A Temporal Reference Framework for Multimedia Synchronization[1]

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Abstract–The synchronization problem for audio/visual reproduction has consumed engineers since the advent of recorded audio and images and the first multimedia productions. As computers have evolved to support programmed reproduction of multimedia information, the complexity but not the character or interest have changed. In the digital domain, synchronization problems exist due to data distribution and communications, random events caused by human-computer interaction, and general computer and communications performance limitations. This rich research domain has led to numerous approaches to the modeling and execution of multimedia synchronization scenarios. Unfortunately, these approaches are difficult to compare and evaluate due to their varied theoretical bases and modeling techniques.

In this paper we develop a uniform, theoretical foundation for discussing multimedia synchronization and temporal specification. We propose a temporal reference framework and use it to compare existing temporal specification schemes and their relationships to multimedia synchronization. The ensuing comparison of existing specification and synchronization techniques demonstrates the utility of the framework.

Keywords: Models of time, temporal specification, temporal reference framework, multimedia synchronization.

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1 Introduction

Multimedia synchronization is about providing coherent playout of orchestrated audio and visual information. It is a controversial topic in the multimedia computing community. On the one hand, providing "lip-sync" or "slide-show" capability requires no more than fast buses, buffering, and hardware decompression devices. On the other hand, complex multi-party human-computer interaction coupled with live and preorchestrated presentations are difficult to deal with in any formal or ad hoc manner. For these scenarios (e.g., the construction of virtual environments), the behavior of each participant must be understood and represented in the temporal domain. Once such a characterization is achieved, the nuances of the operating environment (communications, operating system, and playout devices) must be dealt with to achieve the desired multimedia presentation outcome.

For this reason, we divide the general multimedia synchronization problem into two parts. The first is one of modeling, representing, and specifying timing requirements of multimedia scenarios. The second problem is to achieve the temporal specification via synchronization. In this decomposition, synchronization reduces to the rendering of a temporal specification using some technique. In this paper we focus on the former problem; that of the specification of timing requirements. However, we also show the relationship between temporal specification and the rendering of a temporal specification (synchronization).

To appreciate the temporal specification problem (modeling and representing included) requires a basic understanding of formal specification techniques. These techniques isolate a *semantic domain* (i.e., the meaning of a specification and language) and a *syntactic domain* (i.e., the alphabet, and grammar of the specification language). Theory focuses on the semantics; however, the theory must be supported by models which require tools for visualization. These visualization tools exist as a syntax. Therefore, when we think we deal only with semantics, we are often crippled by a syntax as well. We have found this problem to arise quite frequently when considering models of time and their use in specifying *temporal scenarios*–sequences of events in time.

Consider the analogous problem of specifying or representing physical objects by computer. Computers can provide artificial representations of our real world (e.g., three dimensional rendering of objects on a computer screen). For obtaining these representations we need to find models to capture the nature of the real objects, mechanize the models, and find algorithms to transform (render) the mechanized models (representations) into the display space of the computer. Usually, more than one model can be found to represent a

single object from the real world. For example, Fig. 1 shows simple models characterizing a table from the real world. The left-hand side describes the table. The middle illustrates three models and their corresponding representations. The right-hand side shows the object rendered on a computer display. The example illustrates different geometric modeling and representation approaches that can yield equivalent renderings of the synthesized object.

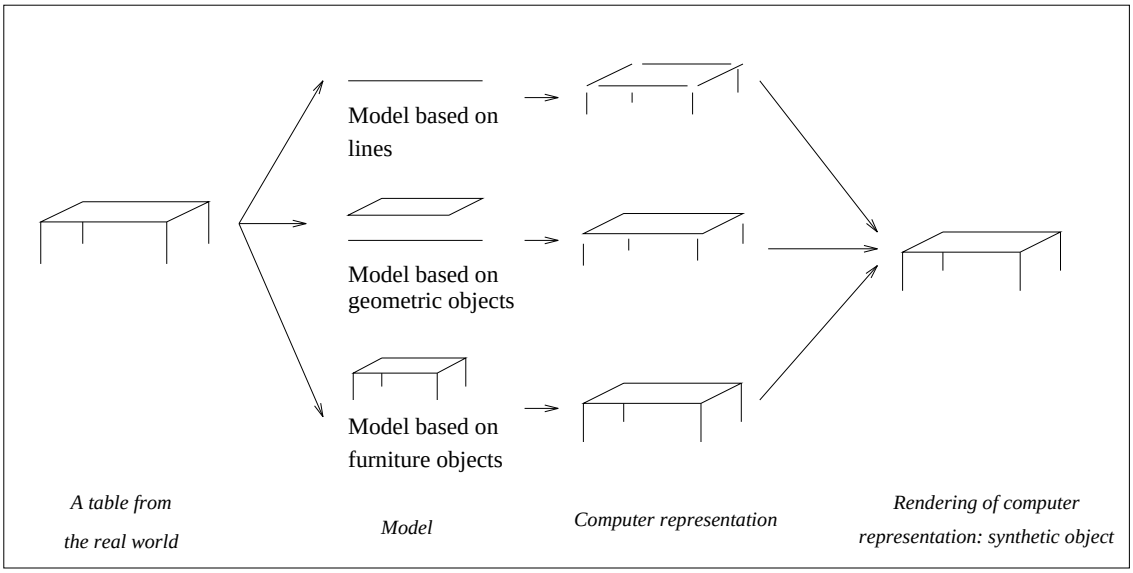

Figure 1: Geometric Representations of a Table

Time is another aspect of the real world that can be modeled. As in the case of the spatial example of Fig. 1, several models of time can be used to represent the same sequence of events. Consider Fig. 2 as an example of a short movie that has been recorded from the real world. We present four possible ways to describe the sequence of events in the time domain.

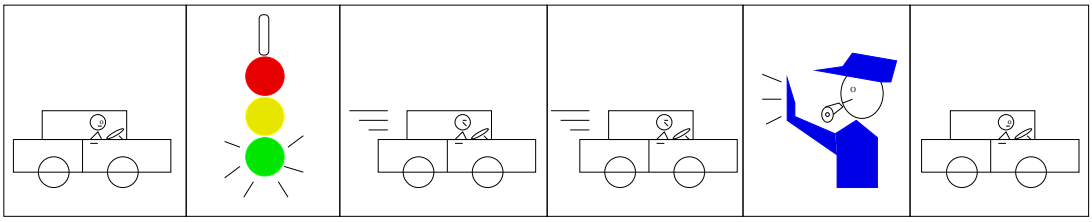

Figure 2: Frames Representing a Movie Recorded from the Real World

1. **An English description**: The car was initially stopped. Subsequently, the traffic

light turned green and the car began moving. The car remained in motion until a gendarme signaled it to stop.

2. **A time of occurrence description**: At $t = 0$, the stopped car appears (beginning of the movie). At $t = 5$, the traffic light turns green. At $t = 5$, the car starts moving. At $t = 25$, a gendarme signals the car to stop and the car stops immediately. At $t = 29$, the movie ends.

3. **An instant-based/temporal relationship description**: The car started moving at the same time the traffic light turned green. The car stopped moving at the same time the gendarme signaled the car to stop.

4. **An interval-based/temporal relationship description**: The car was initially stopped for 5 seconds; the traffic light was red for the same 5 seconds. After the first period, the car traveled for 20 seconds. Subsequently, the car stopped for 4 seconds (until the end of the movie) while the gendarme signaled the car to remain stopped.

Like the rendering of the table (Fig. 1), any of the descriptions above will lead to an appropriate temporal sequence for the movie, provided that we have suitable rendering mechanisms. This example illustrates how a single scenario can be modeled by a range of different approaches (models of time). The ensuing representations can be very different yet yield the same results. In the example, four different models capture the same scenario.

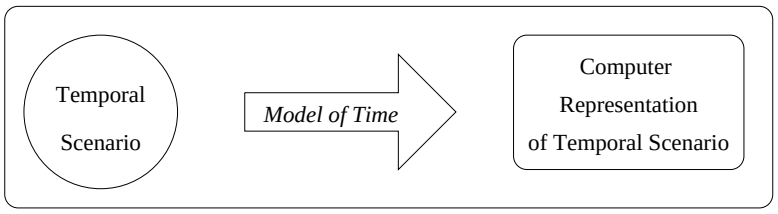

Figure 3: Modeling Temporal Information

The process of modeling temporal information is represented in Fig. 3. The left-hand side captures the *temporal scenario* that we seek to model. The right-hand side captures the representation of the scenario. The transformation from the scenario to the representation is achieved by various temporal modeling techniques. Once a representation is achieved, mechanisms are required for final rendering in the time domain. For multimedia data presentation, this is equivalent to multimedia synchronization.

Our contribution is the development of a *temporal reference framework*: a uniform, theoretical basis for discussing multimedia synchronization and temporal specification. The

proposed framework is most useful in the comparison and synthesis of temporal specification schemes. The remainder of the paper deals with the modeling and rendering process for temporal information in multimedia systems. In Section 2 we characterize temporal scenarios and present our terminology for models of time. Section 3 describes the proposed temporal reference framework. In Section 4 we show how the framework can be used to compare various existing specification approaches for multimedia object timing. Section 5 concludes the paper.

2 Modeling Temporal Information

To develop a unified theory for multimedia synchronization and representation, we require common terminology. Here we develop and define the basic terms that we use in the framework development, introduce and characterize the models of time used for multimedia specification, and present representations suitable for mechanization.

First we consider a definition of the temporal activities we wish to model within the realm of computer-based multimedia applications.

2.1 Temporal Scenarios

A **Temporal Scenario** represents an instance of a set of activities that are in some way related in time. For example, consider the temporal scenario describing an instructor lecturing with slides. The time that each slide stays in the projector depends on the time expended in explanation. In this way, the activity called "slide in projector" is dependent on the activity called "instructor explains slide." These two activities are *related* in time as well as *dependent* on time. This relation/dependency must be captured by a model of time.

There are two types of temporal scenarios: **determinate**, and **indeterminate**. Determinate temporal scenarios represent a set of real-world activities. As they are real-world activities, the temporal constraints are completely defined and determined by the physical world. There is no indeterminacy in the temporal scenario. Fig. 2 is an example of such a scenario.

For indeterminate temporal scenarios there is uncertancy or non-determinism. Fig. 4 shows an example of such a case. The left-hand side of the figure describes a symbolic description of an indeterminate temporal scenario. It consists of a common sequence of

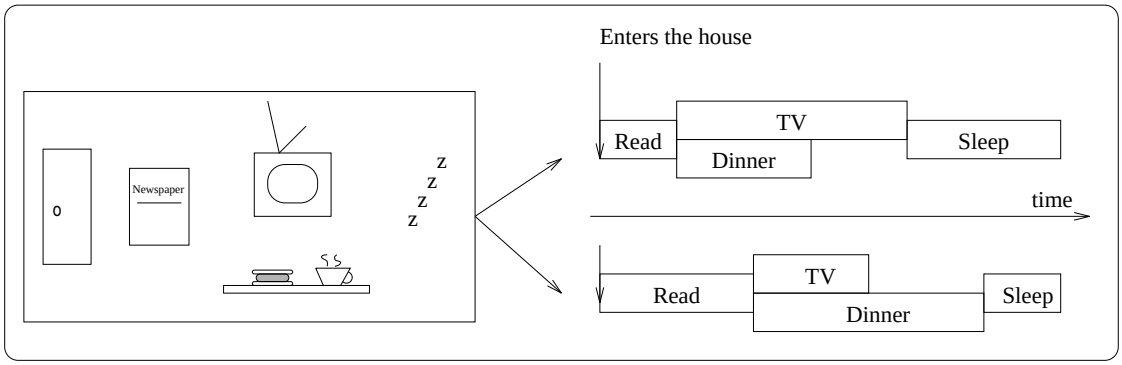

Figure 4: Example of an Indeterminate Temporal Scenario

activities that an individual might do in the evening: opening the door, reading the newspaper, watching TV while eating dinner, and sleeping. This temporal scenario is the same every evening, but each day it has different realizations (e.g., arrival time, time spent reading the newspaper). Two of these realizations are illustrated on the right hand side of the figure. In these cases we need models of time that can deal with indeterminate cases.[3] When generating a model, we have sufficient information to describe the indeterminate temporal scenario, but the final realization is not specified or determined. Therefore, the description of the temporal scenario represents a superset of all possible final realizations. Ultimately, the final rendering or realization of the temporal scenario depends on external factors (e.g., human interaction). These cases of indeterminacy contrast scenarios that are determinate and therefore possess a unique temporal realization (e.g., the movie of Fig. 2).

Note that a temporal scenario does not imply a specific temporal model.[4] Temporal models should be able to capture the relationships and dependencies among activities for both determinate and indeterminate temporal scenarios. We now consider models of time for translation of temporal semantics to formal specification languages.

2.2 Models of Time

Activities in the temporal scenario are called **events**. To clarify this term, it is defined as follows:

Definition 1 *An* **event** *is an occurrence in time that can be instantaneous or can occur over some time period.*

[3]Indeterminate temporal scenarios are studied because in multimedia systems there are two clear sources of indeterminacy: user interaction, in which the final realization is not known until the user interacts, and system failures, where the final realization is not known until run-time.

[4]*Model of time* and *temporal model* are used interchangeably throughout the paper.

Using an English language description, Fig. 5 presents examples of descriptions of a temporal scenario. Note that we can describe the temporal scenario either as a set of independent events (top of Fig. 5) or as a description that captures some temporal relationships among the events (bottom of Fig. 5).

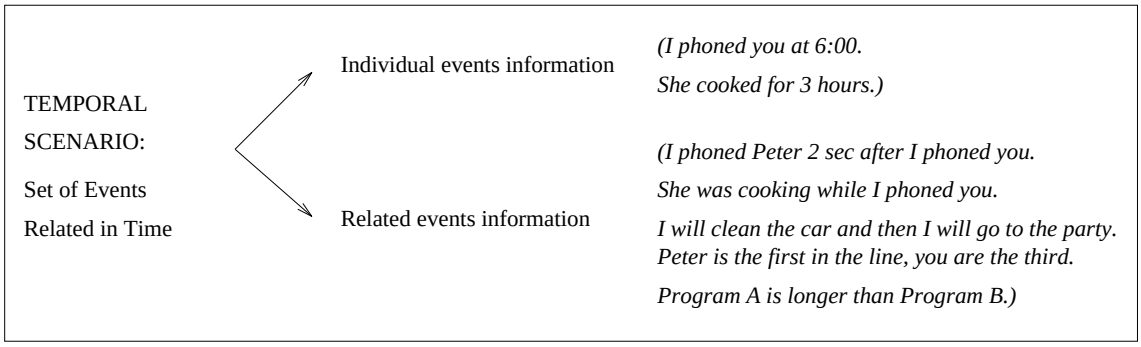

Figure 5: Possible Descriptions of a Temporal Scenario

In order to capture and describe the temporal scenario, we require the services of a model of time. The use of such a model forces us to stray from a discussion of only semantics (i.e., we must choose some syntax).[5] A model of time can be viewed as the temporal semantics that are applied to yield a formal specification technique, language, and representation. Typically, these semantics are associated with a particular syntax for visualization purposes.

We characterize a **model of time** through three related components: the **basic time unit** of the model, the **contextual information** associated to the basic time units and, the **type of time representation technique** expressing the basic units and their associated information. These three concepts completely describe a specific model of time and its power of expressivity.

The basic time unit. The basic time unit is the temporal unit used in characterizing a temporal scenario. There are two types of basic units: instants and intervals, defined as follows:

Definition 2 *An* **instant** *is a zero-length moment in time [15].*

[5]Recall from Section 1, formal language of specification technique is comprised of syntactical and semantic components.

Definition 3 *Let $[S, \leq]$ be a partially ordered set, and let a, b be any two elements (time instances) of S such that $a \leq b$. The set $\{x \mid a \leq x \leq b\}$ is called an* **interval** *of S denoted by $[a, b]$. Furthermore, any interval $[a, b]$ has the following properties [26]:*

1. $[a, b] = [c, d] \Longleftrightarrow a = c \wedge b = d$
2. *if* $c, d \in [a, b], e \in S$ *and* $c \leq e \leq d$ *then* $e \in [a, b]$
3. $\#([a, b]) \geq 1$

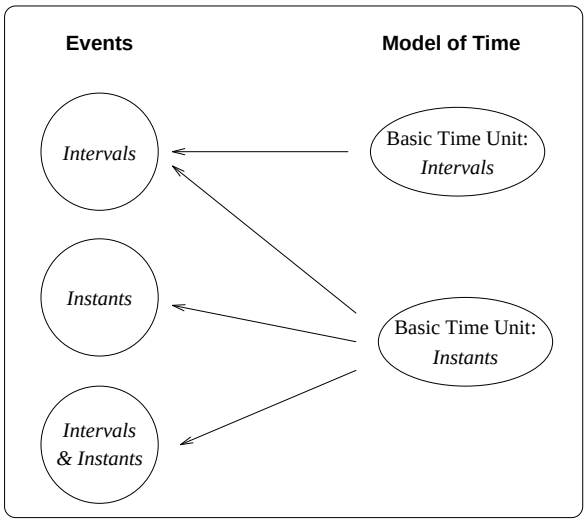

Figure 6: Modeling Events in a Temporal Scenario with Basic Time Units

The events of the temporal scenario are modeled through the basic time unit. Fig. 6 shows the relationships among the events in the temporal scenario and the basic time units of a model of time. The mapping from the temporal scenarios to the models of time is described by the following:

- Models of time with intervals as basic time units can only model interval events.
- Models of time with instants as basic time units can model interval, instants, and interval & instants together.[6]

[6]We could also think of modeling instants through intervals and consider the possibility of modeling interval & instants together through intervals. However, modeling instants through intervals is not very useful. Moreover, modeling instants and intervals through intervals is not always achievable. To the knowledge of the authors, there are no temporal techniques developed for this approach and we do not pursue the topic further.

Contextual Information. The contextual information comprising the model of time specifies the type of temporal information that can be associated with the basic time units of the model. The contextual information is a key principle in the selection of a model of time that is capable of expressing the semantics of a temporal scenario (relations/dependencies among events and indeterminacy included). The contextual information can be described as either quantitative or qualitative:

Quantitative information. Quantitative information is temporal information that can be expressed in time units (e.g., $t_1 = 6$ pm; $\#[a, b] = 3$ hours). Quantitative information can refer to any temporal axis (*absolute* or *relative*) and can be expressed using a real or virtual measure of time (e.g., seconds, minutes, or bits in a constant-bit-rate stream).

Qualitative information. Qualitative information is the temporal information that is not quantifiable. For example, total and partial orderings of basic time units represent qualitative information. Other qualitative information relating basic time units are the following:

- The **basic binary temporal relationships between instants** define the three ways in which two instants can be related [34]: `before`, `after`, and `at_the_same_time`. Only one basic temporal relation can hold between two instants.
- The **basic binary temporal relationships between intervals** define the thirteen ways in which two intervals can be related [15]. Only one basic temporal relation can hold between two intervals. These relationships are illustrated elsewhere [26]. Similarly, **n-ary temporal relationships among intervals** define the ways in which n intervals can be related in time [28]. Like the binary temporal relations, there are thirteen possible n-ary temporal relations, which reduce to the seven cases after eliminating their inverses; and a set of constraints can be identified for the timing parameter relationships among intervals of the n-ary cases.
- **Indefinite temporal relationships** are those temporal relations between basic time units that are not explicitly or unambiguously given. Usually, these indefinite relations are expressed as disjunctions of the basic temporal relationships. The number of indefinite relationships is calculated as the set of all possible disjunctions of the basic ones. For instance, there are three basic binary relations between instants, therefore, the number of indefinite relations is $2^3 = 8$. Two examples are the following {`before` or `at the same time`}, {`at the same time`

or `after`}. For intervals, there are thirteen basic binary relations between intervals. Therefore, the number indefinite relations is $2^{13} = 8192$. Three examples are the following {`starts` or `equals`}, {`finishes` or `overlaps`}, {`meets` or `after` or `overlaps`}. An enumeration of these indefinite temporal relationships has been performed by Ladkin [23] and van Beek [33].

- **Duration relationships** describe how the durations of two temporal intervals can be related [1]. Considering two intervals, $[a, b]$ and $[c, d]$, some examples are the following:

  1. $[a, b]$ is `shorter` than $[c, d]$ iff $\#[a, b] < \#[c, d]$
  2. $[a, b]$ is `longer` than $[c, d]$ iff $\#[a, b] > \#[c, d]$

  Duration relationships are usually specified in conjunction with temporal relationships among intervals.

Time Representation Techniques A time representation technique describes how time can be captured and mechanized in a computer environment. A particular representation occurs as a result of the application of a model of time. This is a concept that is intrinsically associated with the basic time units and contextual information of a model of time, i.e., a particular model of time will produce a specific time representation and will indicate the theory that will be required to interpret a resultant temporal specification.

To identify the type of time representation technique we follow Allen's terminology and classification [2]. There are three types of time representation techniques: dating schemes, constraint propagation schemes, and duration schemes. A more detailed analysis of representation techniques is described by Pérez-Luque [31].

- A **dating scheme** is a representation technique that expresses time in the form of dates or times of occurrence. These techniques consider either the exact times of occurrence (e.g., 6 pm), or intervals of possible times of occurrence (e.g., between 6:00 pm and 6:02 pm). Related to dating is pseudo-dating. Pseudo-dating does not use absolute time units (e.g., 6 pm), but units of ordering that indirectly express time of occurrence. This order means partial ordering and total ordering [3].

- A **constraint propagation scheme** is a representation technique that expresses time in the form of temporal constraints. Examples of temporal constraints include temporal relationships and duration relationships. Propagation of the constraints is provided by application of temporal logic.

- A **duration scheme** is a representation technique that expresses time in the form of temporal durations (e.g., 3 s). Additional total or partial ordering information can be added to this representation to yield a complete temporal specification.

2.2.1 Classification of Models of Time

The three previous concept, the basic time unit, contextual information, and type of time representation, completely describe a *specific* model of time. There are five general types of models of time to which we have assigned names (Fig. 7). These are:

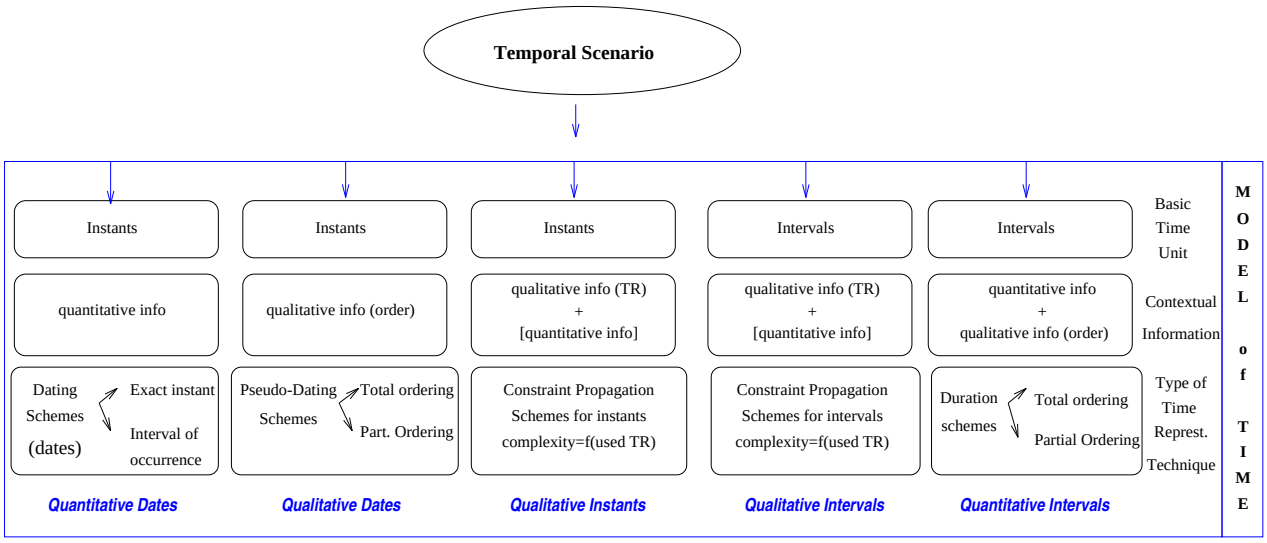

Figure 7: General Models of Time

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

2. **Qualitative dates.** The basic time unit is an instant. The associated information is qualitative in the form of ordering information. The type of time representation technique used is a pseudo-dating scheme. The specific contextual information (total order or partial order) determines the specific model of time within the category.

3. **Qualitative instants.** The basic time unit is an instant. The associated information is qualitative (temporal relationships) with optional quantitative information. The

type of time representation technique used is a constraint representation for instants. The specific contextual information (type of temporal relationships used) determines the specific model of time within the category.

4. **Qualitative intervals.** The basic time unit is an interval. The associated information is qualitative (temporal relationships) with optional quantitative information. The type of time representation technique used is a constraint representation technique for intervals. The specific contextual information (type of temporal relationships used) determines the specific model of time in the category.

5. **Quantitative intervals.** The basic time unit is an interval. The associated information is quantitative (durations) and qualitative (ordering). The type of time representation technique used is a duration-based. The specific contextual information (type of ordering information used) determines the specific model of time within the category.

With this general classification of temporal modeling approaches we now seek to identify the expressive power and general utility of each technique for representing temporal scenarios.

2.2.2 Expressive Power of the Models of Time

The previous section described five general classes of models of time from which a temporal specification scheme can be derived. However, when one seeks to model a particular temporal scenario, many questions arise: Can a specific model be used for a given temporal scenario or for a set of temporal scenarios? Do certain models have the same power of expressivity (i.e., are they equivalent)? How can we study the equivalences? To answer these questions, we first evaluate the expressive power of each model and then provide a comparison (Section 2.2.3).

The expressive power describes the ability of a model of time to represent temporal scenarios. It can tell us about the expression of semantics for the temporal scenario and the type of events that can be modeled; the way relations/dependencies among events and the indeterminacy in the temporal scenario are captured by the model. Note that the expressive power characterizes the model of time rather than the temporal scenario. It is not possible to define the set of temporal scenarios that can be modeled with a model of time. The expressive power for each general class of models of time is as follows:

1. **Quantitative dates.** This class models dates (times of ocurrence). The relations among events in the temporal scenario are captured through the specification of the

appropriate dates; however, this model does not directly express any type of temporal relation. The associated information is quantitative. If the contextual information corresponds to the exact date of occurrence, then no indeterminacy can be described with this model. If the contextual information corresponds to the modeling of the exact interval of occurrence then a limited indeterminacy can be described by specifying the two extremes of possible occurence. This can be useful for instants, intervals, and instant & intervals.

2. **Qualitative dates.** This class models dates in the form of qualitative ordering information. The temporal scenario can only be described with ordering relationships. As the contextual information is qualitative, indeterminacy in temporal scenarios can also be modeled. The level of indeterminacy depends on the contextual information. If it corresponds to fully ordered information, then the indeterminacy refers to the exact date of occurrence, but the order of occurrence is completely determined. On the other hand, if it corresponds to partially ordered information, then the indeterminacy is captured in the order of ocurrence, and therefore, on the exact dates of occurrence. This scheme is useful for instants, intervals, and instant & intervals.

3. **Qualitative instants.** The model characterizes temporally related events through temporal relationships between the basic units of the model (instants). Apart from the qualitative information, the model can also use quantitative information. The temporal scenarios that can be modeled range from completely defined (using quantitative information) to completely indeterminate (using only qualitative and indefinite information). The complexity of the contextual information gives the specific level of indeterminacy. The contextual information corresponds to the temporal relationships among the basic time units (instants). If no quantitative information is added, there is indeterminacy in the exact instant of occurrence (e.g., one can specify that an instant is `after` the other, but not how much after); but also indeterminacy in temporal relationships can be specified (i.e., by the use of indefinite temporal relations). Therefore, the specific expressive power must be determined as a function of the contextual information. This is useful for instants, intervals, and instant & intervals.

4. **Qualitative intervals.** This model considers that the events in the temporal scenario are related and model the relation through different types of temporal relationships among intervals. It uses qualitative information and quantitative information optionally. This approach can model completely defined temporal scenarios as well as temporal scenarios with indeterminacy, depending on the contextual information used. If

quantitative information is not specified, indeterminacy in the duration of the intervals can be described. Also, indeterminacy in the temporal relationships between basic time units (intervals) can be specified by the use of indefinite relationships. The specific contextual information within this general class dictates the level of indeterminacy that can be described. This scheme is useful only for intervals.

5. **Quantitative intervals.**

   This model considers that the events in the temporal scenario occur over a period of time and models this time (duration) directly. The fact that the events are related is understood as an ordering relationship. The scheme uses quantitative information and additional qualitative information. The duration of the intervals is always defined, and therefore no indeterminacy in durations can be specified. The model uses qualitative information, in the form of ordering relationships (fully or partially ordered). Therefore, indeterminacies in the specific dates of occurrence (beginning of the interval) can be modeled. This is seful only for intervals.

The statements above delineate the expressive power of the general models of time. However, as mentioned, each model must be supplemented by the use of contextual information. For example, consider two models of time belonging to the general category *qualitative intervals*. Model 1 uses basic binary relations between two intervals. Model 2 uses indefinite binary relations, i.e., it can model more than one basic relation between two intervals. They belong to the same general category and they can model interval events, but the use of different contextual information leads to different powers of expression. Model 2 can define indeterminacy in the temporal relationships between two intervals while Model 1 can only model one fixed temporal relation.

2.2.3 Equivalent Models of Time

The previous section presented the concept of the expressive power for a model of time. As we saw in the example illustrated in Fig. 2, two or more models of time can be used to capture the same multimedia scenario. In this case the models are equivalent for the scenario; however, they are not necessarily completely equivalent. In this section we analyze the equivalences between the models of time.

Fig. 8 presents a graphical description of the possible equivalences between two models of time. Model of time A, belonging to the general class I, is able to describe a subset of

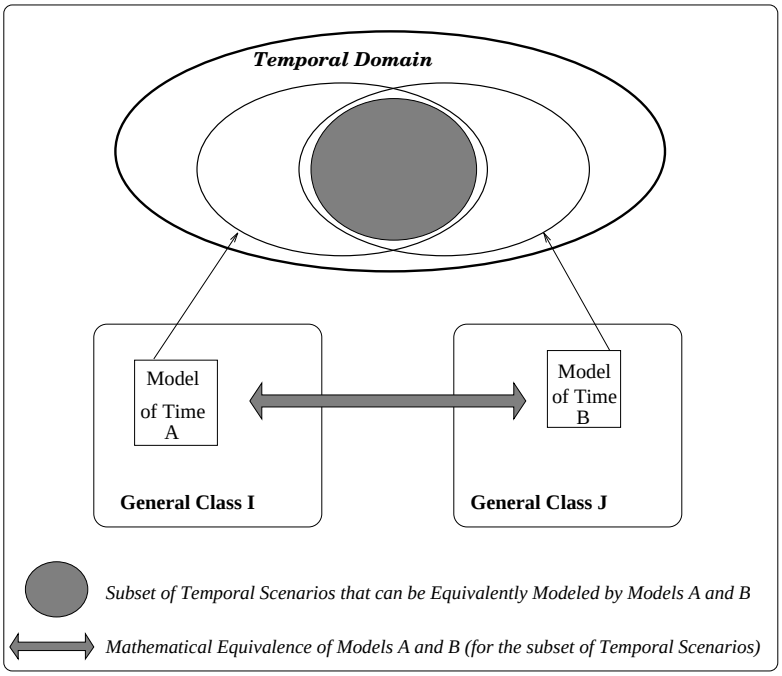

Figure 8: Equivalences Among Models of Time

temporal scenarios within the temporal domain[7] (ellipse on the left).[8] Model of time B, belonging to the general class J, is able to describe another subset of temporal scenarios within the temporal domain (ellipse on the right). If they were completely equivalent the two ellipses would coincide. In the figure, the two models of time are equivalent for a subset of temporal scenarios (the greyed circle), i.e., they can model equivalently the marked subset of temporal scenarios (intersection of subsets of model A and model B). This intersection cannot easily be identified because the concept of an temporal scenario is too abstract; however, the equivalence of the corresponding descriptions following the different models of time can be identified mathematically, and transformations among them can be found. If the temporal semantics are equivalent (horizontal greyed arrow between the models), transformation between the syntactic domains is possible. If two models of time are partially equivalent, the translation from the less powerful to the more powerful is always achievable.

The following are two examples of equivalent models of time for *particular* temporal scenarios. The first one considers the case of modeling a determinate temporal scenario that it is completely defined a priori. It is a temporal scenario composed of interval events. The second example considers an indeterminate temporal scenario comprised of interval events.

[7]The set of all temporal scenarios (TS) comprise the **Temporal Domain** (TD), i.e., $TS_i \subset TD$, the universe of temporal scenarios.

[8]The symbols A, B, I, and J, have no particular meaning except to distinguish themselves.

Example 1 *A video of 2 minute duration is presented in parallel with its video title.* There is no indeterminacy in the temporal scenario. In this example, we can think of at least two equivalent models of time for that particular scenario: *Quantitative Dates* (i.e., a definition of the exact dates for the starting and endings points of both events), and *Qualitative Instants* with three basic binary relationships plus quantitative information (i.e., a definition of the equivalent temporal relationship between the starting and ending points of the events). Fig. 9 presents these two cases and a possible representation for each of them (S means Starts, E Ends, V Video, and VT Video Title).

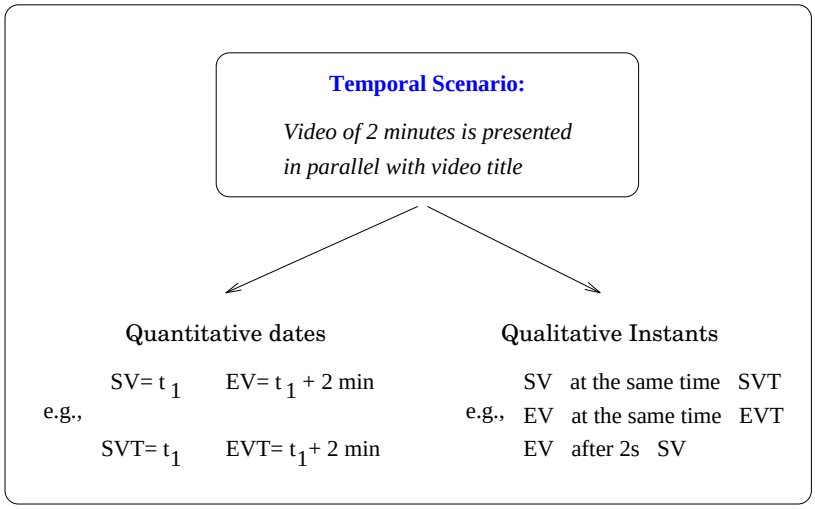

Figure 9: Example 1: Equivalent Models of Time for a Determinate Temporal Scenario

Example 2 *There are two events of unknown duration; they start at nearly the same time; event* 1 *finishes before event* 2. For this example, we require a model of time that is capable of describing an indeterminate temporal scenario (i.e., a unique description that can yield a range of different realizations). Two equivalent models are apparent: *qualitative instants* with the three basic binary relationships, and *qualitative intervals* with indefinite binary temporal relationships. Here we cannot use a quantitative date model because its expressivity does not include the required indeterminacy. Fig. 10 presents these two cases with a possible representation for each (S means starts, E ends).

These examples illustrate situations in which the models of time are equivalent for a *particular* temporal scenario. The *complete* equivalence of two models of time must be studied mathematically by comparing the basic time unit and the contextual information for each model of time.

Some studies have been undertaken to determine equivalences among existing models of

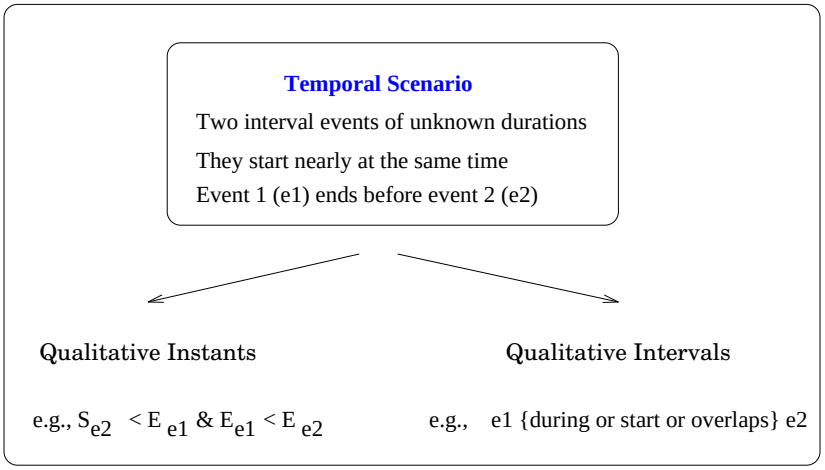

Figure 10: Example 2: Equivalent Models of Time for an Indeterminate Temporal Scenario

time. These demonstrate mathematically the complete or partial equivalence of some models. For example, the equivalence between qualitative instants and qualitative intervals models in which the contextual information consists of temporal relations is extensively studied by Ladkin [23] and van Beek [33] (e.g., the indefinite temporal relations between instants is equivalent to 181 indefinite temporal relations between intervals). Wahl and Rothermel [35] have also studied these equivalances. For example, they demonstrate that a qualitative date model (for the exact time of occurrence) is equivalent to the rest of the models if the temporal scenario is determinate.

We can also examine the equivalences among other models of time (e.g., qualitative dates model with partial ordering as contextual information vs. qualitative intervals model with the thirteen basic relationships). These comparisons are yet to be undertaken. We know that the general models can be used for representing the same particular temporal scenarios, but the complete (or partial) equivalence among them is still unknown.

2.3 Computer Representations

The goal of modeling temporal information is to find techniques for representing temporal scenarios for subsequent computer rendering and reproduction (Fig. 3). Following our terminology, we say that a mechanized representation corresponds to a *temporal specification*. More formally, a temporal specification is defined below.

Definition 4 *A* **temporal specification** *is a well-formed sentence satisfying a particular*

temporal specification language.

A specification language is the result of the definition of semantic and syntactic domains. Section 2.2 deals with the temporal semantics of the modeling process. Here we introduce the concept of syntactic domain and its influence in the resulting specification language.

The syntactic domain is defined in terms of a set of symbols (constants, variables, operators, etc.) and a set of grammatical rules. These symbols can either be textual or graphical in nature. The external appearance of a specification language corresponds to the combination of the syntactic symbols following the syntactic grammar. Many different specification languages can and have been defined for temporal representations because (1) different temporal semantics can be used for the same temporal scenario and (2) the same semantics can be represented in very different syntactic domains.

As long as the semantics of a specification language are correct, we can use any of the representations to describe a particular temporal scenario. Therefore, many different temporal specifications can be found for the same temporal scenario. In Section 4 we compare some of these representations.

In synopsis, the concept of a model of time has been introduced as influenced by three attributes: the basic time unit, contextual information, and the type of time representation technique. From these attributes, models of time are classified in five general categories. The ability of a model of time to describe a temporal scenario is determined by the expressivity of the model. The general class to which the model belongs provides a rough characterization. However, its specific expressiveness can be identified. More than one model of time can be found for the description of a concrete temporal scenario. Complete equivalence of two models of time must be demonstrated mathematically. If two models of time are completely equivalent, a translation between their representation is achievable. Finally, the syntactic domain must be selected to achieve a specification langage for a model of time, and this can be achieved with diverse syntax.

3 Temporal Reference Framework

Based on the terminology and concepts presented in Section 2, we now introduce our framework for the modeling and comparison of multimedia specification and synchronization techniques.

Multimedia synchronization techniques have been developed for the satisfaction of multimedia scenarios specified in some temporal language. In the design of these techniques, there are three processes that are clearly different (1) the definition of the specification language for a set of temporal scenarios, (2) the description of the multimedia scenario with the specification language, and (3) the creation of the synchronization mechanisms to render descriptions within the specification language. To clarify the relationship between a multimedia scenario and a temporal scenario we present the following definition:

Definition 5 *A* **multimedia scenario** *is the spatial and temporal semantics of a multimedia presentation session, i.e., the orchestration of media in time and space that should be delivered to a user.*

A temporal specification language is used to provide a temporal specification for a multimedia scenario.[9] The synchronization mechanisms try to achieve the multimedia scenario that is described in the temporal specification. These terms and their relationships are illustrated in Fig. 11 and are defined as follows.

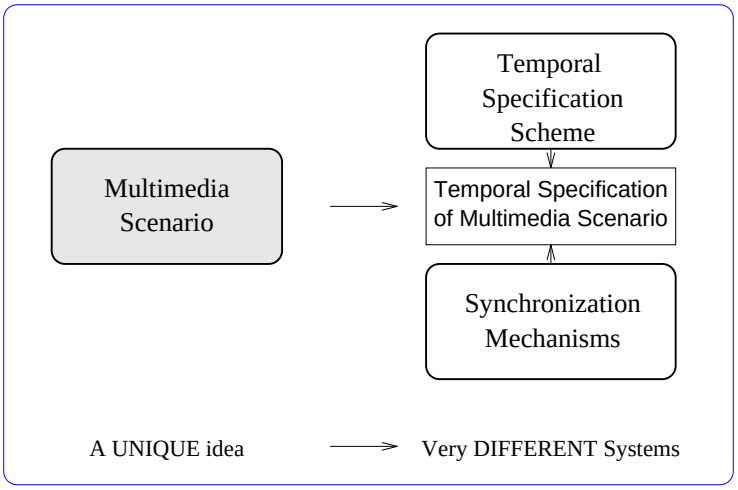

Figure 11: General View of Multimedia Synchronization Techniques

Definition 6 *A* **temporal specification scheme** *is a specification language that is used to describe multimedia scenarios.*

This specification language is defined by a semantic and a syntactic domain. The temporal specification scheme is equivalent to the time representation scheme. In multimedia

[9]In the remainder of the paper we only consider the temporal aspect of multimedia scenarios.

applications, the former usually is not restricted to temporal information, and we distinguish the two definitions. We also reiterate our distinction between specification and satisfaction of a specification in the definition of a synchronization mechanism.

Definition 7 *A* **synchronization mechanism** *is a service or process that realizes a multimedia scenario.*

The synchronization mechanisms can be one that interprets general temporal specifications (e.g., from authoring tools) or one that is restricted to particular applications (e.g., lip-sync in audio and video). These mechanisms are varied and depend on the infrastructure, the architecture of the system, and the specific media types. Therefore, although they each share the common objective of satisfaction of a temporal specification (the multimedia scenario), they must combine temporal information with other types of atemporal information in different ways.

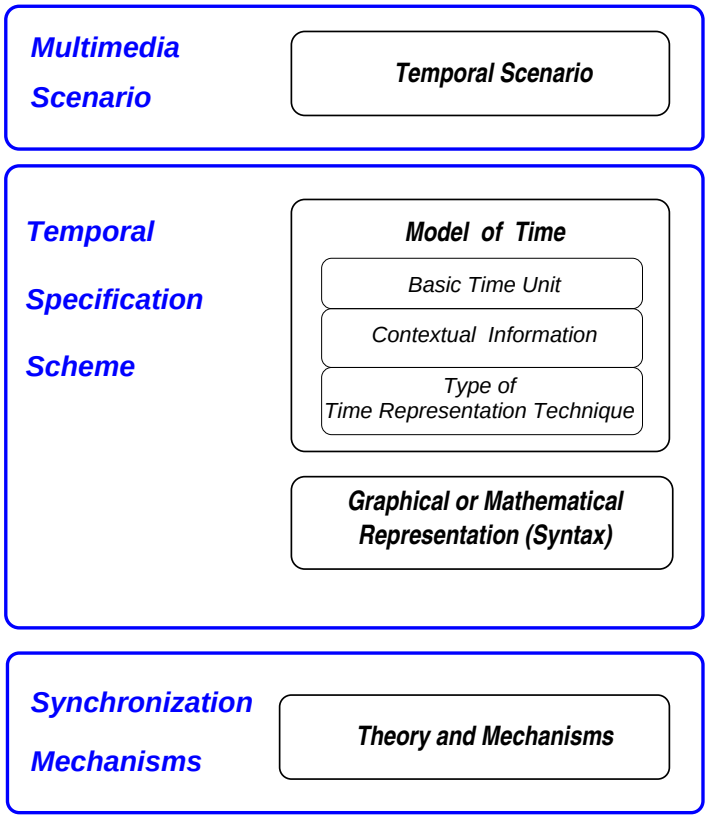

Figure 12: The Temporal Reference Framework

Fig. 12 shows the integrated view of the temporal reference framework: the **multimedia scenario**, the **temporal specification scheme**, and the **synchronization mechanisms**. On the left-hand side of the figure are the multimedia definitions; on the right-hand side are the corresponding temporal definitions.

Our temporal reference framework aims to facilitate the system analysis process by providing the necessary concepts for a unified temporal study. By comparison of components, we can use the framework to compare many synchronization techniques that attempt to realize the same multimedia scenarios. This is represented in Fig. 11: the unique idea of the left hand side does not lead to a unique solution on the right hand side. Several temporal specification schemes can be used for the temporal specification 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 system realizations can accomplish the same goal.

In a distributed multimedia system (DMS), the synchronization is achieved by the combined effort of the different parts of the system (databases, network, operating systems, etc.). We call this integration the system realization, defined below.

Definition 8 *The* **system realization** *is the specification of system components, temporal specifications, and mechanisms to carry out the multimedia scenario in a distributed multimedia system.*

Our temporal reference framework is also useful in the analysis of the components of distributed multimedia systems. It can help to identify the temporal specification schemes of each component and the exchange of temporal information among the different parts of the system.

4 Use of the Framework for Analysis and Comparison of Approaches

In this section, we analyze a number of temporal specification and synchronization techniques that have appeared in recent literature. Our analysis, based on the temporal reference framework, focuses on models of time and begins with an investigation of temporal specification schemes and concludes with a study of the temporal aspects of several distributed multimedia systems.

4.1 Temporal Specification Schemes

Recent temporal specification schemes include Firefly [6], OCPN [26], and many others. To compare these schemes we apply the proposed temporal reference framework as a guide. Each temporal specification scheme is compared in terms of structure of specification language (semantic and syntactic domain) and equivalence of the models of time used (at the semantic level). The main differences between techniques are illustrated with figures.

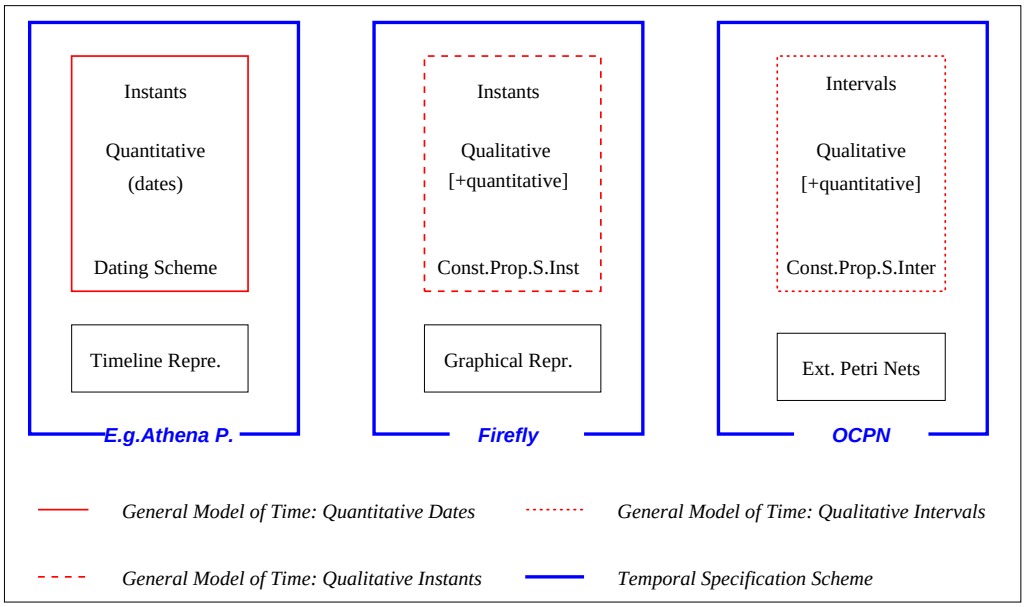

Figure 13: Comparison of Timeline, Firefly, and OCPN: Three Models of Time belonging to Different Classes of the General Classification

Fig. 13 shows a comparison of temporal specification schemes for (1) the timeline, (2) Firefly, and (3) the OCPN. As summarized in the figure, these three temporal specification schemes are distinct because of their different use of models of time. Therefore, they belong to different categories of our classification scheme. The timeline representation belongs to *quantitative dates*, Firefly belongs to *qualitative instants*, and OCPN belongs to *qualitative intervals*. As they use different models of time, they also use different syntax in their specification. Each is described in the following.

The timeline approach The timeline representation is the most basic method used for temporal specification. It consists of a dated timeline. A synchronization mechanism for this representation scheme can interpret the timeline and execute the appropriate actions at the indicated moments in time. Several synchronization systems use a timeline for the

representation of the timing constraints (e.g., the Athena Muse Project [16] and Gibbs et al. [13, 14]).

The model of time used for the timeline belongs to the general category of *quantitative dates*. The contextual quantitative information corresponds to the exact date ("at") of the basic time unit. The scheme can model homogeneous or heterogeneous temporal scenarios, but not ones with uncertainties.

Firefly Buchanan and Zellweger [6, 7] 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 used by Firefly belongs to the general category of *qualitative instants*. The contextual information corresponds to the basic binary temporal relationships between instants (i.e., only a single relationship between two instants). Associated quantitative information can also be used optionally. For modeling instants in the temporal scenario, no indeterminacy can be expressed in the temporal relations. For modeling intervals in the temporal scenario, indeterminacy in the temporal relationships can be expressed by a combination of the basic binary relationships between basic time units (instants). In any case, indeterminacy in the exact instant of occurence can be described. A graphical representation (syntax) is used to capture the relations between the specified instants.

OCPN Little and Ghafoor [26] proposed the OCPN, a temporal specification scheme for the description of general multimedia scenarios. The authors also present algorithms for deriving a playout schedule from a specification of a temporal scenario [27, 12].

The model of time used for the OCPN belongs to the general category of *qualitative intervals*. The contextual information is both qualitative and quantitative. The temporal relationships considered are the thirteen basic binary temporal relationships. No indeterminacy can be expressed in the temporal scenario because the temporal relations are fixed (no indefinite temporal relations), and modified by quantitative information, which completely determines the scenario. The graphical representation (syntax) is based on an extended type of Petri net and retains most conventional Petri net semantics.

Fig. 14 shows a comparison of three related temporal specification schemes: Hoepner's path operators, the OCPN, and Wahl and Rothermel's operators [35]. In this comparison, the models of time of the temporal specification schemes belong to the same general cat-

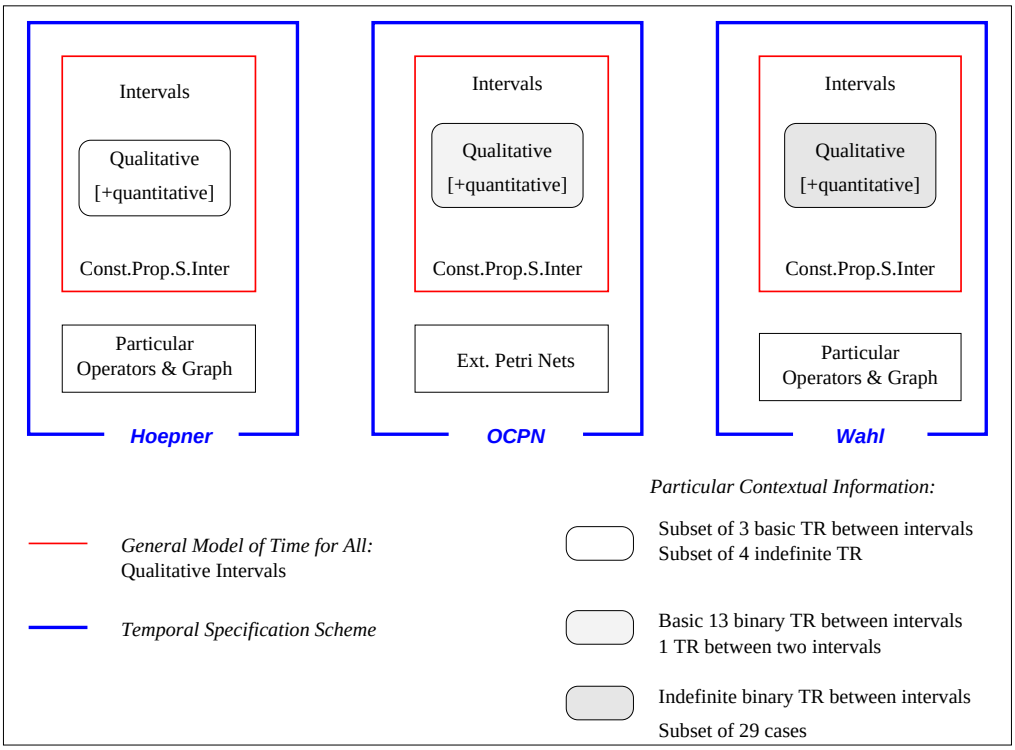

Figure 14: Comparison of Hoepner's Path Operators, OCPN, and Wahl's Specification: Same Class of General Models of Time, Different Contextual Information.

egory: *qualitative intervals*. The particular models of time used by each differ because of the contextual information that they consider. Furthermore, each technique uses a different representation. They are described in the following.

Hoepner's Path Operators Hoepner [17, 18] defines a temporal specification scheme for the description of general multimedia scenarios. Her scheme consists of a set of path operators with an associated graphical representation. These operators are valid for any synchronization mechanism that can interpret them. One such mechanism is described in reference [18].

The model of time used belongs to the general category *qualitative intervals*. The specific contextual information for the qualitative information corresponds to a subset of the basic binary relationships (three) and to a subset of the indefinite temporal relationships (four) between intervals. In this temporal specification scheme, the syntax limits the extent of the possible temporal semantics, i.e., the path operators limit the number of binary temporal relationships that can be modeled. The expressive power is reduced to model only a subset

of the possible temporal relations of the intervals in the temporal scenario. Indeterminacy in the temporal relationships (four indefinite relations) can be expressed.

Wahl and Rothermel's Temporal Specification Scheme Wahl and Rothermel [35] have proposed a temporal specification scheme for multimedia scenarios. A common set of operators describe the temporal relationships between intervals and the possible variations due to user interaction. A synchronization mechanism for realizing the specification has not been reported.

For this scheme, the model of time belongs to the general category of *qualitative intervals*. The contextual information is qualitative and can use quantitative information optionally. The temporal relationships consided are a set of 29 indefinite binary temporal relationships. Ten operators are used in conjunction with parameters to cover all possible cases and can be illustrated graphically. Indeterminacy of interval durations in the temporal scenario can be expressed in addition to indefinite temporal relationships between pairs of intervals.

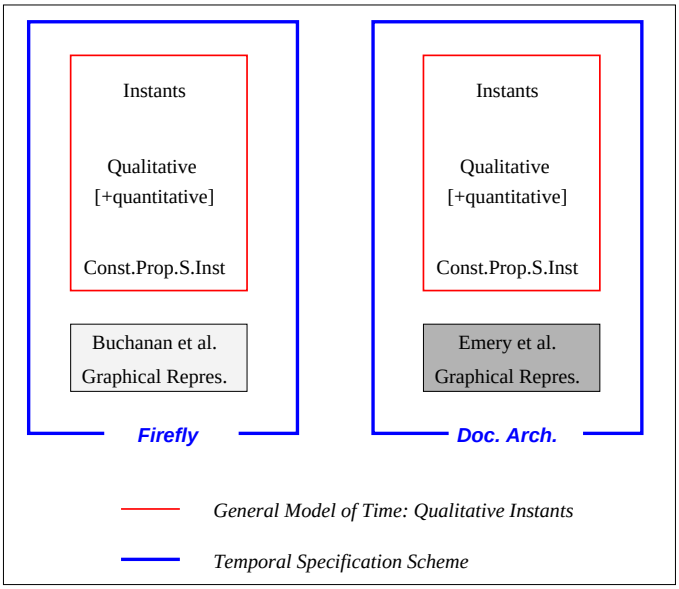

Figure 15: Comparison of Firefly and Emery's Document Architecture: Same Model of Time, Different Graphical Representations.

Fig. 15 and Fig. 16 present comparisons of temporal specification schemes with identical temporal semantics but different syntactic domains. In the case illustrated by Fig. 15, the model of time used is *qualitative instants* with the three basic binary relationships between instants and quantitative information. In the case illustreated by Fig. 16, both approaches use a *qualitative interval* model with the thirteen basic binary relationships and quantitative

information. Emery's and Filali's approaches are explained as follows. (The expressivity of these models is equivalent to Firefly and the OCPN, respectively.)

Emery's Temporal Specification Scheme Emery [8] et al. propose a temporal specification scheme for the description of general multimedia scenarios. The temporal semantics are the same as Buchanan's approach. (In this comparison we do not consider the concept of flexibility that is introduced by Buchanan; we are comparing this from the temporal specification perspective.) The graphical representation is different as are the synchronization rendering mechanisms of the system. Buchanan's approach has been developed in conjunction with a scheduling system, while Emery's has been developed for a run-time system.

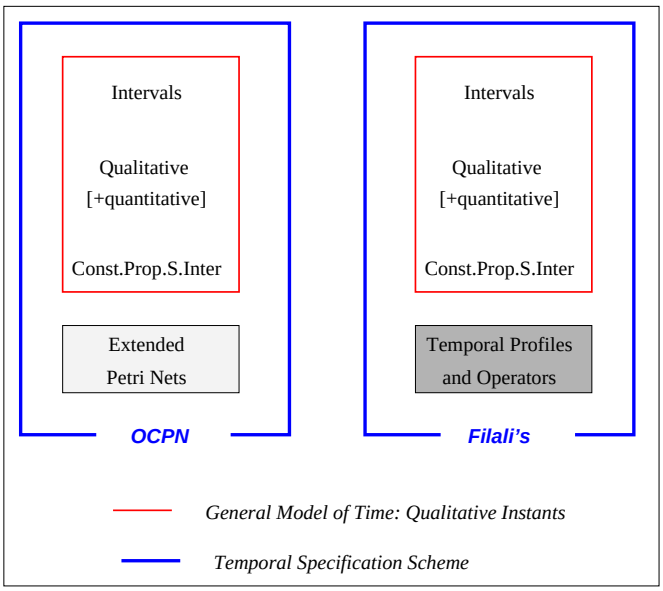

Figure 16: Comparison of OCPN and Filali's Specification: Same Model of Time, Different Graphical Representations.

Filali's Temporal Specification Scheme Filali [11] has proposed a formal language for the definition of multimedia scenarios. The syntactic domain corresponds to the elements and the grammar of the specification language. The temporal semantics are the same as OCPN, but the syntactic domains are different. He has also proposed a scheduling algorithm, i.e., the associated theory necessary for system realization from the formal language.

Fig. 17 illustrates two synchronization mechanisms that have been designed for the same temporal scenario: the synchronized delivery of audio and video. In both cases, the temporal specification is created in run-time with a time-stamping mechanism.

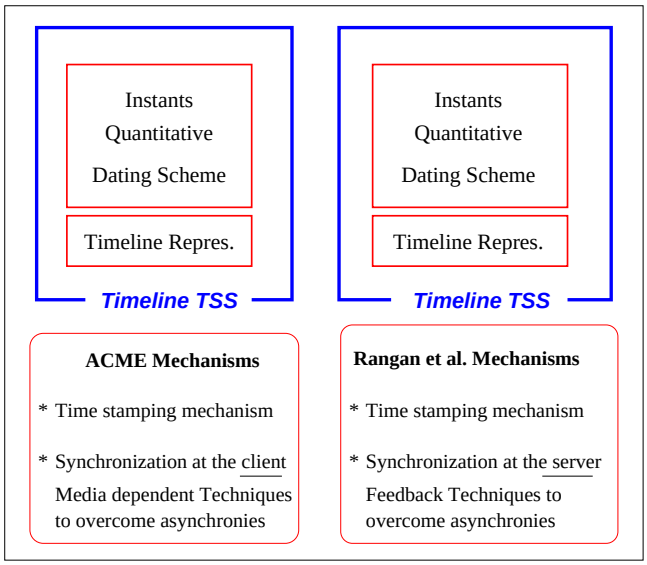

Figure 17: Comparison of the ACME System and the system of Rangan et al.: Same Temporal Specification Scheme, Different Mechanisms.

In this case, the re-synchronization mechanisms are different: the ACME [4] system tries to overcome asynchronies at the client side, while the system proposed by Rangan et al. [32] tries to solve the asynchronies at the server side. The different architectures of the systems also has an influence on the mechanisms. We illustrate these approaches to highlight that a temporal specification can be achieved by very different system architectures and mechanisms.

Discussion The aforementioned specification schemes can be examined for equivalence of temporal specification schemes. Fig. 18 shows a multimedia scenario and three possible temporal specification schemes for its representation. Using a natural language, the scenario can be described as a video of a person anchoring the news, a title of the broadcast company presented for the duration of the news broadcast, and two graphics that appear during the exposition. The Timeline, Firefly and OCPN schemes can be used for its specification. The resultant temporal specifications are shown at the bottom of Fig. 18. The temporal specifications are different but equivalent for this particular multimedia scenario.

Although several temporal specification schemes might be equivalent for a particular multimedia scenario (e.g., Fig. 18), this does not imply that their temporal semantics are equivalent in all cases. In the analysis of equivalence (and translation) of temporal speci-

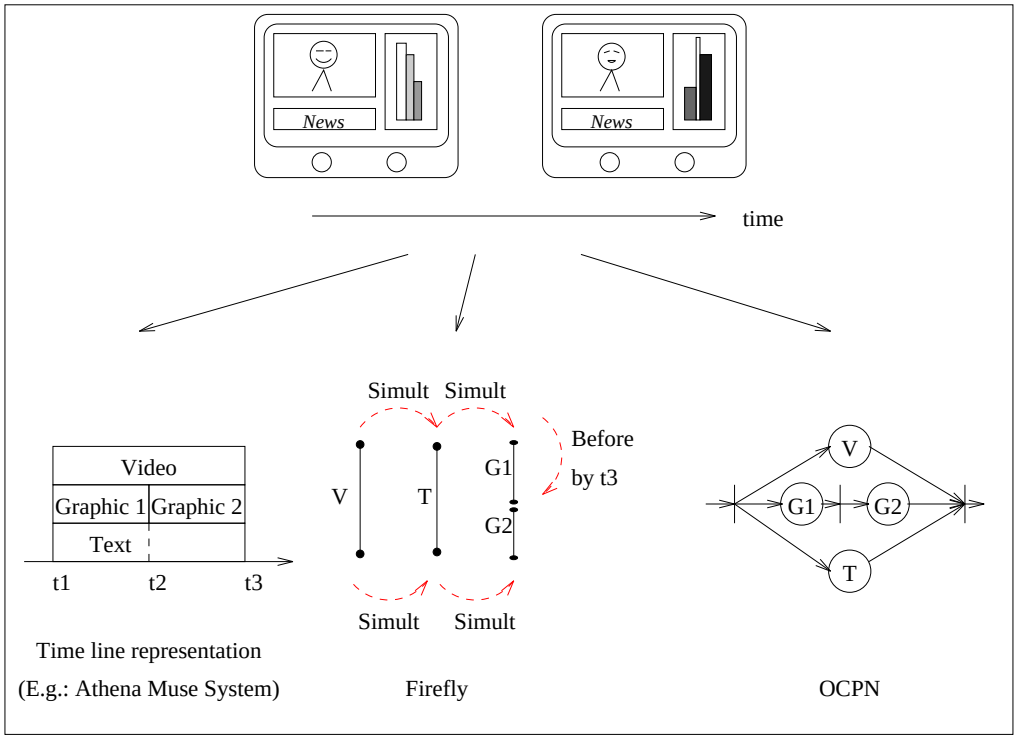

Figure 18: Several Temporal Specifications of a Particular Multimedia Scenario

fication schemes, three steps are required: (1) separation of the syntactic domain from the temporal semantic domain for each specification scheme under evaluation, (2) evaluation of the equivalences at the semantic level (Section 2.2.3); two temporal specification schemes are equivalent if and only if their models of time are equivalent, and (3) indentification of the translation at the syntactic level. If the models of time are equivalent, the translation is always possible.

Few studies dealing with equivalent temporal specification schemes have been reported. Wahl and Rothermel [35] present a mathematical comparison of the equivalences among some temporal specification schemes: Timeline (e.g., [16]), OCPN [26], Firefly [6], MHEG [21], and Wahl and Rothermel's operators [35]. The results of this study indicate that the listed approaches are equivalent for scenarios with no indeterminacy; however, only two of them (Firefly and Wahl and Rothermel's technique) can be used for modeling indeterminate scenarios. Fig. 19 illustrates four of these schemes and the scenarios that they can model. Although this study effectively compares the equivalences at the semantic level, it does not examine translations among the schemes at the syntactic level.

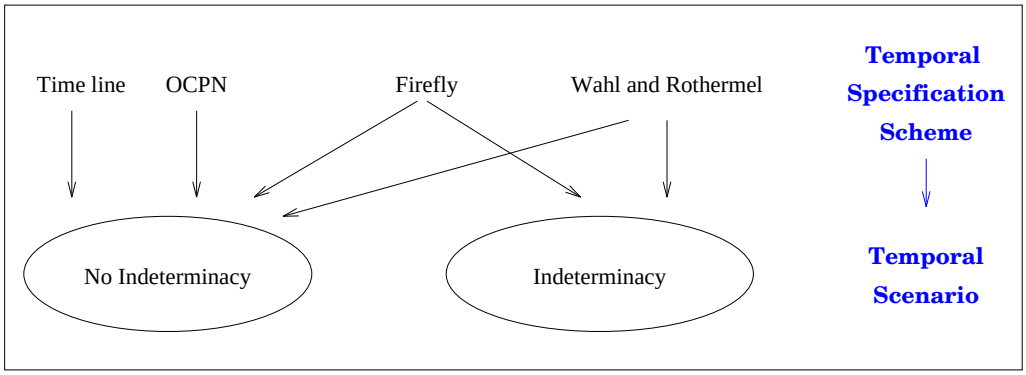

Figure 19: Equivalences of Temporal Specification Schemes

In contrast, Erfle [9] studies possible translations among three temporal specification schemes. He proposes translations at the syntactic level, but does not use an adequate theoretical foundation for sufficient comparison at the semantic level. Compared schemes are OCPN [26], MODE [5], and Firefly [6], studied for the purpose of translation into HyTime [20, 29]. Because HyTime uses a timeline model [22, 30], the study results in a comparison of four temporal specification schemes. He demonstrates that HyTime is able to specify the same temporal constraints as the other three schemes, and details the equivalent syntactic translations for particular temporal scenarios. He admits that for user interaction (indeterminate temporal scenarios), there are some indeterminate semantics that cannot be translated directly to HyTime. A mathematical justification for these results (with the exception of MODE) can be found in reference [35].

Iino et al. [19] propose an object-oriented scheme for spatio-temporal synchronization of multimedia information. They also study the translation between the OCPN [26] and their proposed model. Their temporal specification scheme differs from the OCPN in two respects: (1) the contextual information associated with the OCPN consists of the basic binary temporal relationships, while the their model considers the *n-ary* basic temporal relationships [28]; and (2) the syntax of their model includes additional spatial and "processing" capabilities. We note that any scenario modeled with the OCPN can also be modeled with Iino's scheme. The translation between the two temporal specification schemes is achievable.

4.2 Distributed Multimedia Systems

It is particulary interesting to observe how the various system components follow different models of time in a complete distributed multimedia system. In this section we briefly show the utility of the temporal reference framework in the analysis of distributed multimedia

systems. Again, our focus is on the identification of the different models of time used in each component.

Fig. 20 illustrates a system realization of the Firefly system (temporal specification plus scheduler). The figure shows the temporal specification scheme for a multimedia scenario that considers user interaction, i.e., indeterminacy in the final realization. With a language description it can be described as follows: "Object 2 is presented before object 3, and during the presentation of objects 2 and 3, object 1 is presented. Also, two related unpredictable events are also considered, event 4 triggers event 5 after 2 seconds, and they end together (the end is unpredictable)." For this system we see two models of time appearing: the Firefly temporal specification scheme, and the derived schedules. The former originates from the Firefly authoring tool in the specification of the multimedia scenario (*qualitative instants*), and the latter from the presentation playout schedules of the presentation system (*quantitative dates*). Because user interaction is considered, the derived presentation schedules are provisional, and they are merged properly in real-time following the user's interaction.

Fig. 21 illustrates the operation of the distributed system proposed by Little and Ghafoor [27] for the same multimedia scenario of the previous example (unpredictable events are not considered here). The system uses a derivation of a playout schedule for presentation. As it assumes a distributed architecture, delay and jitter variations are anticipated during the presentation process. To overcome these problems, a secondary schedule is derived [12]. The system shown uses a scenario specification through the OCPN (*qualitative intervals*), and a playout specification (*quantitative dates*). The communication system also works according to the same model of time as the playout schedule. The quantitative information in the case of the playout schedule is different than the information used in the retrieval schedule (here, the dates are derived from the presentation playout schedule).

The identification of temporal structures in the overal multimedia system is very useful for comparison. Systems that are intended for different applications, and that appear to have little resemblance can have identical temporal structures. Fig. 22 compares temporal structures of two distributed multimedia systems: the OCPN system presented above, and a possible implementation following the temporal specification scheme proposed by Li Li et al. [24, 25]. In this case, the systems have the same temporal structure: (1) a temporal specification scheme for the multimedia scenario, on the left-hand side, OCPN, on the right-hand side, Temporal Graph Model (TGM); (2) the presentation system, both of them follow a presentation schedule that has been derived from the specification of the multimedia scenario (a *quantitative dates* model of time); (3) a communication system that follows a retrieval

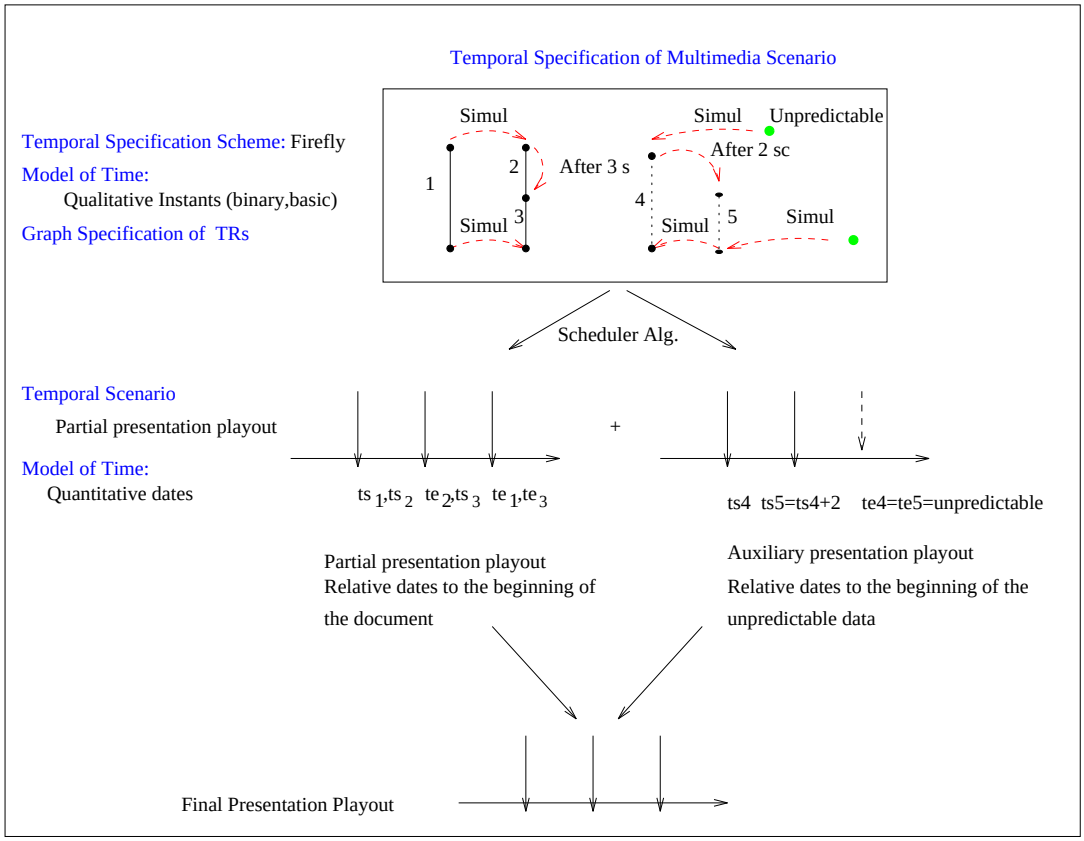

Figure 20: Firefly

schedule that has been derived from the presentation schedule. Although the temporal specification schemes and the theory and mechanisms to derive the schedules and carry them out are different, the temporal structures are the same.

Discussion The identification of the temporal models used in each component of the system clarifies the way in which different approaches can be combined. For example, Amer et al. [3] have designed a communications protocol which takes advantage of partial orderings to improve transmission bandwidth utilization. One can envision the use of a specification scheme such as the OCPN for the description of a multimedia scenario, the use of a presentation schedule for the playout mechanism, and the use of the aforementioned communications protocol for the transmission of the media units. To achieve this combination we need an algorithm that generates a partial ordering from the OCPN temporal specification.

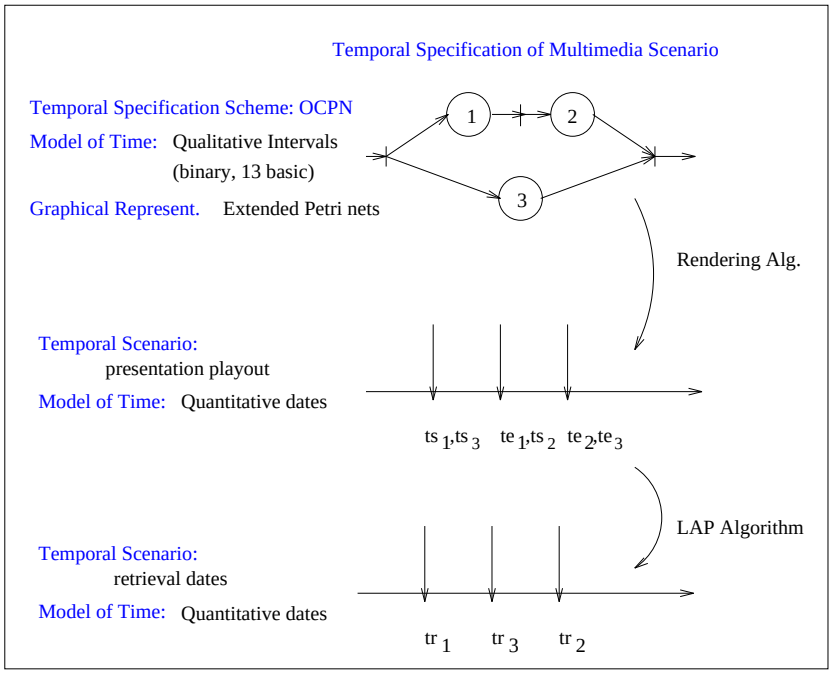

Figure 21: OCPN System

Escobar has proposed another protocol for the communication system: the Flow Synchronization Transport Protocol [10]. It has been designed for media units generated in real-time, and provides a constant virtual delay between sources and destinations. This protocol can also be used for the transmission of stored data by using a prespecified retrieval schedule (Fig. 23).

Fig. 24 illustrates several alternatives for the construction of distributed multimedia systems by combining a temporal specification scheme with different mechanisms for satisfying the communications component. The models of time for each part of the system are highlighted. In this figure, an OCPN specification is shown with a rendering algorithm that generates quantitative dates. This is linked to the LAP algorithm and might also be linked to the Flow Synchronization Transport Protocol through some (undefined) algorithm X. The OCPN can also be applied to techniques such as the partial order protocol of Amer et al. through some (undefined) translation Y or to other communications approaches not considered here. In all cases the unifying basis is a model of time.

Fig. 25 shows another example of the combination of techniques to yield multimedia

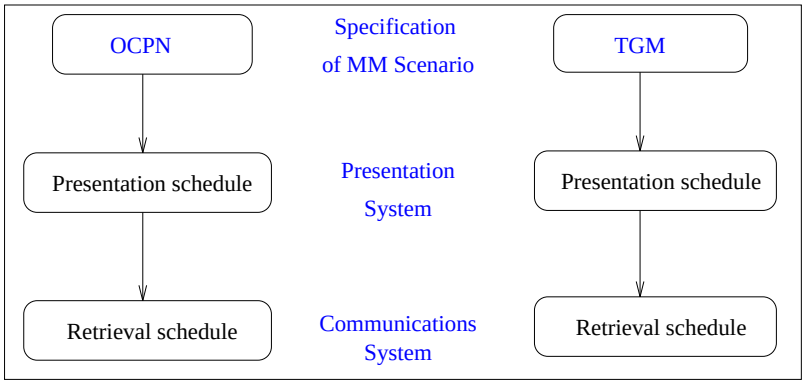

Figure 22: Comparison of Systems Derived from Li Li et al. and the OCPN

synchronization. Here we use the same communication system for different temporal specification schemes when uncertainties do not exist. From any of the temporal specification schemes we can derive a presentation schedule. With some (undefined) algorithm (X) we can transform presentation schedules into retrieval schedules, and then use the flow transport protocol for communications.

5 Conclusion

In this paper we have divided the general multimedia synchronization problem into two parts: one of modeling, representing, and specifying timing requirements of multimedia scenarios; and the other of achieving a temporal specification via synchronization methods. The former problem was the focus in our development of a temporal reference framework that can be used to evaluate and synthesize temporal specification schemes for the support of multimedia synchronization.

The temporal reference framework is based on existing temporal theory and modeling techniques and attempts to unify the terminology applied towards temporal specification for multimedia. The framework was applied to the comparison of existing approaches for multimedia synchronization to illustrate the differences of modeling power and to justify the development of the framework.

Our comparison of existing approaches indicates the utility of the framework. In addition, the analysis explains why there are so many synchronization frameworks, how a multimedia

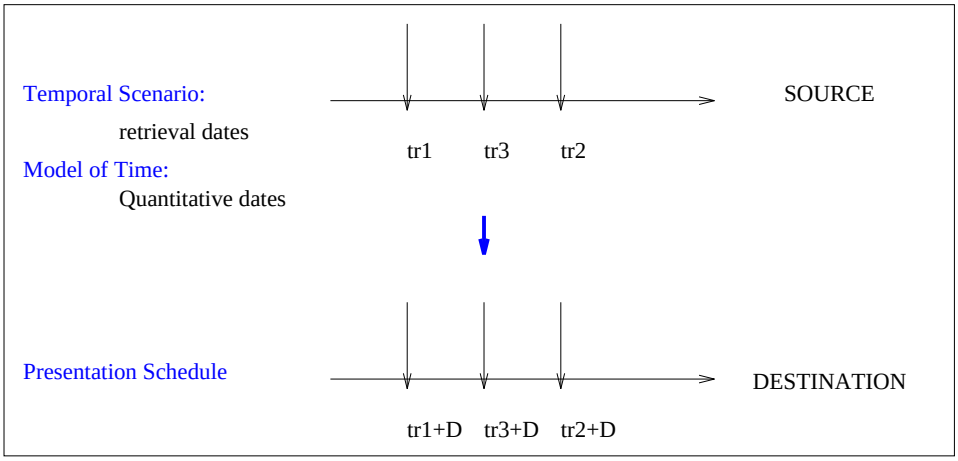

Figure 23: The Flow Synchronization Protocol

scenario can be represented with different temporal specification schemes, and why some specification schemes cannot model all scenarios.

References

[1] Allen, J.F. Maintaining Knowledge About Temporal Intervals. *Communications of the ACM*, 26(11):832–843, November 1983.

[2] Allen, J.F. Time and Time Again: The Many Ways to Represent Time. *International Journal of Intelligent Systems*, 6:341–355, 1991.

[3] Amer, P.D., Chassot, C., Connolly, T.J., Díaz, M., and Conrad, P. Partial Order Transport Service for Multimedia and Other Applications. *IEEE/ACM Trans. on Networking*, 2(5):440–456, October 1994.

[4] Anderson, D. and Homsy, G. A Continuous Media I/O Server and Its Synchronization Mechanism. *Computer*, pages 51–57, October 1991.

[5] Blakowski, G., Hübel, J., and Langrehr, U. Tools for Specifying and Executing Synchronized Multimedia. In R.G.Herrtwich, editor, *Proc. Network and Operating System Support for Digital Audio and Video*, pages 271–282. Springer-Verlag, 1991.

[6] Buchanan, M.C. and Zellweger, P.T. Specifying Temporal Behavior in Hypermedia Documents. In *Proc. of the ACM European Conference on Hypertext*, pages 262–271, Milan, Italy, December 1992.

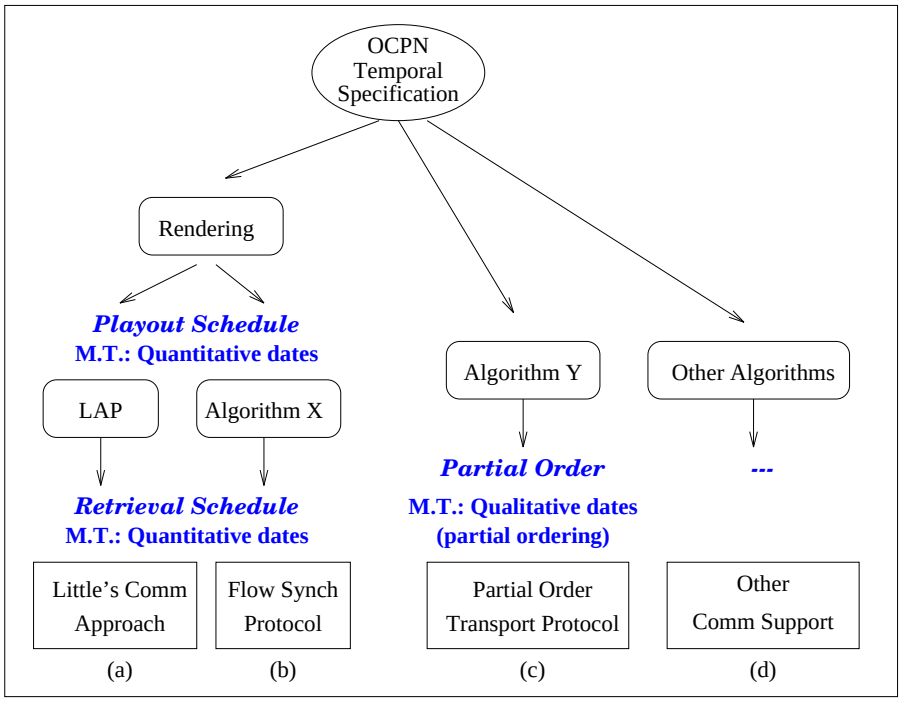

Figure 24: Using the OCPN with Different Communications Protocols

[7] Buchanan, M.C. and Zellweger, P.T. Automatic Temporal Layout Mechanisms. In *Proc. ACM Multimedia 93*, pages 341–350, Anaheim, CA, August 1993.

[8] Emery, J. and Karmouch, A. A Multimedia Document Architecture and Rendering Synchronization Scheme. In *Second International Conference Broadband Islands (Bridging the Services Gap)*, pages 59–69, June 1993.

[9] Erfle, R. HyTime as the Multimedia Document Model of Choice. In *Proc. IEEE Intl. Conference on Multimedia Computing and Systems*, pages 445–454, Boston, MA, May 1994.

[10] Escobar, J., Deutsch, D., and Partridge, C. Flow Synchronization Protocol. *IEEE/ACM Trans. on Networking*, 2(2):111–121, April 1994.

[11] Filali, M. The Specification of the Temporal Behaviour for Multimedia Scheduling. *Annals of Telecommunications*, 49(5-6):315–323, May-June 1994.

[12] Gibbon, J. and Little, T.D.C. Real-Time Data Delivery for Multimedia Networks. In *Proc. of the 18th Annual Conference on Local Computer Networks*, pages 7–16, Minneapolis, MN, September 1993.

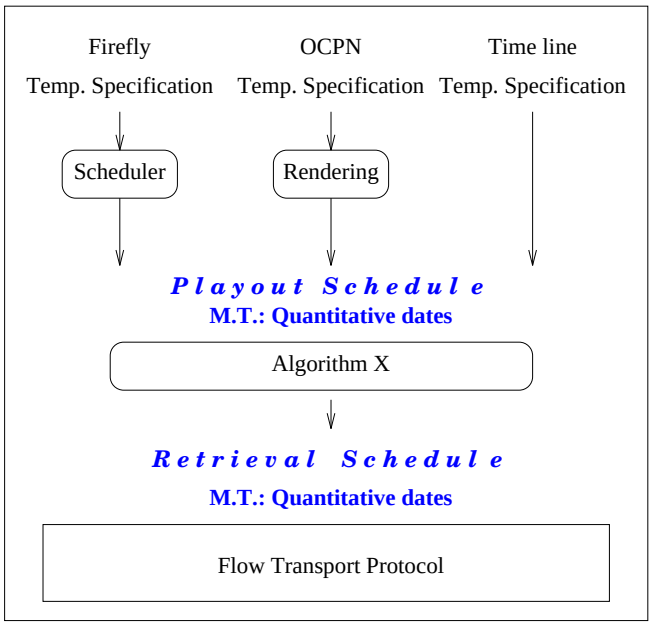

Figure 25: Using the Flow Synchronization Protocol for Several Temporal Specification Schemes

[13] Gibbs, S. Composite Multimedia and Active Objects. In *Proc. Object-Oriented Programming Systems, Languages and Applications (OOPSLA'91)*, pages 97–112, 1991.

[14] Gibbs, S., Dami, L., and Tsichritzis, D. An Object Oriented Framework for Multimedia Composition and Synchronization. In *Proc. Eurographics Multimedia Workshop*, Stockholm, Sweden 1991.

[15] Hamblin, C.L. Instants and Intervals. In *Proc. of the 1st Conf. of the Intl. Society for the Study of Time*, New York 1972.

[16] Hodges, M. and Sasnett, R. "Synchronization". *Multimedia Computing: Case Studies from MIT Project Athena*, Addison-Wesley, 1993.

[17] Hoepner, P. Presentation Scheduling of Multimedia Objects and its Impact on Network and Operating System Support. In R.G.Herrtwich, editor, *Proc. Network and Operating System Support for Digital Audio and Video*, pages 132–143. Springer-Verlag, 1991.

[18] Hoepner, P. Synchronizing the Presentation of Multimedia Objects. *Computer Communications*, 15(9):557–564, November 1992.

[19] Iino, M., Day, Y.F., and Ghafoor, A. An Oject-Oriented Model for Spatio-Temporal Synchronization of Multimedia Information. In *Proc. IEEE Intl. Conference on Multimedia Computing and Systems*, pages 110–119, Boston, MA, May 1994.

[20] ISO. Hypermedia/Timed Based Document Structuring Language (HyTime). *ISO/IEC IS 10744*, April, 1992.

[21] ISO. Information Technology Coded Representation of Multimedia and Hypermedia Information Objects (MHEG). ISO/IEC JTC1/SC29/WG12. Standards document, February, 1993.

[22] Koegel, J.F., Rutledge, L.W, Rutledge, J.L, and Keskin, C. Hyoctane: A HyTime Engine for and MMIS. In *Proc. ACM Multimedia 93*, pages 129–136, Anaheim, CA, August 1993.

[23] Ladkin, P. and Maddux, R. On Binary Constraint Networks. Technical Report Palo Alto, CA, Krestel Institute, 1988.

[24] Li, L., Karmouch, A., and Georganas, N.D. Multimedia Teleorchestra with Independent Sources: Part 1 – Temporal Modeling of Collaborative Multimedia Scenarios. *ACM/Springer Multimedia Systems*, 1(4):143–153, 1994.

[25] Li, L., Karmouch, A., and Georganas, N.D. Multimedia Teleorchestra with Independent Sources: Part 2 – Synchronization Algorithms. *ACM/Springer Multimedia Systems*, 1(4):154–165, 1994.

[26] Little, T.D.C. and Ghafoor, A. Synchronization and Storage Models for Multimedia Objects. *IEEE Journal on Selected Areas in Communications*, 8(3):413–427, April 1990.

[27] Little, T.D.C. and Ghafoor, A. Scheduling of Bandwidth-Constrained Multimedia Traffic. *Computer Communications*, 15(6):381–387, July/August 1992.

[28] Little, T.D.C. and Ghafoor, A. Interval-Based Conceptual Models for Time-Dependent Multimedia Data. *IEEE Transactions on Knowledge and Data Engineering*, 5(4):551–563, August 1993.

[29] Markey, B.D. HyTime and MHEG. In *Proc. COMPCON Spring 1992*, pages 25–40, San Francisco, CA, February 1992.

[30] Newcomb, S.R., Kipp, N.A., and Newcomb, V.T. HyTime. *Communications of the ACM*, 34(11):67–83, November 1991.

[31] Pérez-Luque, M.J. Un Marco de Referencia Temporal para Técnicas de Sincronización Multimedia. *PhD Dissertation*, E.T.S.Ingenieros de Telecomunicación, Universidad Politécnica de Madrid 1995. (Also available in English as: A Temporal Reference Framework for Multimedia Synchronization Techniques).

[32] Rangan, P.V, Vin, H.M., and Ramanathan, S. Designing an On-Demand Multimedia Service. *IEEE Communications Magazine*, pages 56–64, July 1992.

[33] van Beek, P. and Cohen, R. Exact and Approximate Reasoning about Temporal Relations. *Computational Intelligence*, 6:132–144, 1990.

[34] Vilain, M. and Kautz, H. Constraint Propagation Algorithms for Temporal Reasoning. In *Proc. AAAI-86, Artificial Intelligence*, pages 377–382, Philadelphia, August, 1986.

[35] Wahl, T. and Rothermel, K. Representing Time in Multimedia Systems. In *Proc. IEEE Intl. Conference on Multimedia Computing and Systems*, pages 538–543, Boston, MA, May 1994.