Temporal Models for Multimedia Synchronization[1]

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Abstract–Multimedia synchronization has been studied by many researchers. Many approaches have been developed, some exist as proposals, others as established implementations. This fact, instead of being an advantage, is causing a great deal of confusion amongst researchers in communications, authoring, and user interface development. There is a lack of unified vision of the whole issue and it is difficult to evaluate and compare existing systems.

In order to address this problem, we have developed a Temporal Reference Framework which unifies existing theories. It gives the necessary definitions for referencing and evaluating individual systems and enables the comparison of different synchronization schemes. In this paper, we focus on the foundation of our Temporal Reference Framework: models of time. We do this by first presenting a detailed survey of what time is and how it can be modeled. We describe models of time following a consistent terminology. We then introduce our framework. Finally, we illustrate this study with current implementations of multimedia synchronization techniques.

Keywords: Models of time, temporal specification, synchronization techniques.

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1 Introduction

Multimedia synchronization plays a central role in distributed multimedia systems. Technical problems like network delays, database latencies, and limited/shared operating system resources have led researchers to define and create a big variety of multimedia synchronization techniques. Experts in synchronization have proposed classifications of existing techniques from different perspectives [3, 7, 16, 19]. These classifications are useful, but they have little in common. The field is very broad. It is very difficult to compare and evaluate systems because they do not share a common theoretical language.

The synchronization field lacks something that is very important. There is no *unified vision* of the synchronization issue that spans the areas of communication, user interaction, etc. With our research, we aim to solve this problem by providing the necessary theory. As a consequence of our studies, we have defined a *Temporal Reference Framework* that achieves the following goals:

- Unifies existing theories and explains what synchronization is and how it can be defined,
- enables the comparison of multimedia synchronization techniques and identifies similarities and differences among them, and
- gives guidelines for the design of new synchronization techniques and for the re-use (when possible) of already defined techniques.

Our reference framework is called *temporal* because we emphasize that the concept of time is fundamental to any synchronization technique. Time is the unification factor among all definition and enforcement mechanisms. Our temporal reference framework results from a study of time and its projection to the common technical problems of distributed multimedia systems: media types, user interaction, authoring systems, user interfaces, multimedia applications, communications, operating systems, quality of service, and databases.

In this paper we present the foundation of our temporal reference framework: time. The main contribution of this paper is a detailed study of what time is and how it can be modeled. We present a survey of classical ways of representing time and we define time and models of time following a consistent terminology. Also, we introduce our temporal reference framework and present some examples of its application to existing synchronization techniques.

The remainder of the paper is organized as follows. Section 2 presents the background information in which we have based our study. Section 3 presents our view of modeling time. We analyze the temporal information that we want to characterize and we describe the concept of models of time. Section 4 presents the projection of the models of time into multimedia synchronization techniques, and we introduce our temporal reference framework. Examples of synchronization techniques are presented in Section 5. Section 6 concludes the paper.

2 Background

Representing time in computer systems has been the topic of research for many years [4]. A lot of studies have been done and as a result a wide range of techniques have been proposed [1, 10, 14, 21, 23]. The main purpose of this section is to present a survey of time representation techniques. This survey is the background for our subsequent work on temporal models.

For our study we follow Allen's classification of time representation techniques [2]. He divides the proposed techniques in three general cases: dating schemes, constraint propagation schemes, and duration schemes (Fig. 1). We use this classification to discuss each one of these techniques in detail. We also present a comparison of them in Section 2.4.

2.1 Dating Schemes

A dating scheme is the classical representation of time for **instantaneous** events. It models the time **when an event occurs** (or must occur). Each event has associated time information indicating its occurrence date. Depending on the available information about the time of the events, we can divide this representation in time dates and pseudo-dates.

- If the available information consists of **time dates**, there are two possibilities.
  - **Points**: the exact time of the events is known. Each event is defined by a point in time (absolute or relative) (Fig. 2).
  - **Occurrence Intervals**: the interval within which the event is going to happen is known. The event is bound to occur between the latest and the earliest times of the interval (see Fig. 3). Again, the dates of the boundaries of the interval might be described in absolute or relative terms.

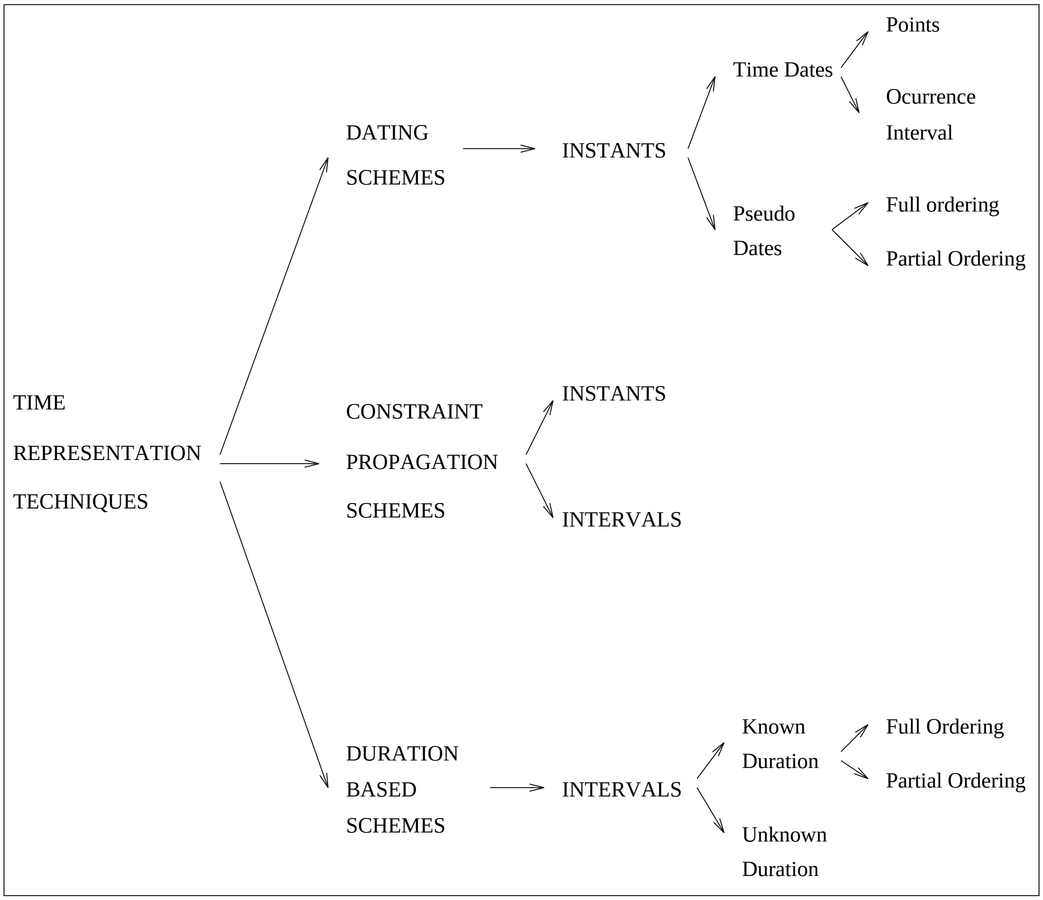


Figure 1: Classification of Time Representation Techniques

In both cases, the duration between two events is easily derivable. For points, it is a direct subtraction, and in the case of an interval of occurrence two possible values of the duration are obtained, minimum and maximum.

Discussion Although dating schemes are instant based representations, we can use them to represent intervals. We can model intervals through instants by establishing the starting point of the interval as an event in time (e.g., t_1) and the end point of the interval as another event in time (e.g., $t_2 = t_1 + duration$).

- If the available information is not time units and some information about the order of occurrence is known, the ordering information can be interpreted as pseudo dates and a **pseudo-date** scheme can be built. There are two cases:
  - **Full ordering**: the exact order of occurrence is known. The events follow a full linear order. Each event is characterized by the appropriate order in the sequence (see Fig. 4).

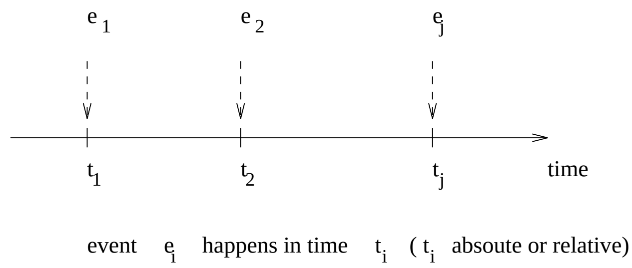


Figure 2: Data Scheme: Time Dates - Points

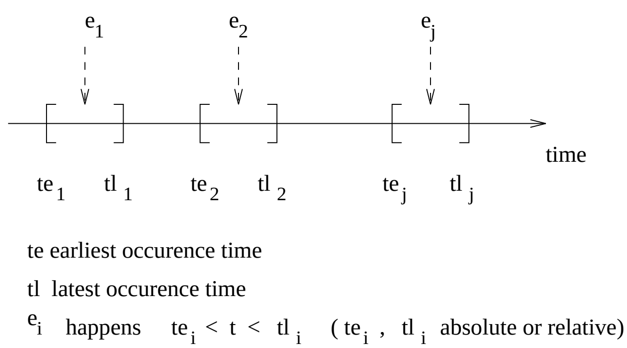


Figure 3: Data Scheme: Time Dates - Occurrence Interval

– **Partial ordering**: The exact order of the events is unknown, but some ordering relations among individual events are available. An example is shown in Fig. 5. It corresponds to the characterization of a *personal schedule*. We do not know the dates of the events, but we know certain relationships among them. It is known that we have to book the tennis court before going to play; that we have to go to buy food before cooking; that we have to be awake before doing activities; and that we have to play tennis and cook before eating. With this information

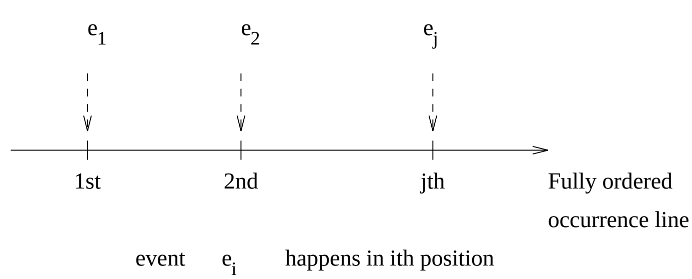


Figure 4: Pseudo-Date scheme: Fully Ordered

we can derive a partial order: two events are fixed as the first (awake) and the last (eating), but nothing is said about the relation between the other activities. Several orderings are allowed as illustrated in Fig. 5.

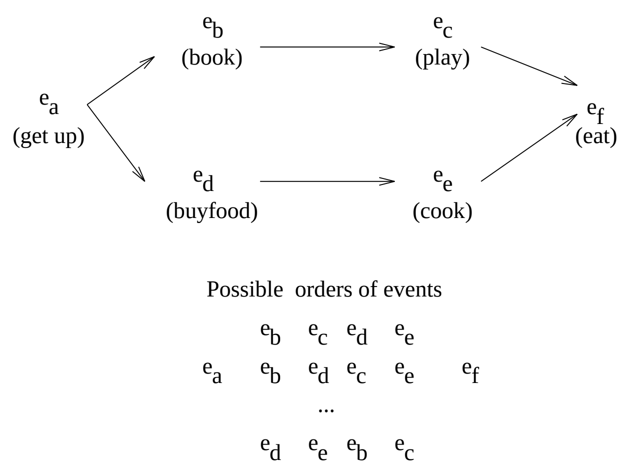


Figure 5: Pseudo-Date scheme: Partially Ordered

Discussion In both cases (pseudo-dating schemes, full and partial order), all information about the duration between events is lost. Therefore, we cannot model interval information with this technique. However, we can model intervals through pseudo-dates by assigning ordering information to starting and ending points of intervals, but without the possibility of defining anything about their duration.

2.2 Constraint Propagation Schemes

These techniques focus on the definition of **temporal relationships** between events. Graph-based representations are very useful, although other types of mathematical operators might also express these temporal relationships. These techniques consider events either as **instants** or **intervals**, as described below.

- **Instants**. Temporal relationships are expressed between instants of time. There are three basic relations between two instants of time: {`before, after, at_the_same_time`} $(<, >, =)$ (Fig. 6). More than one basic relationship can be specified between two instants. We can establish disjunctions of temporal relationships. For example, we can

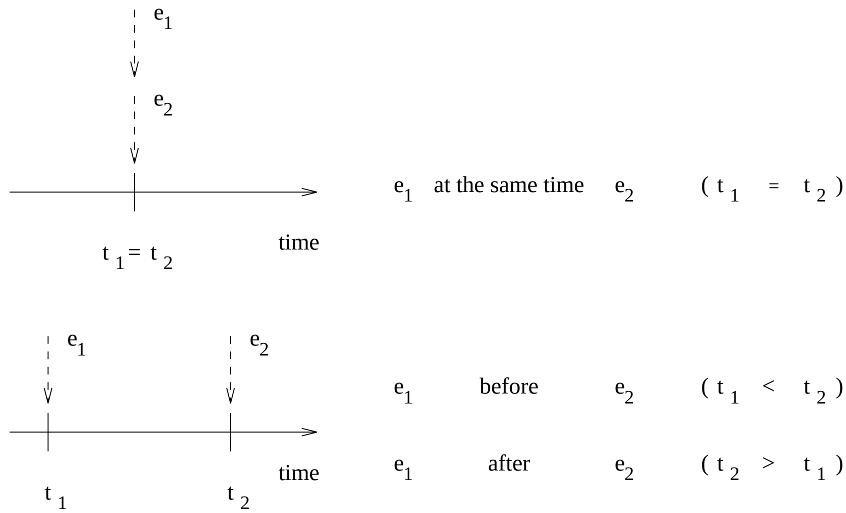


Figure 6: Three Basic Temporal Relationships between Two Instants

say e_1 is either `before` e_2 or `at_the_same_time` as e_2). The two possibilities are equivalent. In a graphical representation (Fig. 7), events are related with arcs. The arcs express the relationship or possible relationships between them. Notice that more than one temporal relationship can be specified between two instants.

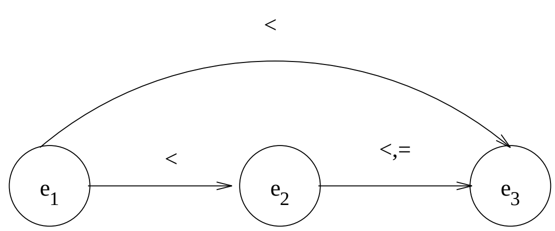


Figure 7: Graphical Representation for Instant Based Constraint Propagation Schemes

- **Intervals.** Temporal relationships are expressed between intervals. There are thirteen basic relationships between two intervals [10]. The thirteen cases can be reduced to seven (the other six are inverse cases). They are {`before, meets, overlaps, starts, during, finishes, equals`} (Fig. 8), with their inverses {`bi, mi, oi, si, di, fi`}.

  More than one temporal relationship can be specified between two intervals. We can establish that the relationship between two events is a disjunction of temporal relations (e.g., e_1 {`before,meets,overlaps`} e_2) [20]. The temporal information can also be represented as a graph. Fig. 9 presents the representation graph for an example

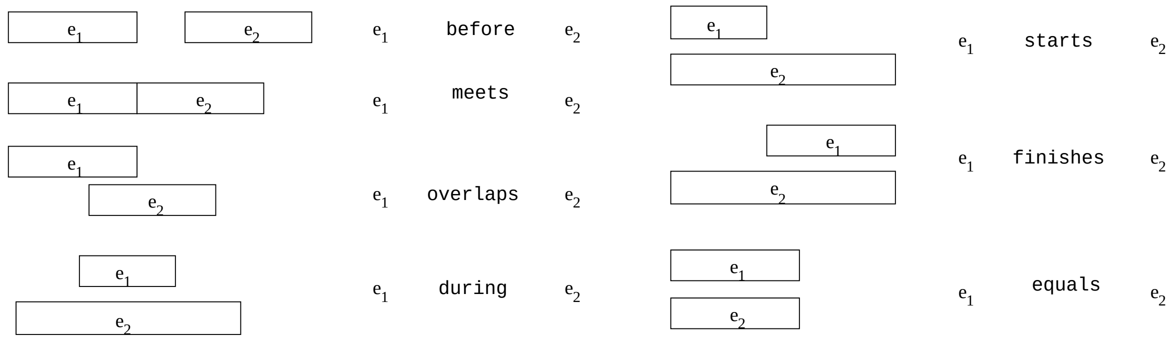
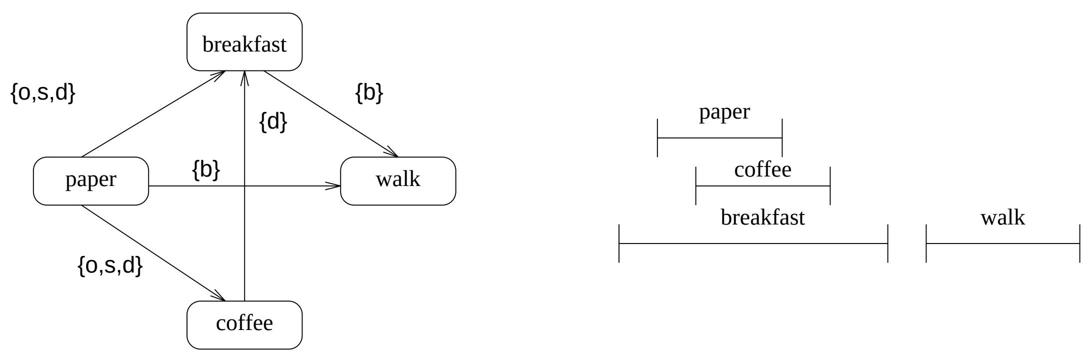


Figure 8: Seven Basic Interval Relations (plus Inverses, Thirteen)

where several relationships are specified between intervals. Fig. 9 (a) represents the translation of the temporal situation we want to model: "John was reading the paper while eating his breakfast. He put the paper down and drank the last of his coffee. After breakfast he went for a walk". Following the graph, we see that three relations between *paper* and *breakfast* are true. From the specification with various possibilities, a final solution with only one temporal relationship between two events must be found. Fig. 9 (b) presents a consistent solution for the specification in (a).



(a) Temporal relations **(b) A consistent solution**

Figure 9: Graphic Representation for Interval Based Constraint Propagation Schemes

In both cases (instants and intervals), the expression of the temporal relationships can be done in a quantitative or qualitative way (e.g., *event 1* occurs 3 seconds `after` *event 0* (quantitative); *event 1* occurs `after` *event 0* (qualitative)). If only basic relations with quantitative information are described, the possible solutions to the specification are reduced to one. But if we describe the temporal objective with qualitative information and more than one basic relationship is described for a pair of events, the final result is not completely determined, and we need specific algorithms to decide which is the result which best match the specifications. Algorithms are needed for dealing with incomplete and indefinite qualitative information [1, 21].

Discussion The instant based constraint propagation schemes have been used for modeling instants of time; but, as well as in the case of dating schemes, they also can be used to express interval relationships through starting and ending points of intervals [23]. Two examples of how to translate the interval relationships into instant relationships are shown in Fig. 10. On the left hand side, the interval relationship `before` is translated to one instant relationship between the end point of the first interval and the starting point of the second interval ($E_1 < S_1$). On the right hand side, the interval relationship `during` is translated into a combination of two instant relationships between the ending and starting points of the intervals $((E_2 < S_1)\,\&\,(E_2 > E_1))$.

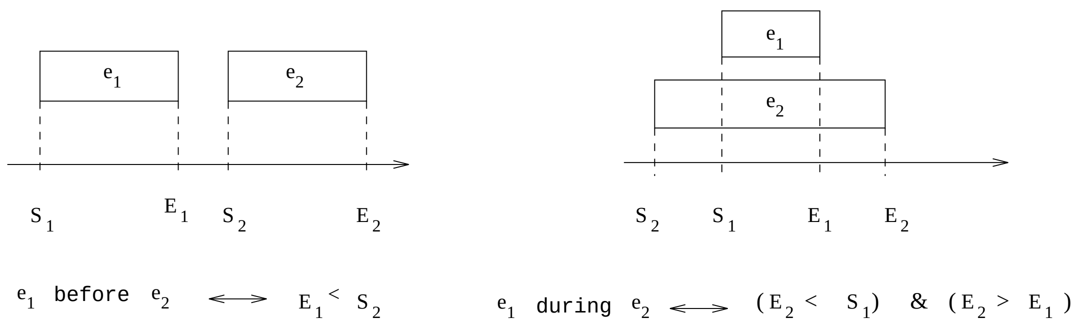


Figure 10: Translation between Interval and Instant Representations

The translation between the two ways of reasoning is true for all the basic relations but is not for all the possible set of complex interval relationships [15]. The problem arises when defining disjunctions of temporal relationships between intervals. This translation is examined in the following points.

- There are three basic relations between instants. Therefore, if we want to define more than one temporal relationship between two instants, all the possible cases are disjunctions of the basic ones. As a result, for two instants we can describe $2^3 = 8$ different situations (e.g., {`before` or `equals`} , {`equals` or `after`}).
- There are thirteen basic relations between intervals. Therefore, all the possible cases between two intervals are disjunctions of the basic, and are $2^{13} = 8192$ (e.g., {`starts` or `equals`}, {`finishes` or `overlaps`}, {`meets` or `after` or `overlaps`}).
- The expression of interval relationships can be done through combinations of instants relationships among the starting and ending points of the involved intervals (Fig. 10).

- The translation from the wide range of interval representations (basic relationships plus disjunctions, 8192) to the instant based representation (3 basic, 8 disjunctions, and combinations of them) is done without loss of information in 181 of the 8192 cases [15] (to find an enumeration of the translation of all the possible cases, see also [22]). These 181 cases are enough for most of the applications that consider time [23]. Nevertheless, not all these cases are usually considered.
- The basic instant relationships and combinations of them (no disjunctions) are capable to model up to 29 interval relationships (basic 13 plus disjunctions of them) [24]. For some applications, these 29 are enough, and it might be easier to work with a instant based representation with no disjunctions.

Therefore, for working with those 181 cases, or even more frequently only with the basic relations, the selection between instant or interval is up to the designer. Both are valid as long as the appropriate translation between the representations is known. The advantage of working with interval based representations is that they capture the relation directly and are more intuitive. The advantage of working with instant based representations is that for representing less than those 29 interval relationships, no disjunctions are required.

2.3 Duration-Based Schemes

In this case, the timing problem is addressed considering events as **intervals**, which are defined by their temporal **duration**. We can distinguish two cases:

- **Known Duration**. We consider the duration of events as an absolute and known entry to the definition of the event. This scheme requires the previous knowledge of the duration of all the involved events.

  For describing individual events temporal duration is enough, but for describing related events, we need some additional information. The techniques described in this group add ordering information to the duration of events. Depending on the exact knowledge of the order, we can divide the techniques in two others classes:

  - **Full order**. The exact order of the events is known. We have a description of a line with associated durations (see Fig. 11).
  - **Partial Order**. The exact order of the events is not known, but a partial order is. The basic technique of this type is the PERT network. PERT techniques

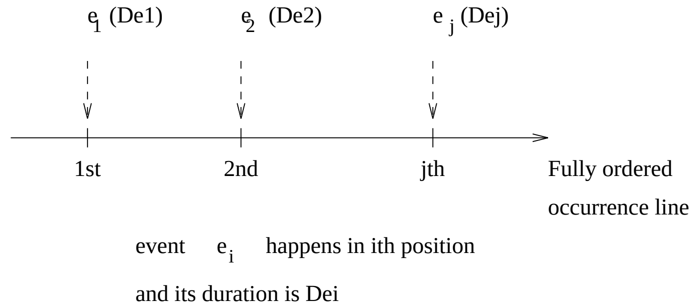


Figure 11: Duration based Scheme: Fully Ordered

receive as entries the duration of each event, and a relative idea of the order of occurrence, and build a graph. This representation maintains a partial ordering of events. It is basically used for scheduling applications. From the partial order and the duration information, deadlines are derived.

- **Unknown Duration**. There are some techniques that deal with the case where the exact duration of events is unknown. Most of them are efficient in case of having a set of possible durations (e.g., between 4 and 6 hours). But no one of them can deal with the most difficult case to admit a duration in $[0,+\infty]$. The simple techniques can be reduced to any of the previously studied, and people usually work directly with one of them. These are not presented here.

2.4 Discussion

Dating schemes are basically used for determining dates requirements. They also can express temporal relationships and durations indirectly. They are valid for representing instants, and intervals through instants. Constraint propagation schemes are used for expressing directly temporal relations between events. From the information of the temporal relationships among the events, individual information about them can be derived. They are valid for representing instants, intervals, and intervals through instants. Duration schemes are basically used for expressing duration of events. Based on them one can derive a dating scheme, and/or the corresponding temporal relations among the duration-specified events. They are valid for representing intervals.

We now compare dating schemes with temporal constraints techniques. Much of our temporal knowledge of time is relative and cannot be described by dates. Dating schemes can be derived from a constraint propagation definition. If the information about temporal relation is quantifiable, then the derivation of the dating scheme is direct. But even in the case when only qualitative information is available, and temporal logics are more complex, then a dating scheme can always be derived.

If we compare pseudo-dating scheme with known duration schemes, we observe that they work with the same type of qualitative information (order), but applied to different types of events (instants or intervals).

Interval temporal constraint propagation schemes and known duration schemes understand events as intervals. In the case of PERT, once the network has been calculated, temporal relations between events can be derived. Depending on the particular specification, the events will be related either by the basic temporal relationships or by disjunctions of them. There are some temporal relations but they cannot be expressed directly.

Finally we discuss the unknown duration techniques. They are not very well developed for complex cases. It is easier to work with constraint propagation schemes. They deal with the uncertainties in the temporal relations that arise as a consequence of the unknown duration of events. In general, constraint propagation techniques are more flexible to define temporal relations and therefore they are usually preferred.

3 Modeling Temporal Information

Computers are required to transform our real world into mathematical or computerized representations (e.g., mathematical models to render three dimensional objects that look as if they were real). The translation between the two worlds is a matter of having the appropriate models to capture the nature of real things: the more perfect the model, the more accurate the computer representation. We want to do the same with temporal information. We want to represent temporal behavior in a computer system.

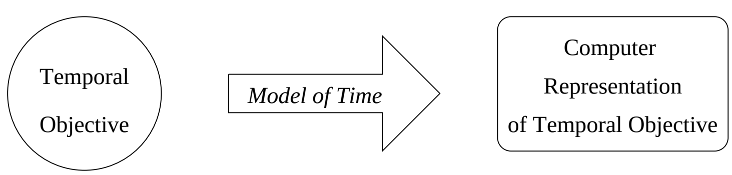


Figure 12: Modeling Temporal Information

Based on the background of time representation techniques that we have presented in Section 2, we present in this section our view and our terminology of the process of modeling temporal information (Fig. 12). On the left hand side, the temporal objective. It represents the temporal information that we want to model. On the right hand side, the computer representation of the temporal objective that has been achieved by using a model of time. Section 3.1 presents a general analysis of the temporal objective. Section 3.2 presents the definition of the idea of model of time and the general classes of models of time. Finally, Section 3.3 discusses the selection of the appropriate model of time for a temporal objective.

3.1 Temporal Objective

The **temporal objective** is the temporal behavior (e.g., a system behavior, a personal schedule) that we want to represent in a computer system. It is called objective because we want the system to achieve it. It is important to determine the characteristics of the temporal objective in order to find the appropriate model of time. In this section we present a general study of the temporal objective.

The **temporal objective** is composed of basic elements that we call **events**. In order to describe the objective, we need to define:

- the information about individual events, and
- the information about the relationships between individual events.

With these two pieces of information, any temporal objective is completely characterized.

The temporal objective may be composed of two types of events: instantaneous events, and events happening over an interval of time [1, 10, 14]. A summary of the associated information to each type is depicted in Fig. 13.

- **Instant**. The event occurs in an instant of time. The duration of the event is considered as zero.

  Instants are characterized by points in time. The only available information about an instantaneous event is the time it occurs. Depending on the available knowledge, we may have either the exact point in time or an interval of occurrence.

- **Interval**. The event occurs over a period of time, which is precisely the duration of the event.

  Intervals are described by the interval information (interval duration) and by associated point information (just like instants).

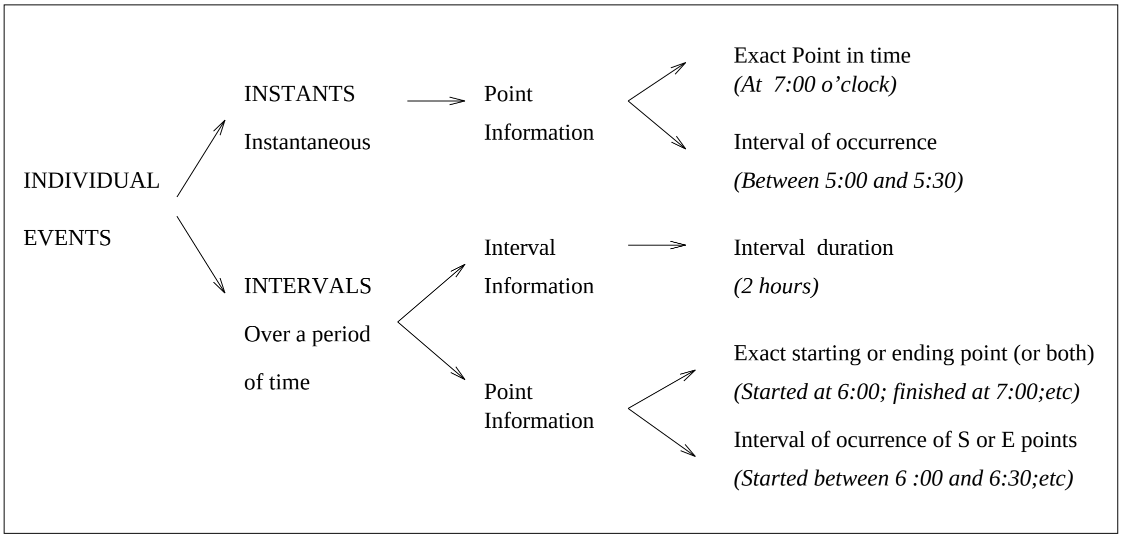


Figure 13: Individual Events: Temporal Information

The temporal objective is composed by a set of events, that we call **related events** (Fig. 14). The temporal information is defined by the individual events information and the information about the temporal relationships between individual events. The individual event information corresponds to instants and intervals as already described, and the information about temporal relationships can be of two types:

- **Quantitative information**. The relation is quantifiable, it can be expressed in specific units. These units can be referred to any kind of temporal axis (*absolute* or *relative*) and their value can be expressed either in a standard measure of time (e.g., seconds, minutes) or in some virtual measure of time (e.g., bits in a constant bit rate stream).
- **Qualitative information**. The relation is not quantifiable, it only can be expressed using qualitative terms. This qualitative terms are usually expressed as *ordering relations* or *temporal relations.*

The temporal objective (the set of related events) can be classified in two types:

- **Homogeneous**: either all the events are instantaneous or all the events are intervals.
- **Heterogeneous**: some events are instants and some events are intervals.

Fig. 13 and Fig. 14 present all the information that can be provided to characterize a temporal objective (homogeneous or heterogeneous). From them we can easily see two

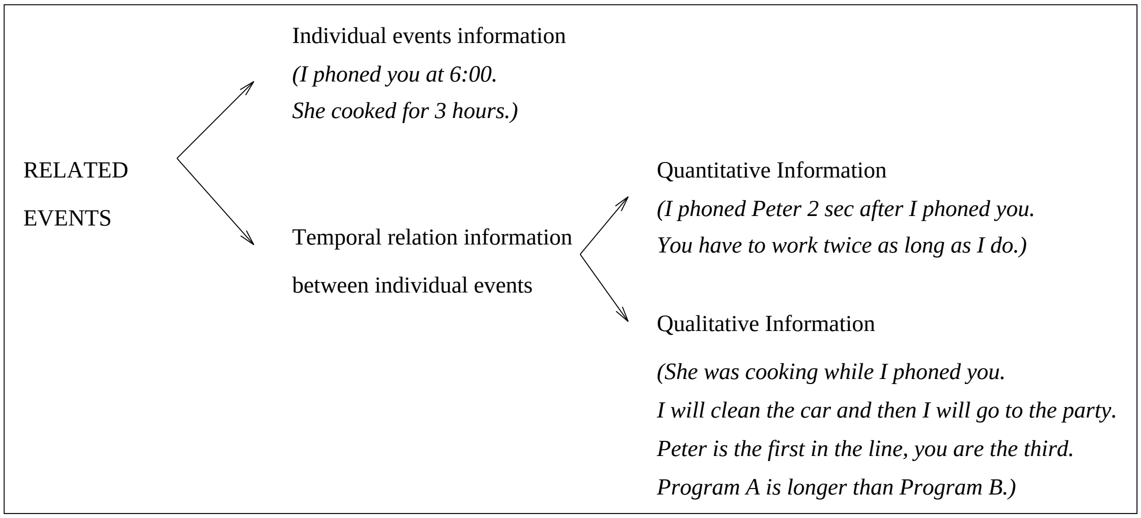


Figure 14: Related Events: Temporal Information

facts: (1) not all that information is needed, some information can be derived; (2) not all that information will be available. Therefore, it is necessary to find the appropriate model of time to characterize and define the desired objective. The model of time will be chosen according to the type of temporal objective, the temporal information that should be described, and the amount of uncertainty on the temporal objective.

The next section defines the idea of models of time. Section 3.3 gives guidelines for the selection of the appropriate model of time for a given temporal objective.

3.2 Models of Time

A model of time is an abstract concept that we derived that specifies the way in which the temporal objective is described (i.e., temporal elements, temporal information and the way to combine them). The expressivity power of a particular model of time determines its capability to model a temporal objective.

3.2.1 Definitions

We characterize a **Model of Time** through three concepts that, although they are interrelated, they can be divided into: the **Basic Time Unit** of the model, the **Contextual Information** associated to the basic time units and the **type of Time Representation Scheme** expressing the basic units and their associated information. These three concepts completely describe a specific model of time and its expressivity power. They are described as follows.

Basic Time Unit: specifies the atomic temporal unit of the model (instants or intervals). The events of the temporal objective are modeled through the basic time unit. Fig. 15 presents the relation between the events in the temporal objective and the basic time units of a model of time. The mapping from the two types of temporal objectives to the models of time is the following:

- Homogeneous temporal objectives: (1) instants, modeled through instants; (2) intervals, modeled either directly through intervals, or indirectly through instants.
- Heterogeneous temporal objectives: always modeled through instants. Instant based modeling is the choice to model instantaneous events and interval events through a common basic time unit.[3]

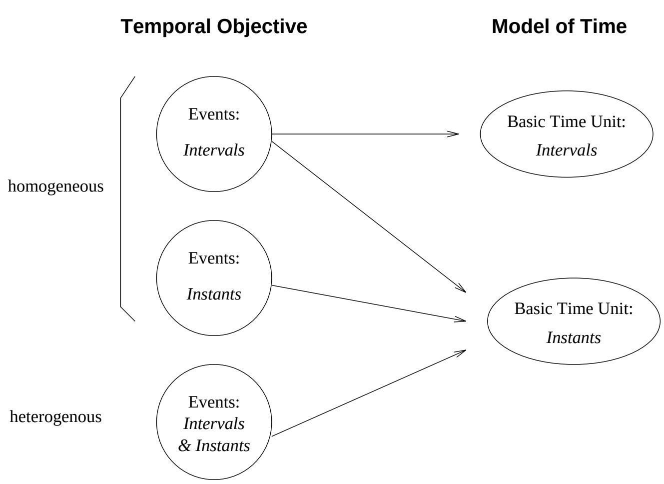


Figure 15: From Events in the Temporal Objective to Basic Time Units in Model of Time

Contextual Information: specifies what type of temporal information is associated to the basic time units of the model (qualitative or quantitative) and how it is expressed. In case of modeling qualitative information, contextual information determines the specific qualitative information that is considered:

[3]We could also think of modeling instants through intervals and consider the possibility of modeling heterogeneous temporal objectives through intervals. The objection is that to model instants through intervals is not very useful. Moreover, modeling instants and intervals through intervals might not be achievable. To the knowledge of the authors, there are no temporal techniques involving either of them. We do not consider them here.

- Ordering information: full or partial.
- Type of the temporal relationships that the model can express: binary (between two basic time units), n-ary (among n-basic time units), one temporal relation between one or n basic time units, several temporal relationships among one or n basic time units (i.e., uncertainty about the temporal relation).

The contextual temporal information concept is very important. It defines, specifically, the type of temporal information that the model of time is considering. The clear description of the contextual information distinguishes the various models of time. It is a key point in the determination of the expressivity power of a model of time (see Section 3.2.3).

Type of Time Representation Technique The type of time representation technique is a concept that is intrinsically associated to basic time unit and contextual information. The purpose of differentiating it is to achieve a better description of the model of time. In this way it is easier to grasp at a glance the essence of the model of time. It also gives an idea of the type of theory that will be required to interpret the specification of temporal objective and carry it out. To identify the type of time representation technique we follow the classification that was introduced in Section 2.

The three previous concepts describe completely a *particular* model of time. We have classified all the possible models of time into five general classes. This classification is presented in next section.

3.2.2 Classification of Models of Time

There are five general types of models of time. They are represented in Fig. 16. We have designated a name for each one. They are described as follows (from left to right):

1. **Quantitative dates.** The basic time unit is an instant. The associate information to the instants is quantitative information. The type of time representation technique is a dating scheme for time dates. The specific value of the contextual information (exact date, or interval of occurrence) determines the particular model of time within this general line.

2. **Qualitative dates.** The basic time unit is an instant. The associated information to the instants is qualitative information (ordering information). The type of time representation technique is a pseudo-dating scheme. The specific contextual information (full order or partial order) determines the particular model of time within this general line.

3. **Qualitative instants.** The basic time unit is an instant. The associate information to the instants is qualitative information (temporal relationships) and quantitative information optionally. The type of time representation technique is constraint representation technique for instants. The specific contextual information (type of temporal relationship used) determines the particular model of time within this general line.

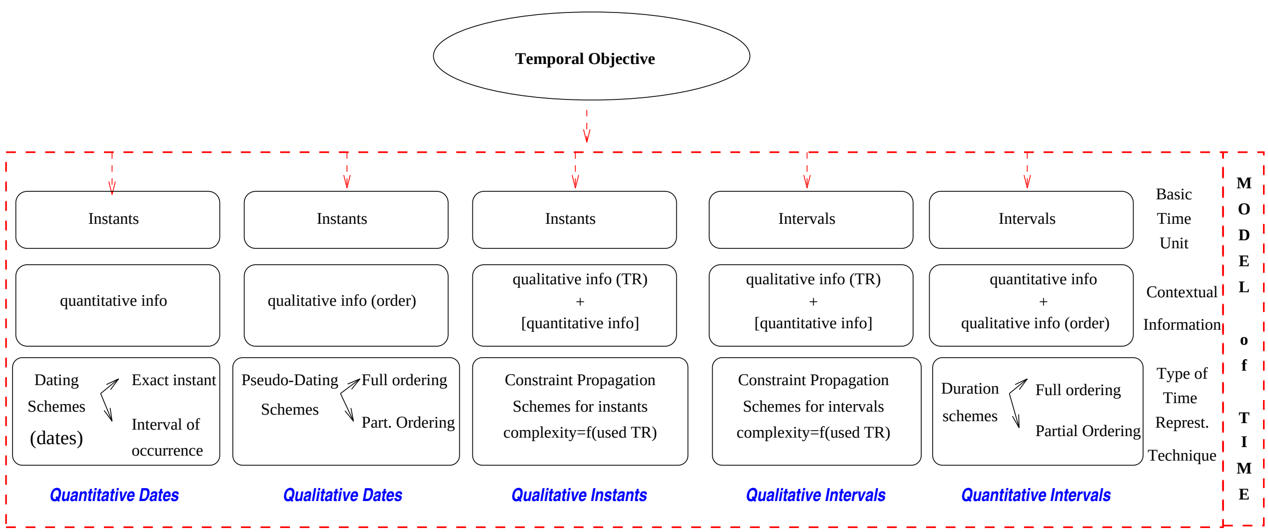


Figure 16: General Models of Time

4. **Qualitative intervals.** The basic time unit is an interval. The associate information to the intervals is qualitative information (temporal relationships) and quantitative information optionally. The type of time representation technique is constraint representation technique for intervals. The specific contextual information (type of temporal relationship used) determines the particular model of time within this general line.

5. **Quantitative intervals** The basic time unit is an interval. The associate information to the intervals is quantitative (durations) and qualitative information (ordering information). The type of time representation technique is duration-based schemes.

The specific contextual information (type of ordering information used) determines the particular model of time within this general line.

3.2.3 Expressivity Power of Models of Time

The expressivity power of a particular model of time determines its capability to model a temporal objective. We have studied the expressivity power of the five general categories of models of time. This study provides a first assessment of the possible temporal objectives that can be modeled. For example, if a model of time is classified as *quantitative dates*, we need the exact timing of all the events beforehand, and therefore, we know that we cannot model temporal objectives with uncertainties.

Nevertheless, this first assessment is not enough for determining the expressivity power of a particular model of time. This is determined by the particular contextual information. For example, consider two models of time belonging to the general category *qualitative intervals*. Model A uses the basic binary relations between two intervals. Model B uses the basic binary relations, but it can model more than one relation between two intervals. They belong to the same general category but they are different because they consider different contextual information. Model B can define uncertainties in the temporal relationships between two intervals in the temporal objective, while model A can only model one fixed temporal relationship. As a result, the temporal objectives that they can model are different.

Model of time	Temporal Objective		
	Type of T.O.	Temporal Information	Uncertainties
Quantitative dates	Hom. Inst. & Inter. Heterogeneous	* Dates directly * Durations indirectly * Basic Temp relations indir.	– No Uncertainty – Fixed Quantitative info
Qualitative dates	Hom. Inst. & Inter. Heterogeneous	* Ordering info directly	– Uncertainty in dates
Qualitative instants	Hom. Inst. & Inter. Heterogeneous	* Inst. Temp relations directly * Inter. Temp relations indirec. * Duration indire. (optional)	– Fixed/uncertain temp rel inst – Fixed/uncertain temp rel inter – Uncertain durations
Qualitative intervals	Hom. Intervals.	* Inter. Temp relations directly * Duration direc. (optional)	– Fixed/uncertain temp rel inter – Uncertain durations
Quantitative intervals	Hom. Intervals.	* Duration directly * Ordering infor directly	– Fixed duration – Uncertainty in dates

Table 1: Summary of Expressivity Power for General Models of Time

Table 1 presents a summary of the general study of the expressivity power for the five types of models of time. The left column represent the type of model of time. The right column represent the description of the temporal objective that can be modeled with them. The temporal objective is divided into three columns: the type of temporal objective, the type of temporal information that can be modeled, and the uncertainty that can be expressed on the temporal information.

This table gives the guidelines for the general types of models of time. The contextual information of a particular model of time modifies those general guidelines. In case of quantitative dates, it determines the uncertainty on the instant occurrence, exact point or within an interval (in Table 1 we say that there is not uncertainty in dates in this type of model of time because although the exact moment of occurrence is unknown, the boundaries are); in case of qualitative dates, the uncertainty in the ordering information; in case of qualitative instants and intervals, the type of used temporal relations and therefore, the amount of uncertainty that can be expressed; and in case of quantitative intervals, the type of uncertainty in the ordering information.

Summarizing, the expressivity power of a particular model of time defines the type of temporal information that can be modeled and the amount uncertainty that can be expressed in the temporal information.

3.3 From the Temporal Objective to the Models of Time

The choice of a model of time for modeling a temporal objective is based on the determination of required expressivity power. Any model of time having the required (or more) expressivity power will be able to model the temporal objective. Among all the possibilities the designer will choose the most appropriate.

We present two simple examples. Fig. 17 presents the case of modeling a temporal objective that it is completely defined in advance. It is a homogeneous objective composed of interval events. It could be described as follows: *a video of 2 minutes of duration is presented in parallel with the video title.* Because we have intervals in the temporal objective, in principle, we could choose any model of time. All the temporal data about individual and related events is known in advance. There are no uncertainties in the temporal objective. In the example, three of the possible general models of time are shown (from left to right): *Quantitative Dates* (i.e., defining the exact dates for the starting and endings points of both events), *Qualitative Instants* (i.e., defining the equivalent temporal relationship between the starting and ending points of the events) and *Qualitative Intervals* (i.e., defining the interval relationship between the two events). All of them can be used for that temporal objective.

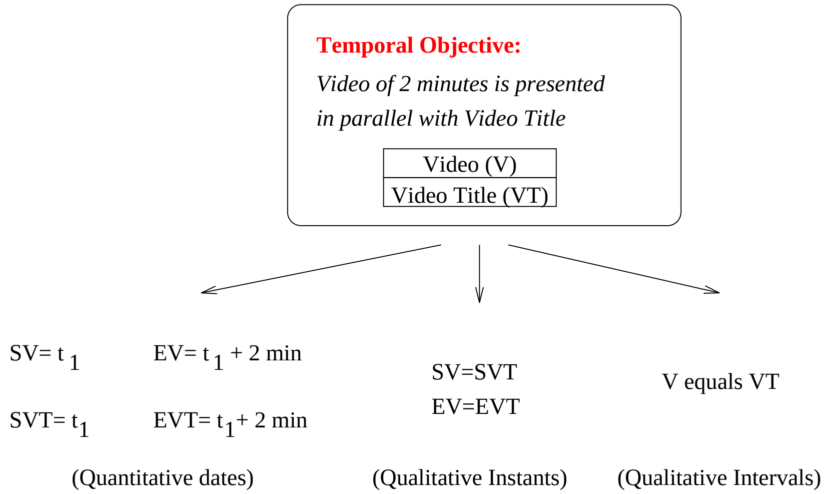


Figure 17: Example 1: from a Temporal Objective to a Model of Time

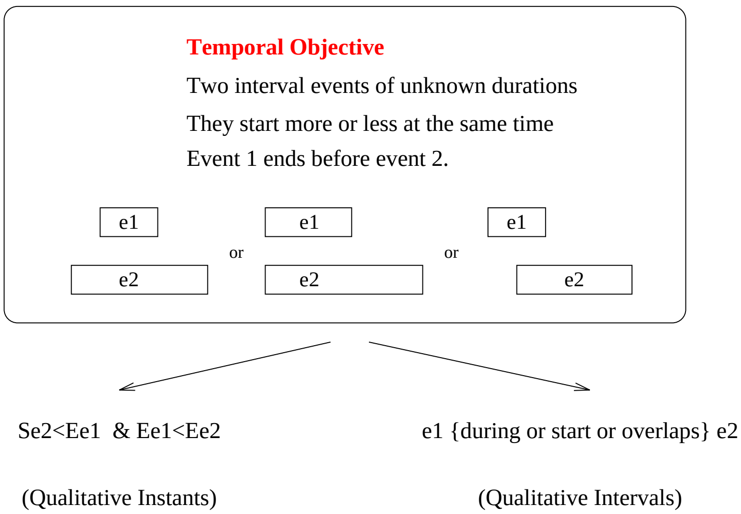


Figure 18: Example 2: from a Temporal Objective to a Model of Time

Fig. 18 presents another example. The temporal objective is composed by interval events. The temporal objective could be described as follows: *two events of unknown duration; they start more or less at the same time; event 1 finishes before event 2.* Because we have intervals in the temporal objective, in principle, we could choose any model of time. The type of temporal information we want to model is qualitative, and to some extent undefined. We do not know the durations of the events, but we know some of the possible temporal relationships between them. In this case, we need a model of time capable of modeling uncertain qualitative information in the form of temporal relationships. Therefore, we have two possibilities: *Qualitative Instants* (i.e., defining the equivalent temporal relationships between the starting and ending points of the events), and *Qualitative Intervals* (i.e., defining the possible relationships between the two events). For both general models, the specific contextual information be defined. In case of qualitative instants, only the three basic relationships are required. Through them, we can define uncertainties in the interval relations of the temporal objective. In case of qualitative intervals, we can use the basic thirteen binary relationships, but the model must be able to specify uncertainties in those relationships. The selection of one of these two types models is up to the designer because both can be used. The advantage of using a qualitative instant model is that the contextual information that is needed is simple: three basic binary relations between instants; the drawback is that we need to know the exact combination of instants relations. In contrast, the advantage of using a qualitative intervals model is that it captures the relations directly; the disadvantage is that the required contextual information is more complex, it requires the specification of more than one temporal relationship between two intervals. A particular model of time with a complex contextual information can also be used to model simple situations.

4 Proposed Temporal Reference Framework

Section 3 has presented the concepts of temporal objective and models of time for general systems. In this section, we apply those concepts of modeling temporal information to multimedia systems. The result is our temporal reference framework for multimedia synchronization techniques.

Our view of synchronization is presented in Fig. 19. On the left hand side, we have the multimedia scenario that we desire for the multimedia application. On the right hand side we have the system realization of the multimedia scenario. The system realization can be divided into the following two blocks.

- The **temporal specification scheme**. It is used to describe the multimedia scenario in the computer system.

  The temporal specification scheme is completely described by two other concepts: the model of time, which gives the expressivity power, and the graphical (or mathematical) representation which gives the graphical (or mathematical) means to specifically express the temporal requirements.

- The **synchronization mechanisms**. Used to carry out the multimedia scenario following the temporal specification scheme.

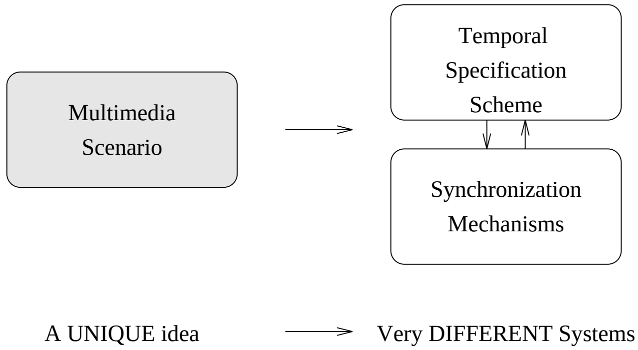


Figure 19: General View of Multimedia Synchronization Technique

The unique idea of the left hand side (Fig. 19) does not lead to a unique solution on the right hand side. Several temporal specification schemes can be used for the definition of the same multimedia scenario and several mechanisms can be designed for the enforcement of the same temporal specification scheme. As a result, very different systems can accomplish the same goal. The framework that we present in this section, helps to identify the inner structure of the different system components and to determine its capabilities.

Our Temporal Reference Framework has four components. An integrated vision of multimedia synchronization with our temporal reference framework is shown in Fig. 20. The four components of the framework are described as follows.

1. **Temporal Objective.** The temporal objective consists of the temporal constraints of the totality of events that we want to model. The characteristics of the temporal objective determine the models of time that can describe it (see Section 3.1). In a multimedia application, the temporal objective is identified with the desired multimedia scenario (e.g., presentation of a video clip is an interval event).

2. **Model of time.** This is the core of the temporal specification scheme, and it determines its expressivity power. A model of time is described by the basic time unit, the contextual information and the type of time representation technique (see Section 3.2).

3. **Representation (Mathematical or Graphical).** The graphical or mathematical representation is the external form of the model of time. It gives the *representation* of the temporal objective. A look at the mathematical operators or to the graph provides the goal of the temporal objective.

   Sometimes, the concept of the temporal specification scheme is confused with the graphical or mathematical representation, because the later is what it is seen. Although the graphical representation is the "external" side of the temporal specification

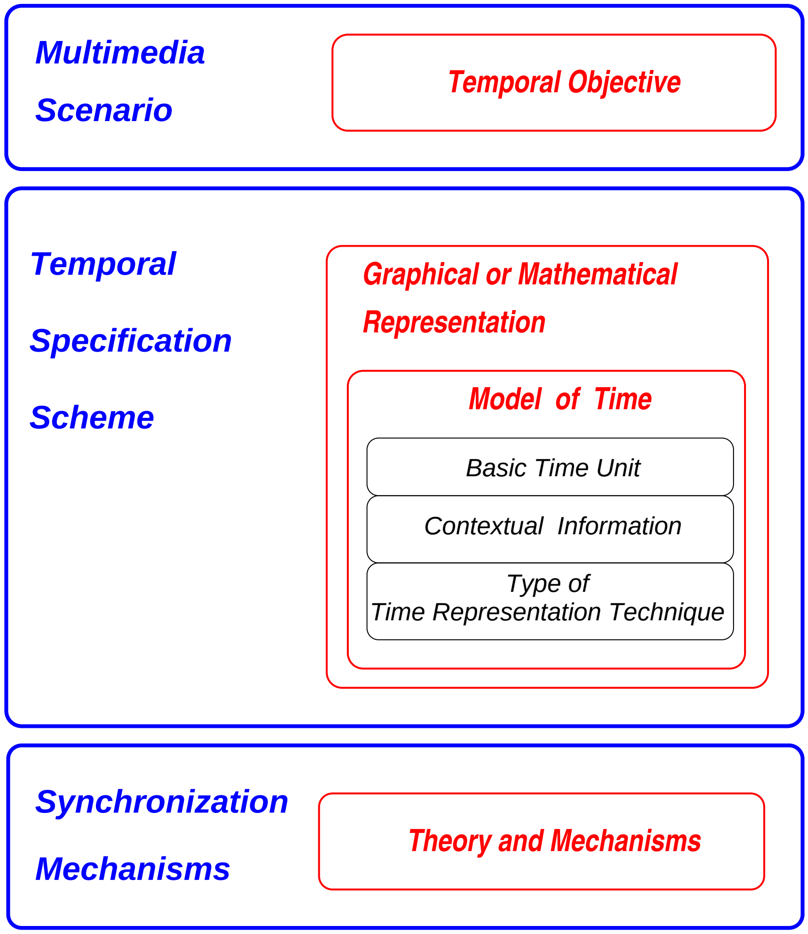


Figure 20: Temporal Reference Framework

scheme, we cannot forget the "internal" side, its core, the model of time. The same model of time can lead to different graphical representations or to different sets of mathematical operators. The expressivity power resides in the model of time. Two different representation techniques may have the same expressivity power although they may look very different.

In the design process, we always look at the temporal objective(s) we want to model and find the appropriate model of time for them. After that, the most appropriate graphical or mathematical representation is chosen for the selected model. This selection depends on the rest of the system and the criteria for this selection is based on which of them is easier to enforce.

In the analysis of a temporal specification scheme we need to extract the concept of the model of time that is behind that representation, identify its expressivity power, and see what type of temporal objectives can be modeled through it.

4. **Theory and Mechanisms.** Synchronization is the process of achieving the temporal

specification. Therefore, theory and mechanisms have to be developed so that understanding the representation of the temporal specification scheme, they make the temporal objective possible.

The mechanisms and the theory are varied and depend on the infrastructure, the architecture of the systems, and the specific media types. They pursue the achievement of a temporal objective, that it is defined following a model of time, but as they deal directly with systems, they usually have to combine temporal information with other types of atemporal information.

5 Examples of Multimedia Synchronization Techniques

In this section we analyze some of the temporal specification schemes that have been proposed in the recent literature. We now focus on the models of time that they use.

Time-line approach It is one of the first approaches used to specify synchronization. It consists of a time line with events attached to points. The synchronization mechanisms read the time line and execute the events in the appropriate moment. Several synchronization systems use a time line for the representation of the timing constraints (e.g., Athena Muse Project [11], Gibbs et al. [8, 9]).

This model of time belongs to the general category of *quantitative dates*. The contextual quantitative information corresponds to the exact date ("at") of the basic time unit's occurrence.

It can model homogeneous or heterogeneous temporal objectives, but not uncertainties in the temporal objective can be expressed.

Firefly Buchanan and Zellweger [5, 6] propose a temporal specification scheme for the definition of general multimedia scenarios. They also develop algorithms for deriving the appropriate schedules for achieving the specified scenario.

The model of time of Firefly belongs to the general category of *qualitative instants*. The contextual information corresponds to the basic binary temporal relationships between instants (only one relationship between two instants). Associated quantitative information can be included optionally. They have proposed a graphical representation which captures the relations between the specified instants.

It can model homogeneous or heterogeneous temporal objectives. In case of modeling instants in the temporal objective, no uncertainties can be expressed, but in case of modeling intervals in the temporal objective, uncertainties in the temporal relationships can be expressed by combination of the basic binary instant relationships.

Hoepner's Path Operators Hoepner [12, 13] defines a temporal specification scheme for the description of general multimedia scenarios. It consists of a set of path operators, although a graphical representation is also proposed. These operators are valid to work with any mechanism which understands them. In [13] she proposes a possible mechanism.

This model of time belongs to the general category *qualitative intervals*. The specific contextual information for the qualitative information corresponds to a subset of the basic binary relationships between two intervals. Not all the basic binary temporal relationships between intervals are considered (less than the thirteen). A particular set of operators and graphical representation has been proposed.

The model can only deal with homogeneous temporal objectives composed of intervals. The expressivity power is reduced to model only a subset of the possible temporal relations of the intervals in the temporal objective, and no uncertainties can be expressed.

OCPN Little and Ghafoor [17] present OCPN, a temporal specification scheme for the description of general multimedia scenarios. They also present algorithms to derive the playout schedule from the scenario specification, and present synchronization mechanisms for the achievement of the scenario in distributed multimedia systems [18].

The model of time belongs to the general category of *qualitative intervals*. The contextual information is both qualitative and quantitative. The temporal relationships that it considers are the thirteen binary temporal relationships, specified one between two intervals. The graphical representation is based on an extended type of Petri nets.

It can only model homogeneous temporal objectives composed of intervals, and no uncertainties in the temporal objective can be expressed.

Temporal Specification Scheme proposed by Wahl and Rothermel Wahl and Rothermel [24] have proposed a temporal specification scheme. They aim to provide a specification scheme that can specify, through the same operators, the temporal relationships between intervals and the possible variations due to user interaction. They have not yet proposed synchronization mechanisms to carry the scenario out.

The model of time belongs to the general category of *qualitative intervals*. The contextual information is both qualitative and quantitative. The temporal relationships that it considers are the binary thirteen temporal relationships, but it can specify more than one temporal relationship between two intervals. They have created ten operators that cover all the possible cases using parameters. They have also developed a graphical representation of the operators.

The approach can only model homogeneous temporal objectives composed of intervals. Uncertainties in the temporal objective can be expressed through the specification of all the possible temporal relationships between two intervals.

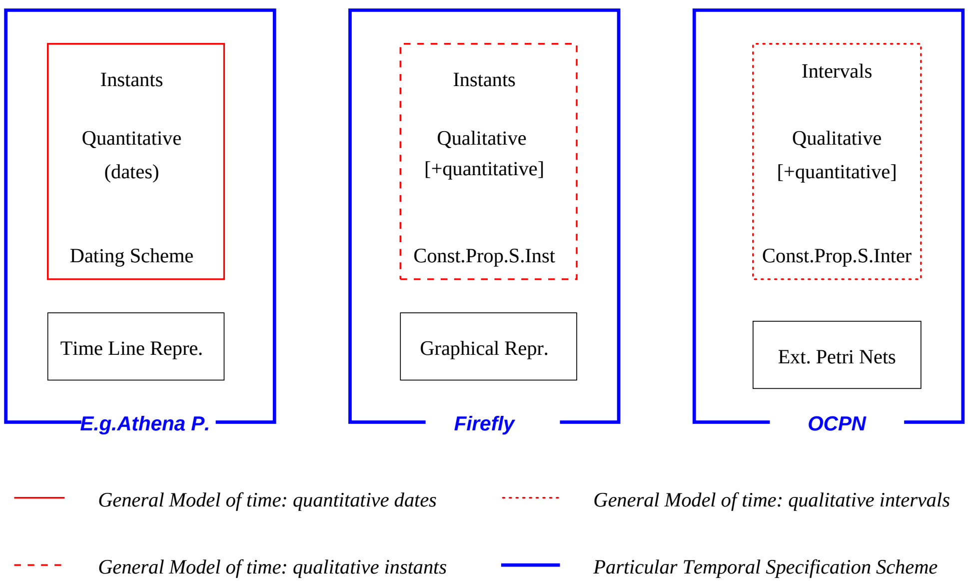


Figure 21: Comparison of Temporal Specification Schemes

A comparison among the presented temporal specification schemes is now discussed. Fig. 21 presents the comparison of the time line specification scheme, Firefly, and OCPN. They represent three different temporal specification schemes. The models of time that they use belong to different classes: time line belongs to quantitative dates, Firefly to qualitative instants, and OCPN to qualitative intervals. As they use different models of time, they also use different representations. Fig. 22 presents the comparison of Hoepner's path operators, OCPN, and Wahl's operators. In this case, the models of time of the three time specification schemes belong to the same general category: qualitative intervals. The particular models of time are different because of the contextual information they consider. Also, each one uses a different representation.

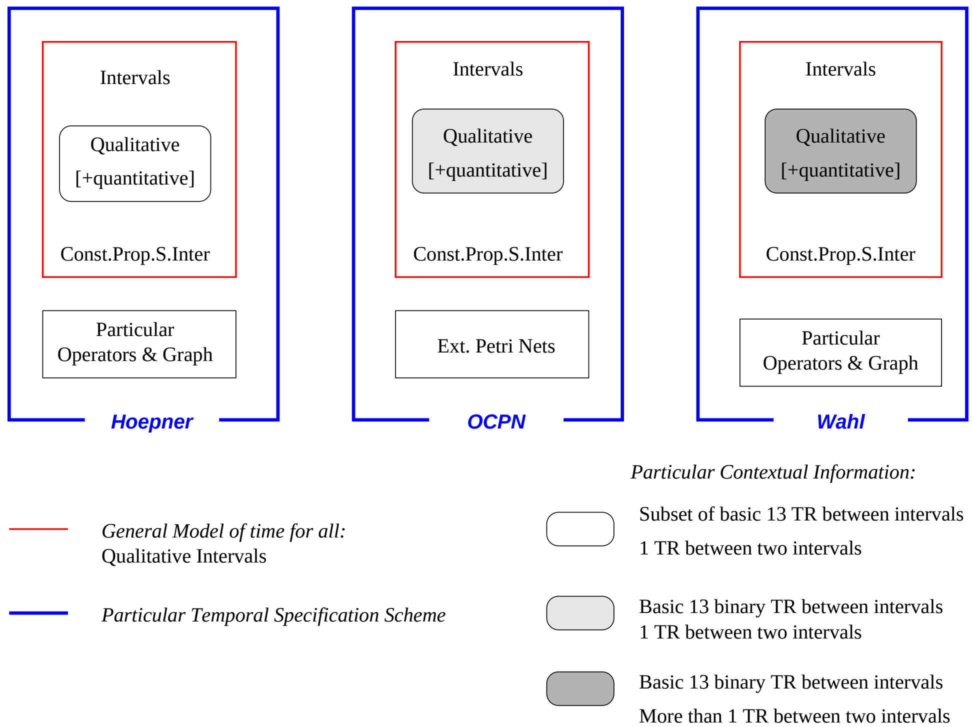


Figure 22: Comparison of Temporal Specification Schemes

We conclude that with our temporal reference framework, specially with the concept of models of time, we can (1) evaluate the expressivity power of the various temporal specification schemes and (2) compare them.

6 Conclusion

We have presented the foundation of our temporal reference framework for multimedia synchronization techniques. An in depth study of time has been carried out, and as a consequence, the following concepts have been defined: temporal objective, model of time, and expressivity power of the model of time. We have presented a classification of models of time in five general categories with their associated expressivity power. We also have discussed the selection of the model of time for a temporal objective as a function of the expressivity power. The integration of the concepts of modeling temporal information with multimedia leads to our Temporal Reference Framework that has also been introduced. Some examples have been analyzed with respect to our models.

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