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A Causal Time Ontology for Qualitative Reasoning

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Abstract

Aiming at explicit description of temporal meaning of causal relations generated by qualitative reasoning systems, this article proposes a causal time ontology which defines a set of general time concepts in qualitative models, called *causal time scales*. Each of them associated with a modeling technique represents a temporal granularity and/or an ontological viewpoint. They allow us to specify temporal performance of the reasoning engines and to identify a general causal reasoning scheme together with sophisticated feedback analysis. Lastly, we present a causal time resolution required to derive causal relations in fluid-related systems and a reasoning system satisfying it.

1 Introduction

Causality plays a crucial role in human understanding of behavior of physical systems. A lot of research has been carried out on qualitative reasoning systems in order to derive causal relations from the models of the target systems, e.g.,[de Kleer and Brown, 1984]. Human recognition of causal relations is based on recognition of time delay (i.e., time interval) between the cause and the effect. Little, however, is known concerning temporal meaning of causal relations generated by the reasoning systems, that is, how long (or short) the time intervals in the causal relations in the real physical behavior as discussed in [Iwasaki *et al.*, 1995]. There are the following two explanations for it. First, there are many modeling techniques and representations, each of which implies several temporal relations among variables. Secondly, such models are interpreted by the reasoning engines on the basis of their own time concepts behind their reasoning procedures. For example, using the same qualitative differential equations[1], QSIM [Kuipers, 1994] and the causal ordering procedure proposed in [Iwasaki and Simon, 1994] generate different causal relations together with different temporal meanings. As a consequence of the implicit existence of several time concepts, the temporal meaning of generated causal relations is not clear for the users of the reasoning engines.

[1]Strictly speaking, the causal ordering procedure [Iwasaki and Simon, 1994] needs additional information.

The goal of this article is to reveal the structure of causal time underlying the qualitative models and the causal reasoning engines. We propose a set of general time concepts in qualitative models, called *causal time scales*. Each causal time scale associated with a modeling technique represents a temporal granularity and/or an ontological viewpoint. In other words, the set of the causal time scales aims to enumerate all possible temporal meanings of the models, that is, an ontology of time for causal reasoning. Ontologies are explicit specifications of concepts [Mars, 1995], which can specify assumptions underlying knowledge-based systems [Mizoguchi and Ikeda, 1996].

We have identified 13 causal time scales shown in Table 1. They are classified into four categories each of which represents a modeling technique. They generalize time concepts in the some previous frameworks [de Kleer and Brown, 1984; Iwasaki and Simon, 1994; Kuipers, 1994; Rose and Kramer, 1991].

The utility of the causal time scales includes the following: First, causal relations generated by the reasoning engines can be categorized into one of the causal time scales. It clarifies not only the temporal meaning of the causal relations but also the performance of the reasoning engines with respect to causal ordering, called *causal time resolutions*. For example, causal relations generated by QSIM are categorized into the causal time scale named $Ta3$ associated with the mathematical integral operation. On the other hand, some of those generated by the causal ordering procedure are categorized into the time scale $Ta2$ which is a finer-grained time concept than $Ta3$. Thus, the causal time resolution of the causal ordering procedure is finer than that of QSIM. The time resolutions of other reasoning methods will be shown in section 3.1.

Secondly, we also identified a general causal reasoning scheme which can cope with multiple time scales. It can explain essential parts of the conventional reasoning methods. It will be shown section 3.2.

Lastly, fine-grained time scales enable sophisticated analysis of causality in feedback loop. According to the time scale associated with a feedback loop, the reasoning engine can suppress causal relations without physical meaning and ambiguities of reasoning results as discussed in section 3.3.

In section 4, we discuss a causal time resolution required to derive the causal relations in fluid-related systems. The constituents of the model for the time resolution is also discussed.

In this article, we do not discuss formal ontology based on axiomatization, aiming at getting on agreement on the content and the terminology. Next, we concentrate on ontological issues. For the details of model representation, reasoning engine and its evaluation, see other articles[Kitamura *et al.*, 1996a; Kitamura *et al.*, 1996b].

2 A Causal Time Ontology

2.1 Theoretical Foundation

In our causal time ontology, behavior over time generated by the reasoning engine is represented in terms of events and links among the events, in a similar way in the history model[Forbus, 1984]. An event $e \in E$ represents instantaneous changes of qualitative values of parameters and their resultant values at a time point. Changes of quantitative values are assumed to be continuous and differentiable. A new event e_2 is generated by applying an operators $o \in O$ to an old event e_1 according to the model M. A link $l_1 \in L$ between e_1 and e_2 represents a causal relation according to the model M. There is an open time-interval t_1 between e_1 and e_2, corresponding to the causal relation l_1. The roles of operators $o \in O$ are to propagate changes and to generate new events, time intervals and hence partial temporal relations. Note that the symbol 't' always represents not a time point but a time interval in this article. Although events correspond to time points, we concentrate on time intervals in which changes propagate.

The causal time ontology provides categories of such time intervals, called *causal time scales*. A causal time scale represents a concept of time interval for propagation of effect. The notation $\tau(l) = T$ denotes a time interval t of a causal relation l is categorized into a time scale T. We can say that "the causal relation l is represented on the time scale T".

The ordinal relation $T_1 \prec T_2$ representing a time scale T_1 is shorter (finer-grained) than T_2 is defined as follows;

$$T_1 \prec T_2 \leftrightarrow \forall\, t_1 \in T_1, \forall\, t_2 \in T_2,\ t_1 < t_2$$

In other words, T_1 represents faster events than that T_2 does. This relation is transitive. The relation between $Ta2$ and $Ta3$ where $Ta2 \prec Ta3$ is shown in Figure 1. Although the figure shows the relation among concrete time scales due to limitation of space, we explain the general relation here. When a certain condition becomes true in the reasoning process on a shorter time scale $Ta2$, the reasoning shifts to a neighboring longer time scale $Ta3$. Such a condition is called as a *boundary condition* of $Ta2$ or a *precondition* of $Ta3$. The set of events grouped by the condition $e_{(1,1)}, e_{(1,2)}, ..., e_{(1,4)}$ on $Ta2$ is treated as the instantaneous events $e_{(2,1)}$ on $Ta3$. Then, the *reasoning operator* of $Ta3$ is applied to the event $e_{(2,1)}$. Each time scale has an operator. The resultant values on $Ta3$ can be treated as the initial values on $Ta2$. The same applies to $Ta3 \prec T_4$ cases recursively. In summary, a time scale T can be defined by a tuple of three elements, <Pc, Op, Bc>, where these denote a precondition, an operator, a boundary condition, respectively. The elements of T_1 are denoted by T_1:Pc, T_1:Op and T_1:Bc, respectively.

2.2 Physical Meaning of Causal Relations

The relations l generated by the reasoning engine do not always make sense from the physical viewpoints. There are

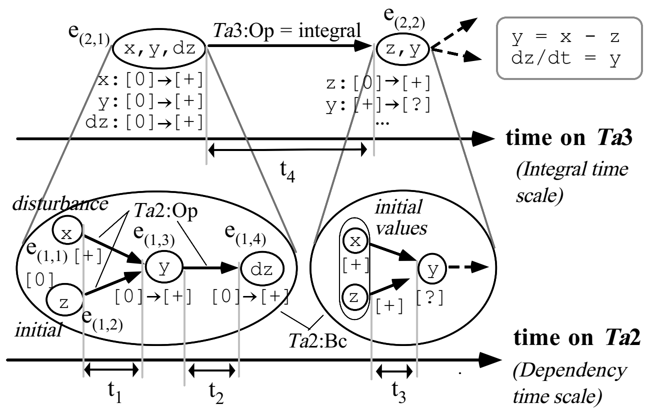

Figure 1: Relation between the time scales $Ta2 \prec Ta3$

such cases where a link l represents an operational order which is not justified by the physical sense. In order to clarify *the physical meaning* of the causal relations, we will discuss two aspects of the physical meaning of each time scale, that is the *interval-meaning* and the *ordinal-meaning*. The former represents a physical justification of existence of the time intervals on the time scale. The latter represents that of order of events on the time scale.

2.3 Causal Time Scales

This section defines 13 causal time scales shown in Table 1. The time scales are classified into four categories each of which represents a modeling technique together with particular modeling rationales. The *direct modeling* is to describe models using the mathematical differential equations which directly represent dynamic behavior over time. The *time constant modeling* is to qualitatively categorize the time constants for modeling of phenomena. The *component structure modeling* is to introduce the concept of "component", aiming at causal relations reflecting the physical structures of the target systems. The *modeling of periods of interest* such as initial responses allows the reasoning engine to neglect changes of no interest. The notation "Tx#" denotes a time scale, where 'x' denotes a category (a,b,c or d) and the number '#' represents ascending order in each category. In Table 1, each condition denoted by a notation "cx#" represents the boundary condition of the time scale listed above and the precondition of that listed below.

(a) Direct Modeling

In the direct modeling, temporal characteristics of the phenomena are represented directly by the mathematical aspect of the models. The precondition of the time scale $Ta3$ is that a set of parameters are *completely determined* where every parameter in the set has values which satisfy all constraints. When the condition holds, the reasoning engine applies the integral operator and hence generates a new event. The integral operator embodies the qualitative mean value theorem $x_{new} = x_{old} + dx/dt$ [de Kleer and Brown, 1984]. The time intervals between the old events and the new events are categorized to $Ta3$:*integral time scale*. The time in QSIM[Kuipers, 1994] corresponds to $Ta3$. Furthermore, $Ta3$ is categorized

Table 1: The causal time scales

(a) Direct Modeling

ca1: changes of parameter values

$Ta1$: *Mutual Dependency time scale*

ca2: a set of inherently simultaneous equations are satisfied.

$Ta2$: *Dependency time scale*

ca3: a set of constraints are completely determined.

$Ta3$: *Integral time scale*

Ta3p: Integral-from-equality time scale

Ta3i: Integral-to-equality time scale

ca4: a set of parameters reaches equilibrium.

$Ta4$: *Equilibrium time scale*

(b) Time Constant Modeling

$Tb1$: *A Faster Mechanism time scale*

cb2: a faster mechanism reaches equilibrium.

$Tb2$: *A Slower Mechanism time scale*

cb3: a slower mechanism reaches equilibrium.

(c) Component Structure Modeling

$Tc1$: *Intra-component time scale*

cc2: all parameters in a component are determined.

$Tc2$: *Inter-component time scale*

cc3: all parameters in a global structure are determined.

$Tc3$: *Global time scale*

cc4: all parameters in the whole system are determined.

$Tc4$: *The Whole System time scale*

(d) Modeling of Periods of Interest

$Td1$: *Initial Periods time scale*

cd1: the first event happens on a time scale.

$Td2$: *Intermediate Transitional time scale*

cd2: the last event happens on a time scale.

$Td3$: *Final Periods time scale*

into two types; $Ta3p$ and $Ta3i$. The former represents the time intervals for integration from the same value as the landmark values to the interval of the landmark values. The latter represents those from the interval to the landmark values. $Ta3p \prec Ta3i$ holds.

On the other hand, until a set of parameters are completely determined, the time intervals are categorized to $Ta2$:*dependency time scale*. The precondition of $Ta2$ is that a set of inherently simultaneous equations[2] are satisfied. The time scale of the causal ordering theory [Iwasaki and Simon, 1994] corresponds to $Ta2$. Until the inherently simultaneous equations are satisfied, the time intervals are categorized to $Ta1$:*mutual dependency time scale*. Although this time scale has the interval-meaning mentioned in section 2.2, it has no ordinal-meaning. On the other hand, $Ta2$ and $Ta3$ can have both kinds of the physical meaning. When a set of parameters achieve its equilibrium, the reasoning shifts to $Ta4$:*equilibrium time scale*.

For example, consider a simple system modeled by the direct modeling, $y = x - z, dz/dt = y$. A variable takes one of the three qualitative values, [+], [0] and [$-$], where the landmark value is 0. In the initial state, all variables take [0] except for a disturbance x = [+]. Figure 1 shows causal relations generated on $Ta2$ and $Ta3$. In this case, the method of constraint satisfaction is simple propagation of values. First, the value of y becomes greater than 0 (denoted by [0] $\rightarrow$ [+] in the figure) according to $y = x - z$. Next, the value is propagated to the derivative of z (denoted by dz in the figure). At this point, every parameter has a value which satisfies all constraints, that is, the precondition of $Ta3$ becomes true. Then the reasoning shifts to the longer time scale $Ta3$. On the scale $Ta3$, the integral operator is applied to z, then z becomes greater than 0. Next, on $Ta2$, the new value of z is propagated to y and so on. Note that the change of y and that of dz happen at the same time point on the time scale $Ta3$ and then there is no causal relation between y and dz on $Ta3$, while the change of y causes that of dz after a small time interval t_2 on the time scale $Ta2$.

When model builders describe a phenomenon in terms of differential equations, the modeling rationale is to capture dynamic changes in the transitional behavior in $Ta3$ to its equilibrium. In general, it implies that the time interval to achieve its equilibrium is longer than the other phenomena.

(b) Time Constant Modeling

In order to represent differences in time constants, this modeling technique divides the target system into such parameter sets where the time intervals to achieve equilibrium $Ta4$ are extremely different from each other. In such a model, the (relatively) faster mechanism firstly reaches the equilibrium on the time scale $Tb1$. Then the reasoning shifts to the time scale $Tb2$. This kind of modeling is found in [Iwasaki and Simon, 1994; Kuipers, 1994]. This modeling has an advantage in reasoning efficiency because of separation of the reasoning space.

(c) Component Structure Modeling

This modeling is to divide the whole system into subparts according to component structures based on the device ontology [de Kleer and Brown, 1984]. In this article, devices in the minimum grain size are called "components". $Tc1$ represents internal behavior in components, while $Tc2$ represents behavior between neighboring components. Interactions between the global structures containing components are represented by $Tc3$. Those between more coarse-grained global structures are also represented by $Tc3$. $Tc4$ represents that the whole system eventually reaches equilibrium. The ordinal relations among these time scales reflect structural distances.

Although $Tc2$ and $Tc3$ have the interval-meaning, the connection information alone cannot give the ordinal-meaning to them. We will discuss additional knowledge for the ordinal-meaning later. On the other hand, $Tc1$ has no physical meaning in any sense. This modeling technique implies such modeling rationales that the causal relations should reflect functioning components and the medium flow along the structures.

(d) Modeling of Periods of Interest

This modeling allows the reasoning engine to treat only particular temporal periods of interest such as initial behavior. The time scales constrain not length but the number of time intervals. For example, QUAF [Rose and Kramer, 1991] reasons only the initial changes $Td1$ and the final responses $Td3$ without the intermediate transient behavior. This technique

[2] This term represents such simultaneous equations which cannot be solved by substitution alone, borrowed from [de Kleer and Brown, 1984].

Table 2: Causal time scales in reasoning systems

QSIM [Kuipers, 1994]	$T1_{qs} : Ta3, T2_{qs} : Ta4$
QSEA [Kuipers, 1994, ch.7]	$T_{qa} : Ta4$
Time-Scale [Kuipers, 1994, ch.12]	$T1_{ts} : Ta3$ & $Tb1$, $T2_{ts} : Ta4$ & $Tb1$, $T3_{ts} : Ta3$ & $Tb2$, $T4_{ts} : Ta4$ & $Tb2$
QUAF [Rose and Kramer, 1991]	$T1_{qf} : Ta3$ & $Td1$, $T2_{qf} : Ta3$ & $Td3$
Mythical Time [de Kleer and Brown, 1984]	$T1_{mt} : Ta1$ & $Tc1$, $T2_{mt} : Ta1$ & $Tc2$, $T3_{mt} : Ta3$ & $Tc4$
Causal Ordering [Iwasaki and Simon, 1994]	$T1_{co} : Ta2$, $T2_{co} : Ta3$
Abstraction [Iwasaki and Simon, 1994]	$T1_{ab} : Ta2$ & $Tb1$, $T2_{ab} : Ta3$ & $Tb1$, $T3_{ab} : Ta2$ & $Tb2$, $T4_{ab} : Ta3$ & $Tb2$

contributes to disambiguation of reasoning results and avoiding reasoning costs.

3 Causal Time Scales in Reasoning Systems

3.1 Causal Time Resolutions

Let us characterize some of the existing reasoning systems in terms of the causal time scales. In general, a time resolution of a reasoning system is specified by a set of combinations of the primitive time scales discussed thus far. The notation $T_1 : Tx_1 \& Tx_2$ represents that the time scale T_1 consists of Tx_1 and Tx_2. Table 2 shows the time scales which can be treated by some conventional qualitative reasoning systems. For example, QSIM[Kuipers, 1994] can cope with behavior on $Ta3$ and $Ta4$. QSIM uses only mathematical differential equations and adopts a kind of generate-and-test method for constraint satisfaction. Thus, no causal relation among transitional behavior to $Ta3$ is identified. The time of QSIM is corresponds to $Ta3$. QSEA[Kuipers, 1994, ch.7] treats only equilibrium states represented by $Ta4$. The time-scale abstraction[Kuipers, 1994, ch.12] is a kind of the time constant modeling represented by Tb. QUAF[Rose and Kramer, 1991] reasons only the initial changes $Td1$ and the final responses $Td3$ on the integral time scale $Ta3$.

The method proposed in [de Kleer and Brown, 1984] can generate causal relations among more fine-grained time scale $Ta1$, called "mythical time", on the basis of the concept of device. Causal relations on $T1_{mt}$, however, do not always have the physical meaning because $T1_{mt}$ consists of $Ta1$ and $Tc1$. On the other hand, in order to give the ordinal-meaning to $T2_{mt}$, de Kleer and Brown employ general heuristics representing physical intuitions. Causal relations generated by them, however, are ambiguous due to the arbitrariness of heuristics application.

The causal ordering theory [Iwasaki and Simon, 1994] derives causal relations on $Ta2$, which have the ordinal-meaning representing mathematical dependency. The theory, however, does not try to derive those on $Ta1$. Two abstraction techniques corresponding to Tb are also discussed.

3.2 Primitive Reasoning Scheme

The primitive reasoning scheme of a reasoning system can be specified by the set of time scales which the system can cope with. Let TS be such a set and E_c be a current set of events to be carried out. The generic reasoning scheme for a current time scale T_c and neighboring time scales T_1 and T_2 where $T_1 \prec T_c \prec T_2$ is defined as below.

1. On the time scale T_c, if an event $e_1 \in E_c$ satisies the precondition T_c:Pc, the operator T_c:Op is applied to e_1 and then a new event e_2 and a new link l between e_1 and e_2 are generated. $\tau(l) = T_c$ holds.
2. The reasoning process shifts to the shorter time scale T_1. $T_c \leftarrow T_1$ and $E_c \leftarrow e_2$ and go to step 1 recursively[3].
3. If e_2 does not satisfies the boundary condition T_c :Bc, go back to step 1 and $E'_c \leftarrow E_c - \{e_1\} + \{e_2\}$.
4. If e_2 satisfies the boundary condition T_c:Bc, the reasoning process shifts to the longer time scale T_2. All events in T_c are transferred to the event e_3 on T_2. Go to step 1 recursively.

The reasoning process starts with the minimum time scale T_{min} in TS, given the initial value E_c. This reasoning process repeats recursively until the boundary condition of the maximum time scale holds. There are such cases that T_{min} needs a special operator to satisfy the precondition of T_{min}.

The reasoning processes of the conventional systems can be explained by their time scales shown in Table 2. For example, the reasoning method called time-scale abstraction [Kuipers, 1994, ch.12] starts with the minimum time scale $T1_{ts}$. Since $T1_{ts}$ contains $Ta3$, the operator for $T1_{ts}$ is the integration[4]. When the boundary condition of $T1_{ts}$ becomes true, i.e., the faster system reaches equilibrium, the reasoning process shifts to $T2_{ts}$. Because the system is in equilibrium, no reasoning is carried out in $T2_{ts}$. Then, the reasoning process in $T3_{ts}$ starts and then the slower behavior is generated. In principle, the reasoning process at $T3_{ts}$ backs to the shorter time scales $T1_{ts}$ and $T2_{ts}$. In this case, however, because $T2_{ts}$ is in equilibrium and hence has no more events, only checks of values are needed. The primitive scheme of the algorithm shown in [Kuipers, 1994] is identical with this one.

The reasoning result consists of a set of events E and a set of links L each of which has a time scale $T \in TS$ associated with it where $\tau(l) = T$. If there is a (transitive) causal relation between e_1 and e_2, $\tau(e_1, e_2)$ denoting the time scale representing the time interval between e_1 and e_2 is defined as follows;

$$\tau(e_1, e_2) = \max_{l \in Le} \tau(l)$$

where $L_e \subset L$ consists of the links between e_1 and e_2. This implies that a chain of time intervals represented on a time scale can be represented on the same time scale. In other words, time intervals on a time scale T_1 can never become longer enough to be categorized into the longer time scales

[3]The symbol '$\leftarrow$' denotes substitution

[4]Strictly speaking, the operator of QSIM is not identical with integration. It represents possible transitions over time for reasoning efficiency.

than T_1 unless the boundary condition is satisfied. In the cases of no causal relation, if $\tau(e_0, e_1) \prec \tau(e_0, e_2)$ where e_0 represents the last common event (i.e., the junction event), we only can say that e_1 happens before e_2. If not, there is no temporal order between such events.

3.3 Feedback and Causal Time Scales

Such phenomena that the effect of an event of a parameter is eventually propagated to the parameter itself are called as feedback. The time delay along the feedback loop plays a crucial role in human understanding of feedback. For example, in the cases where the time delay along a feedback is very short and then the modeler has no interest in the transitional behavior of the feedback, it is no need to generate causal relations among events in the feedback loop and to trace the changes of parameter values. Therefore, the reasoning engine can treat feedback according to the following heuristics.

Feedback heuristics : Whether or not a phenomenon is recognized as feedback depends on the time delay for the propagation loop according to the pre-defined threshold values T_{s1} and $T_{s2} \in TS$. Let L be a set of the links contained in the propagation loop and T_l be the time scale for the time delay along the loop.

1. If $T_l \preceq T_{s1}$ then the phenomenon is not treated as feedback. The orders of events in L have no physical meaning. If the new value after the feedback is different from the original value, that is viewed as contradiction at the same time point.
2. If $T_l \succ T_{s1}$ and $T_l \preceq T_{s2}$ then the phenomenon is treated as *semi* feedback. The orders of events in L have the physical meaning. If there is a conflict between the old and new values then the new value is neglected.
3. If $T_l \succ T_{s2}$ then the phenomenon is treated as feedback. The orders of events in L have the physical meaning. The values will be changed after the feedback.

The last one corresponds to the usual feedback. The first two are paraphrased as "the feedback is virtual, produced by the sequential operations of the reasoning method" and "there is no feedback which suppresses the original change instantaneously", respectively.

4 Time Scales for Fluid Systems

This section discusses a causal time resolution required to derive the causal relations in the fluid-related systems. A finer-grained time resolution than those of the conventional systems is required. Our reasoning system satisfying the required time resolution is also mentioned.

4.1 Required Time Resolution

Table 3 shows a time resolution, i.e., a set of time scales, required to derive causal relations in fluid systems based on the device ontology. The necessity to distinguish among these time units is justified by human recognition of causality or some assumptions. Firstly, the device ontology requires the discrimination between $Tc1$ of the $T1$:*inter-component time scale* and $Tc2$ of the $T2$ *inter-component time scale*. Secondly, in order to cope with global phenomena such as

Table 3: Time Scales required for Fluid Systems

Name of time scale	*Definition*
$T1$:*Intra-Component time scale*	$Ta1/2$ & $Tb1/2$ & $Tc1$
$T2$:*Inter-Component time scale*	$Ta1/2$ & $Tb2$ & $Tc2$
$T3$:*Global time scale*	$Ta1/2$ & $Tb2$ & $Tc3$
$T4$:*Globally Simultaneous time scale*	$Ta1/2$ & $Tb1$ & $Tc3$
$T5$:*Integral time scale*	$Ta3$ & $Tb2$ & $Tc3$
$T6$:*Partial Equilibrium time scale*	$Ta4$ & $Tb2$ & $Tc3$
$T7$:*Complete Equilibrium time scale*	$Ta4$ & $Tb2$ & $Tc4$

$T1 \prec T4 \prec T2 \prec T3 \prec T5 \prec T6 \prec T7$

changes in temperatures caused by global heat balances, hierarchical structure ($Tc3$ of $T3$ and $T4$) is needed. The length of time interval of $T3$ is longer than that of $T2$ because of the structural distance represented by $Tc2$ and $Tc3$. There are, however, such cases where changes in non-neighboring components are simultaneous, called *globally simultaneous phenomena*. For example, on the assumption that fluid is incompressible, flow rate of such fluid at each component changes at the same time. Thus, $T4$:*globally simultaneous time scale* which is combination of $Tc3$ and $Tb1$ is needed. Since it is assumed that there is only one level of faster mechanisms which is represented by $T4$, the other scales are on $Tb2$. Because $Tc1$ in $T1$ represents the most primitive concept in the device ontology, $T1 \prec T4$ holds. Because $T4$ represents almost simultaneous phenomena, $T4 \prec T2$ holds.

4.2 A Reasoning System for Fluid Systems

We have developed a reasoning system which can cope with the above seven time scales finer than those of the existing systems [Kitamura *et al.*, 1996a; Kitamura *et al.*, 1996b]. In general, a main issue to discuss is what contents we have to describe in order to build such a model that generates causal relations having the physical meaning. For the required time resolution, we employ the modeling schemes such as hierarchical components modeling, description of time constants and causal characteristics of components. The last knowledge enables the reasoning engine to give the physical meaning of causal relations among components on the $Tc2$ of $T2$. As discussed thus far, additional knowledge is needed for the physical meaning on $Tc2$. Considering components have their own causal characteristics, our approach is to explicitly describe inherent causal characteristics of each parameter in components, called *causal specifications*, context-independently. Although such a description is prone to dependent on context as discussed in [de Kleer and Brown, 1984], categories of causal relations [Kitamura *et al.*, 1996b] helps capture causal characteristics context-independently.

The reasoning method of our reasoning system is based on the general reasoning scheme discussed in section 3.3. The reasoning of feedback is based on the feedback heuristics. In our system, since a part of causal relations in $T1$ have no physical meaning and $T4$ represents a very fast mechanism, the threshold values T_{s1} and T_{s2} are set to $T1$ and $T4$, respectively.

The reasoning system has been successfully applied to a power plant [Kitamura *et al.*, 1996b]. The model of the whole system consists of 27 components, 143 parameters and 102 constraints. All the reasoning results matched those obtained by a domain expert including their ambiguities.

5 Related Work

The time concept in QSIM is discussed in [Kuipers, 1994] from the mathematical viewpoint, which is categorized into Ta or Tb. Iwasaki and Simon show a causal ordering theory for hierarchical sets of variables and discuss how to generate such hierarchical sets according to time scale and strength of interaction among variables [Iwasaki and Simon, 1994]. The causal time ontology allows us to clarify the modeling rationales underlying such sets from the physical viewpoint.

Ontologies of time itself have been discussed elsewhere such as [Allen, 1984] where Allen has identified primitives for representing time itself, and categorized of logical relationship between them. The causal time ontology provides cognitive categories of time intervals from the viewpoint of causal ordering of physical systems.

In [de Kleer and Brown, 1984; Top and Akkermans, 1991], although general causal properties of devices have been identified, causal relations generated by their methods are ambiguous in the case of inherently simultaneous equations. The TQ analysis [Williams, 1984] provides heuristics to analyze limited kinds of feedback according to time delay. A part of our causal specification corresponds to the descriptions of "exogenous parameters" [Iwasaki and Simon, 1994] of each component.

In [Forbus, 1984; Washio, 1989], causal characteristics of physical processes are described. One of our global constraints corresponds to an energy constraint (a global filter) for QSIM [Fouché and Kuipers, 1992].

6 Summary

We have proposed a causal time ontology containing a set of causal time scales shown in Table 1 to reveal the structure of causal time underlying the qualitative models and the causal reasoning engines. Some conventional reasoning systems have been characterized with respect to causal ordering using the time scales shown in Table 2. Furthermore, we present a reasoning system which can generate finer-grained causal relations than the existing systems.

We confined the topic to continuous changes. A discrete model of a phenomenon is, however, often the result of modeling according to such a rationale that the phenomenon is extremely faster than other phenomena, as discussed in [Iwasaki *et al.*, 1995; Nishida and Doshita, 1987]. Thus, such discrete models can be viewed as another kind of temporal modeling techniques discussed in this article. Investigation on such discrete changes remains as future work.

As discussed in section 4, the causal time scales enable us to specify temporal performance required to derive desired causal relations. They can be viewed as specification of goal of design. They will govern the constituents of the models and the reasoning procedures. Investigation on design methodology of causal reasoning systems based on the causal time scales is in progress.

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