Sorts and Operators for Temporal Semantics

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1 Introduction

An essential part of natural language understanding, and hence of formal semantics, is the interpretation of temporal expressions. But the very variety of temporal phenomena—such as tense, aspect, aktionsart, temporal adverbials, and the temporal structure of extended text—has tended to result in formal semantic analyses using a wide variety of formal tools, often of a complex nature. It seems important to try and find unifying perspectives on this work, and above all, to try and gain some insight into the logical resources needed to deal with natural language temporal phenomena.

In this paper, we show how a wide variety of temporal expressions can be analysed using a simple modal language. The underlying language is well known in the AI literature: it's Halpern and Shoham's (1986) monotonic interval-based logic. However, as it stands, this language is insufficient for natural language analysis on at least two counts. The first problem is the Reference Problem: it lacks any mechanisms for temporal reference, which are essential for an adequate treatment of tense, adverbials and indexicals. The second problem is the Ontology Problem: the language doesn't reflect the wide variety of temporal ontologies, stemming from events, states and processes, which are essential for an adequate treatment of NL aktionsart. We will show how these two defects can be removed in a simple and uniform way: *sorting*. Systematic use of sorting will result in simple frameworks suitable for modelling the semantics of a wide variety of natural language temporal expressions; moreover, as we shall see, the framework is strong enough to model them in a variety of ways.

This article falls into three main parts. In the first we will show that many different kinds of referential information can easily be marked in a propositional modal language by means of sorting. There are many kinds of temporal referential information; we will examine Reichenbachian reference times, indexicals and durations. In the second part of the article, we turn our attention to temporal ontology. It's a commonly held view in temporal semantics that in order to treat many temporal phenomena, one must do justice to the rich structures underlying temporal ontology. The classical work in this area is Vendler's (1967), though the ideas stretch back much earlier (Aristotle), and have been developed in many directions since (e.g., Moens and Steedman 1988, Nakhimovsky 1988, Lascarides 1991). We will see how sorting enables some of these ideas to modeled. In the third part we combine our sorted modal languages with ideas from the default logic literature.

2 Halpern and Shoham's language

The syntax of the language is as follows. The primitive alphabet consists of the symbols $\neg$ (negation) and $\wedge$ (conjunction); six modalities, $\langle A\rangle$, $\langle\overline{A}\rangle$, $\langle B\rangle$, $\langle\overline{B}\rangle$, E and $\langle\overline{E}\rangle$; and in addition a denumerably infinite set of atomic symbols **Var**. The elements of **Var** are written as p, q, r, and so on.

From this stock of primitives we make the well formed formulas (wffs) of the language as follows. First we define the set of atomic symbols of our language, **Atom**, to be **Var**. That is **Atom** = **Var**. We then build up wffs out of the elements of **Atom** as follows:

1. All elements of **Atom** are wffs.
2. If ϕ and ψ are wffs, then $\neg\phi$ and $\phi \wedge \psi$ are wffs.
3. If ϕ is a wff, then $\langle A\rangle\phi$, $\langle\overline{A}\rangle\phi$, $\langle B\rangle\phi$, $\langle\overline{B}\rangle\phi$, $\langle E\rangle\phi$ and $\langle\overline{E}\rangle\phi$ are wffs.
4. Nothing else is a wff.

We will make free use of the symbols $\vee$ (disjunction), $\rightarrow$ (material implication), $\leftrightarrow$ (material equivalence), $\top$ (constant true) and $\perp$ (constant false). These will be regarded as abbreviations defined in the usual way. For example, for any wffs ϕ and ψ, $\phi \vee \psi$ is simply shorthand for $\neg(\neg\phi \wedge \neg\psi)$.

Now for the semantics. As we will eventually be wanting to model such matters as temporal duration, and to deal with such special periods of times as 'days' and 'months', it seems sensible, right from the start, to choose a temporal ontology rich enough to support these distinctions. For this purpose we will choose **R** (that is, $\langle R, <\rangle$), the real numbers in their usual order. To some extent this choice is arbitrary. For example, **Q** (that is, $\langle Q, <\rangle$), the rational numbers in their usual order, might do just as well; and less committal choices are also possible (see, for example, the discussion of **Q**-containing frames in Blackburn (1990).) Nonetheless, **R** is certainly a sensible first choice: it is a fundamental mathematical structure that offers us all we will need for the purposes of this paper.

However, to interpret the language we are not so much interested in **R** itself as in certain of the intervals that exist on **R**. Define $int(\mathbf{R})$ to be the set containing all non-empty intervals that have one of the following four forms: the closed intervals $[t_1, t_2]$ (that is, it is the set $\{t \in R : t_1 \leq t \leq t_2\}$); the open intervals (t_1, t_2) (that is, the set $\{t \in R : t_1 < t < t_2\}$); the left opens interval $(t_1, t_2]$ (that is, the set $\{t \in R : t_1 < t \leq t_2\}$); or the right open intervals $[t_1, t_2)$ (that is, the set $\{t \in R : t_1 \leq t < t_2\}$). The interval structure $int(\mathbf{R})$ is the skeleton on which we'll hang our semantics. While on occasions it will be important to be aware of the distinctions between the different types of interval (for example, when we model days), for the most part it will be convenient to ignore them, so we will usually use a notation that suppresses these distinctions. In particular, when we write an interval $\mathbf{t}$ of $int(\mathbf{R})$ as $\langle t_1, t_2 \rangle$, we are being ambiguous between all four possibilities. (Note, however, that $\langle t_1, t_1 \rangle$ is unambiguous: it can only mean $[t_1, t_1]$ as all the other three options are empty, and thus not elements of $int(\mathbf{R})$.) A much more important distinction for us will be distinction between *point intervals* and *extended intervals*. Elements $\langle t_1, t_2 \rangle$ of $int(\mathbf{R})$ where $t_1 = t_2$ will (for obvious reasons) be called *point intervals* (or even just *points*), whereas those intervals where $t_1 < t_2$ will be called will be called *extended intervals*. We denote the set of point intervals by $point(\mathbf{R})$, and the set of extended intervals by $extended(\mathbf{R})$, Clearly $extended(\mathbf{R}) \cup point(\mathbf{R}) = int(\mathbf{R})$, and $extended(\mathbf{R}) \cap point(\mathbf{R}) = \emptyset$.

Although $int(\mathbf{R})$ gives us a useful intervalic skeleton, we are are not yet ready to interpret the language. One more task remains: to flesh out this structure with an information distribution. For this purpose we need the concept of a *valuation function*. A valuation V is a function that takes an atomic symbol as input and returns a set of intervals of $\mathbf{R}$. That is, a valuation is a function whose domain is **Atom** and whose range is the power set of $int(\mathbf{R})$. Intuitively, for any atom, a valuation specifies exactly those intervals at which the corresponding piece of atomic information holds.

We now have everything needed to define our intended models: a model $\mathcal{M}$ is simply an ordered pair whose first component is $int(\mathbf{R})$ and whose second component is a valuation V. That is, a model $\mathcal{M}$ can be written as $\langle int(\mathbf{R}), V \rangle$ for some valuation V. We now interpret the language on models according to the following *satisfaction definition*. For any model $\mathcal{M}$, for any element $\langle t_1, t_2 \rangle$ of $int(\mathbf{R})$, and any wff ϕ we define:

1. $\mathcal{M}, \langle t_1, t_2 \rangle \models \phi$ iff $\langle t_1, t_2 \rangle \in V(\phi)$, for all $\phi \in$ **Atom**.
2. $\mathcal{M}, \langle t_1, t_2 \rangle \models \neg\phi$ iff $\mathcal{M}, \langle t_1, t_2 \rangle \not\models \phi$.
3. $\mathcal{M}, \langle t_1, t_2 \rangle \models \phi \wedge \psi$ iff $\mathcal{M}, \langle t_1, t_2 \rangle \models \phi$ and $\mathcal{M}, \langle t_1, t_2 \rangle \models \psi$.
4. $\mathcal{M}, \langle t_1, t_2 \rangle \models \langle B \rangle \phi$ iff there exists t_3 such that $t_1 \leq t_3$, $t_3 < t_2$ and $\mathcal{M}, \langle t_1, t_3 \rangle \models \phi$.
5. $\mathcal{M}, \langle t_1, t_2 \rangle \models \langle E \rangle \phi$ iff there exists t_3 such that $t_1 < t_3$, $t_3 \leq t_2$ and $\mathcal{M}, \langle t_3, t_2 \rangle \models \phi$.
6. $\mathcal{M}, \langle t_1, t_2 \rangle \models \langle A \rangle \phi$ iff there exists t_3 such that $t_2 < t_3$ and $\mathcal{M}, \langle t_2, t_3 \rangle \models \phi$.
7. $\mathcal{M}, \langle t_1, t_2 \rangle \models \langle \overline{B} \rangle \phi$ iff there exists t_3 such that $t_2 < t_3$ and $\mathcal{M}, \langle t_1, t_3 \rangle \models \phi$.
8. $\mathcal{M}, \langle t_1, t_2 \rangle \models \langle \overline{E} \rangle \phi$ iff there exists t_3 such that $t_3 < t_1$ and $\mathcal{M}, \langle t_3, t_2 \rangle \models \phi$.
9. $\mathcal{M}, \langle t_1, t_2 \rangle \models \langle \overline{A} \rangle \phi$ iff there exists t_3 such that $t_3 < t_1$ and $\mathcal{M}, \langle t_3, t_1 \rangle \models \phi$.

If $\mathcal{M}, \langle t_1, t_2 \rangle \models \phi$ then we say that ϕ is *satisfied* (or, *true*) in $\mathcal{M}$ at the interval $\langle t_1, t_2 \rangle$, and we refer to $\langle t_1, t_2 \rangle$ as the *interval of evaluation* or *current interval*.

Let's consider these clauses. The first three are standard: the first merely says that atomic symbols are to be true at precisely those intervals that bear the corresponding piece of atomic information, while the second and third impose a classical interpretation on $\neg$ and $\wedge$. The interest lies in the last six clauses, that is, in the clauses for the modal operators. The best

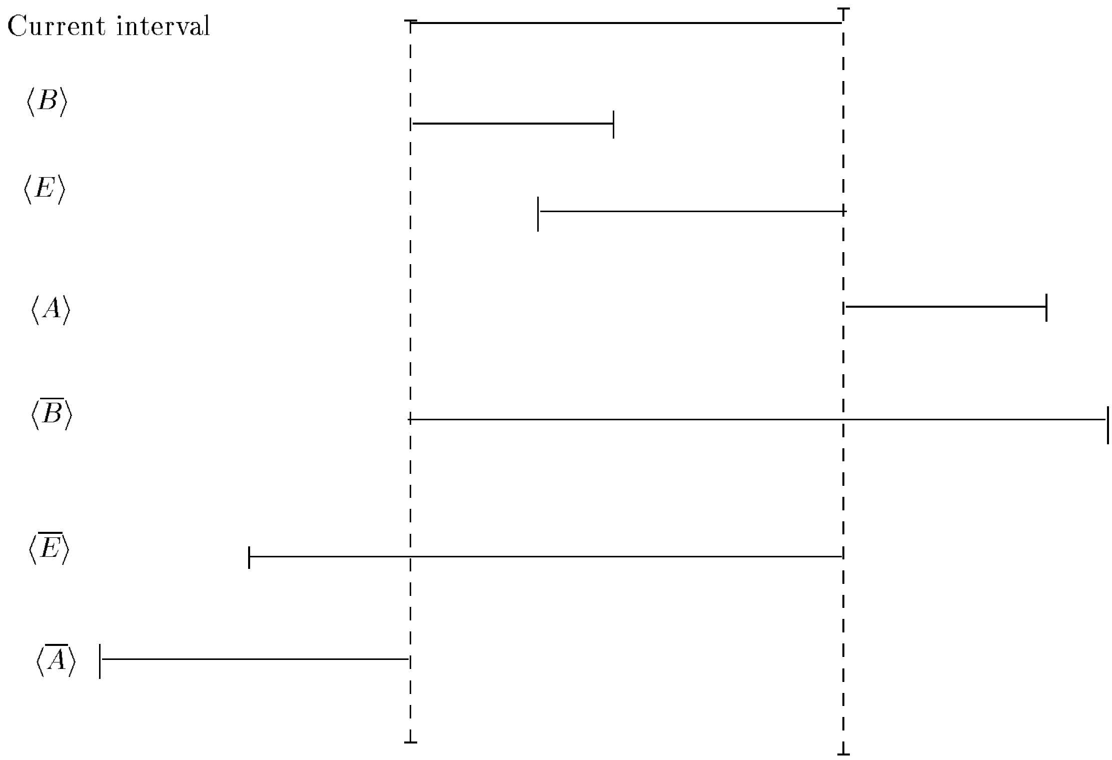

Figure 1: The six basic modal operators

way to understand them is to visualise them. Figure 1 illustrates the effect of the various operators.

As the diagram should make clear, the language is a very natural one. The operators offer a powerful set of tools for 'cutting apart' intervals, and by combining them in various ways we can define a number of useful macros. Let's consider some simple examples.[1]

First, using combinations of the primitive operators, we can define interval based analogs of the familiar Priorean tense operators (see Prior 1967). We define the past tense operator as follows:

$$P\phi =_{def} \langle \overline{A} \rangle \langle \overline{A} \rangle \phi \vee \langle \overline{A} \rangle \phi.$$

Clearly $P\phi$ is true at an interval in some model iff ϕ is true at some interval preceding the interval of evaluation. That is, $P\phi$ insists that ϕ is true at some interval in the past. In similar fashion it is easy to see that:

$$F\phi =_{def} \langle A \rangle \langle A \rangle \phi \vee \langle A \rangle \phi,$$

works like Prior's future tense operator: it insists that ϕ holds at some interval in the future.

Next, note that we can pick out subintervals of the current interval. We define:

$$\downarrow \phi =_{def} \langle B \rangle \phi \vee \langle E \rangle \phi \vee \langle B \rangle \langle E \rangle \phi.$$

[1] The examples given below, though useful in the sequel, hardly begin to scratch the surface of the language's expressivity. For a detailed treatment of expressivity issues, see Venema (1989).

A moments thought shows that $\downarrow \phi$ insists that ϕ is true at some subinterval; that is, $\downarrow$ is a macro that means 'during'. A converse to this operator is also definable:

$$\uparrow \phi =_{def} \langle\overline{B}\rangle\phi \vee \langle\overline{E}\rangle\phi \vee \langle\overline{B}\rangle\langle\overline{E}\rangle\phi.$$

Unsurprisingly, $\uparrow \phi$ means that ϕ is true at an interval of which the current interval is a subinterval. This concept isn't lexicalised in English, nonetheless $\uparrow$ turns out to be useful in formalising temporal discourse.

As a final example of the system's expressivity, we will show that it is possible to define an operator that means 'ϕ is true at all intervals'. As a first step we define an operator M which means 'ϕ is true at some interval':

$$\begin{aligned} M\phi \quad =_{def} \quad & \phi \vee \langle A\rangle\phi \vee \langle\overline{A}\rangle\phi \vee B\phi \vee \langle\overline{B}\rangle\phi \vee \langle E\rangle\phi \vee \langle\overline{E}\rangle\phi \vee \\ & \langle\overline{A}\rangle\langle\overline{A}\rangle\phi \vee \langle B\rangle\langle\overline{E}\rangle\phi \vee \langle\overline{B}\rangle\langle\overline{E}\rangle\phi \vee \langle B\rangle\langle E\rangle\phi \vee \langle E\rangle\langle\overline{B}\rangle\phi \vee \langle A\rangle\langle A\rangle\phi \end{aligned}$$

This is not nearly as gruesome as it appears; in fact it's rather simple. The essential thing to note is that each of the thirteen disjuncts corresponds to one of the thirteen ways that two intervals over a linear structure can be related, as defined in Allen (1984). Consider the first line. The first disjunct tests for the truth of ϕ at the current interval, while each of the other six disjuncts tests the intervals related to the current interval in one of the ways shown in the previous diagram. Now consider the second line. The six disjuncts there (which make use of modality combinations) test the remaining six probabilities. Note that we've already met two of these modality combinations (namely $\langle B\rangle\langle E\rangle$ and $\langle\overline{B}\rangle\langle\overline{E}\rangle$) in the definition of $\downarrow$ and $\uparrow$ above, and the import of the remaining four combinations is easy to determine. To sum up, M looks for an interval where ϕ is true by systematically looking at all thirteen possible locations where such an interval could be found, and thus M really does mean 'at some interval'.

But with M to hand, it is easy to define L, the 'at all intervals' operator:

$$L\phi =_{def} \neg M \neg\phi.$$

It is easy to see that L universally quantifies over all intervals; it is simply the dual of the existential operator M.

This, then, is Halpern and Shoham's modal logic of intervals. Logically, it is a well understood system; Halpern and Shoham (1986) contains a detailed treatment of complexity issues, while Venema (1989) deals with issues of completeness and expressivity. Moreover, it is an extremely elegant system. The reader who experiments with it will soon realise that in spite of its simplicity it is actually a very sophisticated tool for dealing with interval structures. A natural question thus arises: can we put the system to work as part of an interval based semantics of natural language?

3 Reference

In this section we take up the challenge just issued: to put Halpern and Shoham's system to work in natural language semantics. As their system wasn't designed with the analysis of natural language in mind (it was intended for use in AI applications) it is not particularly surprising that, as it stands, the language is inadequate for natural language semantics. What *is* (pleasantly) surprising is how little needs to be done to convert it into a formalism adequate for many natural language phenomena. Let's briefly consider what these problems are and how they might be overcome.

Readers familiar with natural language semantics have probably already compiled a list of various phenomena Halpern and Shoham's language will have problems with: any such list is likely to include difficulties with temporal reference and insensitivity to aktionsart. And indeed, these are the trouble spots: like most other propositional modal logics the language offers no handles on these matters. But suppose we wanted to 'sharpen' the language to deal with these issues — and, more importantly, suppose we wanted to sharpen it in a way that preserved it's simplicity — what should we do?

Halpern and Shoham's system (and indeed most of the propositional modal logics treated in the literature) are 'blunt' in one very obvious area, namely the structure of **Atom**. **Atom** is simply equated with **Var**, an undifferentiated set of atomic symbols — p, q, r and so on — that are completely free in their interpretation. We gain no useful information from the form of the atoms. The symbols are distinguishable from each other and that's about it.

Natural languages simply don't work like this. One of the most obvious facts about natural language is the existence of word classes. Indeed, within word classes there are important (and informative) semantic divisions. For example, within the class of proper nouns there are semantic subclasses: for example, names for people, for countries, and for times. And, within the class of names for times there are further subdivisions: names for years (*1984*), for months (*June*) and for days (*Friday*).

Such semantic subdivisions are useful. When we hear the word '*Friday*' we know that a day and not a year is being spoken. We may have missed the rest of the conversation (it may have been uttered by a pair of passing strangers in the street) and be completely unaware of whether something good or bad was meant to have happened (or to be going to happen) on Friday. But our knowledge of the English lexicon has given us something: whatever the conversation was about, something in it has to do with the day before the weekend begins.

When we say we are going to sort Halpern and Shoham's language, we simply mean that we are going to impose syntactic subdivisions on **Atom** that reflect various semantic properties we are interested in. For example, there will be various sorts of atoms for naming intervals, for measuring the lengths of intervals, and for picking out years. Thus (just like the overheard conversation) we will be able to read off information just from the sort of the atom involved.

We defer further general discussion of the sorting concept till the paper's conclusion. However even from the (rather impressionistic) remarks just made, one thing should be clear: sorting involves minimal tampering with the syntax and semantics of the original system. Thus, while we will be gaining many expressive abilities vital for the analysis of natural language, we will retain the key advantages of the original system.

3.1 The Reference Problem

Let's examine one of the more obvious problems confronting the use of Halpern and Shoham's language, namely what we'll term the Reference Problem. Actually, this is really a collection of problems bound by a common thread: Inability to Refer. Halpern and Shoham's language has no facilities for picking out particular intervals or for picking out intervals of a certain duration.

Let's consider some examples of the difficulties this shortcoming will lead to. First, we have no good representation of even such a simple sentence as (1):

(1) I failed to turn off the stove

As Partee (1973) argues, the simple Priorean representation P(I fail to turn off the stove) is quite inadequate. The normal function of the English simple past is to pick out some contextually determined past time interval, and insist that the event in question occurred or did not occur *at that particular interval.* This is simply something we cannot say in Halpern and Shoham's language. It offers us no mechanism by which intervals can be named. Among other things, this means that most of the ideas of Hans Reichenbach (1947) fail to find adequate expression in this language.

The remaining reference problems can be seen as an elaboration on this basic failing. We cannot pick out lexically determined intervals, such as *yesterday*, *today* or *tomorrow*, nor indeed even such non-indexical intervals such *1954*, *Monday* and *Thursday*. Moreover, we cannot pick out intervals with certain desirable properties, such as being of a certain duration. For example, In order to deal with even such a simple sentence such as (2), we need some mechanism to pick out four minute intervals of time, but no such mechanism is provided in Halpern and Shoham's language.

(2) John ran a mile in four minutes

The principle task of this section is to show that these deficiencies can be removed in a uniform manner without sacrificing the elegance and simplicity of the Halpern and Shoham's original system. We shall progressively modify their language in such a way that all of these shortcomings are removed.

3.2 Introducing Nominals

The first (and most basic) problem that faces us is that we cannot refer to intervals. So let us sort our language in such a way that this problem is overcome. In fact, let us sort the language in such a way that we can refer to either extended intervals or points.

Let **Inom** and **Pnom** be a denumerably infinite set of symbols, distinct from each other and from **Var**. That is, we assume that **Inom**, **Pnom** and **Var** are mutually disjoint. We write the elements of **Inom** as i, j, k and so on and call them *interval nominals*, and we write the elements of **Pnom** as c, d and so on and call them *point nominals*. As the terminology suggests, interval nominals will be used to name intervals, and point nominals will be used name to points—but before we explain how this is to be achieved, let's finish specifying the syntax of the enriched language.

As has already been mentioned, the key syntactic idea underlying sorting is simply to impose structure on the **Atom**. Very well, let us redefine **Atom** as follows:

$$\mathbf{Atom} =_{def} \mathbf{Var} \cup \mathbf{Inom} \cup \mathbf{Pnom}.$$

That is, our set of atomic symbols is now a three sorted structure. This atomic level alteration is the *only* syntactic change we make: we build our wffs over **Atom** exactly as before.

The two new sorts are meant to be bearers of different sorts of semantic information: the elements of **Inom** are meant to pick out extended intervals, whereas the elements of **PNom** are meant to pick out points. Thus we must impose constraints on the interpretation of these symbols. To put it another way, whereas we were (and still are) completely cavalier about how the elements of **Var** are to be interpreted, we *cannot* be cavalier in our interpretation of **Inom** and **Pnom**. Valuations must respect the semantic distinctions we wish to make. This motivates the possible definition:

> A valuation is a function V with domain **Atom** and range $Pow(int(\mathbf{R}))$ that reflects the following constraints. First, for all interval nominals i, $V(i)$ contain exactly one extended interval. Second, for all point nominals c, $V(c)$ contain exactly one point interval.

These constraints on the interpretation of the atomic symbols are the *only* semantic changes we make. As before we define a model $\mathcal{M}$ to be a pair $\langle int(\mathbf{R}), V\rangle$, where V is a valuation, and we interpret wffs on models exactly as before.

But the atomic level constraints do make a difference. Essentially we have insisted that each interval nominal is true at exactly one extended interval in any model, and that each point nominal is true at exactly one point nominal in every nominal. Thus our sorting has introduced a mechanism for naming extended intervals or points: nominals 'name' the unique interval at which they are true. Let's see how we can put this ability to work.

3.3 Tense

First of all, we now have a way of capturing the semantics of the English simple past. We would represent (1) by

$$P(i \wedge \text{I fail to turn off the stove}).$$

This WFF makes a much stronger demand than did the Priorean representation. It doesn't assert a failure to turn off the stove at some unspecified past time, rather, it asserts *at the particular interval named by i*, I failed to turn off the stove. That is, the interval nominal i is here being used in an essentially Reichenbachian way: to pick out the reference time.[2]

This basic idea enables us to deal systematically with all the tenses of English.[3] For example, consider the past perfect sentence (3):

(3) I had eaten the crocodile

[2] A purist might object that the analysis isn't completely Reichenbachian, as Reichenbach used points, not intervals, in his account of reference times. Now we could make the analysis 'completely Reichenbachian' by using a point nominal here instead of an interval nominals; but as the reference time in this example is clearly an extended interval, this does not seem particularly sensible. Instead we'll simple say that we find it perfectly reasonable to think of Reichenbach's ideas in terms of intervals. This is the course followed in Partee (1984) and Comrie (1985) for example.

[3] For a systematic tabulation, see Blackburn (1990) or Blackburn (1992).

We can represent this by:

$$P(i \wedge P(\text{I eat the crocodile})).$$

Again note that this is essentially the Reichenbachian analysis; a reference time in the past is picked out (by i), and the event of interest (the eating of the crocodile) is asserted to hold before then.

In short: nominals can be used to pick out Reichenbachian reference times. Our sorting language enables us to incorporate Reichenbach's ideas into the centre of a tense logic: Prior meets Reichenbach without fighting.

However, there is one point that we wish to stress very strongly: we are not *forced* to make such an analysis. What is being presented in this paper is a tool for the analysis of temporal expressions, and like any tool, it can be put to a variety of uses. Thus there are other natural analyses of (3) that can be expressed in the language. For example, some have argued (Kamp (1991) and Eberle and Kasper (1991)), that the past perfect should be defined as a relation between *four* times, rather than Reichenbachian tripartite relation. This is captured in the truth conditions of the following formula, whose satisfiability conditions depends on the relationship between the time of evaluation, the time named by i, the time named by j and the time where *I eat the crocodile* holds:

$$P(i \wedge P(j \wedge \text{I eat the crocodile}))$$

In short, though the sorted languages discussed in this paper are just simple propositional systems, they are rich enough to model diverse analyses of natural language. We think this important. It enables the various proposals in temporal semantics to be precisely compared in a common framework, and gives an (admittedly, at present, fairly crude) measure of the sort of logical resources that are needed for temporal phenomena in natural language.

3.3.1 Tense in Texts

A second application of nominals is the representation of the 'forward movement' of time in narrative discourse. (Actually, this is essentially to lift the 'Reichenbachian use' of nominals from the sentential level to the level of text.) Let's consider a simple example.

(4) John opened the door. The room was dark. He fumbled around for his cigarettes.

(4′) $P(i \wedge \text{John open the door}) \wedge$
$P(i \wedge \text{The room be dark}) \wedge$
$P(j \wedge \langle\overline{A}\rangle i \wedge \text{John fumble around for his cigarettes})$

Here, the earlier mentioned analogy drawn between nominals and discourse entities in DRT should be clear. In fact what we have done is literally to model Partee's (1984) analysis of narrative text.[4] The nominals are used to name the times where the eventualities hold. To be more specific, i names an interval where both a door opening occurred, and a state of darkness

[4]Similar analyses were given in Blackburn (1990). However, in these earlier analyses, use was made of a rather simple point based language. Thus the truly intervalic flavour of Partee's analysis was not captured.

obtained, and j names an interval where a fumbling for cigarettes took place. The important part, however, is the way these intervals are related. First of all, note that it follows from our semantics, that the interval named by j immediately follows the interval named by i. That is, the interval named by j occurs 'just after' the interval name by i, thanks to the semantics of $\langle \overline{A} \rangle$. This is a slight improvement on Partee's treatment. She mentions the problem of representing the relation 'just after' in her language; here this relation corresponds to Halpern and Shoham's $\langle \overline{A} \rangle$ operator. We believe that this is one of the places where the expressive power of the underlying language pays off in NL analysis.

To close this section, two remarks. The first is methodological. Just as the use of nominals doesn't commit us to a particular analysis of tense, the use of nominals doesn't commit us to any particular analysis ot tense-in-text (such as the Parteean analysis). In fact, what we find interesting about this approach is precisely that it has isolated certain simple and general logical tools. These tools can then be combined with other tools in various ways; the hope is that such combinations point towards better analyses and clearly 'lay open' the structure of the proposed solution(s). We will give an example of this mode of analysis later, when we combine our sorted modal languages with default logic.

Secondly, a logical remark. The sorted language we are using here can be straightforwardly translated into a first order classical logic. The particular details need not concern us here (though the interested reader will find discussion of various aspects of the required translation in issue in van Benthem (1991), Shoham (1988) and Blackburn (1993)). What *is* of interest for the present discussion is how nominals are translated into first order logic: they translate as free variables. In short, the link between nominals and the discourse referents of DRT is not mere analogy. Both the use of nominals and the use of DRT discourse referents are essentially free variable treatments of anaphora.

3.4 Sorts that measure time

We have seen how we can model the semantic behaviour of Reichenbachian reference times using nominals. Reference times *locate* eventualities on the time line. Adverbials of duration, on the other hand, describe the 'length' of the interval where eventualities hold, wherever those intervals may be on the time line. In this section we will introduce additional sorts to measure duration.

Consider the adverbial of duration in (5).

(5) Max ran for four minutes

To define the semantics of *for four minutes*, we introduce a new sort into our object language. We will call this sort **Measure**, and typical of the items it contains are:

$$10secs, 3mins, 5hrs, 2days, 8years, 15centuries, \ldots.$$

The items in this sort will be given the obvious semantics. For example, the item $3mins$ will be true at all and only the intervals of length three minutes. This will enable us to represent the above sentence as follows:

$$P(i \wedge 4mins \wedge \text{Max run}).$$

That is, there is a past interval (picked out by i) of duration four minutes, and Max was running during this interval. More generally, for any element m of **Measure**, and any wff ϕ we will be able define a simple FOR macro: $FOR(m, \phi)$ is just $m \wedge \phi$. Thus the previous example could be written as:

$$P(i \wedge FOR(4mins, \text{Max run})).$$

Let's make this a little more precise. We won't formally itemize the syntactic items in **Measure**; the above examples ilustrate what is intended. We'll simply assume that some such choice has been made, that the choice of durations is sensible (basically this means that there are no negative durations; we won't have such items as $-3secs$); and that **Measure** is pairwise disjoint from our other sorts. This done, we enlarge **Atom** to include the items of **Measure**.

To define the constraints on valuation required by this new sort, we need some measuring conventions. Here are ours. First of all, if $\langle t, t' \rangle \in Int(\mathbf{R})$, then by the *length* of this interval is meant $t' - t$. Next, we define the set of days as follows:

$$Days = \{[z, z+1) : z \text{ is an integer}\}.$$

Note that under this convention the length of any day is one. We take the length of a day as our fundamental unit for defining such items as hours, minutes and seconds. For example, an hour is any interval of length 1/24, and so on. With these conventions in place we simply place the obvious constraints on our valuation function. For example:

$$V(4mins) = \{\langle t, t' \rangle : t' - t \text{ is four minutes long}\}.$$

Doubtless our conventions are a little crude: but it should be clear that they give a semantics of duration sensible enough to cope with natural language examples such as that above.

But it should also be clear that there are problems we haven't begun to touch. Consider, for example, the semantics of ϕ *in four minutes*, as in (6):

(6) Max ran a mile in four minutes.

Analysing (6) purely in terms of $FOR(m, \phi)$ won't do, because $FOR(4mins, \phi)$ entails that $FOR(3mins, \phi)$ is also true in the model, whereas (6) doesn't entail that Max ran a mile in three minutes. So the entailments from $FOR(4mins, \phi)$ conflict with the intuitive consequences one draws from (6).

The crucial thing that's missing from the picture is the notion of *culmination*. Unlike *Max ran*, *Max ran a mile* has a definite endpoint, and (6) is true only if that endpoint is included in the four minute period. In contrast, if *Max ran* is true at an interval i, then it is possible that it's also true at subintervals lacking the endpoint of i. We have not provided the mechanisms as yet for making these distinctions. In other words, we have not done justice to the rich temporal ontologies described by Vendler (1967) and others. We return to this point shortly, and show that by further sorting, the mechanisms for describing ontology are incorporated into the framework. And through this sorting, we can then provide an analysis of (6).

3.5 Indexicals

We now investigate how sorting can be used to model the semantics of indexicals like *now*, *today* and *yesterday*, thereby explaining the difference in acceptability between (7) and (8).

(7) Max ran yesterday

(8) $*$ Max will run yesterday

We introduce a time c which is any fixed real number. We think of c as *now*. In line with Montague (1970), Kamp (1971) and Kaplan (1979), we change the truth definitions of the language so that all WFFS are evaluated at pairs $[t, c]$, where t is an interval in I. Now we introduce sorting for modelling indexicals.

- $INDEXICAL =$ *now*, *yesterday*, *today*, ...
- $V(now) = c$
- $V(today) =$ unique day containing c
- $V(yesterday) =$ unique day immediately preceding *today*.

The logical form of (8) is (8′).

(8′) $F(j \wedge \uparrow yesterday \wedge \text{Max run})$

(8′) is unsatisfiable at $[t, t]$ for all intervals t, as intuitions would dictate. (8′) is true in a model M at $[t, t]$ iff $j \wedge \uparrow yesterday \wedge \text{Max run}$ is true in M at $[t', t]$, where $t \prec t'$. This is true iff (a) $V(j) = t'$; (b) $\uparrow yesterday$ is true at $[t', t]$; and (c) Max run is true at $[t', t]$. (b) holds only if $t' \prec t$. But by the semantics of F, $t \prec t'$. So (8′) is false in M at $[t, t]$.

4 Ontology

We've seen how sorting can solve the Reference Problem. Let's now see how it can solve the Ontology Problem. We'll use sorting to model the distinctions that exist in NL temporal ontology. It's very natural to attempt this. But unless one wishes to indulge in extremely stipulative temporal metaphysics, it's a rather delicate process. We do not wish to be stipulative. Instead, we're going to introduce a combination of sorts and classification operators, and show how these will enable various theories about temporal ontological classification to be expressed.

In this paper, we are not going to assume a particularly strong theory of temporal ontological classification. Rather, we simply wish to indicate that such operators have potential interest for NL semantics. Because we have internalised the vocabulary of temporal classification into our object language, we have the capacity to delimit the rather subtle interactions that depend in inference on sorts. In particular, we will be able to define sortally specific operators, such as *cum* (for culmination), *prep* (for preparatory phase), and *prog* (for progressive). Moreover, although this is not a theme that will be explored in detail in this paper, we believe that it is precisely such a move that is required in order to create a simple logical framework, in which more powerful ideas like those based on default formalisms can be formulated.

As a first step, let's mirror a rather naive classification of temporal ontology in our object language, by introducing sorts. In particular, we'll introduce atomic statements that correspond to each of the classes: event, state and process.

- *EVENTS*: $e_1, e_2, \ldots$
  STATES: $s_1, s_2, \ldots$
  PROCESSES: $p_1, p_2, \ldots$

But what constraints on valuation are we to impose on these sorts? Dowty (1979) and many others have argued that events, processes and states are to be distinguished along the following lines: events are heterogeneous (i.e., their truth at an interval i entails their falsity at subintervals of i); processes are homogeneous down to subintervals of a certain appropriate size (i.e., their truth at i entails their truth at all subintervals j of i down to a certain limit in size); and states are homogeneous right down to points of time (i.e., their truth at i entails their truth at all times contained in i).

We first investigate how this Heterogeneous Strategy for modelling ontology can be captured in our logic, via constraints on valuation. We then investigate a less traditional method of distinguishing Vendler's classes, where all atomic WFFs are assumed to be homogeneous (i.e., the truth of an atomic WFF at an interval i entails its truth at all subintervals of i). We provide new constraints on valuation for modelling ontology, while maintaining homogeneity. And we show how these new constraints affect our definitions of aspect and adverbials. This exercise will demonstrate the utility of using the simple mechanism of sorting. We can entertain various strategies for defining temporal reference and ontology in a single framework, thus providing the first forum in which we can compare directly the various strategies for defining temporal semantics that have been proposed in the literature.

4.1 The Heterogeneous Strategy

We investigate how we can capture the heterogeneous analysis of events, proposed by Dowty (1979) and Taylor (1985), among others, in our framework. That is to say, if an event occurs over an interval i, it does not occur over any subinterval of i. This subinterval constraint on events is defined as follows:

- $t \in V(e)$, then $\forall t' \subset t$, $t' \notin V(e)$.

The subinterval property of processes and states can roughly be captured as follows:

- $t \in V(p)$, then $\forall t' \subset t$, $t' \in V(p)$

- $t \in V(s)$, then $\forall t' \subset t$, $t' \in V(s)$

We say 'roughly' because processes are modelled as totally homogeneous, rather than homogeneous up to a certain limit in size. In fact, these constraints on valuation don't distinguish processes from states at all. We forego supplying further distinctions for the sake of simplicity, since we wish merely to convince the reader that sorting has utility in capturing distinctions generally. And this point can be made by considering the difference between events on the one hand, and states and processes on the other.

Apart from it being difficult to draw meaningful distinctions between the various temporal sorts simply in terms of valuation on interval structures, there is a potentially more serious problem. It simply isn't obvious how these various classes are closed under the logical operators. Such problems are well known, and very difficult to solve. Rather than attempt solve these problems here, we shall provide a mechanism in which the various answers can be expressed. We shall add classification operators to the object language: $Event$, $Process$ and $State$.

- $Event(\phi)$: ϕ is an event
- $Process(\phi)$: ϕ is a process
- $State(\phi)$: ϕ is a state

The weakest theory that could be assumed, is simply that $Event(\phi)$, $Process(\phi)$ and $State(\phi)$ are satisfiable only if ϕ is an atomic symbol of the sorts $EVENT$, $PROCESS$ and $STATE$ respectively. Note that if s is a state atomic symbol, then $State(s)$ holds, but $State(s \wedge s)$ does not. A slightly stronger theory that could be assumed, and the one we shall assume here, is that in addition, we have $Event(\phi)$ and $Event(\psi)$ implies $Event(\phi \wedge \psi)$ and $Event(\phi \vee \psi)$. (Also for $Process$ and $State$). Using these operators that model the sorts, we can define directly in the language the formulae that reflect the constraints on valuation (where $\Downarrow \phi =_{def} \neg \downarrow \phi$:

- $(Event(\phi) \wedge \phi) \rightarrow \Downarrow \neg\phi$
- $(Process(\phi) \wedge \phi) \rightarrow \Downarrow \phi$
- $(State(\phi) \wedge \phi) \rightarrow \Downarrow \phi$

With this new view on events, we can define the operator $prep$, which picks out the preparatory process of the event. The idea is that the preparatory process occurs at initial subintervals of those at which the event occurs. This temporal relation is captured in the following definition of $prep$.

- $prep(\phi, \psi) =_{def} Process(\phi) \wedge Event(\psi) \wedge \phi \wedge L(\psi \rightarrow \langle B \rangle \phi)$

$prep(\phi, \psi)$ guarantees that if ψ is true at t, then the process ϕ is true at the initial subinterval of t. On the other hand, $prep(\phi, \psi)$ doesn't guarantee that ψ is true anywhere, even if ϕ is, thus reflecting the intuition that a preparatory process like building a house can occur without the house ever being completed.

prep is not part of Dowty's theory of aspect. One important difference between his theory and ours is that his definitions exploit possible worlds, whereas ours forego this machinery. Nevertheless, by exploiting heterogeneity, the above definition of *prep* can solve the imperfective paradox, as we now show.

4.1.1 The Imperfective Paradox

According to intuitions, (9) entails (10), but no entailment holds between (11) and (12).

(9) Max was running

(10) Max ran

(11) Max was winning the race

(12) Max won the race

A solution to the *imperfective paradox* must explain why this is so. This involves two tasks: first, we must characterise the semantic distinction between (10) and (12) as indicated by their different behaviours with the progressive; second, we must define the semantics of the progressive so that it is sensitive to this distinction and so results in a solution to the imperfective paradox.

We have already modelled a semantic distinction between (10) and (12) in terms of aspectual classification. The former is a process and the latter an event. These different sorts have different temporal behaviours, as defined by the constraints on the valuation function. We will exploit this in our definition of the progressive. We define the progressive operator as follows:

- $Prog(\phi) =_{def} \uparrow \phi \wedge \neg Event(\phi)$

In words, the progressive works on sentences that *aren't* events, and states that they hold now, started sometime before and haven't yet stopped; in other words, the non-progressive sentence is in progress. The logical form of (11) features *prep*, for note that $PROG$(Max win the race) is unsatisfiable, and so to uses Moens and Steedman's terminology, the event must be coerced into a process before it can combine with the progressive. Here, this amounts to applying the operator *prep* to the event. In contrast, $PROG$(Max run) is satisfiable. So, the logical forms of the sentences (9) to (12) are as follows:

(9′) $P(i \wedge PROG(\text{Max run}))$

(10′) $P(i \wedge \text{Max run})$

(11′) $P(i \wedge PROG(prep(p, \text{Max win the race})))$

(12′) $P(i \wedge \text{Max win the race})$

The propositional variable p in (11′) is input to the translation process from natural language to logical form. One can think of it as the perspective from which the eventualities are viewed:

the perspective from which the event is viewed will determine which process is relevant in the interpretation of "Max was winning the race", and hence will determine the value of p. By the semantics we've given of our sorts and operators the following hold: (9) is equivalent to (10); (11) doesn't entail (12); and (12) entails (11) is true just before, as long as we can find an appropriate process p.

Using the Heterogeneous Strategy to define semantic constraints on sorts, we have mirrored some aspects of Dowty's (1979) analysis of aspect in our framework. We could go on, and show how to define adverbials and connectives that will work in tangent with the temporal ontology we have built in an intuitive way. But Lascarides (1988) argued that although this Heterogeneous Strategy for modelling aktionsart is intuitively compelling, capturing as it does that events and processes take time, it leads to tensions and conflicts when it comes to explaining the natural language data. In particular, it is not possible to provide a uniform semantics for *at 3pm*, which provides the intuitively correct truth conditions for both (13) and (14).

(13) Max won the race at 3pm.

(14) Max ran in the race at 3pm.

For this reason, we now press on to propose how these same devices can define ontology in our logic in a different way. And we investigate how this alternative can capture the same entailments for NL expressions as the Heterogeneous Strategy captures, but in a different way.

4.2 The Homogeneous Strategy

We now consider the distinctions to be made between events, processes and states based on a Homogeneous Strategy, where we assume that if an event, process or state is true at an interval i, then it is true at all subintervals of i. Since events are homogeneous, they are punctual (cf. Lascarides 1991; 430–431). For otherwise we are committed to the culmination occurring at every point in the extended interval where the event is true, or events aren't associated with culminations at all in the semantics. In contrast, states and processes can extend in time. These constraints are defined below, and we assume they replace the constraints defined in the Heterogeneous Strategy:

- $t \in V(e)$ only if t is a point.
- $t \in V(s), V(p)$ and $t' \subseteq t$, then $t' \in V(s), V(p)$

In fact, just as in the Heterogeneous Strategy, these constraints on valuation can be defined in the object language:

- $e \rightarrow \neg \uparrow e$
  $s \rightarrow \Downarrow s$
  $p \rightarrow \Downarrow p$

We will explore the impact of these constraints on the rest of the sorts we have introduced.

4.2.1 Preparatory Processes and Consequent States

Given the homogeneous analysis of event sentences, the existing definition of *prep* won't do. The temporal relation between an event and its preparatory process can no longer be defined in terms of the initial subinterval where the event holds, because there are no such subintervals. So, how can we provide a semantic interpretation of the preparatory process of the event, given our new interpretation of this sort?

As in the Heterogeneous Strategy, we propose to define the process that leads to the culmination of an event and the consequent state that ensues in terms of the event itself. The temporal relations they encode are as follows: a preparatory process invariably precedes its culmination, which in turn invariably precedes the consequent state. The following connective captures this invariably precedes relation:

- $invpr(\phi, \psi) = L(\psi \rightarrow \langle\overline{A}\rangle\phi)$

Using this, we can re-define preparatory processes and culminations:

- $prep(\phi, \psi) = Process(\phi) \wedge Event(\psi) \wedge \phi \wedge invpr(\phi, \psi)$
- $cum(\phi, \psi) = Process(\phi) \wedge Event(\psi) \wedge \psi \wedge invpr(\psi, \phi)$

Note that $prep(\phi, \psi)$ doesn't entail that ψ occurs at any time, just as before. This captures the intuition that someone can be building a house, but never complete it. In contrast, $cum(\phi, \psi)$ entails that both the process ϕ and the event ψ occur. These are probably the strongest definitions of these concepts that are possible without bringing in intensional apparatus. We will shortly investigate the utility of bringing in intensional apparatus to refine the definitions, in the form of defaults. Suffice for now to say that the above definition of *prep* solves the imperfective paradox in the Homogeneous Strategy, using the existing definitions of the past tense and the progressive, and the same logical forms of the NL sentences.

Other flavours of the Moens and Steedman (1988) aspectual network can also be captured in this logic, for example, the inceptive reading of states:

- Inceptive States:
  $inc(\phi) = State(\phi) \wedge \langle A\rangle(\phi \wedge \neg \uparrow \phi)$

4.2.2 Adverbials and Connectives

We now show how to define the semantics of (15) using the apparatus we have built up.

(15) Max won the race in four minutes

We define the adverbial *in four minutes* as follows:

- $IN(4mins, \phi) =_{def} \phi \wedge \langle\overline{A}\rangle(FOR(4mins, prep(p, \phi)) \wedge \neg \uparrow p)$

So the logical form of (15) is (15′):

(15′) $P(i \wedge IN(4mins, \text{Max win the race}))$

In words, (15′) is true if at the time named by i which precedes now, there was a Max winning the race event, and the associated preparatory process, which occurs just before i, took exactly four minutes (and no more). So (15′) entails Max won the race, and that the length of the preparatory process was four minutes.

We define the temporal aspects of the connectives *while*, *before* and *after* as follows:[5]

- $after(\phi, \psi) =_{def} \phi \wedge F\psi$
- $before(\phi, \psi) =_{def} \phi \wedge P\psi$
- $while(\phi, \psi) =_{def} \phi \wedge \downarrow\uparrow \psi$

We have shown how sorting solves the Ontology Problem. We proposed two alternative ways in which sorting can do this: the Heterogeneous Strategy and the Homogeneous Strategy. Needless to say, there are other alternatives. This is an advantage of our approach. It supports a variety of strategies for NL temporal semantics, and so provides a forum in which the various proposals in the literature can be compared directly, in an elegant and well-understood logic.

5 Defaults

We have so far used only temporal machinery to define the semantics of temporal expressions. But clearly, there are intensional aspects to their semantic behaviour. We suggest here how the analysis we have proposed can be extended to handle the intensionality. We look at two cases: progressive sentences, and the behaviour of tense in text.

5.1 Preparatory Processes and the Progressive

Intuitively, a preparatory process of an event, say, *Max wins the race*, is going on now so long as, whatever that process is, if it were to continue uninterrupted, it would lead to the culmination of the event. Our analysis of preparatory processes does not capture this intuition, because it lacks the intensionality underlying it. Dowty (1979) used inertia worlds, which were inspired by Lewis' (1973) counterfactual worlds, to capture this relationship between a preparatory process and its culmination. Lascarides (1991) showed that there were technical difficulties in his definition. Here, we indicate how the intuition can be captured in our logic, by adding *defaults*.

The idea that a progressive of an event entails by default that the culmination occurs is not new. Asher (1992) argues persuasively in favour of this view. The idea is that if *Max is winning the race* is true now, then unless there is information to the contrary, we can conclude that he will eventually win the race. Or to put it another way, *Max is winning the race* by default entails *Max will win the race*.

[5] See Hamman (1987) and Lascarides and Oberlander (1993) for arguments as to why a purely temporal analysis of the connectives is inadequate when it comes to modelling their role in multi-sentence discourse.

We can add this default entailment between the progressive and non-progressive to our analysis, by adding a default conditional to the language, and adding to the model the elements that are necessary for defining its semantics. Let us assume that $\phi > \psi$ is to be read as: if ϕ, then normally ψ. And let us assume that the semantics of this conditional is defined so that it verifies Defeasible Modus Ponens ($\models\!\approx$ stands for "nonmonotonically entails"):

- **Defeasible Modus Ponens:** $\phi > \psi, \phi \models\!\approx \psi$
  If Tweety is a bird then normally Tweety flies, Tweety is a bird $\models\!\approx$ Tweety flies.
- **Defeat of Defeasible Modus Ponens:** $\phi > \psi, \phi \neg\psi \not\models\!\approx \psi$
  If Tweety is a bird then normally Tweety flies, Tweety is a bird, Tweety doesn't fly $\not\models\!\approx$ Tweety flies.

There are several candidate truth definitions for $>$ which fulfill this requirement; for example see Asher and Morreau (1991), Delgrande (1992), Boutilier (1992). The exact truth definitions don't concern us here. Rather, we just investigate the implications of adding a conditional $>$ that supports the above pattern of inference.

Using the default conditional, we fold the default nature of the progressive into our framework, by adding the following axioms: The first states that the progressive of an event ϕ by default entails the event ϕ actually holds at some point in the future.

- $Prog(prep(\psi, \phi)) > F\phi$

So far, our semantics of progressive sentences has guaranteed that wherever the event is true, the progressive is true just before. Now, the above axiom ensures a temporal relationship 'going the other way': wherever the progressive is true, the event is true eventually by default. The above analysis doesn't mean (11) entails (12), and so we haven't forfeited a solution to the Imperfective Paradox. Rather, (11) now entails (12) by default, in agreement with intuitions. And this default will interact straightforwardly with the Heterogeneous Strategy and the Homogeneous Strategy that we have used for defining ontology.

The second axiom states that by default the progressive modifies a process:

- $Prog(\phi) > Process(\phi)$

This to some extent accounts for the awkwardness of the progressives with states.

5.2 Tense in Text

We have offered a proposed analysis of iconic text in our extension of Shoham's logic, which mirrors the principles governing Partee's (1984) analysis. But as it stands, this analysis doesn't extend in a straightforward way to non-iconic text. Partee (1984) suggests that in order to account for non-iconic text, the analysis of narrative discourse must be enriched. It is well known that the temporal structure of a text isn't necessarily linguistically marked. Texts (16) and (17) have the same syntax, and yet their interpretations are different: the textual order of events mirrors temporal order in the former, whereas there is a mismatch of the textual and temporal orders in the latter.

(16) Max stood up. John greeted him.

(17) Max fell. John pushed him.

The different temporal structures underlying (16) and (17) stem from the reader's background knowledge concerning the typical causal relationships that occur when connecting the events together (Lascarides 1992).

Partee suggests adding a discourse parameter which, at the first stage of processing, does not receive a value. Because this discourse parameter determines the temporal relationship among the sentences, the temporal structure underlying the text is left undetermined at this stage. Subsequent stages of processing, which take into account the reader's background knowledge, will determine a value for this parameter, and this value in turn specifies the temporal relationship between the events described in the text.

Lascarides (1992) argued that the value of this parameter must be worked out via a nonmonotonic logic, and she gives a detailed account of how the DRT analysis of tense can be extended to handle the nonmonotonic inferences concerning temporal structure that are necessary, in order to model the role of the reader's background knowledge in interpretation. We don't repeat the details of this analysis here. Rather, we indicate that the logic we've presented provides a clean, precise framework in which the analysis can be rationally reconstructed, and so compared with other accounts of tense in text in a direct manner. The logical form of (16) is now (16′), where $r(i, j)$ in words means that there is some temporal relationship between i and j. This is essentially Partee's parameter for temporal structure.

(16) Max stood up. John greeted him.

(16′) $P(i \wedge \text{Max stand up}) \wedge P(j \wedge r(i, j) \wedge \text{John greet Max})$

We now reason about the value of the parameter via default rules. The pragmatic maxim that the textual order of events normally matches the temporal order is expressed in the following law, and exactly captures the intuitions that underly the law Narration in Lascarides (1992; 961), but in a much more succinct way.

- **Narration:** $r(i, j) > j \wedge Pi$

Narration states that if i and j are temporally related by r, then by default j is after i. This is a cleaner representation of the default law Narration in (Lascarides 1992), in that we don't have to define what the main eventuality of a sentence is; nor do we have to reason about update functions during text processing.

In the analysis of (16) it is assumed that this is the only default law whose antecedent is verified, and so by Defeasible Modus Ponens, its consequent is nonmonotonically inferred. Therefore, i is before j, and since i and j name respectively the intervals where *Max stand up* and *John greet Max* hold, the standing up precedes the greeting, in line with intuitions.

In the analysis of (17) it is assumed that a more specific default rule which captures the causal knowledge about pushings and fallings overrides Narration, and so different inferences about the temporal structure of (17) are achieved. The details of how this works are provided in Lascarides (1992). Suffice to say here that this analysis can be straightforwardly folded into the framework we've developed.

6 Conclusions

By applying sorting to Shoham's logic, we hope we've demonstrated that this logic provides a good base for the temporal part of natural language analysis. There were two definciences with Shoham's logic: its lack of ability to refer to times in the language, and the lack of machinery for expressing the rich multitude of temporal ontologies expressed in natural language temporal expressions. We solved the Reference Problem straightforwardly by sorting the language. Sorting was also used to measure time, and provide analysis of temporal adverbials that express duration, such as *for four minutes* and *in four minutes*. We showed how solving the Ontology Problem could be achieved, by a combination of sorting and additional operators in the language that express aktionsart classifications.

Finally, we proposed that adding default reasoning would have utility in capturing further intuitively compelling patterns of inference involving NL temporal expressions.

7 References

Allen, J. F. [1984] Towards a General Theory of Action and Time, *Artificial Intelligence*, **23**, 123–154.

Asher, N. [1992] A Default, Truth Conditional Semantics for the Progressive, *Linguistics and Philosophy*, **15** 5, pp463–508.

Asher, N. and Morreau, M. [1991] Common Sense Entailment: A Modal Theory of Non-monotonic Reasoning. *Proceedings of the 12th International Joint Conference on Artificial Intelligence*, Sydney Australia, August 1991.

van Benthem, J. [1991] *The Logic of Time*, 2nd edition, Kluwer, Dordrecht.

Blackburn, P. [1990] *Nominal Tense Logic and Other Sorted Intensional Frameworks*, PhD. thesis, Centre for Cognitive Science, University of Edinburgh.

Blackburn, P. [1992] Tense, Temporal Reference and Tense Logic, in Dekker, P. and Stokhof M. (eds) *Proceedings of the Eighth Amsterdam Colloquium*, Institute for Logic, Language and Computation, University of Amsterdam.

Blackburn, P. [1993] Nominal Tense Logic, *Notre Dame Journal of Formal Logic*, **34**, pp56–83.

Boutilier, C. [1992] *Conditional Logics for Default Reasoning and Belief Revision*, PhD Thesis, The University of British Columbia, Technical Report 92-1.

Comrie, B. [1985] *Tense*. Cambridge University Press

Delgrande, J. P. [1988] An Approach to Default Reasoning based on a fFrst-Order Conditional Logic: Revised Report, *Artificial Intelligence* **36** 1, 63–90.

Dowty, D. [1979] *Word Meaning and Montague Grammar*, D. Reidel, Dordrecht.

Eberle, K. and Kaspar, W. [1991] Tense, Aspect and Temporal Structure in French, in Kamp, H. (ed.) *Tense and Aspect in English and French*, DYANA deliverable 2.3b, available from Centre for Cognitive Science, University of Edinburgh.

Halpern, J. and Shoham, Y. [1986] A Propositional Modal Logic of Time Intervals, in *Proceedings of the First IEEE Symposium on Logic in Computer Science, Cambridge, Massachusetts*, Computer Society Press, Washington, pp279–292.

Hamman, C. [1987] English Temporal Clauses in a Reference Frame Model, in Schopf, A. (ed.) *Essays on Tensing in English*, Volume II: *Time, Text and Modality*, pp31–153.

Kamp, H. [1971], The Formal Properties of "now", *Theoria*, **37**, pp227–273.

Kamp, H. [1981] A Theory of Truth and Semantic Representation, in Groenendijk, J. A. G., Janssen, T. M. V. and Stokhof, M. B. J. (eds.) *Formal Methods in the Study of Language* **136**, 277–322. Amsterdam: Mathematical Centre. Tracts.

Kamp, H. [1991] The Perfect and Other Tenses in French and English, in Kamp, H. (ed.), *Tense and Aspect In English and French*, DYANA deliverable 2.3B, available from the Centre for Cognitive Science, University of Edinburgh.

Kaplan, D. [1979], On the Logic of Demonstratives, in Peter A French, Theodore E Uehling Jr., Howard K Wettstein (eds.) *Contemporary Perspectives in the Philosophy of Language* University of Minnesota Press, Minneapolis, pp401–412.

Lascarides, A. [1988] *A Formal Semantic Analysis of the Progressive*, PhD. thesis, Centre for Cognitive Science, University of Edinburgh.

Lascarides, A. [1991] The Progressive and the Imperfective Paradox, *Synthese*, **87**, pp401–447.

Lascarides, A. [1992] Knowledge, Causality and Temporal Representation, *Linguistics*, **30**, pp941–973.

Lascarides, A. and Oberlander, J. [1993] Temporal Connectives in a Discourse Context, in *Proceedings of the Sixth European Chapter of the Association of Computational Linguistics*, pp260–269, Utrecht, Holland, April 1993.

Lewis, D. [1973] *Counterfactuals*, Blackwells, Oxford England.

Moens, M. and Steedman, M. [1988] Temporal Ontology and Temporal Reference, *Computational Linguistics*, **14**, pp15–28.

Montague, R. [1970] Universal Grammar, *Theoria*, **36**, pp379–398.

Nakhimovsky, A. [1988] Aspect Aspectual Class, and the Temporal Structure of Narrative, *Computational Linguistics*, **14** 2, pp29–43.

Partee, B. [1973] Some Structural Analogies between Tenses and Pronouns in English, *Journal of Philosophy*, **70**, pp601–609.

Partee, B. [1984] Nominal and Temporal Anaphora, *Linguistics and Philosophy*, **7**, pp243–286.

Prior, A. N. [1967], *Past, Present and Future*, Clarendon Press.

Reichenbach, H. [1947] *Elements of Symbolic Logic*. London: Macmillan.

Shoham, Y. [1988] *Reasoning About Change: Time and Causation frmo the Standpoint of Artificial Intelligence*, MIT press, Cambridge Mass.

Taylor, B. [1985] *Modes of Occurrence: Verbs, Adverbs and Events*, Blackwell, Oxford.

Vendler, Z. [1967] Verbs and Times, *Linguistics and Philosophy*, pp97–121.

Venema, Y. [1990] Expressiveness and Completeness of an Interval Tense Logic, *Notre Dame Journal of Formal Logic*, **31**, pp529–547.