SITUATION CALCULUS WITH CONCURRENT EVENTS AND NARRATIVE

John McCarthy, Stanford University

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Abstract

Concurrent events are treated merely by not forbidding them. Narrative is treated as a collection of situations and events and relations among them. Narrative is easier than planning, because it does not require that the effects of events be guaranteed. Prediction is harder than planning, because it requires that the actions be inferred from the motives of the actors.

1 Introduction—Objectives of Situation Calculus

The logic approach to AI ([McCarthy, 1959] and [McCarthy, 1989]) is to make a computer program that represents what it knows about the world in general, what it knows about the situation it is in, and also its goals all as sentences in some mathematical logical language. It then infers logically what action is appropriate for achieving its goal and does it. Since 1980 it has been widely known that nonmonotonic inference must be included. The actions it can perform include some that generate sentences by other means than logical inference, e.g. by observation of the world or by the use of special purpose non-logical problem solvers.

Simpler behaviors, e.g. actions controlled by servomechanisms or reflexes can be integrated with logic. The actions decided on by logic can include adjusting the parameters of ongoing reflexive actions. Thus a person can decide to walk faster when he reasons that otherwise he will be late, but this does not require that reason control each step of the walking. [1]

Situation calculus is an aspect of the logic approach to AI. A situation is a snapshot of the world at some instant. Situations are *rich* objects in that it is not possible to completely describe a situation, only to say some things about it. From facts about situations and general laws about the effects of actions and other events, it is possible to infer something about future situations. Situation calculus was first discussed in [McCarthy, 1963], but [McCarthy and Hayes, 1969] was the first widely read paper about it.

In this formalization of action in situation calculus, we treat three kinds of problem—*narrative*, *planning* and *prediction*.

Of these, narrative seems to be the simplest. A narrative is an account of what happened. We treat it by giving some situations and some events and some facts about them and their relations. Situations in a narrative are partially ordered in time. The real situations are totally ordered, but the narrative does not include full information about this ordering. Thus the temporal relations between situations in different places need only be described to the extent needed to describe their interactions.

In situation calculus as it was originally envisaged and has been used, events (mainly actions) in a situation produce next situations, e.g. $s' = result(e, s)$. The original theory did not envisage more than one event occurring in a situation, and it did not envisage intermediate situations in which events occur. However, rarely did people write axioms that forbade these possibilities; it's just that no-one took advantage of them. [2]

Our present formalism doesn't really change the basic formalism of the situation calculus much; it just takes advantage of the fact that the original formalism allows treating concurrent events even though concurrent events were not originally supposed to be treatable in that

[1]Thus I protect my flank from the disciples of Rod Brooks.

[2]Reiter and Lifschitz did write such axioms.

formalism. Gelfond, Lifschitz and Rabinov [**?**] treat concurrent events in a different way from what we propose here.

In a narrative, it is not necessary that what is said to hold in a situation be a logical consequence (even nonmonotonically) of what was said to hold about a previous situation and known common sense facts about the effects of events. In the first place, in stories new facts about situations are often added, e.g. "When Benjamin Franklin arrived in London it was raining". In the second place, we can have an event like tossing a coin in which neither outcome has even a nonmonotonic preference.

Nevertheless, some narratives are anomalous. If we record that Junior flew to Moscow, and, in the next situation mentioned, assert that he is in Peking, a reader will feel that something has been left out, some Gricean implicature [Grice, 1989] has been violated. We want to introduce a concept of a *proper narrative*, but it isn't clear exactly what it should be. The fluents holding in a new situation should be reasonable outcomes of the events that have been reported, except for those fluents which are newly asserted, e.g. that it was raining in London when Franklin arrived. Perhaps the assertions that do not follow from previous events should sometimes be tagged as such. The word "but" does this in ordinary language, so maybe we want a *but* construction. Of course, "but" is used in discourses that are not narratives.

In interpreting the following formalizations, we regard situations as rich objects and events as poor. In fact, we are inclined to take a deterministic view within any single narrative. In principle, every event that occurs in a situation and every fact about following situations is an inevitable consequence of the facts about the situation. Thus it is a fact about a situation that a coin is tossed and that it comes up tails. However, such facts are only occasionally consequences of the facts about the situation that are actually stated in the narrative.

Perhaps narrative seems easy, since it is not yet clear what facts must be included in a narrative and what assertions should be inferrable from a narrative.

2 Nonmonotonic Reasoning from Narratives

This section is informal, because we want to discuss what the consequences of a narrative should be before discussing how to make circumscription or some other nonmonotonic formalism do what we want. Here are some kinds of inference we want to be able to make.

Preconditions An action has only those preconditions that can be inferred from the facts at hand.

Ramifications Only the effects of an event that can be inferred from the narrative are relevant to the future course of the events mentioned in the narrative.

Presence of objects The only objects satisfying certain fluents in a situation are those for which it follows from what is stated. Some of the "it follows" assertions are inferred nonmonotonically. One child will infer that another child has parents but not that the child has a dog.

Normal effect An event has its normal effect unless something prevents it.

Occurrences Only such events occur in a situation or its successors as are asserted or inferred or which don't affect conclusions that might be drawn from their nonoccurrence.

This condition must be formalized very carefully, as is apparent when we elaborate a particular event as a sequence of smaller events. "How did he buy the Kleenex? He took it off the shelf, put it on the counter, paid the clerk and took it home." A narrative that just mentions buying the Kleenex should not allow nonmonotonic reasoning that excludes this particular elaboration. Moreover, if we elaborate in this way, we don't want to exclude subsequent elaboration of component events, e.g. elaborating paying the clerk into offering a bill, taking the change, etc.

Inertia Events change only those fluents they can be inferred to change. Fluents or fluent valued functions may be declared to be dependent by statements like

$$dependent(distance). \tag{1}$$

This statement would have the effect of making

$$distance(x, y)$$

change with changes in x and y and have no inertia of its own.

Processes that have started in a situation continue until something changes their course or they terminate as called for in their axiomatizations.

Obstacles Only such obstacles arise to events having their normal effects as can be inferred.

Actions Minimize unmotivated actions.

We will very likely use something like the Reiter and Levesque technique of a two stage minimization. (Reiter's Research Excellence lecture and subsequent discussions.) (Advice to use this technique may serve as an example of the declarative expression of heuristics.)

3 Glasgow, London, Moscow and New York Narratives

The object of this section is to give narratives illustrating the treatment of concurrent events in two cases. The first is when two sub-narratives do not interact, and the second is when they do. The first sub-narrative is ordinary block stacking (as discussed in many situation calculus papers), and we suppose the stacking to be done by a person called Daddy in New York. In the second sub-narrative, the actor is named Junior, and he wants to fly from Glasgow to Moscow via London. The story is taken from an earlier unpublished but widely circulated manuscript [McCarthy, 1992] discussing how circumscription could be used to treat an unexpected obstacle to a plan. In this case, Junior may or may not lose his ticket in London. The change is made by adding a single sentence to the facts. Without that sentence, one can conclude that flying to London and then to Moscow will get Junior to Moscow. With it he must buy another ticket in London, i.e. we can no longer conclude that the original sequence of actions will work, but we can conclude that the revised sequence that includes buying a ticket in London will work.

Because we want to treat interacting events, we make life more complicated for Junior. If he loses his ticket, he must wire Daddy in

New York for money. Daddy, who normally indulges Junior, has to interrupt his block stacking and sell a block in order to get the money to send Junior.

Narrative 1

In this narrative Junior doesn't lose his ticket and gets to Moscow without asking for help. Daddy stacks blocks in New York. There is no interaction, and nothing is said about the time relations between the two sub-narratives.

$$holds(at(Junior, Glasgow), S0) \tag{2}$$

$$holds(has(Junior, Ticket1), S0) \tag{3}$$

$$holds(has(Junior, Ticket2), S0) \tag{4}$$

$$is\text{-}ticket(Ticket1, Glasgow, London) \tag{5}$$

$$is\text{-}ticket(Ticket2, London, Moscow) \tag{6}$$

$$holds(exists\text{-}flight(Glasgow, London), S0) \tag{7}$$

$$holds(exists\text{-}flight(London, Moscow), S0) \tag{8}$$

$$occurs(does(Junior, fly(Glasgow, London)), S0) \tag{9}$$

$$S0 < S1 \tag{10}$$

$$holds(at(Junior, London), S1) \tag{11}$$

When Junior is in London, inertia gets us that the flights still exist, and Junior still has Ticket2. As for Ticket1, we would infer that he still has it unless we brought in the fact that a ticket is used up when one takes the flight the ticket is for. That is certainly a part of the knowledge of anyone who travels using tickets. Thus someone who had travelled by bus would infer it about airplane travel. Indeed it could be inferred from more general principles about commerce, e.g. that a seller doesn't want to allow the buyer to get an arbitrary number of what he has a paid for one of. However, anyone who travels has the more specific information and doesn't need to infer it from general principles about commerce. Indeed he may never have formulated any general principles about commerce.

$$occurs(does(Junior, fly(London, Moscow)), S1) \tag{12}$$

$$S1 < S2 \tag{13}$$

$$holds(at(Junior, Moscow), S2) \tag{14}$$

Now we begin Daddy's life as a block stacker. We have stated no relation between the situations $S0$ and $S0'$ and know nothing of their temporal relations. If we asserted

$$time\ S0 < time\ S0' < time\ S1, \tag{15}$$

then we could conclude that Junior still had the tickets in $S0'$. Also asserting $S0' = S0$ would do no harm to the conclusions drawn about either subnarrative. We have asserted that Daddy has the three blocks mentioned, and we would like to be able to draw the nonmonotonic conclusion that these are all the blocks he has.

$$holds(at(Daddy, NY), S0') \tag{16}$$

$$holds(has(Daddy, Block1), S0') \tag{17}$$

$$holds(has(Daddy, Block2), S0') \tag{18}$$

$$holds(has(Daddy, Block3), S0') \tag{19}$$

$$holds(on(Block1, Table), S0') \tag{20}$$

$$holds(on(Block2, Table), S0') \tag{21}$$

$$holds(on(Block3, top\ Block1), S0') \tag{22}$$

$$occurs(does(Daddy, move(Block3, Table)), S0') \tag{23}$$

$$S0' < S1' \tag{24}$$

$$holds(on(Block3, Table), S1') \tag{25}$$

$$occurs(does(Daddy, move(Block2, top\ Block1)), S1') \tag{26}$$

$$S1' < S2' \tag{27}$$

$$holds(on(Block2, top\ Block1), S2') \tag{28}$$

$$occurs(does(Daddy, move(Block3, top\ Block2)), S2') \tag{29}$$

$$S2' < S3' \tag{30}$$

$$holds(on(Block3, top\ Block2), S3') \tag{31}$$

We can imagine that blocks being clear is a precondition for moving them. The preceding subnarrative does not violate this precondition, but in a narrative we don't ordinarily have to show that preconditions are satisfied. We should be able to conclude via inertia that Daddy has the three blocks in the final situation.

Narrative 2

Now Junior loses the ticket and sends a telegram to Daddy asking for money. Daddy, who normally indulges Junior, sells a block and sends Junior the money, who buys a London-Moscow ticket and goes on to Moscow. I chose a telegram rather than a telephone call, because I would not want to tell about a telephone call as a sequence of statements by Junior and Daddy but rather to regard its result as a joint action, e.g. an agreement that Junior and Daddy would do certain actions.

Note also we haven't treated what Daddy now knows as the result of the telegram. It seems that treating knowledge and treating agreement are similar in their requirement for treating intentional entities. The intentional state that Junior has requested that Daddy send him the money is not merely that Daddy knows that Junior wants Daddy to send him the money. Also the agreement is likely to have something like a bit of narrative as an argument, e.g. a set of actions that Junior and Daddy will do with only partial time relations between the actions.

$$holds(at(Junior, Glasgow), S0) \tag{32}$$

$$holds(has(Junior, Ticket1), S0) \tag{33}$$

$$holds(has(Junior, Ticket2), S0) \tag{34}$$

$$is\text{-}ticket(Ticket1, Glasgow, London) \tag{35}$$

$$is\text{-}ticket(Ticket2, London, Moscow) \tag{36}$$

$$holds(exists\text{-}flight(Glasgow, London), S0) \tag{37}$$

$$holds(exists\text{-}flight(London, Moscow), S0) \tag{38}$$

$$occurs(does(Junior, fly(Glasgow, London)), S0) \tag{39}$$

$$S0 < S1 \tag{40}$$

$$holds(at(Junior, London), S1) \tag{41}$$

Up to here, narrative 2 is the same as narrative 1. Also insert here the sentences between equations (16) and (31).

$$occurs(loses(Junior, Ticket2), S1) \tag{42}$$

We want to regard losing the ticket as something that happens to Junior rather than as something he does. That's why we don't write $does(Junior, lose\ Ticket2)$. The bad consequences of doing the latter would arise when we get around to writing laws that quantify over voluntary actions.

We will use some of the same names now for situations that are different than in narrative 1.

$$S1 < S2 \tag{43}$$

$$\neg holds(has(Junior, Ticket2), S2) \tag{44}$$

$$value(cash\ Junior, S2) < value(airfare(London, Moscow), S2) \tag{45}$$

$$e1 = does(Junior, telegraph(Daddy, request\ send\ airfare(London, Moscow))) \tag{46}$$

$$occurs(e1, S2) \tag{47}$$

$$S2 < S3' \tag{48}$$

$$occurs(receives(Daddy, telegram\text{-}from(Junior, request\ send\ airfare(London, Moscow))), S3') \tag{49}$$

$$value(cash\ Daddy, S3') < value(airfare(London, Moscow), S2) \tag{50}$$

$$occurs(does(Daddy, sell\ Block3), S3') \tag{51}$$

$$S3' < S4' \tag{52}$$

$$value(cash\ Daddy, S4') > value(airfare(London, Moscow), S2) \tag{53}$$

$$occurs(does(Daddy, send(Junior, airfare(London, Moscow), S2)), S4') \tag{54}$$

$$\neg holds(has(Daddy, Block3), S4') \tag{55}$$

$$S4' < S3 \tag{56}$$

$$value(cash\ Junior, S3) > value(airfare(London, Moscow), S3) \tag{57}$$

$$occurs(does(Junior, buy\ Ticket3), S3) \tag{58}$$

$$is\text{-}ticket(Ticket3, London, Moscow) \tag{59}$$

$$S3 < S4 \tag{60}$$

$$holds(has(Junior, Ticket3), S4) \tag{61}$$

$$occurs(does(Junior, fly(London, Moscow)), S4) \tag{62}$$

$$S4 < S5 \tag{63}$$

$$holds(at(Junior, Moscow), S5) \tag{64}$$

Interpolating unconnected situations and events into a narrative should not harm the conclusions. For example, we could put situations $S0.5$ and $S0.7$ between $S0$ and $S1$, i.e. $time(S0) < time(S0.5) < time(S0.7) < time(S1)$, and suppose that Junior reads a book on the airplane during the inner interval. The previous statements about what holds when Junior arrives in London should still seem ok. However, suppose we postulate that Junior spent time in Peking on the way from Glasgow to London. This would make the narrative anomalous, but some geograhical knowledge is required to make the anomaly apparent.

4 Elaboration of Narratives

Suppose we are asked, "How did Junior fly from Glasgow to London?" and want to respond with facts about taking a taxi to the airport, presenting his ticket at the check-in counter, going to the gate, getting on the airplane, taking his assigned seat, etc. We can add this additional narrative with its intermediate situations, and we can throw in reading the book if we like. There is no reason to discard $occurs(does(Junior, fly(Glasgow, London)), S0)$. We merely have a redundant way of reaching the same conclusion. However, we would like a sentence relating the more detailed narrative to the less detailed narrative, i.e. of asserting that one *realizes* the other. For this we will at least need narratives as objects, and this has not yet been introduced.

Note that the relation $elaborates(N2, N1)$, when we get around to introducing it, will not be like the relation between a subroutine call and the subroutine. $N1$ will not in any sense be the definition of $N2$. $N2$ could be realized in a number of ways, only one of which corresponds to $N1$.

The elaboration involved in telling about Junior reading a book is of a different kind from that involved in telling about his taking a taxi to the airport, because reading the book is a parallel operation rather than a means of accomplishing part of the travel. Reading should be simpler to treat. In fact it may be more like Daddy stacking blocks in New York.

Suppose, however, that we want to treat reading the book as a simple sequential situation calculus account using the function $result(a, s)$. We will need to encapsulate the reading narrative in some way. The obvious way to do it is by using a context in which we do the reasoning about reading, e.g. what has to be read first in order to understand the subsequent chapters of the book, etc. It is not obvious what to call this context, but for now let's give it an arbitrary name $c21$. By the way, using the context theory of [**?**] requires that the sentences of the whole narrative be true in an outer context—call it $c0$.

What should be the language of this context $c21$, and what should the initial sentences p such that $ist(c21, p)$? $c21$ should also have some nonmonotonic rules specific to reasoning within it. For example, it may assume some kinds of normality of the reader, e.g. that he knows the language of his reading material. This assumption will be realized by applying some defaults to facts in the common sense database about reading.

There are two possible approaches to forming $c21$, i.e. to asserting what is true in it. The first approach is to derive these facts from the situation in some way. The second approach is to state them by fiat. (As Russell put it, the advantages of the axiomatic method are the same as the advantages of theft over honest toil.) We take the latter approach with the consequence that we will later have more work to do when we want to lift conclusions from $c21$ to an outer context. $c21$ should be adapted to precisely the reasoning that has to be done about Junior's reading. Thus if we have the formalism in good shape, nothing about the fact that Junior is travelling by airplane should need to affect $c21$.

5 Planning

We would like to treat the circumstances of the previous narrative from the point of view of planning. In that case we need to be explicit about the consequences of actions and other events.

6 Prediction

Let us consider the purposes of Junior and Daddy and predict what actions they will take and what the outcome will be. Of course, Junior losing the ticket will be an unpredicted event. We just throw it in, but then we should be able to predict what Junior and Daddy will subsequently do.

7 Elaborations

Events are composed of subevents and objects are composed of subobjects. In the real world, such elaborations have detail far beyond what a human or robot can know. Moreover, events and objects, etc. can be elaborated in a variety of ways.

7.1 I

n section 2 we mentioned elaborating the purchase of a box of Kleenex. Since buy a box of Kleenex might be accomplished in a variety of ways we need to write something like

$$realizes(take(Kleenex1); place(Kleenex1, Counter1); pay(Clerk1); take(Kleenex1), buy(Kleenex1 \tag{65}$$

This is too simple, because it is sequential. I suppose the answer is that an event is realized by a subnarrative. If so one is tempted to the further complication of allowing events that result in many situations.

7.2 Elaboration of Narratives

Here is a start on a formalization. Narratives are first class objects. We will be interested in a relation $elaborates(N2, N1)$ asserting that narrative $N2$ is an elaboration of narrative $N1$. Intutively, narratives are collections of events and situtaions and relations among them. Tentatively, we will not use sets in our formalism. Instead we make the narrative an additional parameter of sentences concerning situations and events—thus we have $occurs(e, s, N)$. Entering a context associated with the narrative N permits writing $occurs(e, s)$ as has been our custom.

There are two ways of looking at narratives that elaborate other narratives, and maybe we need both of them.

Suppose we have $elaborates(N2, N1)$. We may be asserting that $N1$ occurred, and $N2$ also occurred and gives more detail. On the other hand, we may regard $N2$ as a mere hypothetical elaboration of $N1$, even a counterfactual elaboration.

We need parts of narratives, and an axiom saying that an elaboration of a part of a narrative extends to an elaboration of the whole in the obvious way.

7.3 Elaboration of Objects

The elaboration of objects is presumably like the elaboration of events, but it is likely to be more complicated, because objects are three dimensional.

8 Role of Context

It might be a good idea when starting a narrative or to achieve a goal to begin with an almost empty context, e.g. with just the task in it.

Then the narrative itself comes in sequentially and related facts are retrieved from the common sense database. This permits nonmonotonic reasoning that the only events that have certain effects are those that can be shown to do so on the basis of the facts that have been retrieved.

9 Philosophical Considerations

Reality is the determinist limit of nondeterminist approximations. In what a human or robot can know about the world, many events are not inevitable. In any human account, it did not have to be raining when Benjamin Franklin first arrived in London. Indeed maybe it wasn't. Even if the world is deterministic, any achievable description of it is nondeteterministic. Elaborations of particular narratives sometime remove some of the nondeterminism by accounting for the causes of particular events and for fluents holding in the results of these events.

Therefore, it may be worthwhile to regard the world as determinist and suppose that every event has causes whether we know them or not. Thus any particular nondeterminism is potentially eliminable.

It might be supposed that quantum mechanics vitiates these considerations, but I don't think it requires modifications on the common sense level. Free will in a determinist world is discussed in [[McCarthy and Hayes, 1969]].

10 Other Approaches

11 Remarks

1. I have always felt that the careful classification of the ways in which events can overlap is unnecessary for almost all common sense reasoning. I think this article shows it. Moreover, it is also usually unnecessary to combine concurrent events into compound events as do Gelfond and Lifschitz [**?**].

12 Acknowledgments

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13 Scaffolding

This section will be removed from the final paper. It is included now only so that its remarks will appear when the document is latexed.

The word "but" can play a role in narrative. Suppose an event leads to a situation, but the properties being asserted about the situation are not what would normally follow from the occurrence of the event. Perhaps a good narrative should label the anomalous fluents of the new situation with "but".

cannot

We have not yet treated being able to prove that a person cannot accomplish something or that something cannot happen. The easiest way to think about this may be to have Junior try to prevent Daddy from doing something.

quotes from Russell and Bell

common sense informatic situation

facts vs. what is known

It seems that ¡ should not be transitive. Narratives should be objects.

Fluents should be inferred to persist as long as there is no event in the narrative or directly following from the narrative that would change this.

It may be advantageous to treat processes by introducing a fluents that persist and whose persistence determines that some secondary fluents change in a specified way, e.g.

$$falling \supset s = 1/2gt^2. \tag{66}$$

We need to be able to declare some fluents as dependent on others so that their change or persistence is not inferred separately, e.g.

$$depends(distance(x, y), location(x), location(y)) \tag{67}$$

Actually it might suffice to write

$$dependent(distance) \tag{68}$$

Probably Vladimir has thought about this possibility and should be asked. Whether a fluent is dependent may depend on context. Maybe we should distinguish between asserting the dependence of fluents and that of functions whose value is a fluent (as in the present example).

It looks like we may need priorities to handle the rules about what persists because of the narrative or what follows from the narrative.

Somehow he got to Moscow after losing his ticket. What is the semantics of "somehow"?

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Events:
losing ticket
buying ticket
moving block
selling block
sending telegram with messaage
sending money
fly(x,y)
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Can these be handled in a uniform way? An event is realized by a sequence of subevents, actually by a subnarrative. Indeed suppose that how a person performs an action involves delegating some of the work to another person. It is usually unnecessary to completely specify the sequential or temporal relations of the work performed by the different people.

The biggest strain on the single history interpretation will come with counterfactuals or trying to compare the outcomes of different strategies. That's where the *free will approximation* comes in. Thus free will is an approximate theory in a determinist world.

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