TR-697

Temporal Disambiguation in Qualitative Reasoning Based on the Hierarchical Time-Scale of Local Information

by

H. Shinjo, M. Ohki, E. Oohira &
M. Abe (Hitachi)

October, 1991

ICOT

Mita Kokusai Bldg. 21F
4-28 Mita 1-Chome
Minato-ku Tokyo 108 Japan

(03)3456-3191 ~ 5
Telex ICOT J32964

Institute for New Generation Computer Technology

Temporal Disambiguation in Qualitative Reasoning Based on the Hierarchical Time-Scale of Local Information

Hiroshi Shinjo, Masaru Ohki, Eiji Oohira and Masahiro Abe

Central Research Laboratory, HITACHI, Ltd.
Higashi-koigakubo, Kokubunji, Tokyo 185, Japan

ABSTRACT

Temporal ambiguity is an intrinsic problem of qualitative reasoning in predicting complex systems, because many quantized variables in a system may change simultaneously and qualitative reasoning therefore cannot determine the correct temporal order of transitions in the system. Conventional methods for temporal disambiguation require total model representation, which provides global system information, but constrains the reasoning. A method is introduced which uses a total model, but reasoning is done with local information, represented by variables and local relations among variables. This new reasoning method reduces the temporal ambiguity using local information without global information, where the variables are given hierarchical structure according to a time-scale of transitions. Variables within each hierarchy are treated separately, so faster and slower transitions are predicted independently. Predicting the faster transitions is given priority. After each slower transition prediction, predication is shifted back to the faster transitions. Therefore, the prediction is more accurate than with conventional methods. As a result, this method can deal with cyclic, behavior in addition to monotonic behavior.

1. Introduction

Qualitative reasoning is a prime method for simulating behavior of physical systems with incomplete knowledge. Various kinds of qualitative reasoning methods and their applications have been studied in several engineering fields [Nishida 88a, Nishida 88b].

As qualitative reasoning predicts behavior by using only behavior characteristics based on qualitative values, which are represented by plus, minus, or zero, the complexity of qualitative reasoning computation is lower than that of numerical simulation. But, because of the qualitative values, qualitative simulation has more prediction ambiguity.

Temporal ambiguity is an intrinsic problem in predicting complex physical systems. A complex system may have many variables, but each variable changes independently. Since qualitative values are used, qualitative reasoning cannot derive the correct temporal order of transitions in the system. Therefore, it cannot determine the next state of the faster transitions. This ambiguity results in multiple transition state possibilities. Figure 1 shows an example of temporal ambiguity in the case of two variables.

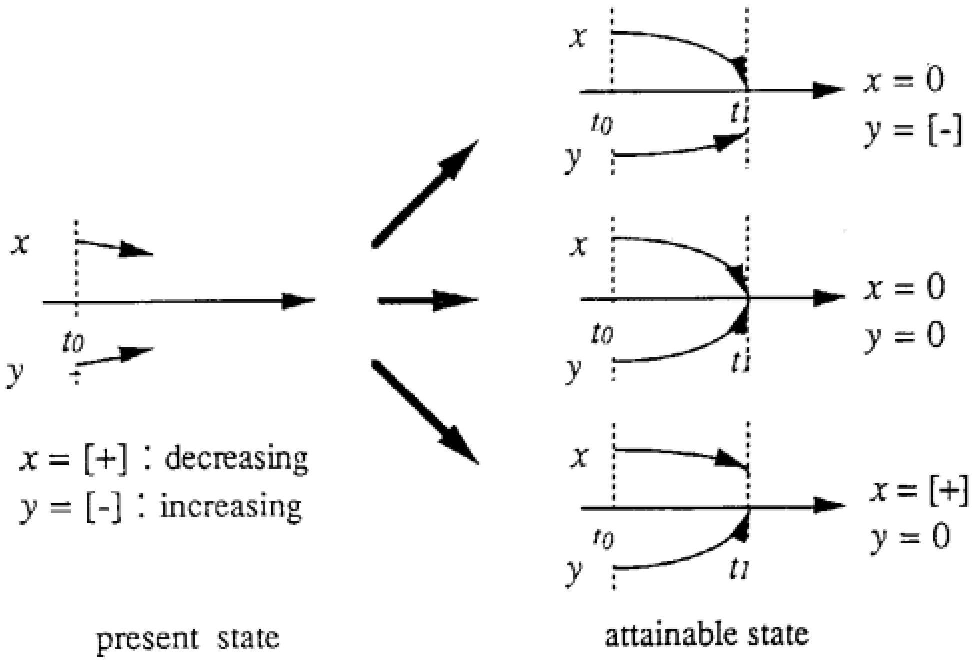

Figure 1. Temporal ambiguity in the case of two variables

Conventional researches have tried to reduce this temporal ambiguity. Kuipers used a hierarchical structure to reduce the temporal ambiguity between the water and the sodium balance mechanisms in medical physiology [Kuipers 84]: hierarchy is useful in reducing ambiguity and the complexity of computation, because it reduces the numbers of next state possibilities. Tanaka also used hierarchy to reduce temporal ambiguity [Tanaka 88].

However, Kuipers' method uses a total system model, which contains global relations and constraints. This method defines system mechanisms in a hierarchical structure. A mechanism is described by qualitative equations based on global constraints. Global constraints influence the method of reasoning. In comparison, other methods predict behavior by constructing a global model based on local information, which is represented by variables and local relations among variables. QPT [Forbus 84] and Qupras [Ohki 86, Ohki 88] are included in this latter method. Our qualitative reasoning system extends Qupras.

We will first present a new method for qualitative reasoning using local information. This reasoning method cannot use a hierarchical structure due to global information as well as Kuipers' method, because the reasoning is based on local information. If global information representing the total model is used, the hierarchy is structured based on the functions which describe the dynamics among the model variables. But, If reasoning uses only a local model, these functions cannot be used. Therefore, a hierarchy is structured based on variables.

Next we will address cyclic behavior using a hierarchy based on the time-scale of transitions which are influenced by variables. In other words, a hierarchy of variables that uses only local constraints is used. Without the influence of global constraints, our method can predict system behavior. And faster and slower transitions are also treated separately based on the hierarchy. In communicating information across hierarchies, local relations are propagated. As a result, our method can deal with cyclic, as well as equilibrium, behaviors, whereas Kuipers' method deals only with equilibrium behavior and Tanaka's method cannot deal with cyclic behavior.

2. Description of Qupras

Qupras is a qualitative reasoning system, which uses the physical lows found in physics and engineering [Ohki 86, Ohki 88]. The characteristics of Qupras are as follows:

(1) Qupras uses three primitive representations to describe an object system: physical rules (laws of physics), objects, and events.

(2) Qupras uses reasoning to determine the dynamic behaviors of a system without being given a total representation of the object system. It builds a complete expression for the object system using its knowledge of physical rules, objects and events.

(3) Qupras uses equations which describe the basic laws of physics qualitatively and quantitatively.

(4) Qupras does not require quantity spaces in advance. It locates quantity spaces itself during the reasoning process.

(5) Object expressions can inherit the definitions of their super objects. Due to this feature, physical rules can be defined generally by using the super definitions.

Qupras is similar to QPT [Forbus 84] in that each of them constructs a model representing an object system. Modeling is based on local information which is described by local relations. A key difference between Qupras and QPT is that Qupras uses only equations without influences. Qupras aims to represent the physical laws found in physics and engineering. These physical laws are described not by using influences, but by using only equations. Another key difference is that Qupras can deal with not only qualitative, but also quantitative values for representations. When quantitative values are derived, they are used in reasoning which results in less ambiguity than when only qualitative values are used.

Qupras qualitative reasoning consists of two types of reasonings: propagation reasoning and prediction reasoning. Propagation reasoning determines the state of the physical system at a given moment (or during a given time interval). Qupras constructs a model of an object system using simultaneous differential equations. The model applies the laws of physics, objects and events to a given state. These are considered local information. Propagating these constraints determines the state of system. Prediction reasoning analyzes the landmarks which the variables in the physical system may reach at the next instant. After this prediction, propagation reasoning determines the next states of the complete physical system by using the results of the prediction reasoning.

3. Hierarchy of variables based on time of transition

There are many transitions in a complex system. Some transitions are faster, some are slower, and others are much slower. For example, consider the case of flashlight. If the switch is turned on, the light bulb is quickly turned on but the battery discharges more slowly. In this case, turning on the light bulb is a fast transition, whereas the battery discharge is a slow transition.

Changing some variables can change particular transitions from one state to other state in a system. In the case of the flashlight, a light bulb turns on due to a quick increase of the electric current, and the battery discharges due to the continuous slow voltage-use.

An effective modeling method is to break a complex system into several manageable transitions based on variables. If each change variable is separable, we can reduce the ambiguity in separating faster and slower transitions. In brief, the faster transitions are first predicted until they reach the same state which has already reached. Then the slower transitions are predicted. This procedures is repeated recursively.

Therefore, in order to reduce temporal ambiguity in qualitative reasoning, we separate the system variables in a hierarchical structure, based on the time-scales of transition to the next state. When the faster and slower variables do not interact, developing this hierarchy is simple. The faster ones go into a faster hierarchy and the slower ones into a slower hierarchy. When the faster and slower variables do interact, the hierarchy is still similar. For example, when the interactions are assumed to be as follows:

$$x = f_1(s),\ y = f_2(x,t),\ z = f_3(y,u)$$

where x is the fastest variable, y is slower than x, and z is the slowest, and x depends on variable s, y depends on variables x and t, and z depends on variables y and u. The fastest transition is f_1, f_2 is the second fastest, and f_3 is the slowest.

The fastest hierarchy includes x and s, the second fastest includes y and t, and the slowest includes z and u.

4. Hierarchical Control of Qualitative Reasoning

4.1 Analysis of transitions within each hierarchy

Our method decomposes a complex system into several hierarchical structures using transitions separated by time-scales. We therefore need to determine on which transition discipline to focus, and how variables should change. The fundamental disciplines are as follows:

(1) The faster transitions have priority for change over slower ones, when both of them are progressing and the present state differs from all states which the system has already reached. The faster transition variables change the next values (landmarks), while the slower variables are regarded as progressing slowly, and do not change to the next values.

(2) The slower transitions have higher priority for change over faster ones, when both are progressing, but the present state is the same as one which the system has already reached. After the slower variables change to the next values, the analysis shifts back to the fastest transitions of all. In short, After each slower variable change, the focus of attention is shifted back to the fastest transitions.

4.2 Communication of Information across Hierarchies

We need to communicate the information derived within each hierarchy when the focus of attention shifts from one hierarchy to another. The information must flow in two directions: one is from faster to slower, and from slower to faster. Both information flows are handled as follows.

If a present state is the same as the already predicted state due to the change-faster variables, this state will reach an equilibrium state or be one state during cyclic transition. The slower variables are then changed to their next landmarks. At this point, the slower variables have priority in determining the state of the whole system. The slower variables are first propagated and they determine a portion of the state. Then the final values of the faster variables in the previous state are propagated. If there are constrains between the faster and slower variables, they are also propagated. If the final values of the faster variables are consistent with the partially determined state, they are adopted. Otherwise they are not adopted. Not all focus shifts are smooth transitions. With discontinuous transitions, the final values of the faster variables are not always the same as the initial values of the faster variables in the slower variable transitions.

When a present state is the same as the already predicted state due to change-slower variables, the focus of attention shifts back to the fastest variables of all. The initial values of the next transition are the final values of the slower transition, because the slower variables and constraints have been propagated. Since the focus of attention shifts back to the fastest transition variables after each change of the slower variables, our method can handle cyclic behavior. When faster transition is cyclic, if attention continues to be focused on the slower variables, cyclic behavior during one step of the slower transition cannot be predicted and is ignored. Since the faster transitions have priority, various types of motion can be predicted.

Our method, of course, can handle a system that includes equilibrium or monotonic transitions. If the faster variables reach an equilibrium state, the focus of attention shifts to the slower variables. After the slower transitions are analyzed, focus shifts back to the faster ones and an analysis of the faster variables is made. But if the faster transitions have reached an equilibrium and have not changed, focus shifts back to the slower ones again, without changing the faster variables. This procedure repeats recursively.

4.3 Algorithm

The algorithm for our process is as follows.

(1) Pick up the changing variables from each level of the hierarchy.

(2) Change the values of all changing variables to their landmarks and shift the system to the next state, if their condition of change is instant state, which changes to another state immediately.

(3) Change the fastest changing variables to their landmarks and shift the system to the next state, if their condition of change is an interval state, which continues for a moment.

(4) Repeat steps (1) to (3) until the present system state is the same as the already predicted state.

(5-1) If there are no second fastest changing variables, regard the behavior of the system as repeating the motion of the past predicted states. Therefore, stop the prediction.

(5-2) Otherwise, change the second fastest changing variables to their landmarks and shift the system to the next state.

From (5-2)

(6) Shift the focus of attention back to the fastest transition.

(7) Repeat steps (1) to (6) until the present system state is the same as the already predicted state again.

(8-1) If there are no third fastest changing variables, regard the behavior of the system as repeating the motion of the past predicted states. Therefore, stop the prediction.

(8-2) Otherwise, change the third fastest changing variables to their landmarks and shift the system to the next state.

From (8-2)

(9) Repeat the above steps and change all variables within all hierarchies.

(10) If the next state is the same as the already predicted state after changing variables within all hierarchies, or there are no changing variables, stop the prediction.

5. Example

In order to illustrate our method, let us consider the gasoline engine shown in Figure 2. In this case, we simplify the problem, by considering only the back and forth motion of the piston and the consumption of gasoline. The piston motion is a quick and cyclic transition, but the consumption of gasoline is a slow transition. If we try to predict this problem without separation of transitions, multiple answers are possible due to the influence of temporal ambiguity of qualitative reasoning. Because the nonseparation method cannot distinguish the difference in speed between the piston motion and the consumption of gasoline, the following three answers are possible:

(1) The gasoline may run out after the piston repeats it cyclic motion.

(2) The gasoline may run out before the piston completes one motion cycle.

(3) The gasoline may run out before the piston starts its motion.

Normally we do not consider (2) and (3).

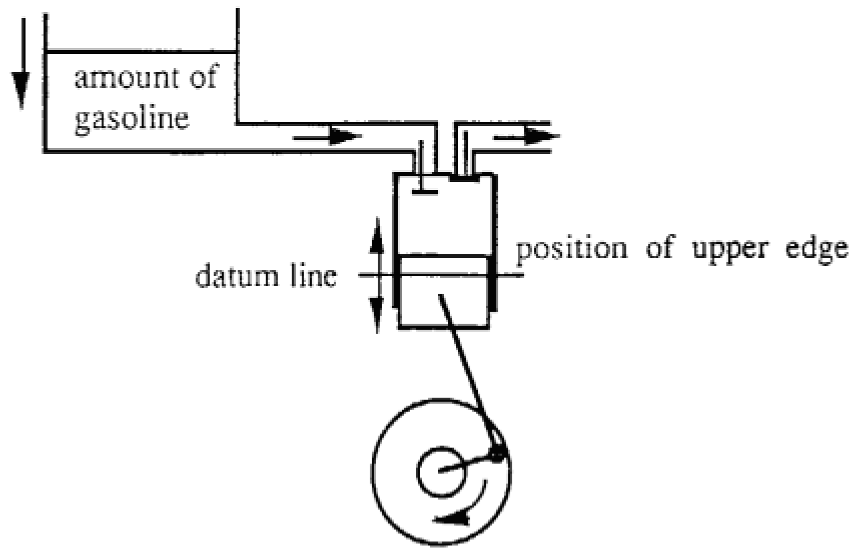

Figure 2. Piston and gasoline

The faster transition is the movement of the piston and the slower transition is the consumption of gasoline. Therefore the faster variables are the velocity and the acceleration of the piston and the slower variable is the amount of gasoline-used.

In order to simplify this problem, we regard piston movement as a simple harmonic motion. This harmonic motion and the consumption of gasoline are represented by the following:

$$x = -k\,a \qquad (1)$$

$$\frac{dx}{dt} = v \qquad (2)$$

$$\frac{dv}{dt} = a \qquad (3)$$

$$\frac{dG}{dt} < 0 \qquad (4)$$

where x is the displacement of the upper edge of the piston, v is the velocity, a is the acceleration, G is the amount of the gasoline, t is time, and k is a constant value. The initial values of these variables are defined as:

$$x = 10\,,\ v = 0\,,\ G = 0,\ k = -1.0 \qquad (5)$$

Tables 1 and 2 summarize an example of monitoring the gasoline engine in a series of reasoning steps. For each state, the table shows the qualitative or quantitative values of the piston, which are the displacement, the velocity and the acceleration of the piston. A bar indicates that the value is unknown due to predicting using qualitative values. The direction of the arrows shows the differential sign of the variables. An upward arrow represents a plus differential sign, which means the variable is increasing. A downward arrow represents a minus differential sign, which means the variable is decreasing. There are two types of states: instant state and interval state. An instant state changes to another state immediately: an interval state continues for a moment.

Table 1. Result of reasoning (normal case)

state	x	v	a	condition
1	—	0 ↓ (-10)	—	instant
2	10 ↓	- ↓ (-10)	-10 ↑	instant
3	+ ↓	- ↓	- ↑	interval
4	0 ↓	—	0 ↑	instant
5	- ↓	- ↑	+ ↑	interval
6	—	0 ↑	—	instant
7	- ↑	+ ↑	+ ↓	interval
8	0 ↑	—	0 ↓	instant
9	+ ↓	+ ↓	- ↓	interval
10	—	0 ↓	—	instant
11	+ ↓	- ↓	- ↑	interval
12	0	0	0	stop

-, 0, + : value of variable
↑, ↓ : direction of change (increasing, decreasing)
— : actual value is unknown
value in parentheses : differential value of variable
State 11 is same as state 3. So the focus of attention shifts to decrease of gasoline.
At state 12, the amount of gasoline is zero and the piston motion stops.

Table 2. Result of reasoning (special case)

state	x	v	a	G	condition
1	—	0 ↓ (-10)	—	10 ↓	instant
2	10 ↓	- ↓ (-10)	-10 ↑	+ ↓	instant
3	+ ↓	- ↓	- ↑	+ ↓	interval
4	0 ↓	—	0 ↑	+ ↓	instant
5	- ↓	- ↑	+ ↑	+ ↓	interval
6	—	0 ↑	—	+ ↓	instant
7	- ↑	+ ↑	+ ↓	+ ↓	interval
8	0 ↑	—	0 ↓	+ ↓	instant
9	+ ↓	+ ↓	- ↓	+ ↓	interval
10	—	0 ↓	—	+ ↓	instant
11	+ ↓	- ↓	- ↑	+ ↓	interval
12	+ ↓	- ↓	- ↑	0	shift the focus
13	0 ↓	—	0 ↑	0	instant
14	- ↓	- ↑	+ ↑	0	interval
15	—	0 ↑	—	0	instant
16	- ↑	+ ↑	+ ↓	0	interval
17	0 ↑	—	0 ↓	0	instant
18	+ ↓	+ ↓	- ↓	0	interval
19	—	0 ↓	—	0	instant
20	+ ↓	- ↓	- ↑	0	interval
21	—	—	—	—	no landmark

State 11 is same as state 3. So the focus of attention shifts to decrease of gasoline.
After state 12, the amount of gasoline is zero.
At state 20 is the same as state 12, and the state cannot change.
At state 21, there are no landmarks to change.

Table 1 is explained as follows. At state 1 and 2, the displacement of the piston begins to move at its maximum point, velocity begins at zero, and the gasoline begins decreasing slowly. From state 3 to state 10, the piston repeats instant and interval states, while the consumption of gasoline continues in a decreasing interval state. At state 11, the piston motion reaches the same state as at state 3. After state 11, the state of the piston repeats from state 3 to state 10 and the consumption of gasoline continues in a decreasing interval state. Therefore, the behavior of the piston does not need to be predicted any longer. At state 12, the focus of attention shifts to the consumption of gasoline, where gasoline runs out. The focus of attention then shifts back to the behavior of the piston, and piston stops due to the lack of gasoline.

Table 2 differs from Table 1 in the initial conditions, in order to clearly demonstrate the merits of our method. It assumes that the piston continues in simple harmonic motion even after the gasoline has been consumed. From state 1 to state 11, Table 2 is identical with Table 1. After state 11, the behavior of the piston is interpreted as a repeating cyclic motion, until the amount of the gasoline decreases to zero. At state 12, the focus of attention shifts to the consumption of gasoline, where gasoline runs out. After state 13, the focus of attention shifts back to the behavior of the piston, which is continuously analyzed. From state 13 to state 20, the behavior of the piston is identical with that from state 3 to state 11. At state 20, the motion of piston is the same as at states 3 and 11. At State 21, the attention shifts to the consumption of gasoline, but gasoline has already run out. From states 13 to 20; no variables change, in short, there are no landmarks. So the prediction is confirmed.

6. Discussion

It is hard for reasoning to consistent with low complexity of computation and high accuracy of simulation. Generally speaking, qualitative reasoning requires low complexity of computation but cannot derive fully accurate behavior of systems, whereas numerical simulation derives accurate behavior at the cost of high complexity of computation. Kuipers and Tanaka changed the situation by introducing the concept of hierarchical structures. Their methods improved the accuracy of qualitative reasoning without considerable increase of computation. Their methods handle equilibrium transitions in medical physiology, however, they cannot handle cyclic transitions. Since the attention continues to focused on the slower variables after the faster transitions reaches at the equilibrium state, their methods cannot distinguish cyclic from equilibrium behavior. Our method is better in the sense that it can handle the cyclic behavior. But the increase of computation is inevitable. Our method shifts the attention back to the fastest transitions of all after each slower transitions change. Thus the detail analysis of the behavior increases the complexity of computation. If our method is applied for the prediction of the equilibrium transitions which Kuipers can deal with, higher complexity of computation is required compared to Kuipers' method.

Our method separates the variables into hierarchical structures, whereas Kuipers separate the qualitative equations into hierarchical structures. This difference comes from the fact that a total system model is not given in our method. In other words, our method is able to predict behavior by constructing the total model by itself from the given local information, namely variables or local relations. Global information such as used in Kuipers' method is not available in our method

Our method can reduce the temporal ambiguity to some extent, but not completely. It cannot handle more complex systems such as the transitions change simultaneously and the time-scales are not clearly separated to hierarchical structures. Qualitative value alone is not sufficient for obtaining the accuracy in reasoning perfectly. In order to get more accuracy, qualitative reasoning needs to integrate quantitative values, depending on the situation. From this point of view, Forbus combine numerical simulation with qualitative reasoning [Forbus 90]. And our reasoning method is based on Qupras, which deals with quantitative values when they are available. We plan to extend this approach by introducing further quantitative treatment. For example, integration calculation can be effectively used for reducing the temporal ambiguity in circuit behavior which includes capacitors or inductors. The framework of our method has flexibility to integrate quantitative reasoning and qualitative reasoning when it is necessary.

7. Conclusion

We have discussed our method for reducing temporal ambiguity in qualitative reasoning. The characteristics of our method are as follows.

(1) A model is constructed to represent an object system. Reasoning is based on local information, thus it is not influenced by global constraints.

(2) To break the system into manageable transitions, the variables are separated into hierarchical structures, based on the time-scale of their transitions. This hierarchy of variables uses local constraints.

(3) After each slower transition analysis, the focus of attention shifts back to the fastest transitions of all.

As a result of these characteristics, our method can predict the behavior of various systems without using global constraints. It can handle not only monotonic behavior which has already been accomplished, but also cyclic behavior.

Future work will include expansion of our method to integrate qualitative reasoning and quantitative reasoning depending on the situation, in order to derive flexibility of reasoning and apply to complex systems in the real world.

7. Acknowledgments

Our research was supported by the Institute of New Generation Computer Technology (ICOT). We wish to express our thanks to Dr. Kazuhiro Fuchi, Director of the ICOT Research Center, who provided us with the opportunity to perform this research as past of the Fifth Generation Computer Systems Project. We also wish to thank Dr. Toyoaki Nishida at Kyoto University, for his many insightful comments and discussions.

References

[Forbus 84] Forbus, K. D.: Qualitative Process Theory, Artificial Intelligence, 24, pp. 85-168, 1984.

[Forbus 90] Forbus, K. D. and Falkenhainer, B.: Self-Explanatory Simulations: An Integration of qualitative and quantitative knowledge, Proc. of AAAI-90, pp. 380-387, 1990.

[Kuipers 84] Kuipers, B.: Commonsense Reasoning about Causality: Deriving Behavior from Structure, Artificial Intelligence, 24, pp. 169-203, 1984.

[Kuipers 87] Kuipers, B.: Abstraction by Time-Scale in Qualitative Simulation, Proc. of AAAI-87, pp. 621-625, 1987.

[Nishida 88a] Nishida, T.: Recent Trend of Studies with Respect to Qualitative Reasoning (I), Progress of Fundamental Technology, pp. 1009-1022, 1988 (in Japanese).

[Nishida 88b] Nishida, T.: Recent Trend of Studies with Respect to Qualitative Reasoning (II), New Research Area and Application, pp. 1322-1333, 1988 (in Japanese).

[Ohki 86] Ohki, M. and Furukawa, K.: Toward Qualitative Reasoning, Proc. of Symposium of Japan Recognition Soc in 1986, or ICOT-TR 221, 1986.

[Ohki 88] Ohki, M., Fujii, Y., and Furukawa, K.: Qualitative Reasoning based on Physical Laws, Trans. Inf. Proc. Soc. Japan, 29, pp. 694-702, 1988 (in Japanese).

[Tanaka 88] Tanaka, M. and Tsumoto, S.: Temporally-hierarchical Qualitative Reasoning and Its Application to Medicine, Proc. of the Logic Programming Conference 88, pp. 11-17, 1988.