Towards a Logic of Dynamic Frames

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Abstract

The paper proposes a synthesis between the traditional frame concept(s) of Minsky and of McCarthy and with the history concept in A.I. Dynamic frames are defined as frames which share the characteristics of those traditions, and where slots take on continuously changing values. Such dynamic frames are proposed as useful in the design of autonomous agents. The paper addresses the problem of defining an adequate logic that captures the informal frame concept.

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1 Frames and Histories

The concept of "frames" emerged in the early A.I. research in the M.I.T. and Stanford environments ([MH69, Min75]). It is often believed that "Minsky frames" and "the McCarthy frame problem" don't have anything in common besides the use of the word 'frame'. I claim this to be incorrect, however, and address the problem of *finding an adequate logic which captures the intuitions underlying the unified concept of "frames"*. This broad issue subsumes the traditional "frame problem". Indeed the method of chronological minimization of discontinuities which is described here, is a generalization of the previously proposed principle of chronological minimization of change for dealing with the classical frame problem.

Furthermore, the unified frame concept is strongly related to the concept of 'histories' introduced by Hayes, and later used by Forbus in his Qualitative Process Theory. In this section we shall substantiate the unified view of frames and histories by a review of how different authors have defined these concepts. For concreteness the review will be expressed in terms of quotations from several of the classical papers in the field[1]. The next section will complement the abstract argument with a concrete example.

The informal frame concept has been described as follows:

> When one encounters a new situation (or makes a substantial change in one's view of the present problem), one selects from memory a structure called a *frame*. This is a remembered framework to be adapted to fit reality by changing details as necessary.
>
> A *frame* is a data-structure for representing a stereotyped situation, like being in a certain kind of living room, or going to a child's birthday party. Attached to each frame are several kinds of information. Some of this information is about how to use the frame. Some is about what one can expect to happen next. ...
>
> For visual scene analysis, the different frames of a system describe the scene from different viewpoints, and the transformations between one frame and another represent the effects of moving from place to place. For nonvisual kinds of frames, the differences between the frames of a system can represent actions, cause-effect relations, or changes in conceptual viewpoint. ... **[Min75]**

Two distinct lines of research have emerged from this 'Minsky view' of frames, corresponding to what Hayes[Hay79b] called the *implementation* and the *metaphysical* interpretations, respectively. On one hand, frames were seen

[1]Although recognizing that quotations can never fully capture the intentions and ideas of an earlier time, I still believe that the best use of these classics today is to read them literally and to analyze what is actually written there, without too much regard for what the authors now say that they then meant.

as candidate language constructs in "very high level programming languages for A.I.", or "knowledge representation languages", such as KRL [BW77]. A concise characterization of this view is given by Hayes:

> A frame is a data structure - we had better say *expression* - intended to represent a 'stereotypical situation'. It contains named '*slots*', which can be filled with other expressions - *fillers* - which may themselves be frames. ... For example, we might have a frame representing a typical house, with slots called *kitchen, bathroom, ...* **[Hay79b]**

The programming language aspect of such *frame expressions* is still alive and well, under both its original name (particularly in expert systems shells), and the new name of "object oriented languages".

More recently the formal study of frame expressions has also begun under the name of *terminological formalisms*[BS85, **?**]. The inheritance or subsumption properties are then at the focus of interest. Terminological formalisms are overshadowed by logic, possibly because Minsky[Min75] initially advocated frames as an *alternative to* logic, rather than as a complement to or component in a logic, and then Hayes analyzed the matter and defined a translation from frame expressions to predicate logic, concluding:

> Apart from this (i.e. processes of reflexive reasoning), there are no new insights to be had there: no new processes of reasoning, no advance in expressive power.
>
> Nevertheless, as an historical fact, 'frames' have been extraordinarily influential. ... But a more serious suggestion is that the *real* force of the frames idea was not at the representational level at all, but rather at the implementation level: a suggestion about how to organize large memories. Looked at in this light, we could sum up 'frames' as a suggestion that we should *store* assertions in nameable 'bundles' which can be retrieved via some kind of indexing mechanism on their names. **[Hay79b]**

In his paper Hayes focused on the implementational or representational aspect of frames, and disregarded what he called their metaphysical aspect. However in the "Naive Physics Manifesto", issued the same year[Hay79a], Hayes proposed a concept that turns out to be strongly related to frames in the latter sense, namely *histories*. A few years later he described 'histories' as follows:

> Events happen in time, but also in space – they have a where as well as a when. They are four-dimensional spatiotemporal entities. So are objects, which have a position and shape and composition at a given time or period, which may differ at other

> times, and have temporal as well as spatial boundaries. All of which suggests that a basic ontological primitive should be a piece of spacetime with natural boundaries, both temporal and spatial. I will call these things *histories*. ...
>
> This vignette of analysis and the "liquids" axiomatization both illustrate a style of axiomatic description in which histories are classified into types and the kinds of relationships they can have with one another are defined by the nature of their boundary surfaces. ... It depends on the use of *taxonomies*, i.e. listings of all the possible kinds of history of a certain type (all the kinds of falling history, or all the kinds of time interval, or all the ways in which a thing can be supported) [**Hay85**]

The intuitions that Hayes invokes here are very similar to the ones described by Minsky when introducing frames. Although the latter are in themselves data structures rather than assumed entities in the world, it still seems to me that Minsky primarily proposes a way of assigning structure to the world, and that his description of frames as a data structure just reflects his methodological stance. Consequently what Minsky goes after with his "frames" appears to be the same thing as what Hayes goes after with "histories". Compare also the following remark by Forbus, who uses Hayes' history concept:

> Histories help solve the frame problem because objects can interact only when their histories meet [**For85**]

with the following remark by McCarthy and Hayes in the early paper where the logical, or 'frame problem' aspect of frames was first introduced:

> We see two ways out of this difficulty. The first is to introduce the notion of frame, like the state vector in McCarthy(1962). A number of fluents are declared as attached to the frame and the effect of an action is described by telling which fluents are changed, all other being presumed unchanged. [**MH69**]

The latter quotation allows either that there should be one single 'frame' parameter vector, or that several 'frames' would be allowed to exist concurrently. In the former case the concept degenerates to a predicate on parameters, specifying whether the parameter is a frame parameter or not. If several such 'frames' exist concurrently then they can be chosen so that each of them characterizes a history.

Since a frame is concretely seen as a data structure or an expression, each frame would then be a history type or a representation for a collection of similar histories, where the histories themselves are objects of the world. The taxonomical structure that Hayes mentions is then a structure over frames.

To summarize, Minsky and McCarthy/Hayes used the same term "frame" but diverged about methodology. Minsky's thinking is implementation oriented; McCarthy and Hayes emphasize not only the use of logic but also (Hayes in particular) the semantical perspective and the necessity of defining the semantics of expressions in terms of their denotations in the outside world. My argument is that the terminological coincidence and the methodological difference should not be allowed to obscure the close relationship of the ontology for Minsky frames, early McCarthy/Hayes frames, and later Hayes histories: a frame is a characterization of a group of similar histories.

2 Dynamic frames

Let us now proceed to a natural generalization of the frame/history concept which we shall call *dynamic frames.* They are introduced through an application example. Suppose one is going to design an electronic co-driver for automobiles, providing the driver with the support of electronic sensing devices (for use especially in difficult driving conditions), recognition and warning for possible accidents, maybe also automatic evasive actions to avoid accidents, etc.[2] An intelligent co-driver system should be knowledge-based, in the sense that it maintains at all times a model of the traffic situation around its own car (in the informal or engineering sense of the word model). The model of the current traffic situation (MCTS) must specify the situation type, for example "our car is the last one of three cars driving after each other on a two-lane road", as well as quantitative parameters, specifying for example the distance and relative velocity to the car in front.

In principle one can make the MCTS arbitrarily complicated and interesting, but in a practical project one must use relatively simple models especially to begin with. The following example of a model for driving on two-lane roads or streets illustrates what level of complexity may be expected. The MCTS consists of five frames: the frame for cars going our way, the frame for meeting cars, the frame for crossing cars (i.e. cars which are going to cross our itinerary, for example at a road crossing), the frame for our own car, and the frame for the road itself.

The frame for cars going our way has a slot for one car behind our own, and one or two cars in front of our own, besides our own car. Each slot is occupied by a car frame or is empty, but the slot contents changes over time. If A is our own car, B and C are in front, and D is behind, then the following configurations are possible: A, AB, ABC, DA, DAB, DABC. Thus in the AB and DAB configurations, we have one car in front, which however is driving at its own chosen speed since it does not in turn have any car in front of it which would constrain its velocity.

[2]The example is inspired by our participation in the pan-European Prometheus project, which is directed towards the development of such driver support systems.

Similarly the frame for meeting cars has three main alternatives: no car meeting, one single car meeting, and two cars after each other meeting. The frame for the road specifies whether the road in front of us is presently inclining, declining or flat, and whether it is straight or we are going towards a curve.

A very pragmatic *raison d'être* for such a reportoire of frames is to hold the quantitative parameters, which change continuously. The distance and relative velocity to the car in front are important to know, and should be measured continuously, but they of course only make sense if there is in fact a car in front. If there is not, the same sensoring capacity can maybe be used for other purposes. Keeping track of the MCTS determines how the system should focus its sensory resources, and where it should store the collected information.

Each choice of frame applies for a limited period of time. Within that time period, parameters in the frame change more or less continuously. At distinct and discrete points in time there is a change of frame, due to a perceived action by some of the cars involved, for example "catch up with" (other car), "let go" (allow car in front to speed away), "overtake", etc. The information that such an action has taken place must come from the sensors, but it has the effect of changing one or more current frames qualitatively.

In an obvious way such a software architecture allows one to combine continuous and discrete information in a joint model of the current traffic situation. The entities that I have here called frames, match well with most of the quotations in the previous section: they are a "data-structure for representing a stereotyped situation" (Minsky); they are state vectors and "a number of fluents are declared as attached to the frame" (McCarthy). In particular the sampled fluents for successive estimates of various continuously varying parameters, such as the distance to the car in front if there is one, are naturally attached to the frame. Also from an ontological point of view a frame represents "a piece of spacetime with natural boundaries, both temporal and spatial" (Hayes).

For these reasons it makes sense to use the term *dynamic frames* for frames where the attached parameters (or the contents of the 'slots') are functions of time during a contiguous time segment of finite duration. Again such a dynamic frame characterizes a collection of similar histories, and it is motivated by a combination of ontological and implementational considerations.

The time axis may either be chosen as the real or rational numbers, or as a set of discrete time points. In the latter case one must only assume that the time-points are so close that a non-trivial number of time-points occur during the frame's time segment.

The main topic of the present paper is then *how such dynamic frames, as well as the histories they describe, can be characterized in logic*, in a way that captures the ontological intuitions, and which also provides a firm basis when the data structure aspect of the frames is realized by an implementation.

3 The frame problem: search for an appropriate inference mechanism

The "frame problem" has been defined not once, but many times. McCarthy recently defined it as follows:

> The frame problem is that of specifying what doesn't change when an event occurs. ... It is most acute when the system must be open-ended, i.e. must be ready to accept descriptions of new kinds of events and new kinds of fluents whose values are in general not affected by events whose descriptions don't mention them. [**McC88**]

If "what changes and what doesn't change" is taken to be propositions, then this is the same as the "persistence problem". Shoham has proposed to generalize the persistence problem into an *extended prediction problem*[Sho88], and has argued that the generalized problem is bound to come up in any logic of time and action, including for example a logic based on the ontology of 'histories'. Related problems, which are sometimes included under the heading of the frame problem and sometimes identified as separate problems, include the *qualification problem* and the *ramification problem*. More extensive reviews of these concepts are abundant in the literature.

These varieties of frame problems, and their proposed solutions share a common underlying assumption: they take as *given that we wish to express our knowledge about the world in a certain way*, and ask *what inference mechanism would be able to take us correctly from a set of given facts, to intended conclusions*. This is also the approach that we are using in the present work. This whole branch of research started when it was recognized that deduction by default was needed or at least would be useful, requiring a concept of non-monotonic deduction[Hew71], and that such deduction has highly non-standard properties such as allowing multiple extensions[San72]. Hayes then proposed to view this a the problem of finding preferred, maximally consistent subsets of a given, inconsistent set, using a preference order on (what we would now call) the non-monotonic antecedents that are obtained from the persistence default[Hay73].

The proof-theoretic point of view dominated in the early literature on non-monotonic logic, particularly of course in Reiter's default logic[Rei80]. In recent years there has been an increasing emphasis on the model-theoretic perspective. The proposed solutions to the 'frame problem' have therefore gradually shifted from new, non-monotonic inference rules to new, non-monotonic semantic entailment conditions.

It would also be reasonable to consider the reversed question: for a given inference mechanism, how should one represent a given body of knowledge, so as to obtain the intended conclusions. This view has been energetically advocated by D. Poole (recent panel discussions).

If one accepts that the identification of appropriate entailment conditions or inference rules is a useful goal of research, the next question would be by what *criteria* will the different proposed solutions or results be evaluated. The criterium that is being used, and presumably the only one which can be used, is of a quite indirect character: an entailment condition is good iff it allows one to express his knowledge base *conveniently*, and still obtain exactly the intended conclusions. More specific preferences such as modularity, legibility, and debuggability are then subsumed under the term 'conveniently'.

In this context it is also interesting to notice that the classical distinction between 'soundness' and 'completeness' of a proposed deductive system, fades away when non-monotonic logic is introduced. In the classical usage of logic, soundness with respect to the application is a minimal requirement without which a formalization would be considered as totally useless, whereas completeness is difficult and often impossible to achieve. In a non-monotonic logic, an incomplete system can also be suspected to be unsound i.e. to admit some non-intended default-conclusions.

The present work follows the standard pattern in the sense that it also addresses the choice of inference mechanism, in our case for characterizing dynamic frames. However we prefer to use a model theoretic approach, identifying appropriate semantic entailment conditions (in particular using preferential semantics), and as a prerequisite identifying the appropriate structure of interpretations corresponding to dynamic frames. In this way we can bypass the intricacies which arise in proof-theoretical approaches to non monotonic logic.

4 Logic characterization of intra-frame change

The logical characterization of dynamic frames consists of two parts:

- *intra-frame change:* characterizing smooth change and occasional discontinuities in the parameters attached to the frame
- *inter-frame change:* characterizing the structure formed by the frames, including structural change (such as the creation and destruction of objects) and the selection of the factors that influence smooth change.

Intra-frame change can more precisely be understood as follows. In many applications the histories of objects can be partitioned into fairly small parts which are internally 'smooth', in the sense that real valued parameters with their derivatives are continuous within the time interval of the history partition. For example if a ball rolls on a horizontal surface and at one point goes over the edge and begins to fall, then the second derivative of its vertical coordinate will change discontinuously (with some simplification) as the ball goes over the edge. That discontinuity point would therefore mark the boundary between two successive, 'smooth' sub-histories.

For processes involving feedback, such as keeping the car on the road, smooth intervals may instead be defined as intervals where a particular set of control equations apply. When the driver (or the vehicle control system) decides to take a new action, for example changing lanes, she shifts over to another set of control equations, and a new smooth interval begins.

Both inter-frame and intra-frame change have been studied in the area of qualitative reasoning, although not in a way that has led up to a formulation in logic using a formal semantics. In a number of earlier papers [San89a, San89c] I have proposed an approach to characterizing intra-frame change in such logical terms. The following is a brief summary of the material in those papers set into the present context.

The simplest version of the problem is to view the real numbers as the only domain in the interpretations, and to map all other aspects of the application model, including the presently applicable set of frames, into the reportoire of parameter names, relation names, etc. In this way the ontological character of the frames is bypassed, and one can concentrate on the choice of semantic entailment conditions.

The proposed method is to combine logic and differential equations, by extending the syntax of formulas so that terms can also represent derivatives. Parameters (including n-th order derivatives thereof) are allowed to be discontinuous at points, and the syntax of formulas also allows reference to the left and right limit value of a parameter in a discontinuity point.

With these extensions, differential equations can be written as axioms which characterize smooth history segments. The machinery of logic is used for two purposes, namely for specifying which differential-equation axioms apply under which conditions, and for specifying the behavior of parameters around their discontinuity points. This role of logic has been aptly described by Hayes:

> Reasoning about the dynamics resembles a process of fitting together a jigsaw of historical pieces in an attempt to fill out spacetime, invoking interface properties of spatial and temporal boundaries at every stage [**Hay85**]

The persistence problem (or 'extended prediction problem') does not of course go away only because continuous time and quantities are introduced. The following approach is proposed. We distinguish between 'actuated' change, i.e. change caused by an agent, and 'mechanical' change i.e.

change obtained by cause-effect in the physical world. For mechanical change, *chronological minimization of discontinuities* is used as the entailment condition. For a given set of axioms (including differential-equation axioms), one model J is preferred over another model J' iff there is some time-point t such that J and J' are identical in all parameters for all time-points before t, *and* if the set of parameters which have a discontinuity at t in J, is a subset of the set of parameters which have a discontinuity at t in J'.

For actuated change this entailment condition does not apply. The difference arises for the following reason: consider a billiards table with several balls on it; one ball is travelling towards the others which are lying still. If there is a preference for minimizing discontinuities in the parameters of motion, then a 'mechanical' billiards ball is *not* going to say to itself "by changing my direction now, i.e. by accepting a discontinuity at the present point in time, I can avoid a large number of parameter discontinuities later on". Its minimization is chronological, since it fails to take one discontinuity now even at the 'expense' of having several later on. An intelligent agent, with a capacity for look-ahead and planning, is however able to make exactly that kind of trade-off. In reasoning about actions we must therefore admit the various plans that the agent may have in mind.

The principle of chronological minimization was proposed by Shoham[Sho86] and Kautz[Kau86], and discussed by Hanks and McDermott[HM86]. It has been criticized by Baker[Bak89] and others as inadequate for general-purpose reasoning about actions. The problem can now be diagnosed as due to having used chronological minimization for the wrong purpose. Shoham, in his book considers mechanical change on a billiards table for his initial example, and then switches to actuated change for later examples. It appears that chronological minimization is adequate for the initial examples that he uses for motivation, but not for the examples where he then applies the approach.

To characterize actuated change, a logical system should admit all interpretations which are compatible with some plan which the agent(s) may have, and is able to carry out, and it should also have axioms which specify how the agent carries out a particular action. The entailment conditions proposed in the papers work as follows: one of the components of an interpretation is the *plan*, i.e. a set of *action instances*, each specifying an action type, a starting time, and an ending time.

For a given plan, the entailment condition minimizes discontinuities chronologically, except discontinuities in a parameter which is 'controlled by' an action, and which occur during the time interval of that action. It is assumed that the axioms characterizing effects of an action, shall also specify the 'controlled by' relation. The extent of this relation is minimized by the entailment condition (so that a property is only considered as controlled during those periods when the axioms require it to be so), before uncontrolled discontinuities are minimized.

The preference between models containing different plans is application dependent. For the purposes of planning in a very rational agent, one would like to have a cost function and prefer the cheapest plan. For plan recognition while the actions of another agent is being observed, one needs an understanding of what plan preference the observed agent has. However, one simple preference which seems to apply in most cases is that redundant actions can be excluded. In other words, if the set of a actions in the plan in one model is a subset of the actions in the plan in another model, then the first model is preferred.

This concludes the summary of the proposed entailment condition for systems with piecewise smooth parameters. Additional technical details can be obtained fromt the full papers[San89a, San89c], which also contain examples of axiomatic descriptions for simple scenarios, for use with the proposed entailment conditions.

The proposed entailment condition for continuous parameters, is a direct generalization of known methods for the discrete case. Discontinuities are of course the generalization of clippings to the continuous domain. If a parameter can only take a discrete set of values, then it is discontinuous at a point in time iff it changes its value there. Chronological minimization was first developed for the discrete domain. Also the technique of using a separate 'controls' predicate for distinguishing actuated change from mechanical change, was first developed for a logic with discrete time and discrete properties[San88, San89b].

The expected property of the entailment condition is that it should be possible to write out the axiomatic description in a "natural" way, for example without a need for some kind of frame axioms. The worked examples in the papers are fairly successful but not perfect from this point of view. An improved ontology which appears to solve most of the known remaining problems, is emerging in current work by Persson and Staflin in our laboratory[PS90].

By focusing on the quantitative parameters, many ontological issues for frames were avoided. Still there are some significant choices which underlie the work described above: time is considered as linear and real-valued[3], and parameters are also considered as real valued. The discrete value spaces which are widely used in qualitative reasoning are not used in the semantics – limited knowledge about a parameter is represented by limited strength in the axioms describing the domain, but each individual model for the axioms is fully specific with respect to parameter values. Similarly, time is considered as linear and therefore totally ordered, within each interpretation. A previous paper[San89a] gives the reasons against using discrete value spaces in interpretations, and also argues against some of the hype that traditionally surrounds them.

[3]The theory could be adapted to rational valued time, if one wants, I think.

5 Inter-frame descriptions

5.1 Structural issues

The method that was described in the previous section, characterizes the piecewise smooth development of quantitative parameters. We now proceed to the other part of the problem i.e. the structural issues. A full-blown logic for dynamic frames should be able to characterize objects which have a limited duration in time, a limited spatial range at each point of time through their duration, and which also have parameters (fluents) attached to them through their duration. Using the logic one should be able to characterize how objects are created, transformed, and terminated, as well as how their parameters change dynamically.

No such logic exists today, of course, but contributions for its ontology may be obtained from research in Qualitative Reasoning and in particular from Forbus's Qualitative Process Theory (QPT), which was first presented in 1981[For81]. For the present discussion we shall use the revised description in[For85]. In particular the quotations are from the latter paper.

5.2 Qualitative Process Theory

Although QPT recognizes naive physics as one of its roots:

> From the perspective of naive physics, qualitative process theory is a *cluster* – a collection of knowledge and inference procedures that is sensible to consider as a module. The introduction of explicit processes into the ontology of naive physics should prove quite useful. ...

still Forbus views logic merely as a less convenient syntax for knowledge-representing expressions:

> Fig. 10 illustrates process specifications for heat flow and boiling. (For fans of logic, Fig. 11 illustrates how the boiling process would look translated into predicate calculus).

and QPT, like other work in qualitative reasoning as far as I know, does not provide a formally defined semantics for the syntactic expressions that it uses for characterizing the application. (The semantics of discrete value spaces has been defined, but that is another matter). What QPT does provide, however, is a supply of potentially useful intuitions relevant for the ontology for a logic of dynamic frames. The following is an attempt to extract in concise form, the central concepts of QPT which would be relevant for such an ontology. Original QPT terminology has sometimes been replaced by the terminology already used in this paper.

The basic concept in QPT is the process:

> **Sole mechanism assumption.** All changes in physical systems are caused directly or indirectly by processes.

More precisely, there are three interdependent, basic concepts: processes, objects (physical objects), and influences. Processes create and terminate objects, and induce influences on objects. Objects have parameters, for example 'temperature', 'velocity', or 'mass', which are functions of time (fluents). The rate of change of a parameter is a function of all currently 'existing' influences on that parameter of that object. Processes are initiated and terminated when parameters reach certain boundary values. These boundary values may be due to physical facts (for example when the water in a kettle reaches boiling temperature), or to spatial boundaries in the physical configuration (for example when a moving object reaches or leaves a solid surface).

The concept of 'influences' is a useful one. Something like it would seem to be necessary for example in order to represent laws such as "the movement of a body is determined by the sum of all the forces acting on it", and several other good uses of influences come to mind easily. If one adopts as a general principle that the change in parameters is determined by the 'sum' of the relevant influences, then one must also specify how the 'addition' is to be performed in the general case – is it a conventional sum of real numbers or vectors, or is it something else? QPT does not have to deal with this question since parameter values are only assumed to range over discrete value spaces, but if interpretations use real time and real parameter values the issue becomes acute.

5.3 Interpretations based on QPT ontology

It is fairly straight-forward to define the structure of interpretations using the ontology of QPT. Basically it would go as follows. A hierarchical type system is used; the primary distinction is between *eternal* and *worldly* types. Eternal types are real numbers, integers, quantities, strings, and so on. The type of quantities has a number of sub-types called *sorts*, for example 'time', 'length', or 'velocity'. Each sort is isomorphic to reals or some other eternal type. In particular 'time' is isomorphic with the reals.

Worldly types have three sub-types, namely processes, physobjects, and influences. Physobjects have common sense sub-types such as 'boxes', 'persons', 'automobiles', 'bananas', and whatever. Processes likewise have subtypes for different kinds of things that may happen. Worldly types are characterized by dynamic frames – this is the point where the system becomes a logic of dynamic frames.

A number of basic functions and relations are defined for these types. All dynamic frames have a creation time and a termination time, which have the type time-points. The period from the creation time to the termination time of a frame, will be called its duration. Each physobject has a creating process and a terminating process; the creation time of the physobject must be within the duration of its creating process, and similarly for termination. Each influence has an inducing process, and its duration is a subset of or equal to the duration of that inducing process. Each influence also has an object and a parameter that it applies to.

There is no need to write out the remaining details; the idea should be clear from the outline so far. In particular, as soon as one has decided what the rule should be for composing influences on a parameter, that rule could also be specified as a condition on interpretations.

There also does not seem to be any difficulty to combine the logic for piecewise smooth parameters, which was described in the previous section, with the kind of logic of dynamic frames described here. In particular the 'actions' used in[San89c] can easily be re-interpreted as processes.

Since not only processes but also influences are reified, one must consider whether the model set should be restricted to models which are minimal with respect to the set of actions and the set of influences in them. This seems like a plausible assumption to make, but has to be determined in the light of example axiom sets.

5.4 Primary and secondary interpretations

The ontology now described has one notable characteristic: it only allows parameters (fluents) of one argument. What about time-dependent functions of two or more arguments, such as the distance between two physobjects? It would introduce considerable complexity to have influences etc. for them as well.

One possible way of dealing with that problem is to make a distinction between primary and secondary functions, where the change in primary functions is posited to always be defined by the totality of influences operating on it, whereas the value of a secondary function at a time is constrained by axioms in the usual way. Typically a secondary function is defined by axioms that relate it to other functions, primary or secondary.

Consequently in the semantics, an interpretation should consist of a primary and a secondary part; the primary part should be as in section 5.3, and the secondary part should be a conventional interpretation for secondary functions and relations. The special entailment conditions, such as chronological minimization of discontinuities, should only apply to the primary part of interpretations.

For example, the *position* of a physobject could be one of its parameters, belonging to the primary part of interpretations, and would change as a result of all the position influences that apply to the object. The distance between two objects would be represented in the secondary part, and an axiom would specify that at each point in time, the distance between two physobjects is the magnitude of the difference between their positions. Under such conventions, and with suitable axioms, the system would for example entail that if two objects repel each other, and there are no other influences on their positions, then their distance increases. Still the entailment would be a *consequence* of underlying principles; there would not and should not be any axiom saying "if two physobjects repel each other, by default their distance increases".

By extrapolation, many functions and relations that are traditionally seen as primary, in the discrete worlds that are usually used in logic-based A.I., would now be in the secondary part of interpretations. Statements such as "block A is on top of block B", "the monkey has the bananas", and maybe even "the turkey is dead" would be secondary predicates defined from primary parameters such as positions of blocks, monkeys, and bananas, or the level of neural activity in the turkey's brain.

A possible argument against such an approach is that concepts like "have" or "on top of" are common-sense concepts in human thought, and they should therefore have primary status in the A.I. formalization as well. It is the same argument as is often used in defense of various "naive X" systems. I believe it is a misguided position: progress in science is obtained when what used to be primary concepts (such as "the sun rises") can be re-interpreted as derived concepts (such as "by earth's revolution, the sun is now visible"). Why hang on to naive common-sense concepts when better models are available?

The possible ontological choice to distinguish between primary and secondary interpretation parts in this way is related to a distinction between physical and conceptual knowledge which was made our recent paper[San90].

5.5 Objects visavis frames

Another important issue is as follows, again with an example from the automobile co-driver system. Suppose we are driving with another car behind us, and that car overtakes so that it comes to be the car in front of us. The approach outlined above would presumably treat each car as one physobject. The secondary function "car in front of (us)" changes value when the other car overtakes. However from an implementation point of view, where a frame is the place to store information from sensors, and where special action rules are associated with possible behaviors of the car in front, it would make more sense to have one single frame which constantly represents the car in front, whenever there is any, and with time-varying slots such as the color and the registration number of the car-in-front.

This example suggests that dynamic frames should be seen as playing an intermediate role between the representation of a history (including an object) and the representation of a history type. As a data structure in an autonomous agent the frame both characterizes phenomena over time (such as histories) and also it itself exists in time. In principle the dynamic frame represents a class of similar histories (objects), but at each point in time it denotes at most one history or object. For example, there are many different cars which at one time or another have driven in front of ours, and the frame for "the car in front of ours" represents them all, but at each point in time it only denotes the car which is presently in front of ours, if any. Operationally it makes good sense to associate such a frame with rules, procedures, or other information which pertains to any car that is in front of ours, and which at the present time shall be applied to the specific car that is presently in that role.

Formally speaking and from the semantic point of view, a dynamic frame can therefore be understood as a term (for example a "constant" symbol) whose denotation is piecewise constant over time, and which during each such interval is either an object(history) or empty, together with "slots" containing current parameters of the object presently denoted by the frame term. For example if c is a such a "frame term" denoting objects in a piecewise constant fashion, and f, g, etc. are parameters i.e. functions from (objects x time-points) to parameter values, then $\langle c, f(c), g(c), ... \rangle$ would be the data structure for the dynamic frame. In this way one can reconcile the ontological view, the implementation view and the semantic view of dynamic frames.

6 Conclusion

In summary, I have argued for a synthesis between the traditional frame concept(s) and the history concept in A.I. I have also defined dynamic frames as frames which share the characteristics of those traditions, and where slots take on continuously changing values. The paper has addressed problems which arise when trying to define an adequate logic that captures the informal frame concept.

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