Dynamic Semantics for Tense and Aspect

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Abstract

A semantics for tense, modality, and aspect in natural language must capture causal and contingent relations between events and states as welt as merely temporal ones The paper investigates a non-reified dynamic logic based, formulation of the situation calculus is a formalism for a computational semantics for *a.* number of temporal categories in English and suggests that some recent claims that dynamic logics are inherently unsuitable for this purpose have taken too narrow a view of the situation calculi

1 Temporal Ontology

The most important thing to observe about the temporal ontology implicit in natural language tense and aspect is that it IR not purely temporal To take a simple example the English perfect when predicated of an event like *losing a watch* says that some contextually retrievable *consequences* of the event in question hold at the time under discussion (Such consequences have sometimes been described under the heading of ""present relevance of the perfect) As a result, conjoining such a perfect with a further clause denying those consequences is infelicitous

(1) I have lost my watch (# but 1 have found it again)

In this respect the perfect stands in contrast to the more purely temporal tenses, such as the past, which make no comparable claim about the consequences of the core event

(2) Yesterday I lost my watrh (but 1 (have) found it again)

It is because categories like the perfect are not purely temporal that it is usual to distinguish them from the tenses proper as ' aspects Another aspect whose meaning is not purelv temporal is the progressive or Imperfective The predication that it makes concerning the core event is a subtle one While the progressive clearly states that *some* event is ongoing at the time under discussion it is not necessarily the event that is actuallv mentioned Thus in a helow there seems to be a factive entailment about an event of writing But in b, there 18 no such entailment concerning an event of writing a sonnet, for b is true even if the author was interrupted before he could complete the action

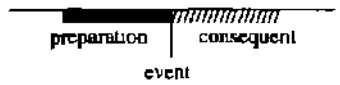

Figure 1 The nucleus

(3) a Keats was writing $\models$ Keats wrote
b Keats was writing a sonnet $\not\models$ Keats wrote a son

Dowty [1979] named this rather surprising property of the progressive the imperfective paradox The imper fective paradox is a sign that we must distinguish various types or sorts of core event in natural language tempo ral ontology This system, which is described at greater length in [Steedman in press.], is briefly summarised as follows

There are two key insights into this system which most theories either build upon or are forced to reinvent I he first concerns the temporal ontolog) itself and is usually attributed to Vendler [1967] though there are precedents in work by Jespersen Kenny and many earlier author itjes including Aristotle Vendler s taxonom) was importantly refined bv \erkuyl and Dowty, and has been further extended by manv others Such taxonomies typically distinguish 'states from events' and divide the latter into a number of wrts or types \endler dislin guished 'activities , (events which have duration but don t change state like *heat* writing),* achievements (events which have no duration but do chang* stat< like *h eats amvmg),* and accomplishments (which hav* duration and change state like *heats writing a sonnet)* Many authors have proposed *recursive* sort hierarchies Moens [1987, 1988] explained the aspectual sort hierarchy and possible coercions among *Akiionsaricn* m terms of a structure of the kind represented schematically in figure 1, representing an association in memory or the knowledge representation of all events with characteristic *preparations* and *consequents,* an idea that has 6ince been adopted in DR. Theory (Kamp and Reyle, [1993, p 557-570] Moens claimed Lhat the preparation is in Vendler's terms an activity, the consequent is a (perfect) state, and that the core event is an achievement Ihere is a great deal more to say about the status of these categories, but we will take it as read here, noting merely that we Bhall follow these authors m assuming that accomplishments like *writing a sonnet* are composites of an activity of *writing* and a culminating achievement of

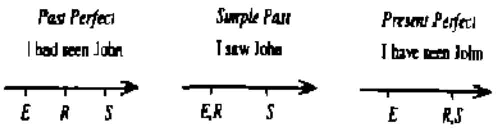

Figure 2 Past vs Perfect (from Reichenbach 1947)

finishing the sonnet

The second key insight concerns *relations among* temporal entities, and is due to Reichenbach ([1947, Chapter VII, sections 48 and 51]) who sketched a semantics for tense in terms of three underlying abstract time-points (Again there are precedents, notably in work by Jespersen) Reichenbach's real innovation was the notion of the reference point, which can be identified with the notion 'the time (or situation, or context) that we are talking about' It is easiest to convey the idea by example Reichenbach offers the diagrams in Figure 2, in which the arrow indicates the flow of time to show the distinctions between the past perfect the simple past (or preterit) and the present perfect (all of which he includes under the heading of 'tenses of verbs') The important insight here is that the simple past is used to make a statement about a past time whereas the perfect is used to make a statement about the present as was noted earlier in connection with the 'present relevance' property of examples like 1 Besides the authors already cited this system has also been extended importantly by Hornstein [1990]

Reichenbach's claim is consistent with the observation that past tense unlike the perfect demands that the past *reference point be explicitly established*, either by a modifier, such as a *when* clause or by the preceding discourse Thus a below is inappropriate as the first utterance of a discourse except to the extent that the reader *accomodates* a temporal referent in Lewis and Stalnaker's sense of that term – that is *introduces* an appropriate individual in the database as one often must at the beginning of a modern novel B is appropriate on the assumption that the hearer can identify the time in the *when* clause

(4) a #Chapman breathed a sigh of relief
  b When Nixon was elected Chapman breathed a sigh of relief

(In many North American dialects of English the past tense does double duty for the perfect I am assuming that this reading is excluded in this case by the most readily accessible aspectual category of *breathing a sigh of relief*)

The fact that the discourse can establish the "anchor for the reference point has led a number of authors including Partee [1973], Isard [1974] Webber [?] and others to identify tense and by implication R as "pronominal" or otherwise anaphoric in character

2 Temporal Relations and the Situation Calculus

One of the most useful and attractive features of the situation calculus of McCarthy and Hayes [1969] was the use of terms like $result(arrive(person), s)$ as individuals denoting situations or states as functions of other situations (Functions like *result* are known as situational *fluents* In the present paper we will reserve the term fluent for this particular kind) Such terms can be used in rules like the following to transparently capture the notion that a person is present in the situation that results from their arriving

(5) $\forall s\ \forall person\ present(person, result(arrive(person), s))$

The STRIPS representation of actions and the associated solution to McCarthy and Hayes frame problem was originally thought of in procedural terms However, Kowalski [1979] (circulated in 1974) showed it to be elegantly realisable in entirely declarative terms via the introduction of a closed world assumption and a more radical use of reification to simulate modal quantification (See Nilsson [1980 p 308-316] for discussion) Related techniques and their relation to ramification and qualification are further explored by by Schubert [1990, 199?] and Reiter [1991, 1993]

Kowalski proposed a predicate *holds*, which applies to a proposition represented as a term and a state In this notation a minimal blocks world can be defined A starting state including three clear blocks is defined as follows

(6) $holds(clear(a), s_0) \wedge holds(clear(b), s_0) \wedge holds(clear(c), s_0)$

The action of putting x on y can be represented as a STRIPS rule as follows The preconditions are defined by the following rule which says that if you can get at x and you can get at y, the preconditions for putting x on y hold

(7) $holds(clear(x), s) \wedge holds(clear(y), s) \wedge (x \neq y) \rightarrow preconditions(puton(x, y), s)$

(In this rule and henceforth, we adopt a convention whereby universal quantification over bound variables is left implicit) The new facts that result from the action of putting x on y can be defined as follows

(8) a $holds(on(x, z), s) \rightarrow holds(clear(z), result(puton(x, y), s))$
  b $holds(on(x, y), result(puton(x, y), s))$

Since we are assuming negation as failure, we do not need to state explicitly that y is no longer clear This fact is implicit in the following frame axiom which is the *only* frame axiom we need for the action of putting x on y It says that any fact which holds in s holds in the result of putting x on y in s *except* the fact that y is clear and the fact that x was on something else z (if it was)

(9) $holds(p, s) \wedge (p \neq clear(y)) \wedge (p \neq on(x, z)) \rightarrow holds(p, result(puton(x, y), s))$

(The use of inequality rather than implication here embodies a Horn-like assumption restricting p to terms in these rules) Kowalski's proposal was followed by much work on tense using reified calculi (Allen [1984] McDermott [1982] Kowalski and Sergot [1986]) It was also closely related to the notion of "circumscription of qualifications" – see McCarthy [1977, esp p 1040), and much other subsequent work collected and reviewed in Ginsberg [1987] In particular Reiter [1991] shows how the restricted frame axioms or successor state axioms can be derived automatically

We can now define a predicate *possible* closely related to the (deontic) modal operator $\Diamond$, over the set of possible states, via the following rules which say that the start state s_0 is possible and the result of an action in a state is possible if its preconditions hold

(10) a $possible(s_0)$
b $possible(s) \wedge preconditions(action, s) \rightarrow possible(result(action, s))$

The earlier goal of stacking a on b on c can now be realised as the goal of finding a constructive proof for the following conjunction

(11) $possible(s) \wedge holds(on(a, b), s) \wedge holds(on(b, c), s)$

These rules can be very straightforwardly realised in Prolog and can be made to yield a proof (although the search problem of finding such proofs automatically remains hard in general), in which

(12) $s = result(puton(a, b), result(puton(b, c), s_0))$

This technique restores declarativity to the logic embodying the STRIPS solution There is a sense in which – despite the involvement of the closed world assumption – it also restores monotonicity, for so long as we do not add new facts (like some previously unsuspected object being present, or a familiar one having fallen off its support) or some new rule or frame axiom (say defining a new action or stating a new precondition on an old one) then we can regard negation-as-failure as merely efficiently encoding classical negation

Of course in the real world we *do* learn new facts and rules, and we encounter exceptions to the closed world assumption of complete knowledge These problems are known in AI as the *ramification problem* (that is, that actions may have indefinitely many unforeseen consequences that our default model does not and cannot predict) and the *qualification problem* (that actions may have indefinitely many preconditions that our default model does not and cannot anticipate) In many recent papers the frame problem is assumed to include these further problems However, if we are in possession of an efficient default model which works reasonably well most of the time, it may well be wiser to regard the problem of coping with its failures as residing outside the logic itself, in the truth maintenance or 'housekeeping' system Rather than a nonmonotonic *logic*, we could think in terms of a system of truth-maintaining transitions *between* entirely monotonic logics, a view that has been proposed by Kowalski

However, there is another way of looking at all of these variants of the situation calculus To the extent that the accessibility relation is defined in terms of a number of different events or causal primitives, possibly a large number it is possible to regard each of these as defining its own distinct accessibility relation, possibly differing from others in properties like transitivity Such systems can then be viewed as instances of the "dynamic" logics that were developed in the first place for reasoning about computer programs – see Pratt [1976], Harel [1984], and Goldblatt [1992] The application of various forms of dynamic logic in knowledge representation and natural language semantics has been advocated by Moore [1980], Rosenschein [1981] Webber [1983], Pednault [1989], and Scherl and Levesque [1993]

Dynamic logics relativise the modal operators to individual actions, events or programs For example if a (possibly nondeterministic) program or command α computes a function F over the integers, then we may write the following

(13) $n \geq 0 \rightarrow [\alpha](y = F(n))$

(14) $n \geq 0 \rightarrow \langle\alpha\rangle(y = F(n))$

The intended meaning of the first of these is for $n \geq 0$, after every execution of α that terminates, $y = F(n)$ That of the second is (dually) that there is an execution of α which terminates with $y = F(n)$

While all of the calculi that we have considered so far are ones in which the elementary programs α are *deterministic* dynamic logics offer a framework which readily generalises to concurrent and probabilistic events offering a notation in which all of the theories discussed here can be compared

The particular dynamic logic that we are dealing with here is one that includes the following dynamic axiom (the operator ; is *sequence* an operation related to composition and to von Wright's T)

(15) $[\alpha][\beta]P \rightarrow [\alpha ; \beta]P$

In this we follow Moore [1980, ch 3] and Rosenschein [1981] The situation calculus and its many variants can be seen as reified versions of this dynamic logic

We achieve an immediate gain in perspicuity by replacing the reified notation in a below by the equivalent dynamic expression b

(16) a $holds((on(a, b) \wedge on(b, c)), result(puton(a, b), result(puton(b, c), s_0)))$
b $[puton(b, c); puton(a, b)](on(a, b) \wedge on(b, c))$

Kowalski's "vivid" version of STRIPS can be very simply represented in this logic The initial state of the world is as follows

(17) $clear(a) \wedge clear(b) \wedge clear(c)$

The axiom defining the preconditions of $puton(x, y)$ is now directly definable in terms of the predicate *possible*, which can now be identified with deontic modal possibility

(18) $\models (clear(x) \wedge clear(y) \wedge x \neq y) \rightarrow possible(puton(x, y))$

The consequences of $puton(x, y)$ are now written as follows

(19) a $\models on(x, z) \rightarrow [puton(x, y)]clear(z)$
b $\models [puton(x, y)]on(x, y)$

The frame axiom is written as follows

(20) $\models (p \wedge p \neq clear(y) \wedge p \neq on(x, z)) \rightarrow [puton(x, y)]p$

The transitive part of the possibility relation is now reduced to the following

(21) $\models (possible(\alpha) \wedge [\alpha]possible(\beta)) \rightarrow possible(\alpha ; \beta)$

This fragment preserves the virtues of Kowalski's treatment in a modal notation That is, the following conjunctive goal can, given a search control be made to deliver a constructive proof that $\alpha = puton(b, c), puton(a, b)$

(22) $possible(\alpha) \wedge [\alpha](on(a, b) \wedge on(b, c))$

The suppression of state variables in dynamic logic affords some improvement in perspicuity over the otherwise equivalent previous proposals of Kowalski, McCarthy, Schubert, and Reiter that it is here used to capture, and makes it easier to extend the calculus.

The above example only concerns non-composite or non-durative events, like the original situation calculus. However, the following dynamic Horn clauses begin to capture the composite events discussed earlier, along the lines suggested by Steedman [1982], Moens [1987] and White [1994]. (The example is greatly simplified and omits many rules needed to capture even this small domain completely.) First we need axioms defining the consequent and preconditions for *starting* and *stopping*. (The latter consequent is trivial under the closed world assumption.)

(23) a. $\models [start(p)]in\_progress(p)$
  b. $\models not(in\_progress(p)) \rightarrow possible(start(p))$

(24) $\models in\_progress(p) \rightarrow possible(stop(p))$

We also need a frame axiom for *stopping* (which could be derived as in Reiter [1991]):

(25) $\models p \wedge (p \neq in\_progress(q)) \rightarrow [stop(q)]p$

Finally we need a definition of the progressive, coercing achievements to accomplishments and accomplishments to preparatory activities. (Note that in b below, we assume, in line with the discussion in section 2.1, that accomplishments are made up of an activity and a culminating achievement. These sorts are here represented as terms in lieu of a proper system of sorts.)

(26) a. $\models in\_progress(act) \rightarrow progressive(activity(act))$
  b. $\models progressive(activity(act)) \rightarrow progressive(accomplishment(activity(act), achievement(ach)))$
  c. $\models preparation(achievement(ach), activity(act)) \wedge progressive(accomplishment(activity(act), achievement(ach))) \rightarrow progressive(achievement(ach))$

The following query asks (slightly artificially) for a plan α yielding a state where Keats is finishing writing the sonnet *In Disgust of Vulgar Superstition*:

(27) $possible(\alpha) \wedge [\alpha]progressive(achievement(finish(write(keats, in\_disgust))))$?

(The function *finish* maps an accomplishment onto its culminating achievement, and is distinct from *stop*, the endpoint of an activity.) To find the plan, we must assume that the knowledge base also makes explicit the relation between *finishing* an activity and its characteristic preparation, the activity itself, implicit in the nucleus of figure 1:

(28) $\models preparation(achievement(finish(e)), activity(e))$

The accessibility relation implicit in definition 21 now gives rise to a proof where

(29) $\alpha = start(write(keats, in\_disgust))$

The proof that generates this plan does not involve the subgoal of showing $[\alpha]finish(write(keats, in\_disgust))$. Indeed the proof would be quite consistent with adding the denial of that fact, because the variable *ach* in rule 26 is not involved in the antecedent, capturing the imperfective paradox.

Of course, asking for a plan to bring about a situation in which Keats is finishing writing *In Disgust of Vulgar Superstition* is slightly artificial, because such states are extensive, and there may be several such plans. For example, consider the effect of adding the following rule defining the consequences and preconditions of arriving:

(30) a. $\models [arrive(x)]present(x)$
  b. $\models not(present(x)) \rightarrow possible(arrive(x))$

The accessibility relation 21 now allows

(31) $\alpha = start(write(keats, in\_disgust)); arrive(x)$
  $\alpha = start(write(keats, in\_disgust)); arrive(x); arrive(y)$, etc.

As plans, these are rather foolish, because of well-known inherent limitations in the simplest STRIPS planners, although incorrect plans such as the following are still correctly excluded for the goal in question:

(32) $\alpha = start(write(keats, in\_disgust)); arrive(x); stop(write(keats, in\_disgust))$

Part of the problem is that we are not yet distinguishing true consequences of fluents, including causal relations among fluents themselves, from facts that are merely coincidentally true in the state that results, because of the inertial property of the frame axiom. Nor are we distinguishing causal relations *between* fluents from mere temporal sequence.

We can remedy this shortcoming by distinguishing the temporal sequence operator, from a causal or contingent sequential operator, which we will write as @, because of its relation to one of Lansky's [1986] operators. Accordingly, we need to add some further rules parallel to 21 reflecting deontic modal causality, including the following:

(33) $\models possible(\alpha) \wedge [\alpha]causes(\beta) \rightarrow possible(\alpha @ \beta)$

We now add a rule saying that anyone else being present causes Keats to stop writing:

(34) $\models present(x) \wedge (x \neq keats) \wedge in\_progress(write(keats, y)) \rightarrow causes(stop(write(keats, y)))$

We can now search for plans which make an event of Keats stopping writing necessarily occur, like a below, as distinct from those that merely make it possible, like b, by constructively searching for a proof that $possible(\alpha @ stop(write(keats, y)))$:

(35) a. $\alpha = start(write(keats, y)); arrive(x)$
  b. $\alpha = start(write(keats, y))$

Again the examples are artificial, their usefulness for an account of tense and temporal anaphora will become apparent in the next section.

3 Temporal Anaphora

The event-based calculus over counterfactual partially specified states discussed in the previous section offers a promising candidate for a representation of Reichenbach's reference point *R*, in the form of deterministic situational fluents [α]. This opens up the possibility of applying the general modal apparatus developed so far not only for quantifying over states but to act as the temporal link between sentences and clauses, as in *when*-clau^es and multi-sentence discourse Several logical and computational approaches have explored this possibility

Temporal anaphora like all discourse anaphora and reference resolution is even more intimately dependent upon world knowledge than the other temporal categories lhat we have been considering In order to control this influence, WP will follow the style of much work in AI drawing moat of our examples from a restricted domain of discourse We will follow Isard [1974] in taking a hoard game as the example domain Imagine that each model in a modal structure is represented as a database, or collection of facts describing not only the position of 1he pieces in a game of chess, and the instantaneous moves at each frame, but the fact that at certain times durative or composite events like *exchanging Rooks* or *White attacking the Black Queen* are in progress across more than one state

Consider the following examples from such a domain

(36) a When I took your pawn you took my queen
b 1 took your pawn You look my queen

The UfAen-clause in a, above establishes a reference point for the tense of the main clause, just as the definite NP *J\ eats* establishes a referent for the pronoun Indeed the TwAcn-clauBe itself behaves like a definite, in that it seems to presuppose that (he event of *my taking your pawn* is identifiable lo the hearer (Of course, the reader will have effortlessly *accommodated* this presupposition in Lewis and Stalnaker s sense of the term) The first sentence in b, above, behaves exaclJv like the *when* clause in setting the reference point for the second I he onl> difference is that the simple declarative / *took your pawn* itself demands a previously established reference point to be anaphoric to, whereas the *when* clause causes a new reference point to be constructed

As has been frequentl) noticed, the state to which the tense in *you taking my queen* refers in a, above, is not strictly the state in which / *took your pawn* It is the slate that *resulted from* that action However, it is not invariably the case that the temporal reference point moves on in this way Most obviously a stative main clause is primarily predicated of the original reference point of the *wht*n-clause

(37) When I took your pawn T did not know it was protected by your knight

(Presumably, the ignorance in question maj have ended with that very move) Events also may be predicated of the original reference point rather than moving the action on

(38) When I took your pawn, I used a. rook

In fact, as Ritchie [1979], Partee [1984], Moens and Steedman [1988], and Kamp and Reyle [1993] have pointed out, in strictly temporal terms, we can find main clauses that *precede* the reference point established by a *when* clause

(39) When I won my only game against Bobby Fischer, we played Australian Rules

These phenomena arise because the temporal referent is *not* strictly temporal Rather than being a time or an interval it is (a pointer to) an event-nucleus of the kind discussed earlier

In the terms of our modal frame, the preparation of an event is the activity or action that led to the state in which that achievement took place The consequent is the consequent state, and includes the entire subtree of states accessible from that state The referent-setting effect of a *when*-clause can then be seen as identifying such a nucleus The main clause is then temporally located with respect to the nucleus This may be by lining it up with the core event itself either as a property of the initial state, as in example 37, or as a property of the transition itself as in 38 Alternatively, since accessibility is defined in terms of the subsequent actions the actual subsequent action is a possible main clause as in 36 Or the main clause may be located with respect to the preparation, as in 39 Which of these alternatives a given example gives rise to is a matter determined by the knowledge representation not by rules of the semantics

On the assumption that the consequent in the nuclear referent includes the entire subtree of future states the information needed by conditionals modals, and other referent-setting adverbials will be available

(40) a If you take my queen, you may win
b If you had taken my queen, you might have won
c Since you took my queen, you have been winning

All of this suggests that states or partial possible worlds in a logic of action deriving ultimately from von Wright and McCarthy and Hayes, with a much enriched ontology involving a rather intimate connection to the knowledge-base are appropriate candidates for a Reichenbachian anaphoric account of tense and temporality But this does not tell us how the temporal referent is set up to act as a referent for anaphora

In the dynamic situation calculus, the history of events is a sequence of fluents such as the following

(41) $start(write(keats\ in\_disgust))\ arrive(chapman)$
$@stop(write(keats\ in\_disgust)$

The referent of a *when*-clause such as *When Chapman arrived* is simply the sequence up to and including $arrive(chapman)$, namely

(42) $start(write(keats, in\_disgust))\ arrive(chapman)$

To identify the referent we need the following definition of a relation we might call *evoke* This is merely a logic-programming device which defines a search for a deterministic situational fluent of the form α, β or $\alpha @ \beta$ over a history in which the sequence operators are "left-associative" (we only give the rules for the operator , here)

(43) a $\models evoke((\alpha, \beta), (\alpha, \beta))$
b $\models evoke((\alpha\ \beta)\ \gamma) \rightarrow evoke((\alpha, \beta), (\gamma\ \delta))$

The referent setting effect of *when* can then be captured to a first approximation in the following rules which first find the current history of events, then *evoke* a suitable reference point, then test for the appropriate relation *when* (Again this is a logic programming hack which could be passed over, and again there are two further rules with @ for , that are omitted here)

(44) a $\models S(history)\ evoke((\alpha\ \beta), history)\ [\alpha,\beta]p$
$\rightarrow when(\beta, state(p))$
b $\models S(history), evoke((\alpha, \beta@\epsilon), history)$
$\rightarrow when(\beta, event(\epsilon))$

The predicate S determines the Reichenbachian speech point, which is a fluent or sequence of fluents $S(history)$ is assumed to be available in the database, as a fact The first rule, a, applies to *when* sentences with state-type main clause propositions, and says that $when(\beta, state(p))$ is true if you can *evoke* a fluent ending in β after which p holds The second applies to *when* sentences with event-type main clauses, and says that $when(\beta, event(\epsilon))$ is true if you can *evoke* a fluent whose last two events are β and then ϵ The question a, below concerning the ensuing state therefore translates into the query b

(45) a When Chapman arrived was Keats finishing writing *In Disgust of Vulgar Superstition*?
b *when((α arrive(chapman)) state(progressive (achievement(finish(write(keats in_disgust))))))*

In our greatly simplified world this is true despite the fact that under the closed world assumption Keats did not finish the poem, because of the earlier elimination of the imperfective paradox

A *when*-question with an event in the main clause as in a below translates as in b

(46) a When Chapman arrived did Keats stop writing *In Disgust of Vulgar Superstition*?
b *when((α arrive(chapman)) event(stop(write(keats in_disgust)))*)

In the case to hand, this last will yield a proof with the following constructive instantiation

(47) *when((start(write(keats in_disgust)) arrive(chapman)) event(stop(write(keats in_disgust))))*

In either case, the enduring availability of the Reichenbachian reference point for later simple tensed sentences can be captured on the assumption that the act of *evoking* a new referent causes a sideffect to the database causing a new fact (say of the form $R(\alpha)$) to be asserted, after any existing fact of the same form has been removed, or retracted (We pass over the formal details here, merely noting that for this purpose a blatantly non-declarative STRIPS-like formulation seems to be the natural one although we have seen how such non-declarativity can be eliminated from the system)

The representation also captures the fact that Keats stopped writing the poem *because* Chapman arrived whereas Chapman merely arrived *after* Keats started writing, not because of it

Of course, it will be clear from the earlier discussion that such a system remains oversimplified Such examples also suggest that the fluents themselves should be considerably enriched on lines hinted at in earlier sections They need a system of types or sorts of the kind discussed in section 1 They should also be structured into *nested* structures of causal or, more generally, contingent sequences

Since we have also observed that main clause events may be simultaneous with, as well as consequent upon, the *when* clause event, fluents must also be permitted to be simultaneous, perhaps using the connective ∩ introduced by Peleg [1987] to capture the relation between embedded events like *starting to write "In Disgust of Vulgar Superstition"* and *starting to write*, generalising the above rules accordingly Partial ordering of fluents must also be allowed The inferential possibilities implicit in the notion of the nucleus must be accommodated, in order to capture the fact that one event may cause the preparation of another event to start, thereby embodying a non-immediate causal effect

Very little of this work has been done, and it may be unwise to speculate in advance of concrete solutions to the many real problems that remain However the limited fragment outlined above suggests that dynamic logic may be a promising framework in which to pursue this further work and bring together a number of earlier approaches In this connection, it is perhaps worth remarking that of the seven putative limitations of the situation calculus and its relatives claimed in the critical review by Shoham and Goyal [1988b p 422-424] five (limitation to instantaneous events, difficulty of representing non-immediate causal effects ditto of concurrent events ditto of continuous processes, and the frame problem) either have been overcome or have been addressed to some extent in the published work within the situation calculus, while the remaining two (the qualification problem and the ramification problem) have not been overcome in *any* framework, possibly because they do not belong in the logic at all

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