend the syntax of the operators $\bullet$, $\bullet\!\!\rightarrow$ and $\leftarrow\!\!\bullet$ by incorporating an offset d (where d may be taken to be a real number) as follows:

(93) $M \models_I \bullet(e + d, \phi)$ if (i) there is a unique $J \subseteq I$ such that $J \in M(e)$ and (ii) there is a $J \in \Omega$ such that $J \subseteq I$, $J + d \subseteq I$, $J \in M(e)$ and $M \models_{J+d} \phi$, where $J + d = \{t + d \mid t \in J\}$

(94) $M \models_I \bullet\!\!\rightarrow (e + d, \phi)$ if (i) there is a unique $J \subseteq I$ such that $J \in M(e)$ and (ii) there are $J, K \in \Omega$ such that $J \subseteq I$, $J + d \subseteq I$, $\mathrm{lgp}(I, K, J + d)$, $J \in M(e)$ and $M \models_K \phi$.

(95) $M \models_I \leftarrow\!\!\bullet(e + d, \phi)$ if (i) there is a unique $J \subseteq I$ such that $J \in M(e)$ and (ii) there are $J, K \in \Omega$ such that $J \subseteq I$, $J + d \subseteq I$, $\mathrm{rgp}(I, K, J + d)$, $J \in M(e)$ and $M \models_K \phi$.

Armed with these operators, we can assign truth-conditions to sentences (91) and (92) as follows:

(96) $\bullet(\langle$Gunner fire the shots $\rangle + (-0{:}05), \diamond(\langle$Ridley enter the drawing room$\rangle))$

(97) $\bullet(\langle$Ridley be killed$\rangle + 4{:}00, \diamond(\langle$Gunner return to the scene of the crime$\rangle))$.

(Thus, we take our units to be hours, and use the notation ':' to indicate 60th's in the obvious way. However, in the sequel, we shall be quite lax about conversion of durations and calendrical times into standard format.)

(iv) Anaphora and indexicality: As we saw in section 2, some temporal prepositions have missing complements. Semantically, such preposition-phrases locate events with respect to the *time of reference*, henceforth denoted tor, which may or may not be identical to the *time of utterance*, henceforth denoted tou. The latter notion is self-explanatory. The former, when it is different from the tou, standardly refers to the time set up by the last-mentioned event in a narrative, with respect to which subsequent events may be located. Thus, the tor, when identical to the tou, can be read as *now*; otherwise, it can be read as *then*.

(98) Gunner was in this room 2 hours ago (= *two hours before now*)

(99) Gunner visited the scene of the crime just after shooting Ridley.
He had been there before (= *before then*).

We shall not attempt a full explanation of how the tor is determined. We can assign truth-conditions to sentences (98) and the second sentence in (99) as follows:

$\bullet(\mathrm{tor} + (-2{:}00), \diamond(\mathrm{point}, \langle$Gunner be in this room$\rangle))$ (N.B. tor = tou.)

(100) $\bullet(\mathrm{tor} + (-2{:}00), \Box(\mathrm{point}, \langle$Gunner be in this room$\rangle))$ (N.B. tor = tou.)

(101) $\bullet\!\!\rightarrow (\mathrm{tor}, \diamond(\mathrm{point}, \langle$He be there$\rangle))$.

(Thus, sentence (98) is taken to be indeterminate between existential and universal readings.) The new resources required are merely the distinguished event-atom tor, which, for the present, we may treat like any other event-atom, true at (unique, short) intervals. We will not express the relationship between the tou and the tor in our translations of English sentences. However, it is a simple matter to express separately in our formalism.

(v) Presupposition and negation: Consider again the sentence

(102) Ridley was working in his laboratory until Gunner arrived.

The truth-conditions given for this sentence require that Gunner arrive (uniquely) within the interval of interest, and that Ridley be working in his laboratory until then. However, there are good grounds for taking the (unique) arrival of Gunner within the interval of interest to be a *presupposition* of (102), rather than a part of its truth-conditions. We mention just one reason here: the effect of *not*.

Negating sentence (102) gives us:

(103) Ridley wasn't working in his laboratory until Gunner arrived.

Now (103) has two meanings: (i) it is not the case that Ridley was working in his laboratory for the whole time prior to Gunner's arrival, and (ii) for the whole time prior to Gunner's arrival, it is not the case that Ridley was working in his laboratory. But what (103) can never mean is that *either* Gunner did not arrive at all, or, if he did, it is not the case that Ridley was working in his laboratory until that time. In fact, (103) seems to imply (or implicate) Gunner's arrival every bit as much as (102). That is: the negation does not affect this aspect of what the sentence conveys; and that indicates a presupposition.

Distinguishing truth-conditions from presuppositions is important when considering the validity of arguments expressed in English. Typically, such arguments are regarded as valid even when the premises do not imply the presuppositions of the conclusion. Consider, for example, the argument:

$$(104)\quad \begin{array}{l} \text{Gunner called at the Soviet embassy before the mole was discovered} \\ \text{Gunner shot Ridley after the mole was discovered} \\ \hline \text{Therefore, Gunner shot Ridley after calling at the Soviet embassy.} \end{array}$$

Intuitively, this argument seems valid. Yet it is a presupposition of the conclusion that Gunner called at the Soviet embassy *once* within the interval of interest; and this is not implied by the premises. Note that it would be wrong, however, to ignore presuppositions altogether when deciding the validity of arguments. For argument (104) is only valid at all given the presupposition of the premises, that the mole was discovered only once within the interval of interest. Thus, presuppositions of the premises must be taken into account when assessing the validity of arguments; but presuppositions of conclusions need not be established. How are we to model this situation formally?

We adopt the following strategy. We continue to translate English temporal prepositions such as *before*, *at*, *after* etc. using the operators $\bullet\!\!\rightarrow$, $\bullet$ and $\leftarrow\!\!\bullet$—effectively building presuppositions into the truth-conditions. Argument (104) thus becomes:

$$(105)\quad \begin{array}{l} \bullet\!\!\rightarrow(\langle\text{the mole be discovered}\rangle, \diamond(\langle\text{Gunner call at the Soviet embassy}\rangle)) \\ \leftarrow\!\!\bullet(\langle\text{the mole be discovered}\rangle, \diamond(\langle\text{Gunner shoot Ridley}\rangle)) \\ \hline \leftarrow\!\!\bullet(\langle\text{Gunner call at the Soviet embassy}\rangle, \diamond(\langle\text{Gunner shoot Ridley}\rangle)) \end{array}$$

In order to understand the validity of arguments, we adopt a strong form of negation, which has no effect on those aspects of a formula's truth-conditions that correspond to presuppositions in English. The semantics of our negation operator are as follows:

$$(106)\quad \begin{array}{l} M \models_I \neg \bullet (e, \phi) \text{ if } M \models_I \bullet(e, \neg\phi) \\ M \models_I \neg\bullet\!\!\rightarrow (e, \phi) \text{ if } M \models_I \bullet\!\!\rightarrow (e, \neg\phi) \\ M \models_I \neg \leftarrow\!\!\bullet(e, \phi) \text{ if } M \models_I \leftarrow\!\!\bullet(e, \neg\phi) \\ M \models_I \neg \diamond (e, \phi) \text{ if } M \models_I \Box(e, \neg\phi) \\ M \models_I \neg\Box(e, \phi) \text{ if } M \models_I \diamond(e, \neg\phi) \\ M \models_I \neg\neg\phi \text{ if } M \models_I \phi \\ M \models_I \neg\phi \text{ if } M \not\models_I \phi \text{ and } \phi \text{ is not one of the above forms} \end{array}$$

Thus, $\neg$ 'passes through' the operators $\bullet\!\!\rightarrow$, $\bullet$ and $\leftarrow\!\!\bullet$ but negates everything else[22].

Armed with this negation operator, we define:

Definition: Let Φ be a set of formulae. We write $\Phi \models \phi$ iff for no interpretation M, $M \models \Phi \cup \{\neg\phi\}$. In that case, we say that the argument from Φ to ϕ is *valid*.

Letting Φ be the premises of argument (104) and ϕ be its conclusion, $\Phi \cup \{\neg\phi\}$ becomes, after moving the negation inwards according to (106):

[22] Beware that this negation operator is merely a technical device within TL, and does not correspond to any claim about the way the word *not* functions in English. In particular, we are not committed to the claim that the *not* in *Gunner did not come one Monday* has wider scope than the *one Monday*! Rather, the special negation operator merely enables a usable account of validity in TL to be formulated while preventing TL from being able to express wide-scope denials of formulae involving $\bullet$, $\bullet\!\!\rightarrow$ and $\leftarrow\!\!\bullet$.

$$
\begin{array}{ll}
 & \{\bullet\!\!\rightarrow(\langle\text{the mole be discovered}\rangle, \diamond(\langle\text{Gunner call at the Soviet embassy}\rangle)) \\
(107) & \leftarrow\!\!\bullet(\langle\text{the mole be discovered}\rangle, \diamond(\langle\text{Gunner shoot Ridley}\rangle)) \\
 & \leftarrow\!\!\bullet(\langle\text{Gunner call at the Soviet embassy}\rangle, \neg\diamond(\langle\text{Gunner shoot Ridley}\rangle))\}
\end{array}
$$

and it is easy to see that these formulae have no model. Thus, our definition of validity has the right effect for argument (104).

Here is another case. Consider the argument

$$
(108) \quad
\begin{array}{l}
\text{Gunner was at the Soviet embassy until 5 hours after control telephoned} \\
\text{Ridley was shot 30 minutes after control telephoned} \\
\hline
\text{Therefore, Gunner was at the Soviet embassy when Ridley was shot .}
\end{array}
$$

The translation into TL is:

$$
(109) \quad
\begin{array}{l}
\bullet\!\!\rightarrow(\langle\text{control telephone}\rangle + 5{:}00, \Box(\text{point}, \langle\text{Gunner be at the Soviet embassy}\rangle)) \\
\bullet(\langle\text{control telephone}\rangle + 0{:}30, \diamond(\langle\text{Ridley be shot}\rangle)) \\
\hline
\bullet(\langle\text{Ridley be shot}\rangle, \Box(\text{point}, \langle\text{Gunner be at the Soviet embassy}\rangle)).
\end{array}
$$

The reader can easily verify that argument (109) is valid according to the above definition.

Of course, the question arises as to whether the validity of arguments in TL can be checked automatically; and the answer is that it can. Like most temporal logics, TL is decidable, and a provably correct decision procedure for a version of this language has been implemented.[23] In the sequel, therefore, we will continue to build presuppositions into truth-conditions, on the understanding that the validity of arguments is to be determined using the strong negation operator defined in (106).[24]

Notice that the treatment of our negation operator $\neg$ makes no claims about negation in English! For we introduced $\neg$ only in the context of determining validity among non-negated English sentences. An account of how to interpret negation in English must be considered beyond the scope of the present paper; we content ourselves with pointing out that the above treatment of presupposition and validity is orthogonal to any such account.

Having dealt with these complications, we may now return briefly to the distinctive feature of TL noted earlier: the use of operators that quantify only over subintervals of the current interval of evaluation. We observe that such operators seem to be just what is needed to give the truth-conditions of sentences containing more than one temporal adverbial. Consider, for example:

(110) Ridley died on Saturday at 5:43

(111) Gunner found out about Ridley's research one Saturday in July

(112) Ridley had been working in his laboratory for 12 hours every day since November.

A striking feature of these examples is that, in each case, all but one of the temporal adverbials function so as to quantify over subintervals of intervals mentioned by another temporal adverbial. Thus, sentence (110) has truth-conditions

(113) $\bullet(\langle\text{Saturday}\rangle, \bullet(\langle 17{:}43\rangle, \diamond(\langle\text{Ridley died}\rangle)))$.

That is: there is a unique Saturday within the interval of interest, and (a short interval surrounding) the unique 5:43 (understood: 5:43 pm) within that Saturday, such that Ridley dies within that interval. Similarly, sentence (111) has truth-conditions:

[23] Note that the decision procedure must resolve inequalities involving numerical offsets arising from cases such as argument (108). The details, though non-trivial, use well-established techniques.

[24] This strategy gives us an *approximation* to the phenomenon of presupposition in such sentences: we get a relatively faithful treatment of negation without truth-valueless sentences. One example of presupposition which is not modelled by our account is provided by the sentence *Gunner did not knock until Ridley had sat down*, which arguably presupposes that Gunner did knock.

(114) $\bullet(\langle\text{July}\rangle, \diamond(\langle\text{Saturday}\rangle, \diamond(\langle\text{Gunner find out about Ridley's research }\rangle)))$.

That is: there is an unique July in the interval of interest, and a Saturday within that July, and an interval within that Saturday, such that Gunner finds out about Ridley's research at that interval.

As a final demonstration, the truth-conditions of (112) follow the same pattern:

(115) $\leftarrow\!\!\bullet(\langle\text{November}\rangle, \Box(\langle\text{day}\rangle, \diamond(\langle\text{12:00}\rangle, \Box(\text{point}, \langle\text{Ridley work in his laboratory}\rangle))))$.

Again, each operator is restricted to quantifying over subintervals of intervals set up by the last: there is a unique interval within the interval of interest stretching from a November to the end of the interval of interest, and, for every sub-interval of that interval which is a day, there is some 12-hour-long interval within that day such that, for every point within that interval, the state of Ridley's working in his laboratory holds at that point.

This tendency of one temporal adverbial to quantify over subintervals of intervals mentioned by another pervades temporal constructions in English, and forms the basis for the semantic approach taken in this paper. That is why the restriction of quantification to subintervals of the current interval is built into the semantics of our operators $\diamond$, $\Box$, $\bullet$, $\bullet\!\!\rightarrow$ and $\leftarrow\!\!\bullet$.

In this section, we have presented a temporal representation language, TL, and we have illustrated, by means of examples, its suitability for giving the truth-conditions of various English sentences involving temporal prepositions and related adverbials. We will have occasion to extend this language in later sections; but the essential features have all been covered. The technical appendices contain more detailed information about TL, as well as the necessary syntactic and semantic information to translate English sentences into TL. (Sections 4 and 5 explain how to use this information.)

It is easy to show that the the language TL needs extending if we are to give a complete account of the semantics of temporal prepositions in English. For example, considerations analogous to those given for argument (104) suggest that the sentence

(116) Gunner forged the note while Ridley was in the drawing room

presupposes that Ridley is in the drawing room over an unique sub-interval of the interval of interest. Such uniqueness presuppositions are modelled in TL by the operators $\bullet$, $\bullet\!\!\rightarrow$ and $\leftarrow\!\!\bullet$. Yet the temporal preposition *while* has, as its complement, a sentence that normally reports a *state*, and (unqualified) state-atoms clearly cannot usefully appear as left-hand arguments of these operators. Or again, consider the sentence:

(117) Ridley was working in his office by 9:00

in which *by* is combined with the progressive aspect. Sentence (117) states not merely that Ridley will work in his office at some time before 9:00, but, rather, that he will do so and in addition will continue to work there until (at least) 9:00. These truth-conditions cannot be expressed in TL; and we must introduce a new temporal operator to capture them.

Such examples may be multiplied almost indefinitely. The reader may, as an exercise, wish to extend TL—while preserving the general spirit of the formalism—so as to deal with sentences (116) and (117). Our central claim is that TL can naturally accommodate (by means of various extensions) temporal constructions with which we have not dealt explicitly here. Bearing in mind the enormous range of temporal constructions in natural language, and the tendency for these expressions to acquire slightly idiosyncratic truth-conditions, piecemeal treatment within a robust yet relatively constrained framework is the only workable approach to a semantic theory for these constructions. A successful extension of TL must not only add the required expressive power, but must do so in a way which does not compromise the reasoning procedures for TL or the simplicity of the overview it provides. For instance, we might require that, if TL is extended, the decision procedure (along with its correctness proofs) be modified to cope with this extension. Ultimately, the test of TL lies in the ease with which semantics for particular expressions (e.g. as given in the technical appendices) can be extended in this way. That is something that cannot be shown in one paper. The most we can hope to have established here is that TL represents a promising framework, the fine details of which can be completed later. As further support for this claim, we show, in the final sections of this paper, how translations from English to TL can be automated.

Along the way, we explain several well-known phenomena concerning temporal preposition-phrases in English.

4 Semantics: right-inserted structures

In section 2, we showed how sentences involving a range of temporal adverbials could be made to generate sentence structures, in which (relevant aspects of) the phrase structure of the original sentences are made explicit. In section 3, we introduced a formal language, TL, for expressing the truth-conditions of these sentences. Our task now is to show how sentence structures can be automatically translated into TL.

Consider the sentence

(118) Gunner visited Ridley one Monday.

This sentence has the structure:

(119) $\mathbf{one}(\langle\text{Monday}\rangle, \langle\text{Gunner visit Ridley}\rangle)$

and its truth-conditions, we agreed, are given by:

(120) $\diamond(\langle\text{Monday}\rangle, \diamond(\langle\text{Gunner visit Ridley}\rangle))$.

We adopt the following method for transforming (119) into (120). First, we decompose (119) into its components by excising the right-hand argument of the functor **one**:

(121) $\mathbf{one}(\langle\text{Monday}\rangle, \_)$
$\langle\text{Gunner visit Ridley}\rangle$.

The first component in (121) corresponds to the temporal adverbial, and its meaning can be given by the following *interpretation rule*:

(122) $\mathbf{one} \mapsto [\diamond, X, O]$ where O is in $\{\diamond, \Box, \bullet, \bullet\!\!\rightarrow, \leftarrow\!\!\bullet\}$.

This rules maps a functor into a data-structure of the form $[\mathit{Operator}_1, X, \mathit{Operator}_2]$, where the variable X will be filled by the functor's *left-hand* argument. We call call such a data-structure an *operator tuple* (in this case, an operator *triple*). Notice that this particular rule allows several choices for the second operator: let us choose $O = \diamond$ to get the mapping:

(123) $\mathbf{one}(\langle\text{Monday}\rangle, \_) \mapsto [\diamond, \langle\text{Monday}\rangle, \diamond]$.

The second component in (121) corresponds to the underlying tenseless sentence, and its meaning can be given by mapping it to the operator tuple:

(124) $\langle\text{Gunner visited Ridley}\rangle \mapsto [\diamond, \langle\text{Gunner visit Ridley}\rangle]$.

(We will explain the general process governing this mapping presently.) Finally, the pair of tuples generated, namely,

(125) $[\diamond, \langle\text{Monday}\rangle, \diamond]$, $[\diamond, \langle\text{Gunner visit Ridley}\rangle]$,

is then re-combined to generate the formula in (120). This recombination process can be informally described as follows: (i) the third component of each tuple merges with the first component of any tuple immediately to its right; (ii) the first component of each tuple is combined with the remaining components as its arguments to form a formula of TL. As we might put it, each tuple (except the first) gets inserted in the tuple immediately to its left. This process is illustrated for the operator tuples (125) in figure 7. We subject this recombination process to the following constraint: when one tuple is inserted inside another, the first operator of the inserted tuple must be identical to the second operator (last component) of the tuple in which it is inserted. The application of this constraint to the current example is indicated by the converging arrows from the two adjacent $\diamond$-operators in figure 7. Since these operators

$$\diamond(\langle\text{Monday}\rangle, \diamond(\langle\text{Gunner visit Ridley}\rangle))$$

$$[\diamond, \langle\text{Monday}\rangle, \diamond],\ [\diamond, \langle\text{Gunner visit Ridley}\rangle]$$

Figure 7: The matching of operators during re-combination

are both $\diamond$ in the current example, the constraint is satisfied. This was of course our reason for choosing $O = \diamond$ in the application of rule (122). Thus, the second operator in a tuple acts as a constraint on the tuples that can be inserted within it. We will see below how this helps to give a neat account of sentences involving multiple preposition-phrases.

Formally, the merging process may be described in 'pseudo-logic code' as follows:

(126)

$$\begin{array}{l}
\texttt{merge([[O}_1\texttt{,X,O}_2\texttt{]|tuples],O}_1\texttt{(X,O}_2\texttt{(Y,Z)))} \leftarrow \texttt{merge(tuples,O}_2\texttt{(Y,Z)).}\\
\texttt{merge([[O,X]],O(X)).}\\
\texttt{merge([[O,X,Y]],O(X,Y)).}
\end{array}$$

The reason for the two base cases will emerge presently.

Exactly the same process works with the sentences:

(127) Gunner visited Ridley every Monday

(128) Gunner visited Ridley on Monday,

which have the sentence structures:

(129) **every**$(\langle\text{Monday}\rangle, \langle\text{Gunner visit Ridley}\rangle)$

(130) **at**$(\langle\text{Monday}\rangle, \langle\text{Gunner visit Ridley}\rangle)$,

respectively. We propose the following interpretation rules for **every** and **at**:

(131) **every** $\mapsto [\Box, X, O]$ where $O \in \{\diamond, \bullet, \bullet\!\!\rightarrow, \leftarrow\!\!\bullet\}$.

(132) **at** $\mapsto [\bullet, X, O]$ where $O \in \{\diamond, \bullet, \bullet\!\!\rightarrow, \leftarrow\!\!\bullet\}$.

These rules map the sentence-structures (129) and (130) to the following lists of operator tuples (using the obvious substitutions for O):

(133) $[\Box, \langle\text{Monday}\rangle, \diamond],\ [\diamond, \langle\text{Gunner visit Ridley}\rangle]$,

(134) $[\bullet, \langle\text{Monday}\rangle, \diamond],\ [\diamond, \langle\text{Gunner visit Ridley}\rangle]$,

whence the procedure (126) generates the truth-conditions:

(135) $\Box(\langle\text{Monday}\rangle, \diamond(\langle\text{Gunner visit Ridley}\rangle))$

(136) $\bullet(\langle\text{Monday}\rangle, \diamond(\langle\text{Gunner visit Ridley}\rangle))$.

Thus, sentences are mapped to formulae by (i) breaking them down into their constituent structures, (ii) mapping the constituent structures to operator tuples by means of interpretation rules, and then (iii) combining the operator tuples into formulae. A list of interpretation rules for the functors introduced by temporal preposition-phrases and other temporal adverbials is given in appendix C. Incidentally, we can now see why the the prepositions *at*, *on* and *in* (in some uses) are all assigned structures involving the functor **at**: since the semantic functions of these prepositions are identical, we might as well associate them with one and the same functor. Interpretation rule (132) will then, without further ado, produce the correct truth-conditions for:

(137) Gunner visited Ridley in January

(138) Gunner visited Ridley at 5 o' clock,

namely:

(139) $\bullet(\langle\text{January}\rangle, \diamond(\langle\text{Gunner visit Ridley}\rangle))$

(140) $\bullet(\langle\text{5 o' clock}\rangle, \diamond(\langle\text{Gunner visit Ridley}\rangle))$.

So far, we have concerned ourselves with event-reporting tenseless sentences. State-reporting tenseless sentences must be handled slightly differently. Consider the sentence:

(141) Ridley worked in his laboratory until 5 o' clock

This sentence generates the sentence structure:

(142) $\mathbf{until}(\langle\text{5 o'clock}\rangle, \langle\text{Ridley work in his laboratory}\rangle)$.

and its truth-conditions are given by:

(143) $\bullet\!\!\rightarrow (\langle\text{5 o' clock}\rangle, \Box(\text{point}, \langle\text{Ridley work in his laboratory}\rangle))$.

These truth-conditions can be generated via the process used for sentence (118), by means of the interpretation rule:

(144) $\mathbf{until} \mapsto [\bullet\!\!\rightarrow, X, \Box]$

and by mapping the state-reporting tenseless sentence as follows:

(145) $\langle\text{Ridley work in his laboratory}\rangle \mapsto [\Box, \text{point}, \langle\text{Ridley work in his laboratory}\rangle]$.

Notice the difference from the corresponding mapping in (124). This difference is motivated by the aspectual classes of the tenseless sentences in question: *Gunner shoot Ridley* reports an event, whilst *Ridley work in his laboratory* reports a state. Mapping the components of (142) thus results in the tuples:

(146) $[\bullet\!\!\rightarrow, \langle\text{5 o'clock}\rangle, \Box]$, $[\Box, \text{point}, \langle\text{Ridley work in his laboratory}\rangle]$.

which combine in the normal way to produce the formula in (143).

State-reporting tenseless sentences should not always be mapped to operator-tuples beginning with $\Box$. For example, the sentence

(147) Ridley worked in his laboratory on 24th January

has the truth-conditions

(148) $\bullet(\langle\text{24th January}\rangle, \diamond(\text{point}, \langle\text{Ridley work in his laboratory}\rangle))$. [25]

[25] It may seem odd to insist only that the state of Ridley's working in his laboratory hold only for a *single* instant. More plausible truth-conditions might be: $\bullet(\langle\text{24th January}\rangle, \diamond(\text{ext}, \Box(\text{point}, \langle\text{Ridley work in his laboratory}\rangle)))$, where ext is true only of non-point intervals. However, in order to avoid unnecessary complication, we will stick with the simpler formulation.

And formula (148) can be generated unproblematically using the interpretation rule (132), provided we map the underlying tenseless sentence as follows:

(149) $\langle$Ridley work in his laboratory$\rangle \mapsto [\diamond, \text{point}, \langle$Ridley work in his laboratory$\rangle]$.

Thus, the rules we adopt for mapping tenseless sentences are:

(150) $X \mapsto [\diamond, X]$ where X is an event-reporting tenseless sentence.

(151) $X \mapsto [\diamond, \text{point}, X]$ where X is a state-reporting tenseless sentence.

(152) $X \mapsto [\Box, \text{point}, X]$ where X is a state-reporting tenseless sentence.

In other words: state-reporting tenseless sentences can take either $\diamond$ or $\Box$ operators, but event-reporting tenseless sentences can take only $\diamond$-operators. The reason for the alternative rules (151) and (152) will become clear below. Notice that rule (150) prevents processing of the sentence:

(153) * Ridley died until 6 o'clock

since the operator-tuples generated, namely:

(154) $[\bullet\!\!\rightarrow, \langle$6 o'clock$\rangle, \Box], \; [\diamond, \langle$Ridley die$\rangle]$,

cannot be made to match up. (Remember the constraint that the last operator of the first tuple must be the same as the first operator of the second tuple.)[26]. It is helpful to contrast sentence (153) with:

(155) Ridley died by 6 o' clock,

where the *until* has been replaced with *by*. Sentence (155) has the structure

(156) $\textbf{by}(\langle$6 o'clock$\rangle, \langle$Ridley die$\rangle)$,

and we propose the functor *by* be given the following interpretation rule:

(157) $\textbf{by} \mapsto [\bullet\!\!\rightarrow, X, \diamond]$.

Thus, (156) generates the tuples

(158) $[\bullet\!\!\rightarrow, \langle$5 o'clock$\rangle, \diamond], \; [\diamond, \langle$Ridley die$\rangle]$.

which unproblematically combine to yield the correct truth-conditions:

(159) $\bullet\!\!\rightarrow (\langle$6 o' clock$\rangle, \diamond(\langle$Ridley die$\rangle))$.

The interpretation of functors with free-floating event-atoms proceeds in the same way. The following interpretation rules work for *for* and *in*:

(160) $\textbf{in} \mapsto [\diamond, X, \diamond]$

(161) $\textbf{for} \mapsto [\diamond, X, \Box]$

These rules allow generation of the correct truth-conditions for sentences such as

(162) Ridley solved the equation in 10 minutes

(163) Ridley worked in his laboratory for 4 hours,

namely:

(164) $\diamond(\langle$4 hours$\rangle, \diamond(\langle$Ridley solve the equation$\rangle))$.

[26] It is widely, though not universally, accepted that tenseless-sentences reporting events can be coerced into state-interpretations if a temporal adverbial such as *for* demands it (Moens and Steedman [25]).

(165) $\diamond(\langle 4 \text{ hours}\rangle, \Box(\text{point}, \langle \text{Ridley work in his laboratory}\rangle))$.

The interpretation rule (161) prevents the processing of

(166) * Ridley solved the equation for 10 minutes.

The reasons are exactly parallel to those for sentence (153). We shall encounter more examples of this phenomenon below.

Notice that the procedure given above assigns truth-conditions (168) to sentence (167):

(167) * Ridley worked in his laboratory in 4 hours

(168) $\diamond(\langle 4 \text{ hours}\rangle, \diamond(\text{point}, \langle \text{Ridley work in his laboratory}\rangle))$.

However, these truth-conditions are logically equivalent to the simpler

(169) $\diamond(\text{point}, \langle \text{Ridley work in his laboratory}\rangle)))$,

since any point is a point in some four-hour-long interval. Thus, in finding sentence (167) odd, our linguistic intuitions function as a filter for redundant adverbials. Such a filter could be easily implemented within the interpretation process outlined here.[27]

Thus, the interpretation rules (160) and (161) account for the familiar *for*/*in*-test for distinguishing between events and states, given the account of the event/state-distinction in section 3.

Having established the basic translation scheme, we now turn our attention to the more interesting case of sentences involving several temporal adverbials, for it is here that our approach comes into its own. In the remainder of this section we show how such a mapping proceeds for right-inserted sentence structures; in the next, we extend this scheme to deal with left-inserted sentence structures. Consider the sentences:

(170) Ridley died on Monday at 5:43

(171) Ridley died at 5:43 on Monday

which we may take to be synonymous. From section 2, we know that these sentences generate both right- and -left-inserted sentence structures. The *right*-inserted structures are, respectively:

(172) $\mathbf{at}(\langle 5{:}43\rangle, \mathbf{at}(\langle \text{Monday}\rangle, \langle \text{Ridley die}\rangle))$

(173) $\mathbf{at}(\langle \text{Monday}\rangle, \mathbf{at}(\langle 5{:}43\rangle, \langle \text{Ridley die}\rangle))$,

and the common truth-conditions are:

(174) $\bullet(\langle \text{Monday}\rangle, \bullet(\langle 5{:}43\rangle, \diamond(\langle \text{Ridley die}\rangle)))$.

How do we generate the formula in (174) from sentence structures (172) and (173)? Decomposing the sentence structures into components and applying the interpretation rule (132) twice gives, in each case, the list of operator tuples

(175) $[\bullet, \langle \text{Monday}\rangle, \bullet]$, $[\bullet, \langle 5{:}43\rangle, \diamond]$, $[\diamond, \langle \text{Ridley die}\rangle]$,

[27] The * against sentence (167) is not entirely correct. The preposition-phrase *in 4 hours* is sometimes used in the sense of either *four hours from now/then* or, alternatively *sometime between now/then and four hours from now/then*, especially if the preposition-phrase comes at the beginning of the sentence. These senses are captured by the interpretation rules $\mathbf{in} \mapsto [\bullet, \text{tou/r} + X, O]$ and $\mathbf{in} \mapsto [\bullet\!\!\rightarrow, \text{tou/r} + X, \diamond]$ in appendix C. In that case, arguably, the sentence is acceptable, and is processed correctly by our method. Notice, however that these senses would normally be signalled by a change of verb-aspect. Compare *Ridley was working in his laboratory in 4 hours* with *Ridley had worked in his laboratory (with)in 4 hours*. However, although these aspect changes lead one interpretation to be preferred over another, it is very difficult to formulate hard-and-fast rules.

the only difference between the two cases being in the order in which the tuples are generated. The formula in (174) can then be assembled as before, namely, by re-combining these tuples inserting one inside the other. Again, we impose the constraint that, when one tuple is inserted inside another, the first operator of the inserted tuple must be identical to the second operator of the tuple in which it is inserted. The values of O in the two applications of rule (132) were of course chosen so that this constraint would be satisfied.

The question remains as to how we determined the order of the tuples in (175), given that the components in question were extracted from sentence structures (172) and (173) in different orders. Why, for example, did we not use different values of O in the two applications of rule (132) to generate the list of tuples

(176) $[\bullet, \langle\text{5:43}\rangle, \bullet],\ [\bullet, \langle\text{Monday}\rangle, \diamond],\ [\diamond, \text{Ridley die}\rangle],$

and thence the truth-conditions:

(177) $\bullet(\langle\text{5:43}\rangle, \bullet(\langle\text{Monday}\rangle, \diamond(\langle\text{Ridley die}\rangle)))$?

The answer, of course, is that truth-conditions (177) are unsatisfiable no matter what happens to Ridley, since there are no 5:43's that contain Mondays. More generally: when constructing a formula expressing the truth-conditions for sentences involving multiple, right-inserted temporal adverbials, the scoping of the relevant operators should be determined by commonsense calendrical knowledge rather than word-order.

The strength of this approach emerges when we compare the sentences:

(178) Gunner visited Ridley one Monday in January

(179) * Gunner visited Ridley on Monday one January.

the second of which sounds very strange. Here, decomposition and mapping produce the lists of operator tuples:

(180) $[\bullet, \langle\text{January}\rangle, \_],\ [\diamond, \langle\text{Monday}\rangle, \_],\ [\diamond, \text{Gunner visit Ridley}\rangle],$

(181) $[\diamond, \langle\text{January}\rangle, \_],\ [\bullet, \langle\text{Monday}\rangle, \_],\ [\diamond, \text{Gunner visit Ridley}\rangle],$

respectively. (The _ simply indicates that we have a free choice for the second operator.) For the former, we can fuse the tuples in the given order to produce the correct:

(182) $\bullet(\langle\text{January}\rangle, \diamond(\langle\text{Monday}\rangle, \diamond(\langle\text{Gunner visit Ridley}\rangle)))$.

For the latter, by contrast, the only possibilities are:

(183) $\diamond(\langle\text{January}\rangle, \bullet(\langle\text{Monday}\rangle, \diamond(\langle\text{Gunner visit Ridley}\rangle)))$

(184) $\bullet(\langle\text{Monday}\rangle, \diamond(\langle\text{January}\rangle, \diamond(\langle\text{Gunner visit Ridley}\rangle)))$

which are both false whatever Gunner did, since no January contains a unique Monday and no Monday contains a January. Thus, in rejecting (179) as unacceptable, our linguistic intuitions again function so as to filter out a pointless combination of adverbials.

The commonsense knowledge alluded to in the preceding paragraphs can be captured straightforwardly and succinctly by means of a semantic network. As our examples show, this network must encode such facts as that a Monday can be a subinterval of a January but not vice versa, that every Monday, and every January 1st is a day, that no two Mondays occur in any one week, and no two January 1st's occur within any one year, and so on. Figure 8 shows the principal features of this semantic network. The solid arrows constitute the subset hierarchy (e.g. a day is a sub-interval of a week), the hollow arrows constitute the is-links (e.g. every Sunday is a day; every 1st January is a day) and the dotted arrows indicate unique inclusion (e.g. there is only one January in any year, there is only one 1st January in any year). The symbol Ω, to which some event-atoms are anchored by a dotted

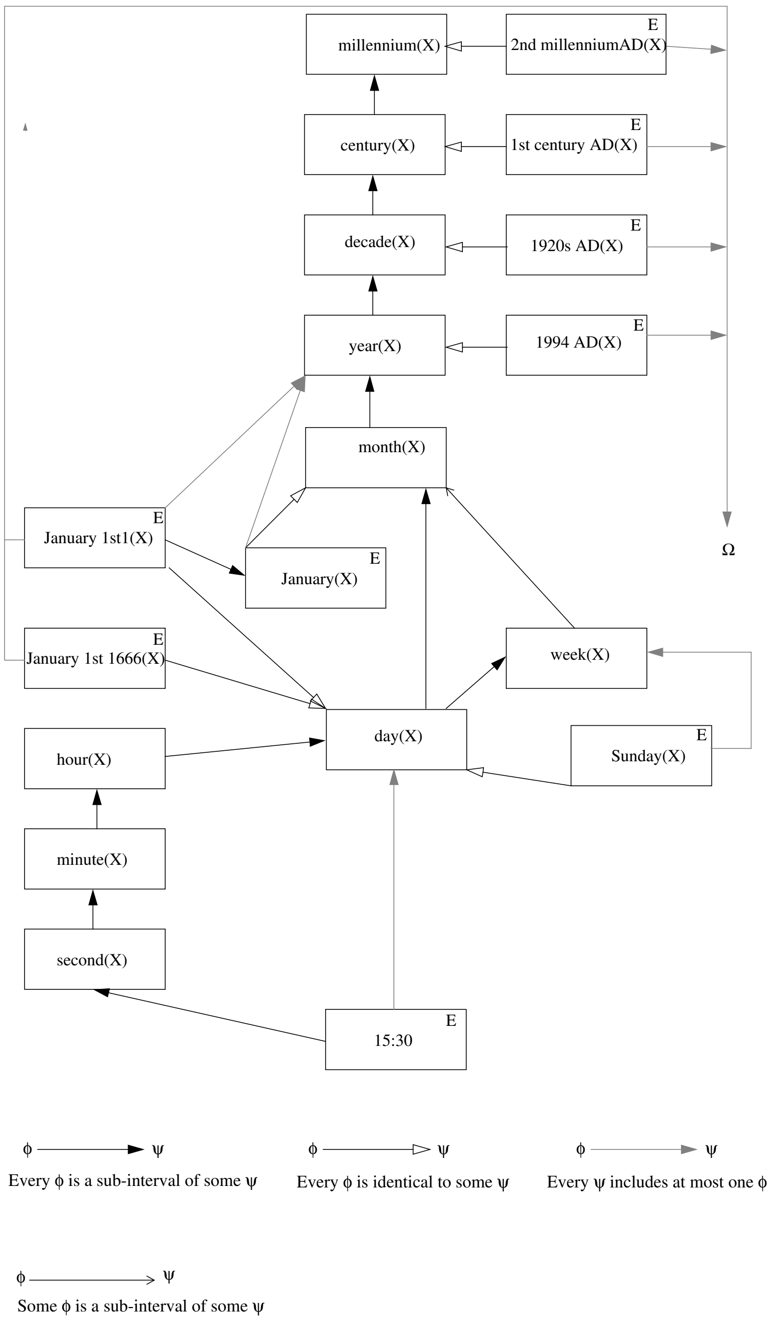

Figure 8: A semantic network of calendrical temporal restrictions

arrow indicates that those event-atoms are instantiated uniquely in history. Thus, there is only one 2nd millennium AD, and only one 1994 AD. The boxes in figure 8 marked "E" are *examples* of classes of nodes. Thus, no sensible implementation of the semantic network would *really* contain any node labelled `January 1st`; rather, it would contains a class of nodes – say, `day-in-year` – instances of which are created as and when necessary, and which are then linked to other nodes in just the way shown for the node `January 1st` in figure 8. But these are all minor implementation details.

Common sense about what fits into what is just as important with free-floating atoms as with event-atoms. Compare the sentences:

(185) Ridley worked in his laboratory every day for eight hours

(186) Ridley worked in his laboratory every day for eight months

which yield the lists of operator tuples

(187) $[\diamond, \langle\text{8 hours}\rangle, \Box]$, $[\Box, \langle\text{day}\rangle, \diamond]$, $[\diamond, \text{point}, \langle\text{Ridley work in his laboratory}\rangle]$

(188) $[\diamond, \langle\text{8 months}\rangle, \Box]$, $[\Box, \langle\text{day}\rangle, \diamond]$, $[\Box, \text{point}, \langle\text{Ridley work in his laboratory}\rangle]$.

These tuples can be combined to yield the correct truth-conditions

(189) $\Box(\langle\text{day}\rangle, \diamond(\langle\text{8 hours}\rangle, \Box(\text{point}, \langle\text{Ridley work in his laboratory}\rangle$

(190) $\diamond(\langle\text{8 months}\rangle, \Box(\langle\text{day}\rangle, \diamond(\text{point}, \langle\text{Ridley work in his laboratory}\rangle$

respectively, provided the tuples are commonsensically ordered. (Notice that, in mapping the state-reporting tenseless sentence, we made judicious choices between the interpretation rules (151) and (152), so that the operator tuples would combine properly.) Similar examples can be constructed with *until*:

(191) Gunner worked in his office at MI5 every day until 5 o' clock

(192) Gunner worked in his office at MI5 every day until 24th March.

The reader can verify that commonsense calendrical knowledge forces an ordering of the operator tuples resulting in the following translations:

(193) $\Box(\langle\text{day}\rangle, \bullet\!\!\rightarrow (\langle\text{5 o' clock}\rangle, \Box(\text{point}, \langle\text{Gunner work in his office at MI5}\rangle$

(194) $\bullet\!\!\rightarrow (\langle\text{24th March}\rangle, \Box(\langle\text{day}\rangle, \diamond(\text{point}, \langle\text{Gunner work in his office at MI5}\rangle$.

The approach taken here predicts scoping ambiguities when the preposition-phrase complements are not constrained by commonsense knowledge. And these ambiguities do seem to arise. Suppose:

(195) Gunner worked in his office at MI5 every day until he received a call from Control.

Did Control telephone once or once a day? Although the most natural reading is probably the former, it is a simple matter to set up contexts favouring either interpretation. So we take (195) to be ambiguous between:

(196) $\bullet\!\!\rightarrow (\langle\text{he receive a call from Control}\rangle, \Box(\langle\text{day}\rangle, \diamond(\text{point}, \langle\text{Gunner work in his office at MI5}\rangle))))$

(197) $\Box(\langle\text{day}\rangle, \bullet\!\!\rightarrow (\langle\text{he receive a call from Control}\rangle, \Box(\text{point}, \langle\text{Gunner work in his office at MI5}\rangle))))$.

Both sets of truth conditions are unproblematically generated by the interpretation procedure outlined in this section by simply re-ordering the list of operator tuples and making the appropriate choices for mapping the underlying tenseless sentences. We remark in passing that this is a lexical scoping ambiguity, and is not due to the existence of multiple phrase-structures.

This is perhaps the appropriate place to admit that the question of ordering temporal adverbials is not as simple as we have been making out. Although English allows considerable latitude in this regard, and although commonsense typically overrides word-order, ordering temporal adverbials from small to large is generally preferred. Thus, for example, *for eight hours every day* is more usual than *every day for eight hours*. Moreover, extra-posed preposition phrases must have wide-scope:

(198) * Until 5 o' clock, Gunner worked in his office at MI5 every day

and some hopelessly scrambled combinations seem not to be allowed

(199) * Gunner worked in his office at MI5 until 5 o' clock for 3 months every day.

We have no fully adequate account of these ordering restrictions here. We shall simplify matters by allowing for *all* re-orderings. Thus, sentence (199) is successfully processed on our approach, which is incorrect.

Sometimes, temporal adverbials are omitted if rendered obvious by other temporal adverbials. For example, the sentence

(200) Gunner arrived at work by 7 a.m. for 3 months

generates the following list of operator tuples:

(201) $[\diamond, \langle \text{3 months} \rangle, \Box]$, $[\bullet\!\!\rightarrow, \langle \text{7 a.m.} \rangle, \lrcorner]$, $[\diamond, \text{Gunner arrive at work} \rangle]$,

which cannot combine in that order (the only calendrically sensible one) because of the clashing operators $\Box$ and $\bullet\!\!\rightarrow$. But sentence (200) is arguably elliptical for

(202) Gunner arrived at work by 7 a.m. *every working day* for 3 months.

Processing sentence (202) gives us the operator tuples:

(203) $[\diamond, \langle \text{3 months} \rangle, \Box]$, $[\Box, \langle \text{working day} \rangle, \lrcorner]$, $[\bullet\!\!\rightarrow, \langle \text{7 a.m.} \rangle, \lrcorner]$, $[\diamond, \text{Gunner arrive at work} \rangle]$,

which, according to the procedure outlined above, re-assemble themselves into the correct truth-conditions:

(204) $\diamond(\langle \text{3 months} \rangle, \Box(\langle \text{working day} \rangle, \bullet\!\!\rightarrow (\langle \text{7 a.m.} \rangle, \diamond(\langle \text{Gunner arrive at work} \rangle))))$.

as required. We offer no account in this paper of the mechanisms governing when temporal adverbials can be omitted; obviously, such an account would rely heavily on non-linguistic knowledge (for example, normal patterns of turning up for work).

Finally, let us return to the problematic sentences (153) and (166), where *until* and *for* were inappropriately combined with an event-reporting tenseless sentence. These sentences are repeated here for reference:

(205) * Ridley died until 6 o'clock

(206) * Ridley solved the equation for 10 minutes.

On our account, such problems are special cases of a more general phenomenon. Consider, for example, the sentences:

(207) * Gunner visited Ridley one day until the 24th January

(208) * Gunner visited Ridley one day for three months

These sentences generate the following lists of tuples (ordered in the only sensible way):

(209) $[\bullet\!\!\rightarrow, \langle \text{24th January} \rangle, \Box]$, $[\diamond, \langle \text{day} \rangle, \lrcorner]$, $[\diamond, \langle \text{Gunner visit Ridley} \rangle]$

(210) $[\diamond, \langle \text{3 months} \rangle, \Box]$, $[\diamond, \langle \text{day} \rangle, \lrcorner]$, $[\diamond, \langle \text{Gunner visit Ridley} \rangle]$

Just as with sentence (205), these lists of tuples refuse to combine because of non-matching operators. Thus, we do not have to worry about whether a complex tenseless sentence such as *Gunner visit Ridley one day* reports a state or an event: when we come to combine it with another temporal adverbial, the assignment of an operator tuple to the adverbial *one day* tells us all we need to know. Similarly for the problematic sentence (167), repeated as sentence (211) for reference, where *in* is inappropriately combined with a state-reporting tenseless sentence.

(211) * Ridley worked in his laboratory in 4 hours

On our account, this problem is again a special case of a more general phenomenon. Consider the sentence:

(212) * Gunner visited Ridley one day in 3 months

This sentence generates the list of tuples:

(213) $[\bullet\!\!\rightarrow, \langle\text{24th January}\rangle, \diamond]$, $[\diamond, \langle\text{day}\rangle, \_]$, $[\diamond, \langle\text{Gunner visit Ridley}\rangle]$

which, when combined into a formula, yields:

(214) $\diamond(\langle\text{3 months}\rangle, \diamond(\langle\text{day}\rangle, \diamond(\text{point}, \langle\text{Gunner visit Ridley}\rangle)))$.

But this is logically equivalent to the simpler:

(215) $\diamond(\langle\text{day}\rangle, \diamond(\text{point}, \langle\text{Gunner visit Ridley}\rangle))$.

As with sentence (211), so with sentence (212), we see our linguistic intuitions functioning as a filter for redundant adverbials. Again, such a filter could be easily implemented for the interpretation process outlined here, without our having to worry about whether *Gunner visit Ridley one day* reports a state or an event.

In this section, we have sketched a procedure for computing truth-conditions for a range of English sentences involving temporal prepositions and related adverbials, where the sentences have right-inserted sentence-structures. Our procedure has the following important characteristics. First, the order of right-inserted operators as they appear in the sentence structure is ignored: this characteristic reflects the relatively free order of adjuncts in English. Second, the procedure relies crucially on commonsense knowledge about what sorts of intervals can fit (or fit uniquely) into what other sorts of intervals: where this knowledge is absent, lexical scoping ambiguities result. Third, the procedure handles in a uniform way the starred examples in this section, where a temporal preposition is combined with an inappropriate adverbial or with a tenseless sentence having an inappropriate aspectual class: such sentences are either not processed at all, or yield truth-conditions with easily detected redundancies.

5 Semantics: left-inserted structures

Our task in this section is to automate the translation of sentences with left-inserted temporal adverbials into TL, and we shall begin with sentence (17) from section 2, which we repeat here:

(216) Ridley will be working in his laboratory until 5 o' clock on Wednesday.

(For ease of explanation, we have changed the tense from past to future, thus making the interval of interest stretch forward from the time of utterance. In addition, in order to make the sentence sound more natural, we have couched it in the progressive aspect.)

Suppose (216) is uttered, say, on Monday at 9:00. At what times must Ridley be working in his laboratory for this sentence to be true? There are two possible answers: (i) from the start of Wednesday until 17:00 that day, and (ii) from when the statement is uttered until 17:00 on Wednesday.[28] Let us call these two readings of (216) the 'short' and 'long' readings, respectively.

We know how to express the short reading within our formalism:

(217) $\bullet(\langle\text{Wednesday}\rangle, \bullet\!\!\rightarrow(\langle\text{5 o' clock}\rangle, \Box(\text{point}, \langle\text{Ridley be working in his laboratory}\rangle)))$.

However, the long reading cannot be expressed using the language introduced in section 3. The problem is that we need to pick out the unique 5 o'clock on the unique Wednesday within the interval of interest, and then quantify over times between the tou and *that* 5 o'clock—that is, across the start of Wednesday. Accordingly, we extend the syntax of the $\bullet\!\!\rightarrow$-operator as follows. Let ϕ be a formula or atom and $e_1, \ldots, e_n$ be event-atoms.

[28] Again, we assume the pm-disambiguation of *5 o' clock*, and we we ignore the fact that Wednesday does not 'start', for work purposes, at 00:00.

(218) $M \models_I \bullet\!\!\rightarrow ([e_1, \ldots, e_n], \phi)$ if (i) counting I as J_0, for each $i = 1, \ldots, n$, there is a unique $J_i \subseteq J_{i-1}$ such that $J_i \in M(e_i)$, and (ii) there exists a K such that $\text{lgp}(I, K, J_n)$ and $M \models_K \phi$.

The idea is that $[e_1, \ldots, e_n]$ is a list of atomic formulae each of which (save the last) is instantiated by a superinterval of an interval instantiating the next. Thus, the e_i identify an interval by narrowing in on it through successive qualification. Armed with this new syntax, we can write down the long truth-conditions for sentence (216) as:

(219) $\bullet\!\!\rightarrow ([\langle\text{Wednesday}\rangle, \langle\text{5 o'clock}\rangle], \Box(\text{point}, \langle\text{Ridley be working in his laboratory}\rangle))$.

as the reader may readily verify.

Thus, sentence (216) has two sets of truth-conditions, namely (217) and (219). Now, we know from section 2 that sentence (216) generates two sentence-structures, namely:

(220) **until**(⟨5 o' clock⟩, **at**(⟨Wednesday⟩, ⟨Ridley be working in his laboratory⟩))

(221) **until**(**at**(⟨Wednesday⟩, ⟨5 o' clock⟩), ⟨Ridley be working in his laboratory⟩).

Of these, (220), which is right-inserted, is processed unproblematically by the procedure of section 4 to produce the truth-conditions (217). This fact in turns leads us to suspect that the ambiguity of sentence (216) is a structural ambiguity, with structure (220) giving rise to the short truth-conditions (217) and structure (221) giving rise to the long truth-conditions (219). This explanation makes some quite specific predictions. In particular, if we could somehow prevent one of the structures being generated, that should block the ambiguity. And this does indeed seem to be the case. In the following, slightly awkward, variant of sentence (216):

(222) Ridley will be working until 5 o' clock in his laboratory on Wednesday.

the verb-phrase adjunct *in his laboratory* has been interposed between the two temporal preposition sequences, which prevents generation of the left-inserted structure (this fact can be seen from the tree of figure 3). As predicted, the ambiguity of sentence (216) disappears in sentence (222), where only the short reading is possible. This observation provides evidence for the claim that structures right-inserted inside **until**-operators cannot give rise to long truth-conditions. (We will encounter evidence for the converse claim, that structures left-inserted inside **until**-operators cannot give rise to short truth-conditions, below.)

Let us return to sentence (216), and the problem of translating sentence-structure (221) into truth-conditions (219). Here is a proposal. We are familiar from section 4 with mapping a structural component to a triple as follows:

(223) $\text{functor}(\text{structure}_1, \_) \mapsto [O_1, \text{structure}_1, O_2]$

where structure$_1$ is a structure incorporating no functors. We propose extending this process to map structures with left-inserted **at**-functors as follows:

(224) $\text{functor}(\textbf{at}(\text{structure}_1, \text{structure}_2), \_) \mapsto [O_1, [\text{structure}_1, \text{structure}_2], O_2]$

where structure$_1$ and structure$_2$ are structures incorporating no functors, and where O_1 is one of $\bullet$, $\bullet\!\!\rightarrow$ or $\leftarrow\!\!\bullet$. Similarly, if we have two left-inserted **at**-functors, the mapping is as follows:

(225) $\text{functor}(\textbf{at}(\textbf{at}(\text{structure}_1, \text{structure}_2), \text{structure}_3), \_) \mapsto [O_1, [\text{structure}_1, \text{structure}_2, \text{structure}_3], O_2]$

and so on. Otherwise, the process of transforming sentence-structures into formulae proceeds exactly as before. Thus, sentence-structure (221) produces the operator triples:

(226) $[\bullet\!\!\rightarrow, [\langle\text{Wednesday}\rangle, \langle\text{5 o'clock}\rangle], \Box]$, $[\Box, \text{point}, \langle\text{Ridley be working in his laboratory}\rangle]$.

which combine in the normal way to produce truth-conditions (219). Notice that this account only covers those cases of left-insertion where (i) the inserted functors are all **at**, and (ii) there is no right-insertion within a left-inserted structure. Notice also that left- and right-inserted **at**-functors are taken to have quite different semantic functions.

Sentence (216) involves a *noun-phrase* prepositional complement which is qualified by a temporal preposition-phrase. But the approach taken here also gives an equally convincing account for *sentential* prepositional complements which are qualified by a temporal preposition-phrase. As an illustration, consider the sentence

(227) Ridley trusted Gunner until he saw him hiding in the shrubbery in June

The most natural reading of this sentence gives it the truth-conditions

(228) $\bullet\!\!\rightarrow([\langle\text{June}\rangle, \langle\text{he see him hiding in the shrubbery}\rangle], \Box(\text{point}, \langle\text{Ridley trust Gunner}\rangle))$.

In other words, there is a unique June in the interval of interest, and a unique episode of Ridley's seeing Gunner in the shrubbery within that June; moreover, Ridley trusted Gunner until the latter (smaller) interval. Assigning to (227) the structure

(229) $\mathbf{until}(\mathbf{at}(\langle\text{June}\rangle, \langle\text{he see him hiding in the shrubbery}\rangle), \langle\text{Ridley trust Gunner}\rangle)$,

the translation process outlined above generates the truth-conditions (227) as required. The short truth-conditions, where the quantification is over the interval from the start of June to the shrubbery incident, is also available, and is generated from the right-inserted sentence structure in the normal way. However, the short reading makes less sense in this context.

Of course our extension of the syntax for the operator $\bullet\!\!\rightarrow$ can be just as easily undertaken for $\bullet$ and $\leftarrow\!\!\bullet$. Proceeding by analogy with (218), we define:

(230) $M \models_I \bullet([e_1, \ldots, e_n], \phi)$ if (i) counting I as J_0, for each $i = 1, \ldots, n$, there is a unique $J_i \subseteq J_{i-1}$ such that $J_i \in M(e_i)$, and (ii) $M \models_{J_n} \phi$.

(231) $M \models_I \leftarrow\!\!\bullet([e_1, \ldots, e_n], \phi)$ if (i) counting I as J_0, for each $i = 1, \ldots, n$, there is a unique $J_i \subseteq J_{i-1}$ such that $J_i \in M(e_i)$, and (ii) there exists a K such that $\text{rgp}(I, K, J_n)$ and $M \models_K \phi$.

This is perhaps an appropriate juncture to ask what happens to sentence (216) if we reverse the order of the preposition sequences:

(232) Ridley will be working in his laboratory on Wednesday until 5 o' clock

Sentence (232), like sentence (222), unambiguously has the short truth-conditions (217). Yet, according to the phrase-structure rules of section 2, we have the following structures for sentence (232):

(233) $\mathbf{at}(\langle\text{Wednesday}\rangle, \mathbf{until}(\langle\text{5 o' clock}\rangle, \langle\text{Ridley be working in his laboratory}\rangle))$.

(234) $\mathbf{at}(\mathbf{until}(\langle\text{5 o' clock}\rangle, \langle\text{Wednesday}\rangle), \langle\text{Ridley be working in his laboratory}\rangle)$.

How can we explain the lack of ambiguity in sentence (232)?

First, we note that the translation method of section 4 unproblematically assigns the short truth-conditions (217) to the right-inserted structure (233). This fact is of course due to the re-ordering step, which we argued should apply to operator triples generated from right-inserted temporal adverbials. But what of the left-inserted structure, (234)? Our procedure, when applied to structure (234), will generate the truth-conditions:

(235) $\bullet\!\!\rightarrow([\langle\text{5 o' clock}\rangle, \langle\text{Wednesday}\rangle], \Box(\text{point}, \langle\text{Ridley be working in his laboratory}\rangle))$.

These conditions are unsatisfied whatever Ridley does, because there is no 5 o'clock which contains a Wednesday. Accordingly, we modify the process described above to insist that, when $[e_1, \ldots, e_n]$, involves canonical calendrical notions, the order of these terms conform to commonsense knowledge of the kind represented in figure 8. If imposed, this requirement will prevent the interpretation of sentence-structure (234), thus eliminating any ambiguity. The implementation of this new requirement is routine.

It might be objected that, since we allowed a re-ordering step for right-inserted structural constituents, we ought to do so for left-inserted ones too. However, there is good independent motivation for treating right- and left-insertion differently in this respect. The independent motivation for allowing free re-ordering of components in right-inserted structures (subject, of course, to calendrical common sense) was that English characteristically allows relatively free orderings of adjuncts to a single phrase. But left-inserted structures do not correspond to multiple adjuncts of a single phrase. Semantically, while we can give a clear sense to the noun-phrase *5 o' clock on Wednesday*—namely, "the 5 o' clock which is on Wednesday"—we can do no such thing for *Wednesday until 5 o' clock*, since "the Wednesday which is until 5 o' clock" does not make sense. Thus: whilst prepositional adjuncts of a common phrase can be re-ordered, prepositional phrases embedded one within the complement of the other cannot be.

In general, common sense seems to dictate whether the left-inserted or right-inserted structures (and hence long or short truth-conditions) dominate. For example, in:

(236) Gunner will deliver the plans to the Soviet embassy by 6 a.m. on Wednesday

(237) Gunner will get up by 5 a.m. on Wednesday. (Brrr!)

sentence (236) naturally takes the long truth-conditions, and sentence (237), the short truth-conditions. However, it is not too difficult to invent contexts in which these expectations are reversed, e.g., if Gunner delivers to his spymasters every day, or if Gunner sleeps for days on end. (Perhaps 'getting up' is what sleeping agents do when they are re-activated.)

An oddity arises if we have two preposition-phrases which generate **at**-functors:

(238) Ridley died at 5:43 on Monday.

This sentence can also be given both right-inserted and left-inserted readings, namely

(239) $\mathbf{at}(\langle\text{Monday}\rangle, \mathbf{at}(\langle\text{17:43}\rangle, \langle\text{Ridley die}\rangle))$

(240) $\mathbf{at}(\mathbf{at}(\langle\text{Monday}\rangle, \langle\text{17:43}\rangle), \langle\text{Ridley die}\rangle)$

giving rise to the sets of truth-conditions:

(241) $\bullet(\langle\text{Monday}\rangle, \bullet(\langle\text{17:43}\rangle, \diamond(\text{true}, \langle\text{Ridley die}\rangle)))$

(242) $\bullet([\langle\text{Monday}\rangle, \langle\text{17:43}\rangle], \diamond(\text{true}, \langle\text{Ridley die}\rangle)),$

which are logically equivalent. Here, we seem to have two phrase-structures without ambiguity.[29]

Let us now redeem our promise of evidence for the claim, following our discussion of sentence (216), that structures with functors left-inserted in **until**-operators cannot give rise to short truth-conditions. The temporal preposition *of* is a familiar component of standard (spoken) calendrical idioms such as *the 31st of March*. For some reason, *of* is unusual with clock-times:

(243) ? Gunner delivered the plans by 3 o'clock of Wednesday.

However, *of* is useful for non-canonical calendar systems found in, for example, schools and universities, thus:

(244) The office will be closed until Wednesday of week 3.

[29] Actually, there are syntactic grounds for taking the left-inserted reading to be dominant here. For one thing, the normal stress-pattern for sentence (238) (with the emphasis on *Monday*), is closer to the stress-pattern for the left-inserted reading of the ambiguous sentence (216) than for its the right-inserted reading. The dominance of the left-inserted sentence-structure might also explain why it sounds so awkward to interpose a verb-adjunct, as in *Ridley died at 5:43 in agony on Saturday.*

We specify the behaviour of *of* (in its temporal use) by means of the structure-assignment:

(245) of $\sharp\ \lambda x[\lambda w[\lambda y[\mathbf{at}(x,y)]]\ /\ \{x : \{\text{not a clock-time}\}\}\ /\ \{x : \{\bar{\bar{\mathrm{N}}}\}, y : \{\bar{\mathrm{N}}\}\}$.

Thus, *of* is taken to have the same semantic function as *at*, *on* and (one sense of) *in*. Note however that the syntactic restriction on y prevents temporal *of* from heading a verb-phrase adjunct, as seems correct:

(246) * The office will be closed of week 3.

Therefore it is instructive to compare sentence (244) with:

(247) The office will be closed until Wednesday in week 3

Sentence (247) is ambiguous between short and long truth-conditions (though the former are probably more sensible): the office might be closed just for the first half of week 3, or all the time from now until the first half of week 3. Sentence (244), by contrast, unambiguously has the long truth-conditions. And this contrast is neatly explained by supposing that functors left-inserted in **until**-operators cannot give rise to short truth-conditions, since *of*, which is incapable of modifying verb-phrases, must generate a sentence-structure with a left-inserted functor.

Can we find examples of three left-inserted prepositional operators? The answer is yes, and to the extent that such sentences are comprehensible at all, they provide confirmation of the approach taken here. Consider

(248) The essays will be marked by 5 o' clock on Wednesday in week 3.

If this is uttered at 9:00 on Wednesday of week 1, by when must the essays be marked for the sentence to turn out true? We claim that such an utterance is ambiguous between three different truth conditions: the 'short' truth-conditions, according to which the essays must be marked on Wednesday of week 3, but before 17:00 hours, the 'middle' truth-conditions, according to which they must be marked in week 3, but any time before 17:00 hours on the Wednesday, and the 'long' truth-conditions, in which the essays may be marked any time between the time of utterance and 17:00 on Wednesday of week three. Let us see what our approach says about sentence (248).

First, we compute the sentence-structure. Since this sentence has three preposition-phrases, the phrase-structure rules of section 2 yield five different sentence-structures, namely:

(249) $\mathbf{at}(\langle\text{week 3}\rangle, \mathbf{at}(\langle\text{Wednesday}\rangle, \mathbf{by}(\langle\text{5 o' clock}\rangle, \langle\text{The essays be marked}\rangle)))$

(250) $\mathbf{at}(\langle\text{week 3}\rangle, \mathbf{by}(\mathbf{at}(\langle\text{Wednesday}\rangle, \langle\text{5 o' clock}\rangle), \langle\text{The essays be marked}\rangle))$

(251) $\mathbf{by}(\mathbf{at}(\mathbf{at}(\langle\text{week 3}\rangle, \langle\text{Wednesday}\rangle), \langle\text{5 o' clock}\rangle), \langle\text{The essays be marked}\rangle)$

(252) $\mathbf{at}(\mathbf{at}(\langle\text{Wednesday}\rangle, \langle\text{week 3}\rangle), \mathbf{by}(\langle\text{5 o' clock}\rangle, \langle\text{The essays be marked}\rangle))$

(253) $\mathbf{by}(\mathbf{at}(\langle\text{week 3}\rangle, \mathbf{at}(\langle\text{Wednesday}\rangle, \langle\text{5 o' clock}\rangle)), \langle\text{The essays be marked}\rangle)$.

(This is a simple matter to check with a computer.) The first four of these sentence-structures can be processed using the approach described above, which will generate the truth-conditions:

(254) $\bullet(\langle\text{week 3}\rangle, \bullet(\langle\text{Wednesday}\rangle, \bullet\!\!\rightarrow(\langle\text{5 o' clock}\rangle, \diamond(\langle\text{The essays be marked}\rangle))))$ (short)

(255) $\bullet(\langle\text{week 3}\rangle, \bullet\!\!\rightarrow([\langle\text{Wednesday}\rangle, \langle\text{5 o' clock}\rangle], \diamond(\langle\text{The essays be marked}\rangle)))$ (middle)

(256) $\bullet\!\!\rightarrow([\langle\text{week 3}\rangle, \langle\text{Wednesday}\rangle, \langle\text{5 o' clock}\rangle], \diamond(\langle\text{The essays be marked}\rangle))))$ (long)

(257) $\bullet([\langle\text{week 3}\rangle, \langle\text{Wednesday}\rangle], \bullet\!\!\rightarrow(\langle\text{5 o' clock}\rangle, \diamond(\langle\text{The essays be marked}\rangle)))$ (short) = (254)

respectively. The fifth sentence-structure, (253), cannot be processed, because the left-inserted component, namely $\mathbf{at}(\langle\text{week 3}\rangle, \mathbf{at}(\langle\text{Wednesday}\rangle, \langle\text{5 o' clock}\rangle))$ itself has a right-inserted sub-component, and so is not of the form envisaged in the process outlined in this section. We propose that sentence-structure (253) be rejected as uninterpretable.[30] Of the four sets of truth-conditions produced, (254) , (255) and (256) correctly express the short, middle and long truth-conditions, while (257) is logically equivalent to (254).

As a final illustration of the strength of the current approach, notice that the more natural-sounding variant of sentence (248):

(258) The essays will be marked by 5 o' clock on Wednesday *of* week 3

has only the 'short' and 'long' truth-conditions, (254)/(257) and (256). The explanation for this phenomenon is simple: since *of* can attach only to noun-phrases, the sentence-structure (250) is not generated; neither, therefore, are the middle truth-conditions (255).

The above account works convincingly for many, but not all, sentences involving left-inserted temporal preposition-phrases. In the remainder of this section, we consider some additional cases. One type of left-insertion met in section 2 can be easily dealt with. Consider the specifier offset prepositions, *after*, *before*, *ago* and *into*. We agreed that they generate left-inserted sentence-structures. For example, the sentences:

(259) Gunner fired the shots 5 minutes after Ridley entered the drawing room

(260) Gunner waited until 5 minutes after Ridley had entered the drawing room

generate the sentence-structures

(261) $\mathbf{at}(\mathbf{after}_1(\langle\text{Ridley enter the drawing room}\rangle, \langle 0.083\rangle), \langle\text{Gunner fire the shots}\rangle)$.

(262) $\mathbf{until}(\mathbf{after}_1(\langle\text{Ridley enter the drawing room}\rangle, \langle 0.083\rangle), \langle\text{Gunner wait}\rangle)$.

(Note that we are using hours as our units of duration.) The interpretation rule for the functor $\mathbf{after}_1$ (i.e. the functor generated by the preposition *after* when both the specifier and complement are present) is

(263) $\mathbf{after}_1(X, W) \mapsto X + W$

This interpretation rule enables us to map the left-inserted structure to a complex temporal restriction as follows:

(264) $\mathbf{after}_1(\langle\text{Ridley enter the drawing room}\rangle, \langle 0.083\rangle) \mapsto \langle\text{Ridley enter the drawing room}\rangle + \langle 0.083\rangle$.

The sentence-structures (261) and (262) can now be processed according to the method of the previous section, treating the complex temporal restriction produced by (264) just like any other (atomic) temporal restriction. The lists of operator triples generated are:

(265) $[\bullet, \langle\text{Ridley enter the drawing room}\rangle + \langle 0.083\rangle, \diamond],\ [\diamond, \langle\text{Gunner fire the shots}\rangle]$

(266) $[\bullet\!\!\rightarrow, \langle\text{Ridley enter the drawing room}\rangle + \langle 0.083\rangle, \square],\ [\square, \text{point}, \langle\text{Gunner wait}\rangle]$,

which fuse in the normal way to give the formulae:

(267) $\bullet(\langle\text{Ridley enter the drawing room}\rangle + \langle 0.083\rangle, \diamond(\langle\text{Gunner fire the shots}\rangle))$

(268) $\bullet\!\!\rightarrow(\langle\text{Ridley enter the drawing room}\rangle + \langle 0.083\rangle, \square(\text{point}, \langle\text{Gunner wait}\rangle))$.

[30] There may be a way of formulating our procedure so that the result is one of the three truth-conditions given above (probably (256)), but little would be gained by doing so.

These are plausible truth-conditions for sentences (259) and (260). (Again, we assume any vagueness to be located in the interpretation of the relevant event-atoms and free-floating atoms.) A parallel treatment would apply to the sentence (269) to give truth-conditions (270):

(269) Gunner fired the shots 5 minutes before Ridley entered the drawing room

(270) $\bullet(\langle\text{Ridley enter the drawing room}\rangle + \langle -\ 0.083\rangle, \diamond(\langle\text{Gunner fire the shots}\rangle))$.

Thus, we think of phrases of the form *d after X* as meaning something like *at* $X + d$, and phrases of the form *d before X* as meaning something like *at* $X - d$

As mentioned in section 3, specifier offset prepositions without complements fix the times of events in relation to the tor. Sentence (98) is repeated here for reference:

(271) Gunner was in this room 2 hours ago (= *two hours before now*)

The proposed truth-conditions were:

$\bullet(\text{tor} + (-2), \diamond(\text{point}, \langle\text{Gunner be in this room}\rangle))$ (tor = tou)

(272) $\bullet(\text{tor} + (-2), \Box(\text{point}, \langle\text{Gunner be in this room}\rangle))$ (tor = tou).

These truth-conditions can be generated in exactly the same way as for sentences (259) and (260). The corresponding sentence-structure is

(273) $\mathbf{at}(\mathbf{ago}(\langle\text{two hours}\rangle), \langle\text{Gunner be in this room}\rangle)$,

and the relevant interpretation rule is,

(274) $\mathbf{ago}(W) \mapsto \text{tor} + W$ (tou = tor).

Notice that the above account also works smoothly in phrases like *until 3 hours ago*.

When specifier offset prepositions are used without a specifier, then the missing specifier is treated as an existentially quantified (positive) indeterminate. For example, given the sentences

(275) Gunner fired the shots after (= sometime after) Ridley entered the drawing room

(276) Gunner waited until after (= until sometime after) Ridley had entered the drawing room

one might try, by analogy with sentences (259) and (260), the truth-conditions:

(277) $\bullet(\langle\text{Ridley enter the drawing room}\rangle + \text{skolem}, \diamond(\langle\text{Gunner fire the shots}\rangle))$

(278) $\bullet\!\!\rightarrow (\langle\text{Ridley enter the drawing room}\rangle + \text{skolem}, \Box(\text{point}, \langle\text{Gunner wait}\rangle))$.

Here, the symbol skolem is treated as an existentially quantified variable, whose values are constrained to be positive numbers. We note in passing that the decision procedure for TL can be modified to cope with this extension. Since sentences (275) and (276) are assigned the sentence-structures

(279) $\mathbf{at}(\mathbf{after}_2(\langle\text{Ridley enter the drawing room}\rangle), \langle\text{Gunner fire the shots}\rangle)$.

(280) $\mathbf{until}(\mathbf{after}_2(\langle\text{Ridley enter the drawing room}\rangle), \langle\text{Gunner wait}\rangle)$.

the above truth-conditions could then be automatically generated using the interpretation rule

(281) $\mathbf{after}_2(X) \mapsto X + \text{skolem}$.

This account explains the behaviour of

(282) Gunner waited until before Ridley had entered the drawing room,

where *before* must mean *just before* and not *sometime before*. The explanation is that, on the *sometime before*-interpretation (which we have assumed above), the sentence's truth-conditions, namely,

(283) $\bullet\!\!\rightarrow$ ($\langle$Ridley enter the drawing room$\rangle$ − skolem, $\Box$(point, $\langle$Gunner wait$\rangle$)),

are trivial. Yet again, we see our linguistic intuitions acting as a filter for logically useless preposition-combinations. We shall not pause here to give the semantics of *just after* and *just before*.

It must be admitted, however, that the above account of specifier offset prepositions suffers from certain difficulties. The most obvious problem is that, according to (277), if the event of Ridley's entering the drawing room occurs over an interval J, then the event of Gunner's firing the shots must occur *within* an interval $J + d$—that is, within an interval no longer than J—a requirement which sentence (275) surely does not impose. Much better truth-conditions might be

(284) $\leftarrow\!\!\bullet$($\langle$Ridley enter the drawing room$\rangle$, $\diamond$($\langle$Gunner fire the shots$\rangle$)),

which avoid unwanted constraint that Gunner's firing the shots takes no longer than Ridley's entering the drawing room. Indeed, the reader may have noticed that, in previous sections, all our examples of sentences containing *before* and *after* without specifiers were given truth-conditions in the style of (284).

The superiority of truth-conditions (284) may, however, be merely apparent—the result of a more general 'resizing' process when interpreting temporal expressions, and nothing to do with the use of skolem. For example, the sentence

(285) Gunner wrote his memoirs ten years after resigning from the KGB

likewise does not seem to require that Gunner wrote his memoirs in less time than it took him to resign. It is not, at the time of writing, entirely clear how to account for this flexibility, which is particularly evident with large offsets like *ten years*.

A different problem is created by the sentence:

(286) Gunner waited until after (= sometime after) the Supergun affair.

On the account proposed here, this sentence would receive truth-conditions

(287) $\bullet\!\!\rightarrow$ ($\langle$the Supergun affair$\rangle$ + skolem, $\Box$(point, $\langle$Gunner wait$\rangle$))

which are the same (infinitesimal differences aside) as

(288) $\bullet\!\!\rightarrow$ ($\langle$the Supergun affair$\rangle$, $\Box$(point, $\langle$Gunner wait$\rangle$))

Here, the problem concerns what happens *during* the Supergun affair. For the force of *after* in (286) is surely to extend the universal quantification associated with *until* up to the *end* of the Supergun affair, while the proposed truth-conditions require merely that he wait until the *beginning* thereof. One way to overcome this problem would be to add to TL the expression end(e), which we take to be true at the end-points of any interval over which the event-atom e is true. For then, the truth-conditions of (286) could be written:

(289) $\bullet\!\!\rightarrow$ ($\langle$end(the Supergun affair)$\rangle$, $\Box$(point, $\langle$Gunner wait$\rangle$))

giving much more plausible truth-conditions. The addition of an end-operator (and its mirror-image, start) to TL is unproblematic: the decision procedure can be modified to cope[31].

Let us leave the topic of specifier offset prepositions and end with a look at a more difficult class of left-inserted temporal preposition-phrases. This section should serve as a corrective to any impression that we are close to a complete semantic theory of temporal prepositions. Consider the following sentence:

(290) Gunner believed in his mission until he had followed Ridley to work every day for 6 months.

[31] As we have already remarked, English is not always entirely clear as to whether *until* means *until the beginning of* or *until the end of*. We note that the use of the perfective in subordinate clauses can have a similar effect to *after* in forcing quantification unambiguously to run to the end of the interval in question, thus: *Gunner waited until Ridley had written the letter.*

On the most natural reading, the sentence-complement of *until* is itself qualified by temporal adverbials, so we have a clear case of left-insertion. The structure is:

(291) **until**(**for**(⟨6 months⟩, **every**(⟨day⟩, ⟨he follow Ridley to work⟩)), ⟨Gunner believe in his mission⟩).

Thus, we have a left-inserted **for**-functor:

(292) **for**(⟨6 months⟩, **every**(⟨day⟩, ⟨he follow Ridley to work⟩)).

In contrast to the examples of left-inserted **at**-functors considered above, structure (292) seems to make a contribution to the truth-conditions of sentence (290) similar to that made by right-inserted occurrences of **for**. Allowing ourselves an additional operator & (with the obvious interpretation), we might write the truth-conditions of (290) as:

$$(293)\quad \begin{array}{l} \bullet\!\!\rightarrow (((\langle 6 \text{ months}\rangle\ \&\\ \quad\quad \Box(\langle \text{day}\rangle,\\ \quad\quad\quad \diamond(\langle \text{he follow Ridley to work}\rangle)))),\\ \quad \Box(\text{point}, \langle \text{Gunner believe in his mission}\rangle)). \end{array}$$

(The indentation serves merely to make the structure clearer.) Taken with a dash of licence, the truth-conditions are plausible: they require Gunner to believe in his mission until the first six-month-long interval on every day of which he followed Ridley to work.[32]

Truth-conditions (293) are of interest, because the first argument of the $\bullet\!\!\rightarrow$-operator is so close to the formula: $\diamond(6 \text{ months}, \Box(\langle \text{day}, \diamond(\langle \text{he follow Ridley to work}\rangle))$ which would have resulted from applying the translation process outlined in section 4 to the inserted structure (292). This observation holds out the prospect that, in mapping sentence-structure (291) into TL, we can process the left-inserted component (292) separately and then treat the result just like any other temporal restriction. The only complication is a little extra work to merge the outer $\diamond$-operator within the $\bullet\!\!\rightarrow$ generated by the *until*. Moreover, the notion of merging modal operators generated by neighbouring adverbials should be familiar from section 4. It is worth remarking that universally-quantifying temporal adverbials cannot be straightforwardly embedded in *until*-complements. Thus:

(294) Gunner believed in his mission until he had followed Ridley to work every day

only makes sense if it is regarded as elliptical for a sentence like:

(295) Gunner believed in his mission until he had followed Ridley to work every *day over that period*

(296) Gunner believed in his mission until he had followed Ridley to work every day *for some time*,

whichever context deems more appropriate. Again, this observation should remind us of our treatment of ellipsis in right-inserted sentence-structures, e.g. in sentence (200).

Despite these positive indications, however, the translation of these left-inserted temporal functors into TL involves complications which, at the time of writing, remain unresolved, and we have no precise account of how this translation should be mechanized. One problem in devising such an account is that the pattern examplified by sentence (290) seems to be much rarer than the very different behaviour exemplified by (216) and (227), and it is difficult to get a clear view of what sorts of things can be naturally expressed. On this rather unsatisfactory note, we must leave this topic.

Let us summarize what we have found in this section. We have encountered three distinct semantic mechanisms associated with left-inserted prepossition-phrases. First, we have sentences such as (216) and (227), where an interval is identified by 'zooming in' on an interval through successive unique

[32] The dash of licence we need is the following: to get plausible truth-conditions, we must take the $\bullet\!\!\rightarrow(\psi, \ldots)$-operator to quantify over the interval finishing with the *end* (not the beginning) of the first (not the unique) interval satisfied by ψ.

identifiers. These sentences all involved left-inserted temporal preposition-phrases associated with the **at**-functor. As we saw in sentences (248) and (258), this mechanism can be used to express relatively subtle distinctions concerning the extent of quantification. Second, we gave a separate account of temporal preposition-phrases headed by *after* and *before*, which give rise to left-inserted **after**-functors. The motivation for taking these prepositions to give rise to left-inserted operators was that the preposition-phrases in question are often complements of other preposition-phrases, as in sentences (260) and (286). Finally, we pointed out that some other other temporal preposition phrases, notably those headed by *for*, as in sentence (290), exhibit a more 'compositional' approach in which the left-inserted temporal preposition functions similarly to the way it functions in right-inserted contexts. However, we did not develop a detailed account of this class of sentences.

6 Conclusion

In this paper, we have presented an account of the semantics of English sentences involving multiple temporal preposition phrases (and some related temporal adverbials). We have introduced a restricted temporal logic into which a wide range of such sentences can be translated, and we have outlined a translation process from English into this logic. Together with specialized procedures for making inferences in this logic (and its fragments), this account holds out the prospect of exploiting the restricted expressiveness of temporal quantification in everyday English to design more effective natural language understanding systems.

The most important observations to emerge from our account concern the way in which temporal preposition phrases 'nest'. With right-insertion (where several preposition phrases successively modify a $\bar{\mathrm{V}}$), we observed that each preposition phrase but one quantifies over sub-intervals of intervals set up by another preposition phrase. We found that the scope of each preposition phrase was influenced by commonsense (mainly calendrical) knowledge, and we described a mechanism for deploying such calendrical knowledge to resolve lexical scoping ambiguities and to reject unacceptable combinations of temporal adverbials. With left-insertion, by contrast, we found a less clear picture. The (apparently) dominant form involves a type of 'zooming in', where each preposition phrase except the last identifies an interval or point uniquely within the interval set up by its successor. We noted that the scoping of left-inserted temporal preposition phrases is fixed by word-order, with the innermost preposition-phrases first. We also gave semantics for some temporal preposition-phrases with durative specifiers, which we also modelled (for convenience) as left-inserted structures. Finally, we noted that some cases of left-insertion exhibit a more 'compositional' behaviour than the model proposed here allows. We noted some similarities between these sentences and various aspects of our account, but did not offer a proper analysis. This was in part because of the difficulty of such sentences and the instability of our linguistic intuitions concerning them.

We argued that, since a (provably correct) decision procedure exists for TL, automating the translation from temporal English into TL gives us a system capable of determining the deductive validity of temporal arguments expressed in English. Such a system has been implemented, and represents a useful development tool for our semantics, since apparent anomalies in the behaviour of this system can be quickly traced to the relevant structure-assignment and interpretation rules in appendices A and C. The ability to determine the precise ramifications of modifying any one part of the total system—the syntax rules of appendix A, the syntax and semantics of TL in appendix B, the interpretation rules in appendix C, or the decision procedure for TL—is crucial for our strategy of piecemeal refinement and extension. The practical applications of a provably correct system for temporal deduction using English input include the design of natural language 'front-ends' and the development of systems for program specification in English.

Much remains to be said about the semantics of temporal prepositions in English that we have not covered here. Many details of prepositional usage have simply not been mentioned, for example, the complexities of of *while*, *when* and *as*, or the use of wider ranges of complements as in expressions like *before long* and *after 3 years of spying on Ridley*. In addition, this paper has largely finessed the questions of the contribution to truth-conditions made by verb-tense and -aspect, and of the delicate and somewhat irregular interactions between verb-tense and -aspect and the various temporal prepositions (though the computer implementation takes tense and aspect into account in simple ways). Likewise, we have not described how temporal prepositions interact with the determiners in their complements, or with a variety of temporally significant qualifiers, for example, in the expressions *in at most 5 minutes* or *for another two years*. Finally, we have ignored altogether the representation of continuous change or problems connected with repeated or habitual events.

However, we claim that this list of omissions supports, rather than undermines, the approach proposed here, with its emphasis on piecemeal extensions to the basis provided by TL. For the truth is that that there is simply too much temporal English to account for in one fell swoop. In proposing TL as a promising basis for giving the semantics of temporal expressions in English, we claim that the extensions necessary to capture a much wider range of of English temporal expressions than considered here can be made gracefully, allowing the decision procedure (and its associated correctness proof) to be extended in step with the expanded linguistic capabilities. The justification for this claim is the relative ease and elegance with which the translation processes outlined in this paper account for the range of examples we have considered involving multiple temporal preposition phrases. But of course the proof of the pudding is, as ever, in the eating.

A Syntactic rules

The (augmented) phrase-structure rules are as follows:

1. $\mathrm{X}\sharp f(a) \to \bar{\mathrm{X}}\sharp a, \bar{\bar{\mathrm{P}}}\sharp\lambda x[f(x)]$ where X is either $\bar{\mathrm{N}}$, $\bar{\mathrm{V}}$ or empty.
2. $\mathrm{X}\sharp\mathbf{at}(b,a) \to \bar{\mathrm{X}}\sharp a, \bar{\bar{\mathrm{P}}}\sharp b$ where X is $\bar{\mathrm{N}}$, and the head of $\bar{\bar{\mathrm{P}}}$ is an offset preposition.
3. $\bar{\bar{\mathrm{P}}}\sharp f(a) \to \mathrm{X}\sharp a\bar{\mathrm{P}}\sharp\lambda x[f(x)]$ where X is either $\bar{\bar{\mathrm{N}}}$, ADV or empty.
4. $\bar{\mathrm{P}}\sharp f(a) \to \mathrm{P}\sharp\lambda x[f(x)], \mathrm{X}\sharp a$ where X is either $\bar{\bar{\mathrm{N}}}$, S or empty.

The lexical entries for the temporal prepositions are as follows:

1. after $\sharp$ $\lambda x[\lambda w[\mathbf{after}_1(x,w)]]$ / $\{w:\{\text{free-floating}\}, x:\{\text{event}\}\}$ / $\{x:\{\bar{\bar{\mathrm{N}}},\mathrm{S}\}, w:\{\bar{\bar{\mathrm{N}}}\}\}$.
2. after $\sharp$ $\lambda x[\lambda w[\mathbf{after}_2(x)]]$ /$\{x:\{\text{event}\}\}$ / $\{x:\{\bar{\bar{\mathrm{N}}},\mathrm{S}\}\}$.
3. afterwards $\sharp$ $\lambda x[\lambda w[\mathbf{after}_3(w)]]$ / $\{w:\{\text{free-floating}\}\}$ / $\{w:\{\bar{\bar{\mathrm{N}}}\}\}$.
4. afterwards $\sharp$ $\lambda x[\lambda w[\mathbf{after}_4]]$.
5. ago $\sharp$ $\lambda x[\lambda w[\mathbf{ago}(w)]]$ / $\{w:\{\text{free-floating}\}\}$ / $\{w:\{\bar{\bar{\mathrm{N}}}\}\}$.
6. as $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{during}(x,y)]]$ / $\{x:\{\text{event}\}\}$ / $\{x:\{S\}\}$.
7. at $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{at}(x,y)]]$ / $\{x:\{\text{very short interval}, \text{weekend}\}, \text{religious festival}\}$ / $\{x:\{\bar{\bar{\mathrm{N}}}\}\}$.
8. before $\sharp$ $\lambda x[\lambda w[\mathbf{before}_1(x,w)]]$ / $\{w:\{\text{free-floating}\}, x:\{\text{event}\}\}$ / $\{x:\{\bar{\bar{\mathrm{N}}},\mathrm{S}\}, w:\{\bar{\bar{\mathrm{N}}}\}\}$.
9. before $\sharp$ $\lambda x[\lambda w[\mathbf{before}_2(x)]]$ /$\{x:\{\text{event}\}\}$ / $\{x:\{\bar{\bar{\mathrm{N}}},\mathrm{S}\}\}$.
10. before $\sharp$ $\lambda x[\lambda w[\mathbf{before}_3(w)]]$ / $\{w:\{\text{free-floating}\}\}$ / $\{w:\{\bar{\bar{\mathrm{N}}}\}\}$.
11. before $\sharp$ $\lambda x[\lambda w[\mathbf{before}_4]]$.
12. beforehand $\sharp$ $\lambda x[\lambda w[\mathbf{before}_3(w)]]$ / $\{w:\{\text{free-floating}\}\}$ / $\{w:\{\bar{\bar{\mathrm{N}}}\}\}$.
13. beforehand $\sharp$ $\lambda x[\lambda w[\mathbf{before}_4]]$.
14. by $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{by}(x,y)]]$ / $\{\ x:\{\text{event}\}\}$ / $\{x:\{\bar{\bar{\mathrm{N}}}\}\}$.

15. during $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{during}(x,y)]]$ / $\{\ x : \{\text{event}\}\}$ / $\{x : \{\bar{\bar{\mathrm{N}}}\}\}$.
16. for $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{for}(x,y)]]$ / $\{x : \{\text{duration}\}\}$ / $\{x : \{\bar{\bar{\mathrm{N}}}\}\}$.
17. in $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{in}(x,y)]]$ / $\{x : \{\text{duration}\}\}$ / $\{x : \{\bar{\bar{\mathrm{N}}}\}\}$.
18. in $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{at}(x,y)]]$ / $\{x : \{\text{week or larger}\}\}$ / $\{x : \{\bar{\bar{\mathrm{N}}}\}\}$.
19. of $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{at}(x,y)]]$ / $\{x : \{\text{event, not a clock-time}\}, y : \{\text{event}\}\}$ / $\{x : \{\bar{\bar{\mathrm{N}}}\}, y : \{\bar{\mathrm{N}}\}\}$.
20. on $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{at}(x,y)]]$ / $\{x : \{\text{day}, \text{qualified day-part}\}\}$ / $\{x : \{\bar{\bar{\mathrm{N}}}(\text{singular})\}\}$.
21. on $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{every}(x,y)]]$ / $\{x : \{\text{day}, \text{qualified day-part}\}\}$ / $\{x : \{\bar{\bar{\mathrm{N}}}(\text{plural})\}\}$.
22. over $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{at}(x,y)]]$ / $\{x : \{\text{essentially temporal event}\}\}$ / $\{x : \{\bar{\bar{\mathrm{N}}}\}\}$.
23. since $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{since}(x,y)]]$ / $\{x : \{\text{event}\}\}$ / $\{x : \{\bar{\bar{\mathrm{N}}}, \mathrm{S}, \bar{\bar{\mathrm{P}}}\}\}$.
24. since $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{esince}(x,y)]]$ / $\{w : \{= \text{“ever”}, x : \{\text{event}\}\}$ / $\{x : \{\bar{\bar{\mathrm{N}}}, \mathrm{S}, \bar{\bar{\mathrm{P}}}\}, w : \{\mathrm{ADV}\}\}$.[33]
25. throughout $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{throughout}(x,y)]]$ / $\{x : \{\text{event}\}\}$ / $\{x : \{\bar{\bar{\mathrm{N}}}\}\}$.
26. until $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{until}(x,y)]]$ / $\{x : \{\text{essentially temporal event}\}\}$ / $\{x : \{\bar{\bar{\mathrm{N}}}, \mathrm{S}, \bar{\bar{\mathrm{P}}}\}\}$.
27. upto $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{until}(x,y)]]$ / $\{x : \{\text{event}\}\}$ / $\{x : \{\bar{\bar{\mathrm{N}}}\}\}$.
28. when $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{during}(x,y)]]$ / $\{x : \{\text{event}\}\}$ / $\{x : \{S\}\}$.
29. whenever $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{every}(x,y)]]$ / $\{x : \{\text{event}\}\}$ / $\{x : \{S\}\}$.
30. while/whilst $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{during}(x,y)]]$ / $\{x : \{\text{event}\}\}$ / $\{x : \{S\}\}$.
31. within $\sharp$ $\lambda x[\lambda w[\lambda y[\mathbf{in}(x,y)]]$ / $\{x : \{\text{duration}\}\}$ / $\{x : \{\bar{\bar{\mathrm{N}}}\}\}$.

B The representation language

The basic terms of the language are:

1. An infinite stock of event-atoms, $E = \{e_1, e_2, \ldots\}$
2. An infinite stock of state-atoms, $S = \{s_1, s_2, \ldots\}$
3. The special atom point
4. The real numbers
5. The connectives $\diamond$, $\Box$, $\bullet$, $\bullet\!\!\rightarrow$ and $\leftarrow\!\!\bullet$.

We shall use the term *atom* to speak indiscriminately of event-atoms, state-atoms and special atoms.

The formulae of our representation language are defined by the following rules:

1. Let e be an event-atom, s a state-atom and r a number. Then $\diamond(e)$, $\diamond(r,e)$, $\diamond(r,s)$, $\diamond(\text{point}, s)$ and $\Box(\text{point}, s)$ are formulae.
2. Let ϕ be a formula and e an event-atom. Then $\neg\phi$, $\diamond(e,\phi)$ and $\Box(e,\phi)$ are formulae.

[33] This structure assignment is somewhat irregular, since we normally insist that an expression of the form $\lambda w[f]$, where f does not contain any free instances of w, can combine *only* with the dummy structure Ω. Here, however, we require that the specifier be the adverb *ever*.

3. Let ϕ be a formula, $e_1, \ldots, e_n$ be event-atoms and r be a real number. Then $\bullet([e_1, \ldots, e_n] + r, \phi)$, $\bullet\!\!\rightarrow([e_1, \ldots, e_n] + r, \phi)$ and $\leftarrow\!\!\bullet([e_1, \ldots, e_n] + r, \phi)$ are formulae. (Note, when $r = 0$, we omit the "+0", and when $n = 1$ we write e_1 instead of $[e_1]$.)

Let Ω be the set of closed non-empty intervals of the real line. In the sequel, we take I, J and K to range over Ω. Included in Ω are the point-intervals of the form $[t, t]$; we shall sometimes speak of such intervals as *points*. An interpretation M is a function $M : (E \cup S) \rightarrow P(\Omega)$ mapping every event-atom to a set of intervals in Ω, every state atom to a set of points in Ω, and the special atom point to the set of all points in Ω. Intuitively, $M(e)$ is the set of intervals at which e is true, and $M(s)$ the set of points at which s is true.

We impose the following 'ontological assumptions':

1. For any $e \in E$, if $I \in M(e)$ and $J \in M(e)$ then $J \cap I = \emptyset$.

2. For any $s \in S$, there exists a set $\Sigma_s \subset \Omega$ such that each member of Σ_s is isolated from the others and $M(s) = \cup(\Sigma_s)$. (An interval I is isolated from a set of intervals Z if I has no points in common with the closure of $\cup Z$.)

Technically, the function of these ontological assumptions is to ensure the formal correctness of the decision procedure for TL.

The semantics of the language are given by the following rules. Let M be an interpretation and I any interval in Ω.

Let e be an event-atom, s a state-atom and r a number. Then:

1. $M \models_I \diamond(e)$ if there exists a $J \subseteq I$ such that $J \in M(e)$

2. $M \models_I \diamond(\text{point}, s)$ if there exists a point-interval $J \subseteq I$ such that $J \in M(s)$

3. $M \models_I \Box(\text{point}, s)$ if, for all point-intervals $J \subseteq I$, $J \in M(s)$

4. $M \models_I \diamond(r, e)$ if there exists a $J \subseteq I$, $|J| = r$ and $J \in M(e)$.

5. $M \models_I \diamond(r, s)$ if there exists a $J \subseteq I$, $|J| = r$ and for all point-intervals $K \subseteq J$, $K \in M(s)$.

Let ϕ be a formula, $e, e_1, \ldots, e_n$ event-atoms and r a number. Then:

1. $M \models_I \diamond(e, \phi)$ if there exists a $J \subseteq I$, $J \in M(e)$ and $M \models_J \phi$.

2. $M \models_I \Box(e, \phi)$ if, for all $J \subseteq I$ such that $J \in M(e)$, $M \models_J \phi$.

3. $M \models_I \bullet([e_1, \ldots, e_n] + r, \phi)$ if (i) counting I as J_0, for each $i = 1, \ldots, n$, there is a unique $J_i \subseteq J_{i-1}$ such that $J_i \in M(e_i)$, (ii) $J_n + r \subseteq I$ and (iii) $M \models_{J_n+r} \phi$ (where $J + r = \{t + r | t \in J\}$).

4. $M \models_I \bullet\!\!\rightarrow([e_1, \ldots, e_n] + r, \phi)$ if (i) counting I as J_0, for each $i = 1, \ldots, n$, there is a unique $J_i \subseteq J_{i-1}$ such that $J_i \in M(e_i)$, (ii) $J_n + r \subseteq I$ and (iii) there exists a K such that $\text{lgp}(I, K, J_n + r)$ and $M \models_K \phi$.

5. $M \models_I \leftarrow\!\!\bullet([e_1, \ldots, e_n] + r, \phi)$ if (i) counting I as J_0, for each $i = 1, \ldots, n$, there is a unique $J_i \subseteq J_{i-1}$ such that $J_i \in M(e_i)$, (ii) $J_n + r \subseteq I$ and (iii) there exists a K such that $\text{rgp}(I, K, J_n + d)$ and $M \models_K \phi$.

Note: the relations lgp and rgp are illustrated in figure 6, section 3.

The rules for negation are somewhat convoluted. Let ϕ be a formula. Then:

1. $M \models_I \neg \bullet (e, \phi)$ if $M \models_I \bullet(e, \neg\phi)$

2. $M \models_I \neg\bullet\!\!\rightarrow (e, \phi)$ if $M \models_I \bullet\!\!\rightarrow (e, \neg\phi)$

3. $M \models_I \neg \leftarrow\!\!\bullet(e, \phi)$ if $M \models_I \leftarrow\!\!\bullet(e, \neg\phi)$
4. $M \models_I \neg \diamond (e, \phi)$ if $M \models_I \Box(e, \neg\phi)$
5. $M \models_I \neg\Box(e, \phi)$ if $M \models_I \diamond(e, \neg\phi)$
6. $M \models_I \neg\neg\phi$ if $M \models_I \phi$
7. $M \models_I \neg\phi$ if $M \not\models_I \phi$ and ϕ is not one of the above forms.

C Semantic rules

The interpretation rules map functors and their left-hand- arguments into operator triples. In each case, X is the left-hand argument of the functor in question. In practice, the choice of interpretation rule is heavily influenced (in somewhat irregular ways) by the tense and aspect of the verb in the qualified verb-phrase. In the interests of brevity, this influence has been ignored, apart from one observation on the interaction between the perfective and **for**.

1. **at** $\mapsto [\bullet, X, O]$ where O is in $\{\diamond, \Box, \bullet, \bullet\!\!\rightarrow, \leftarrow\!\!\bullet\}$
2. **by** $\mapsto [\bullet\!\!\rightarrow, X, \diamond]$
3. **during** $\mapsto [\bullet, X, O]$ where O is in $\{\diamond, \Box\}$
4. **esince** $\mapsto [\leftarrow\!\!\bullet, X, \Box]$
5. **every** $\mapsto [\Box, X, O]$ where O is in $\{\diamond, \Box, \bullet, \bullet\!\!\rightarrow, \leftarrow\!\!\bullet\}$
6. **for** $\mapsto [\diamond, X, \Box]$
7. **for** $\mapsto [\bullet\!\!\rightarrow, \mathrm{tor} + X, \Box]$ (if verb in main clause non-perfective)
8. **for** $\mapsto [\leftarrow\!\!\bullet, \mathrm{tor} - X, \Box]$ (if verb in main clause perfective)
9. **in** $\mapsto [\diamond, X, \diamond]$
10. **in** $\mapsto [\bullet\!\!\rightarrow, \mathrm{tor} + X, \diamond]$
11. **in** $\mapsto [\bullet, \mathrm{tor} + X, O]$ where O is in $\{\diamond, \Box\}$
12. **one** $\mapsto [\diamond, X, O]$ where O is in $\{\diamond, \Box, \bullet, \bullet\!\!\rightarrow, \leftarrow\!\!\bullet\}$
13. **since** $\mapsto [\leftarrow\!\!\bullet, X, O]$ where O is in $\{\diamond, \Box\}$
14. **throughout** $\mapsto [\bullet, X, \Box]$
15. **until** $\mapsto [\bullet\!\!\rightarrow, X, \Box]$

Offset-prepositions generate left-embedded functors that yield temporal restrictions involving the +- and −-operators. The mappings given here show how the temporal restriction in question can be generated from the functor and its arguments.

1. **after**$_1(X, W) \mapsto X + W$
2. **after**$_2(X) \mapsto X + \mathrm{skolem}$
3. **after**$_3(W) \mapsto \mathrm{tor} + W$ (if $\mathrm{tor} \neq \mathrm{tou}$)
4. **after**$_4 \mapsto \mathrm{tor} + \mathrm{skolem}$ (if $\mathrm{tor} \neq \mathrm{tou}$)
5. **ago**$(W) \mapsto \mathrm{tor} - W$ (if $\mathrm{tor} = \mathrm{tou}$)

6. $\mathbf{before}_1(X, W) \mapsto X - W$
7. $\mathbf{before}_2(X) \mapsto X - \text{skolem}$
8. $\mathbf{before}_3(W) \mapsto \text{tor} - W$ (if tor $\neq$ tou)
9. $\mathbf{before}_4 \mapsto \text{tor} - \text{skolem}$ (if tor $\neq$ tou)

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