

# Interval-Based Conceptual Models for Time-Dependent Multimedia Data

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**Abstract**—Multimedia data often have time dependencies that must be satisfied at presentation time. To support a general-purpose multimedia information system, these timing relationships must be managed to provide utility to both the data presentation system and the multimedia author.

In this paper we propose new conceptual models for capturing these timing relationships and managing them as part of a database. Specifically, we introduce and define  $n$ -ary and reverse temporal relations along with their temporal constraints. These new relations are a generalization of our earlier temporal models and establish the basis for conceptual database structures and temporal access control algorithms to facilitate forward, reverse, and partial-interval evaluation during multimedia object playback. The proposed relations are defined to ensure a property of monotonically increasing playout deadlines to facilitate both real-time deadline-driven playout scheduling or optimistic interval-based process playout. Furthermore, we show a translation of the conceptual models to a structure suitable for a relational database.

**Index Terms**—Multimedia databases, scheduling, synchronization, temporal modeling.

## I. INTRODUCTION

MULTIMEDIA refers to the integration of text, images, audio, and video in a variety of application environments. These data can be heavily time-dependent, such as audio and video in a motion picture, and require time-ordered playout during presentation. The task of coordinating sequences of these data requires synchronization among the interacting media as well as within each medium. Synchronization can be applied to the playout of concurrent or sequential streams of data and to the external events generated by a human user including browsing, querying, and editing typical of stored-data applications. This problem of synchronizing time-ordered sequences of data elements is fundamental to multimedia data.

Timing relationships between the media can be implied, as in the simultaneous acquisition of voice and video, or

can be explicitly formulated, as in the case of a multimedia document with voice-annotated text. In either situation, the characteristics of each medium, and the relationships among them must be established in order to provide synchronization in the presence of vastly different presentation requirements. Consider the familiar canned *multimedia slide presentation* in which a series of verbal annotations coincides with a series of images. The presentation of the annotations and the slides occur in a sequential manner. Synchronization points correspond to the change of an image and the end of a verbal annotation, representing a *coarse-grain* synchronization between objects. A *fine-grained* example of synchronization is the lip-sync of audio and video which usually requires 25 or 30 synchronization points per second.

A multimedia system must preserve the timing relationships among the elements of the object presentation at these points by the process of multimedia synchronization. A multimedia database management system (MDBMS) must have the capability for managing the aspects of time required for time-dependent media. This problem is different from the provision of historical databases, temporal query languages [25], [27], or time-critical query evaluation [14]. Time-dependent multimedia objects require special considerations for *presentation* due to their real-time playout characteristics as data need to be delivered from the storage devices based on a prespecified schedule. Furthermore, presentation of a single object can occur over an extended duration (e.g., a motion picture). Fig. 1 illustrates such a time dependency between elements of a composite multimedia object. In this example, a sequence of text and image elements are played-out in succession based on such a prespecified schedule.

The tolerance of data to timing skew and jitter during playout varies widely depending on the medium. Audio and video require tight bounds on the order of hundreds of milliseconds, whereas synchronous text and images can tolerate skew on the order of seconds. Furthermore, audio and video can tolerate different absolute timing requirements during playout as the human ear can discern dropouts in audio data more readily than of video. Based on the data's tolerance to skew and jitter during playout, two approaches to providing synchronous playout of time-dependent data streams have been proposed. These consist of a real-time scheduling approach [19], and an optimistic interval-based process approach as proposed in this paper.

In addition to simple linear playout of time-dependent data sequences, other modes of data access are also possible due to the unique nature of the multimedia data objects and should

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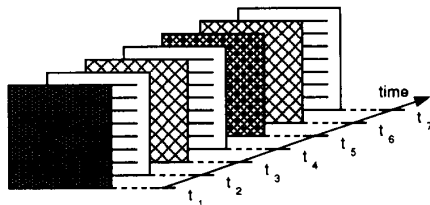


Fig. 1. Time-dependent data presentation.

be supported by a MDBMS. These include

- reverse,
- fast-forward,
- fast-backward,
- midpoint suspension, and
- midpoint resumption.

These *temporal access control* (TAC) operations are feasible with existing technologies; however, when nonsequential storage devices are used with complex data compression algorithms, and random communication delays are introduced due to data distribution, the provision of these capabilities can be very difficult. Examples include viewing a motion picture backwards or reversing an animation of a series of images (sequence reversal), rapid viewing of a long sequence of time-dependent data by increasing the rate of presentation or by skipping some data (fast-forward or fast-backward), and stopping and starting of a motion picture at an arbitrary point (midpoint suspension, resumption, and partial interval evaluation).

In this paper, we propose temporal-interval-based models and constraints which provide a basis for a proposed conceptual data representation and algorithmic support of the aforementioned TAC functionality. The work represents major extension and generalization of our earlier models presented in [17]; however, we do not consider the dynamic properties of user interaction (e.g., Stotts and Furuta [24]). The uncertainty created by random user interaction is an additional complexity in managing time in multimedia information systems.

The remainder of the paper is organized as follows. In Section II, we review related work on time-dependent data storage. In Section III, we describe interval-based modeling schemes, including our proposed models for establishing a conceptual database structure. Section IV describes a conceptual data representation based on the new temporal models, including an example using a relational implementation. Section V describes algorithms for accessing the proposed conceptual models in the context of a database. We discuss characteristics of the overall modeling methodology in Section VI, and in Section VII we conclude the paper.

## II. BACKGROUND AND RELATED WORK

The primary requirements for the support of time-dependent data payout in an MDBMS include the means for the identification of temporal relations between multimedia data objects, temporal conceptual database schema development, physical schema design, and synchronous access for data retrieval. In

this section we briefly describe these requirements, introduce various terminology, and describe related work.

As indicated in the introduction, time-dependent data differ from historical data which do not specifically require timely payout. Typically, time-dependent data are stored using mature technologies possessing mechanisms to ensure synchronous payout (e.g., VCRs or audio tape recorders). With such mechanisms, dedicated hardware provides a constant rate of payout for homogeneous, periodic sequences of data, and concurrency in data streams is provided by independent physical data paths. When this type of data is migrated to more general-purpose computer data storage systems (e.g., disks), many interesting new capabilities are possible, including random access to the temporal data sequence and time-dependent payout of static data (animation). However, the generality of such a system eliminates the dedicated physical data paths and the implied data structures of sequential storage. Therefore, a general MDBMS needs to support new access paradigms including a retrieval mechanism for large amounts of multimedia data, and must provide conceptual and physical database schemata to support these paradigms. Furthermore, a MDBMS must also accommodate the performance limitations of the computer.

At the conceptual level, the temporal aspects of data must be modeled. Data can have *natural* or *implied* time dependencies, (e.g., audio and video recorded simultaneously). These data streams often are described as continuous because recorded data elements form a continuum during payout, i.e., elements are played-out contiguously in time. Static data, which lack time dependencies, can have *synthetic* temporal relationships (e.g., Fig. 1). The combination of natural and synthetic time dependencies can describe the overall temporal requirements of any pre-orchestrated multimedia presentation. Temporal information can be encapsulated in the description of the data using the object-oriented paradigm (e.g., Gibbs [10], Herrtwich [12]). Using such schemes, temporal information such as a time reference, payout time units, temporal relationships, and required time offsets can be maintained for specific multimedia objects. If the data are periodic, this approach can define the time dependencies for an entire sequence by defining the period or frequency of payout (e.g., 30 frames/s for video). For mixed-type, time-dependent data, there have been several proposals for their conceptual modeling and interchange format specification, most based on temporal-interval-based schemes [5], [8], [13], [23]. However, these works either neglect to consider the implications on the development of conceptual database structures to support TAC operations or do not comprehensively model time-dependent data.

Once a conceptual temporal model is established for a multimedia object, the multimedia data must be mapped to the physical system to facilitate database access and retrieval. For time-dependent multimedia data this presents some interesting challenges. Problems arise due to the strict timing requirements for payout of time-dependent data. The multimedia types of audio and video require very large amounts of storage space and must be maintained in secondary storage. In order to meet the presentation requirements for these data, various physical

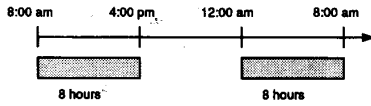


Fig. 2. Instants versus intervals.

storage organizations have been proposed, such as storing data in contiguous blocks on a disk in the same order as playout. Some recent work on data placement on physical storage for audio data retrieval is described by Yu *et al.* [28], [30], Gemmell and Christodoulakis [9], Rangan and Vin [22], and Christodoulakis and Faloutsos [7]. We do not address physical storage organizations here.

The integration of conceptual and physical data models with system support for data delivery yields the functionality necessary to construct multimedia applications. System support for time-dependent data includes the study of real-time operating systems for supporting audio and video synchronization [3], [6], [20], [21], [26], [29]; however, this work is beyond the scope of this presentation. We now describe our proposed conceptual models as a one component required in the construction of a multimedia information system.

### III. INTERVAL-BASED CONCEPTUAL MODELS

In order to support time-dependent data retrieval from a MDBMS, we must provide both conceptual temporal models for describing the data and models for their storage. In this section, we introduce conceptual models that describe temporal information necessary to represent multimedia time dependencies and synchronization. Specifically, this includes a discussion of the various temporal specification methodologies, our proposed reverse and  $n$ -ary temporal relations, and our partial-interval evaluation scheme.

#### 3.1. Basic Temporal Relations

An important and often used representation of time is the temporal interval [1]. Temporal intervals consist of time durations characterized by two endpoints, or *instants*. These interval and instant-based representations are widely investigated in the study of time. A time instant is a zero-length moment in time, such as “4:00 PM.” By contrast, a time interval is defined by two time instants and, therefore, their duration. “100 ms” or “eight hours” represent temporal intervals (see Fig. 2), which we formally define as follows [2]:

**Definition 1:** 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:

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

Time intervals are described by their endpoints (e.g.,  $a$  and  $b$  in Definition 1 above). The length of such an interval is identified by  $b - a$ . The relative timing between two intervals can be determined from these endpoints. By specifying intervals with respect to each other rather than by using endpoints, we

decouple the intervals from an absolute or instantaneous time reference, leading us to temporal *relations*.

Given any two intervals, there are 13 distinct ways in which they can be related [11]. These relations indicate how two intervals relate in time; whether they overlap, abut, precede, etc. Using Allen's representation [1], these relations are shown graphically in Fig. 3, using a timeline representation.

The 13 relations can be represented by seven cases because six of them are inverses (the equality relation has no inverse). For example, *after* is the inverse relation of *before*, or equivalently, *before*<sup>-1</sup> is the inverse relation of *before* ( $\alpha$  equals  $\beta$  is the same as  $\beta$  equals  $\alpha$ ). For inverse relations, given any two intervals, it is possible to represent their relation by using the noninverse relations only by exchanging the interval labels. In Section 3.2, we show how the ordering of deadlines required for the playout algorithms forces the use of some inverse relations. However, this use does not affect our ability to model temporal relations, being only an artifact of existing syntax conventions for temporal relations.

Temporal intervals can be used to model multimedia presentation by letting each interval represent the presentation of some multimedia data element, such as a still image or an audio segment, in what we call temporal-interval-based (TIB) modeling. We define an atomic interval to be one which cannot be decomposed into subintervals, as in the case of the presentation of a single frame of a motion picture. Intervals indicate the start times ( $\pi_\alpha, \pi_\beta$ ), durations ( $\tau_\alpha, \tau_\beta$ ), and end times for data elements  $\alpha$  and  $\beta$ . The relative positioning between them is captured by a delay from the beginning of the first interval ( $\tau_\delta$ ), as is their overall duration ( $\tau_{TR}$ ).

Fig. 4 shows audio and images synchronized to each other using the *meets* and *equals* temporal relations. For continuous media such as audio and video, an appropriate temporal representation is a sequence of intervals described by the *meets* relation because intervals abut in time and are nonoverlapping, by definition of a continuous medium.

In Table I, a set of constraints indicate the timing parameter relationships between simple binary temporal relations. These constraints, identified for the simple unified Object Composition Petri Net (OCPN), are used to show uniqueness in identification of temporal relations [17]. In particular, these constraints can be used to:

- 1) identify a temporal relation from the parameters  $\tau_\alpha, \tau_\beta, \tau_\delta$ , and  $\tau_{TR}$ ;
- 2) verify that the parameters satisfy a temporal relation, TR; and
- 3) identify overall interval duration,  $\tau_{TR}$ , given a temporal relation.

This functionality proved valuable for describing the temporal component of composite multimedia objects as shown by Little and Ghafoor [17]. We reiterate an important result for the determination of durations of related temporal intervals in Lemma 1 below.

**Lemma 1** For binary temporal relations, the duration,  $\tau_{TR}$ , of two related intervals  $\tau_\alpha$  and  $\tau_\beta$  can be uniquely determined by the durations of intervals  $\tau_\alpha, \tau_\beta, \tau_\delta$ , and the temporal relation, TR, between them.

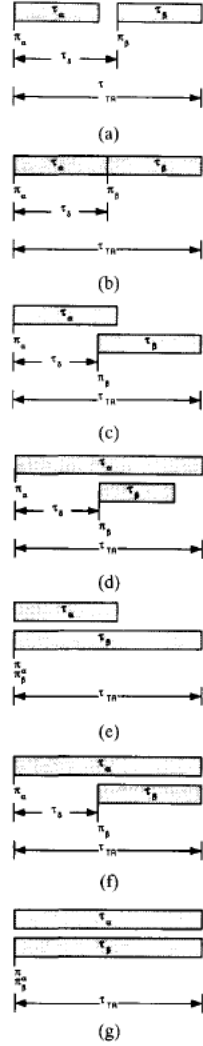


Fig. 3. Binary Temporal Relations. (a)  $\alpha$  before  $\beta$ , (b)  $\alpha$  meets  $\beta$ , (c)  $\alpha$  overlaps  $\beta$ , (d)  $\alpha$  during<sup>-1</sup>  $\beta$ , (e)  $\alpha$  starts  $\beta$ , (f)  $\alpha$  finishes<sup>-1</sup>  $\beta$ , (g)  $\alpha$  equals  $\beta$ .

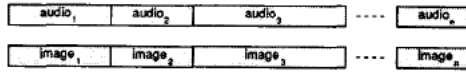


Fig. 4. Synchronization of audio and images represented by temporal intervals.

This lemma and Table I result in the following equations discerning the durations for sequential and parallel temporal relations.<sup>1</sup>For the sequential cases,

$$\tau_{TR} = \tau_\beta + \tau_\delta \geq \tau_\alpha + \tau_\beta \quad (1)$$

and, for the parallel cases,

$$\tau_{TR} = \max\{\tau_\alpha, \tau_\beta + \tau_\delta\} < \tau_\alpha + \tau_\beta. \quad (2)$$

<sup>1</sup> In both cases  $\tau_{TR} = \max\{\tau_{alpha}, \tau_\beta + \tau_{delta}\}$ , assuming  $\tau_{delta} \geq 0$ .

TABLE I  
TEMPORAL PARAMETERS OF UNIFIED MODEL ( $P_\alpha$  TR  $P_\beta$ )

Relation	$\tau_\alpha$	$\tau_\delta$	$\tau_{TR}$
before	$< \tau_\delta$	$\neq 0$	$\tau_\beta + \tau_\delta > \tau_\alpha + \tau_\beta$
meets	$\tau_\delta$	$\tau_\alpha$	$\tau_\alpha + \tau_\beta$
overlaps	$< \tau_\beta + \tau_\delta$	$\neq 0$	$\tau_\beta + \tau_\delta < \tau_\alpha + \tau_\beta$
during <sup>-1</sup>	$> \tau_\beta + \tau_\delta$	$\neq 0$	$\tau_\alpha$
starts	$< \tau_\beta$	0	$\tau_\beta$
finishes <sup>-1</sup>	$\tau_\beta + \tau_\delta$	$\neq 0$	$\tau_\alpha$
equals	$\tau_\beta$	0	$\tau_\alpha$

Using these equations and the OCPN modeling scheme, complex timeline representations of multimedia object presentation can be delineated. In the next section we introduce a major generalization of the binary temporal interval modeling approach which permits a more uniform representation of temporal intervals and supports the aforementioned TAC operations.

### 3.2. n-ary Temporal Relations

Binary temporal relations are sufficient for the temporal characterization of simple or complex multimedia presentations at the level of orchestration. By introducing a relationship among many intervals which we define as a  $n$ -ary temporal relation, we can generalize the binary temporal relations and ultimately simplify the data structures necessary for maintaining the synchronization semantics in a database. The deficiency of the binary construction process [17] is evident when many objects are to be synchronized by a single kind of temporal relation. Although a TIB scheme can easily model this case, a general approach is desired so that an efficient conceptual model for data storage results permitting simple algorithmic data retrieval and other TAC paradigms.

We therefore propose a new kind of homogeneous temporal relation for describing this case. The new temporal relation on  $n$  objects, or intervals, is defined as follows.

**Definition 2:** Let  $P$  be an ordered set of  $n$  temporal intervals such that  $P = \{P_1, P_2, \dots, P_n\}$ . A temporal relation, TR, is called an  $n$ -ary temporal relation, denoted  $TR^n$ , if and only if

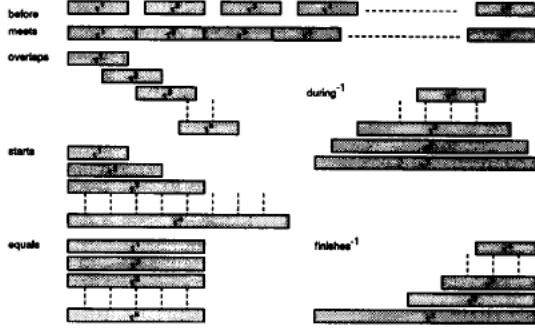
$$P_i TR P_{i+1}, \forall i(1 \leq i < n).$$

Like the binary temporal relations, there are 13 possible  $n$ -ary temporal relations, which reduce to the seven cases indicated in Fig. 5, after eliminating their inverses. When  $n = 2$ , the  $n$ -ary temporal relations simply reduce to the binary ones, i.e., for  $n = 2, P_1 TR P_2$ . Like the binary case, each interval indicates the start time ( $\pi_i$ ), duration ( $\tau_i$ ), and end times for a data element  $i$ . The relative positioning and time dependencies are captured by a delay ( $\tau_\delta^i$ ), as is their overall duration ( $\tau_{TR^n}$ ).

We now investigate the properties of the  $n$ -ary temporal relations including implications of multiple playout deadlines and temporal constraints.

**3.2.1. Property of Monotonic Playout Times:** If we constrain ourselves to  $n$ -ary relations with the property that

$$\pi_i \leq \pi_j, (1 \leq i < j \leq n)$$

Fig. 5.  $n$ -ary Temporal Relations

then we ensure the characteristic of monotonically increasing playout deadlines, which simplify presentation algorithms and the generation of playout deadlines [17], [18]. Therefore, we concentrate on the relations *before*, *meets*, *overlaps*, *during*<sup>-1</sup>, *starts*, *finishes*<sup>-1</sup>, and *equals*. This does not affect our ability to model temporal relations, i.e., we have chosen a set of the 13 temporal relations such that an ordering relationship is always implied and is easily identified in both the forward and reverse directions.

**3.2.2. Deadline Determination:** A complex multimedia data object consists of many subobjects, each with characteristic time dependencies, and can be evaluated for the purpose of identifying the exact playout deadlines of each subobject. This task is necessary for real-time scheduling of the retrieval of objects in the presence of significant system delays [18]. The following theorem describes the relative playout time (deadline) for any object or start point of a temporal interval [19].

**Theorem 1:** The relative playout deadline  $\pi_k$  for interval  $k$  for any  $n$ -ary temporal relation, is determined by

$$\pi_k = c, (k = 1)$$

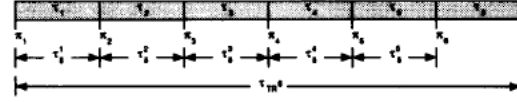
$$\pi_k = c + \sum_{i=1}^{k-1} \tau_{\delta}^i, (1 < k \leq n)$$

where  $c$  is a constant time offset.

**Proof:** Because timing is relative to start of the set of intervals, we let  $\pi_1 = c$ .  $\pi_2 = c + \tau_{\delta}^1$  since  $\tau_{\delta}^1 = \pi_2 - \pi_1$ , by definition of delay for the binary case, and  $\pi_1 = c$ . Suppose,  $\pi_m = c + \sum_{i=1}^{m-1} \tau_{\delta}^i$ , for some  $m$ . We find the  $m+1$ th deadline noting that for intervals  $P_m$  and  $P_{m+1}$ ,  $P_m$  TR  $P_{m+1}$  by Definition 2. Therefore,  $\tau_{\delta}^m = \pi_{m+1} - \pi_m$ , or  $\pi_{m+1} = \pi_m + \tau_{\delta}^m$ , but  $\pi_m = c + \sum_{i=1}^{m-1} \tau_{\delta}^i$ , so  $\pi_{m+1} = c + \sum_{i=1}^m \tau_{\delta}^i$ .  $\square$

Theorem 1 specifies how to generate playout times from an  $n$ -ary temporal relation. In Section 5.2 we show this theorem applied to an algorithm for identifying playout times from our proposed temporal model.

**3.2.3. Temporal Constraints** Like the binary temporal relations described in Section 3.1, a set of constraints can be identified for the timing parameter relationships among intervals of the  $n$ -ary case. Considering only the parallel and sequential  $n$ -ary cases, rather than each relation individually,



(a)



(b)

Fig. 6. Illustration of the timing parameters for the (a) *meets* and (b) *overlaps* relations.TABLE II  
 $n$ -ARY TEMPORAL CONSTRAINTS

Relation	$\tau^i, (1 \leq i < n)$	$\tau_{TR}^n$
<i>before</i>	$< \tau_{\delta}^i$	$\sum_{i=1}^{n-1} \tau_{\delta}^i + \tau^n$
<i>meets</i>	$\tau_{\delta}^i$	$\sum_{i=1}^n \tau^i, \sum_{i=1}^{n-1} \tau_{\delta}^i + \tau^n$
<i>overlaps</i>	$< \tau^{i+1} + \tau_{\delta}^i$	$\sum_{i=1}^{n-1} \tau_{\delta}^i + \tau^n$
<i>during</i> <sup>-1</sup>	$> \tau^{i+1} + \tau_{\delta}^i$	$\tau^1$
<i>starts</i>	$< \tau^{i+1}, (\tau_{\delta}^i = 0)$	$\tau^n$
<i>finishes</i> <sup>-1</sup>	$\tau^{i+1} + \tau_{\delta}^i$	$\tau^1$
<i>equals</i>	$\tau^{i+1}, (\tau_{\delta}^i = 0)$	$\tau^i, (1 \leq i < n)$

we can see that for sequential cases,

$$\tau_{TR}^n = \sum_{i=1}^{n-1} \tau_{\delta}^i + \tau^n \geq \sum_{i=1}^n \tau^i \quad (3)$$

and, for the parallel cases,

$$\tau_{TR}^n = \max\{\tau^1, \sum_{i=1}^{n-1} \tau_{\delta}^i + \tau^n\} < \sum_{i=1}^n \tau^i. \quad (4)$$

Therefore, similar to (1) and (2) of the binary case, we can determine whether an  $n$ -ary temporal relation is parallel or sequential, or if the temporal relation is known, verify its consistency in terms of temporal parameters.<sup>2</sup> Fig. 6 illustrates these parameters for the *before* and *overlaps* relations. A more general set of constraints can be identified for the  $n$ -ary relations as described in the following theorem.

**Theorem 2:** There exists a set of temporal constraints for the  $n$ -ary temporal relations ( $n \geq 2$ ) as shown in Table II.

**Proof:** The  $\tau^i$  are determined by Definition 2 and by noting that adjacent intervals ( $i$ th to  $i+1$ th) form binary relationships for which we can apply the relationships of Table I as follows. For the *before*, *meets*, and *overlaps* relations, assume  $\tau_{TR}^k = \sum_{i=1}^{k-1} \tau_{\delta}^i + \tau^k$ . The  $k+1$ th relation/interval

<sup>2</sup> Similarly to the binary cases,  $\tau_{TR}^n = \max\{\tau^1, \sum_{i=1}^{n-1} \tau_{\delta}^i + \tau^n\}$  for both the parallel and sequential relations, assuming  $\tau_{\delta}^i \geq 0$ .

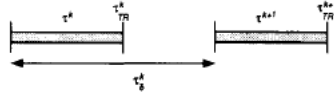


Fig. 7. Interval relations for proof of Theorem 2.

is formed by adding another interval (Fig. 7) as

$$\begin{aligned}
 \tau_{TR^{k+1}} &= \tau_{TR^k} + \tau_{\delta}^k - \tau^k + \tau^{k+1} \\
 &= \sum_{i=1}^{k-1} \tau_{\delta}^i + \tau^k + \tau_{\delta}^k - \tau^k + \tau^{k+1} \\
 &= \sum_{i=1}^k \tau_{\delta}^i + \tau^{k+1} \\
 &= \tau_{TR^{k+1}}.
 \end{aligned}$$

For the *during*<sup>-1</sup> case, clearly  $\tau_{TR^n} = \tau^1$ , since  $\forall i, \tau^i > \tau^{i+1}$ . For the *starts* case,  $\tau_{TR^n} = \tau^n$  and  $\forall i, \tau^i < \tau^{i+1}$ . For the *finishes*<sup>-1</sup> case,  $\tau_{TR^n} = \tau^1$ , since  $\forall i, \tau^i > \tau^{i+1}$ . For the *equals* case,  $\tau_{TR^n} = \tau^1$ , since  $\forall i, \tau^i = \tau^{i+1}$ .  $\square$

The notion of temporal intervals can also support reverse and partial playout activities, i.e., reversing the direction in time of presentation, or beginning the presentation of an object at a midpoint rather than at the beginning or end. For this purpose, reverse temporal relations are proposed in the next section. These relations, derived from the forward relations, define the ordering and scheduling required for reverse playout.

### 3.3. Reverse Temporal Relations

As mentioned earlier, in addition to simple linear playout of time-dependent data sequences, other modes of information access are also viable, and should be supported by a MDBMS. These TAC operations include reverse playout and partial interval evaluation for midpoint suspension and resumption. In this section we describe temporal models for satisfying these aforementioned requirements. In order to facilitate reverse playout, we first characterize reversal of time in temporal intervals, and then show their  $n$ -ary extension.

**3.3.1. Reverse Binary Temporal Relations:** A unique use of temporal interval processing proposed in this paper is the application of temporal relations to provide reverse presentation of objects. We introduce reverse temporal relations as distinct from inverse temporal relations, which are described by commuting the operands, i.e.,  $a * b = b *^{-1} a$ . This characterization is essential for reverse playout of time-dependent multimedia objects, and allows us to playout, in reverse time, as defined by changing the direction of time evaluation of a temporal relation. The following definitions and lemmas characterize reverse temporal intervals and relations:

**Definition 3:** A reverse interval is the negation of a forward interval, i.e., if  $[a, b]$  is an interval, then  $[-b, -a]$  is the reverse interval.  $[-b, -a]$  is clearly an interval since  $a \leq b$  and therefore  $-b \leq -a$ .

**Definition 4:** A reverse temporal relation  $TR_r$ , is defined as the temporal relation formed among reverse temporal intervals.

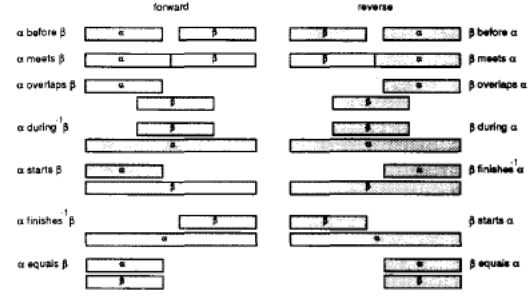


Fig. 8. Forward and reverse relations and intervals.

TABLE III  
TEMPORAL PARAMETER CONVERSIONS ( $P_{\alpha}$  TR  $P_{\beta}$  TO  $P_{\alpha-r}$  TR  $P_{\beta-r}$ )

Forward	Reverse	$\tau_{\alpha-r}$	$\tau_{\beta-r}$	$\tau_{\delta-r}$
<i>before</i>	<i>before</i>	$\tau_{\beta}$	$\tau_{\alpha}$	$\tau_{\delta} + \tau_{\beta} - \tau_{\alpha}$
<i>meets</i>	<i>meets</i>	$\tau_{\beta}$	$\tau_{\alpha}$	$\tau_{\beta}$
<i>overlaps</i>	<i>overlaps</i>	$\tau_{\beta}$	$\tau_{\alpha}$	$\tau_{\delta} + \tau_{\beta} - \tau_{\alpha}$
<i>during</i> <sup>-1</sup>	<i>during</i>	$\tau_{\beta}$	$\tau_{\alpha}$	$\tau_{\alpha} - \tau_{\beta} - \tau_{\delta}$
<i>starts</i>	<i>finishes</i> <sup>-1</sup>	$\tau_{\beta}$	$\tau_{\alpha}$	$\tau_{\beta} - \tau_{\alpha}$
<i>finishes</i> <sup>-1</sup>	<i>starts</i>	$\tau_{\beta}$	$\tau_{\alpha}$	0
<i>equals</i>	<i>equals</i>	$\tau_{\alpha}, \tau_{\beta}$	$\tau_{\alpha}, \tau_{\beta}$	0

Let  $[a, b]$  and  $[c, d]$  be two temporal intervals related by TR, then the reverse temporal relation  $TR_r$  is defined by the temporal relation formed between  $[-b, -a]$  and  $[-d, -c]$ .

**Lemma 2:** The reverse relation is a temporal relation.

**Proof:** Because  $[a, b]$  and  $[c, d]$  are intervals,  $[-b, -a]$  and  $[-d, -c]$  are also intervals. Given two intervals, a relation TR exists between them.  $\square$

In relation to the other temporal models, we deal with relative timing rather than absolute endpoints. As we are more interested in the durations and properties of relative ordering, we can normalize the intervals with respect to the negative values. Consequently, the following lemma relates to the duration of a reversed interval.

**Lemma 3:**  $\#([a, b]) = \#([-b, -a])$ , i.e., reverse intervals have identical durations as their forward counterparts.

**Proof:**  $\#([a, b]) = b - a = -a - (-b) = \#([-b, -a])$ .  $\square$

The reverse relations are summarized in Fig. 8, noting that the reverse intervals are the reflection across a line on the time axis. To identify reverse temporal parameters ( $\tau_{\alpha-r}$ ,  $\tau_{\beta-r}$ ,  $\tau_{\delta-r}$ , and  $TR_r$ ) from the forward temporal parameters ( $\tau_{\alpha}$ ,  $\tau_{\beta}$ ,  $\tau_{\delta}$ , and  $TR$ ), the conversions summarized in Table III can be used, which are derived from the consistency formulas of Table I and by inspection of the binary reverse relations of Fig. 8. These parameters represent the new parameters formed by the new relation when viewed in reverse.<sup>3</sup> Reverse temporal intervals must obey rules for temporal intervals.

**3.3.2.  $n$ -ary Reverse Temporal Parameters:** Like the  $n$ -ary case, we can define reverse  $n$ -ary temporal relations as follows:

<sup>3</sup>The *during*<sup>-1</sup> conversion results in a non-inverted *during* relation outside of our complete set of seven relations (shown in the table). By commuting the operands we close our conversion with respect to the seven relations (and monotonically increasing deadlines) but result in an exception in the handling of the interval ordering.

TABLE IV  
n-ARY TEMPORAL PARAMETER CONVERSIONS

Forward	Reverse	$\tau_r^i, (1 \leq i \leq n)$	$\tau_{\delta-r}^i, (1 \leq i < n)$
<i>before</i>	<i>before</i>	$\tau^{n+1-i}$	$\tau_{\delta}^{n-i} + \tau^{n+1-i} - \tau^{n-i}$
<i>meets</i>	<i>meets</i>	$\tau^{n+1-i}$	$\tau_{\delta}^{n-i} + \tau^{n+1-i} - \tau^{n-i}, \tau^{n+1-i}$
<i>overlaps</i>	<i>overlaps</i>	$\tau^{n+1-i}$	$\tau_{\delta}^{n-i} + \tau^{n+1-i} - \tau^{n-i}$
<i>during</i> <sup>-1</sup>	<i>during</i>	$\tau^{n+1-i}$	$\tau^i - \tau_{\delta}^i - \tau^{i+1}$
<i>starts</i>	<i>finishes</i> <sup>-1</sup>	$\tau^{n+1-i}$	$\tau^{n+1-i} - \tau^{n-i}$
<i>finishes</i> <sup>-1</sup>	<i>starts</i>	$\tau^{n+1-i}$	$\tau^{n-i} - \tau^{n+1-i} - \tau_{\delta}^{n-i}, 0$
<i>equals</i>	<i>equals</i>	$\tau^{n+1-i}, \tau^i$	0

**Definition 5:** Let  $P$  be an ordered set of  $n$  temporal intervals such that  $P = \{P_1, P_2, \dots, P_n\}$ , and let  $TR$  be a temporal relation with reverse relation  $TR_r$ . If  $TR^n$  is a  $n$ -ary temporal relation on  $P$ , then a temporal relation  $TR_r^n$  is called a reverse  $n$ -ary temporal relation, and is defined as

$$P_i TR_r P_{i-1}, (1 < i \leq n),$$

where  $TR_r$  can be found from Table III.

Given the temporal parameters of an  $n$ -ary temporal relation, we can determine the corresponding reverse temporal parameters in a similar manner as is shown in Table III. Ultimately these parameters enable reverse presentation timing given the forward timing parameters. To identify reverse temporal parameters for the  $n$ -ary cases ( $\tau_r^i$ ,  $\tau_{\delta-r}^i$ , and  $TR_r^n$ ) from the forward temporal relations ( $\tau^i$ ,  $\tau_{\delta}^i$ , and  $TR^n$ ), we can apply the following theorem:

**Theorem 3:** Conversion from the forward temporal parameters to the reverse parameters is achieved with the equations shown in Table IV.<sup>4</sup>

**Proof:** The reverse interval durations,  $\tau_r^i$ , are implied by Definition 5 of an  $n$ -ary reverse temporal relation. The reverse delay durations,  $\tau_{\delta-r}^i$ , are found by noting that adjacent intervals ( $i$ th to  $i+1$ th) are instances of the binary case for which conversions are tabulated in Table III.  $\square$

**3.3.3. Partial Interval Evaluation:** A further enhancement for multimedia presentation is the ability to playout only a fraction of an object's overall duration. This operation is typical during audio and video editing, in which a segment is repeatedly started, stopped, and restarted. Another example of partial playout occurs when a viewer stops a motion picture then later restarts at some intermediate point (or perhaps an earlier point to get a recap). In this section we show the basis for achieving partial evaluation or fractional playout for a composite ( $n$ -ary) temporal interval. Later, in Section V, we show an algorithm for partial interval evaluation based on this scheme.

Consider a single temporal interval that represents the overall duration,  $\tau_{TR^n}$ , of a complex  $n$ -ary temporal relationship, as shown in Fig. 9. We seek to present some fraction of this

<sup>4</sup>The same difficulty arises again for the *during*<sup>-1</sup> relation. The conversion of this relation results in a relation outside of our set of seven. The commuting of the operands implies that the correct reverse values on *during*<sup>-1</sup> are equal to  $\tau^i$ , however, this requires a transposition of the interval indexes.

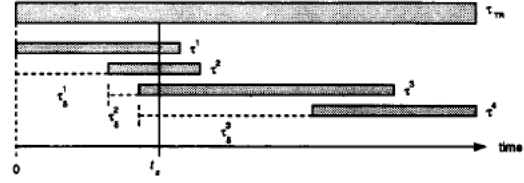


Fig. 9. Partial interval evaluation.

temporal interval beginning at a relative time called  $t_s$ . If  $t_s < 0$ , then it is too soon to consider  $\tau_{TR^n}$ . If  $t_s = 0$ , then the whole interval and corresponding  $n$ -ary intervals must be considered. For  $(0 < t_s < \tau_{TR^n})$ , a fractional part of the  $n$ -ary relation must be evaluated, and finally, for  $t_s \geq \tau_{TR^n}$ , the interval need not be considered for evaluation at all.

A non-decomposable, or atomic, interval does not have an  $n$ -ary decomposition, and can represent the presentation of a data element. For the fractional part, we must consider both non-decomposable and decomposable intervals. For a non-decomposable interval, partial evaluation implies that the data has already been presented and need only be terminated upon expiration of the temporal interval. For a decomposable interval, the problem is to determine where to begin evaluation of the subintervals.

There are two cases, one for parallel temporal relations and the other for sequential relations. The following theorems characterize partial interval evaluation for these cases.

**Theorem 4:** For a sequential  $n$ -ary temporal relation (*before*, *meets*), playout at  $t_s$  implies beginning playout at a subinterval  $k$  such that,

$$\sum_{i=1}^{k-1} \tau_{\delta}^i \leq t_s < \sum_{i=1}^{k-1} \tau_{\delta}^i + \tau^k, (1 \leq k < n).$$

**Proof:** Consider the first interval. If  $t_s < \tau^1$ , then some time is left in  $\tau^1$ . If  $\tau^1 \leq t_s < \tau_{\delta}^1$ , then  $t_s$  falls between intervals  $\tau^1$  and  $\tau^2$ , and no  $k$  exists. For  $t_s \geq \tau_{\delta}^1$ ,  $t_s$  occurs during the next interval  $\tau^2$ . From the Theorem 1, we know that the  $k$ th interval starts at  $\sum_{i=1}^{k-1} \tau_{\delta}^i$ , and ends at  $\sum_{i=1}^{k-1} \tau_{\delta}^i + \tau^k$ .  $\square$

**Theorem 5:** For a parallel temporal relation (*overlaps*, *during*<sup>-1</sup>, *starts*, *finishes*<sup>-1</sup>, and *equals*), playout at  $t_s$  indicates playout of all subintervals  $k$  such that,

$$\sum_{i=1}^{k-1} \tau_{\delta}^i \leq t_s < \sum_{i=1}^{k-1} \tau_{\delta}^i + \tau^k, (1 \leq k < n).$$

**Proof:** For intervals  $k$  such that  $t_s < \pi_k + \tau^k$ , there is clearly time left. However, the ones that will be active are indicated by  $\pi_k \leq t_s < \pi_k + \tau^k$ , but  $\pi_k = \sum_{i=1}^{k-1} \tau_{\delta}^i$  by Theorem 1.

Next, we show how the temporal parameters can be aggregated in a suitable manner for database storage.

#### IV. DATABASE MODELS FOR TIME-DEPENDENT MEDIA

In Section III we have shown a new kind of temporal relation which can describe the timing among sets of multimedia objects. We now show how the proposed relations





show how the conceptual model is applied to a relational data structure.

The organization of a temporal hierarchy is naturally tree-like. We can capture this hierarchy using a relational model by defining a relation called **NODES** to which we can apply temporal constraints. Any *terminal* or *nonterminal* node can be described by a tuple in the relation:

**NODES**(*node.no*, *node.type*, *duration*, *subject*).

Each node is uniquely identified by an integer, *node.no*. The remaining attributes, *node.type*, *duration*, and *subject* characterize the node and describe accompanying temporal relationships. *node.type* describes the kind of temporal integration for assembly of subnodes, if any exist. Values of this attribute are *nonterm.s*, *nonterm.p*, and *terminal*, indicating the sequential, parallel, and terminal cases, respectively. The duration attribute describes the overall temporal interval for a possibly complex object. *subject* is an attribute used to describe the content of the node for illustrative purposes only, however, by using a complementary data schema, it is possible to provide content-based attributes as well [16].

To support a hierarchy of conceptual nodes, we define a second relation to represent the children, or **SUBNODES**, of an arbitrary node described by the relation **NODES**. For any node in **NODES**, multiple subnodes are possible, representing subobjects for temporal integration. A tuple is defined to indicate node-to-subnode links as follows:

**SUBNODES**(*node.no*, *subnode.no*,  
*index.f*, *index.r*, *delta.f*, *delta.r*).

In this case, the attributes *node.no* and *subnode.no* uniquely identify the tuples. *index.f* and *index.r* are attributes indicating the ordering among a set of subnodes with the same parent for forward and reverse payout, respectively. By using these indices, an arbitrary number of subnodes can be specified as required for an *n*-ary temporal relation, as discussed in Section 4.1. Lower values of these indices indicate preceding (in time) subnodes, with increasing values indicating directional traverse of the temporal hierarchy for evaluation of the parent's temporal relation. However, ordering is not necessarily identical for the forward and backwards cases, as established by the reverse *n*-ary relation. *delta.f* and *delta.r* establish the durations,  $\tau_{\delta-f}$  and  $\tau_{\delta-r}$ , for forward or reverse temporal relationships between two adjacent subnodes.

Finally, to locate data corresponding to objects for payout, a relation **TERMINALS** is defined with *node.no* as the unique identifier as follows:

**TERMINALS**(*node.no*, *medium*, *filename*)

This separate relation is defined apart from the **NODES** relation because many nodes are not terminal elements and do not require these attributes. Only a subset of all nodes will indicate terminal elements which capture single-medium base types (e.g., single images, audio segments, etc.). Additional information can be defined as part of these relations such as details of formatting requirements, but are not shown here.

TABLE V  
TUPLES OF THE TERMINALS RELATION

<i>node.no</i>	<i>medium</i>	<i>location</i>
1	image	—
2	audio	—
3	image	—
4	audio	—
5	image	—
6	audio	—
7	image	—
8	audio	—

TABLE VI  
TUPLES OF THE NODES RELATION

<i>node.no</i>	<i>node.type</i>	<i>duration</i>	<i>subject</i>
1	terminal	10	"Venus"
2	terminal	10	"Venus"
3	terminal	5	"Mars"
4	terminal	5	"Mars"
5	terminal	15	"Saturn"
6	terminal	15	"Saturn"
7	terminal	10	"Neptune"
8	terminal	10	"Neptune"
9	nonterm.p	10	—
10	nonterm.p	5	—
11	nonterm.p	15	—
12	nonterm.p	10	—
13	nonterm.s	40	"Planets"

Referring to the *multimedia slide presentation* example, we now illustrate the creation of a relational database to capture a temporal hierarchy. Suppose the slideshow is on a topic of "Planets." The temporal hierarchy for this example is illustrated in Fig. 11. To map this conceptual model to the relational data structures we first identify each node with a unique identifier, and assign each terminal element to a tuple in the **TERMINALS** relation along with its location and media type. These tuples are shown in Table V.

Next, for each node we create a tuple describing whether it is a *terminal*, *nonterm.p*, or *nonterm.s* type. We also identify its duration and a relevant topic or keyword. These tuples are summarized in Table VI.

Finally, the **SUBNODES** relation table is created by identifying the children of each node in the temporal hierarchy. For each node, the position indices and forward and reverse delays ( $\tau_{\delta-f}$  and  $\tau_{\delta-r}$ ) are identified from the conceptual model. Table VII shows these tuples.

## V. ACCESS ALGORITHMS FOR MULTIMEDIA DATABASES

We have presented a specification methodology and conceptual models suitable for database storage of time-dependent multimedia data. In conjunction with these models, we have developed access algorithms that we describe in this section. These algorithms provide functionality for partial interval payout, payout reversal, and payout deadline determination as required for real-time scheduling approaches.

TABLE VII  
TUPLES OF THE SUBNODES RELATION

node.no	subnode.no	index.f	index.r	delta.f	delta.r
9	1	1	2	0	0
9	2	2	1	0	0
10	3	1	2	0	0
10	4	2	1	0	0
11	5	1	2	0	0
11	6	2	1	0	0
12	7	1	2	0	0
12	8	2	1	0	0
13	9	1	4	10	0
13	10	2	3	5	5
13	11	3	2	15	15
13	12	4	1	0	10

### 5.1. Playout Scheduling Approaches

In formulating an approach to media delivery suitable for satisfying the timing requirements for multimedia data, one must realize that most workstation technology lacks sufficient performance to support the playout of complex multimedia objects. Viable applications will be supported either by ample or marginal system performance. For systems with ample performance, data delivery is simplified by system components without bottlenecks or significant latencies. For systems with marginal performance, techniques must be applied to guarantee delivery of data in a timely fashion. For this reason, we perceive two approaches to data delivery: the real-time scheduling approach and the optimistic, or ideal, interval-based process playout approach.

In a real system, latencies exist in storage devices, communications, and multiprocessing that make enforcement of an ideal timing specifications difficult. These delays can be larger than the playout durations of individual data elements requiring synchronization, and a mechanism must be employed for compensation. Methods of overcoming these delays rely on some form of real-time scheduling (e.g., [15], [19]).

As system performance becomes less marginal, or as playout time durations increase, the system delays become less significant, warranting the development of *ideal* presentation algorithms. Images, text, and audio segments can be effectively synchronized with such an ideal scheme because their presentation durations are large (greater than a few seconds), whereas video and audio frames have a very short presentation interval (less than 1 s) and require specific resource scheduling.

For both approaches the objects and their temporal hierarchy must be evaluated. For the real-time scheduled approach this requires a recursive traversal of the hierarchy to identify object deadlines, with subsequent scheduling of playout for the deadlines [19]. For the ideal approach, tree traversal includes immediate presentation of component objects without specific consideration of system latencies, i.e., sufficient system performance is assumed to be available. In the remainder of this section we show we show algorithms for TAC operations in the ideal case and an algorithm for generating deadlines for the real-time scheduled approach. Mechanisms for satisfying a

playout schedule once generated in this manner are described elsewhere [19].

### 5.2. Determination of Playout Time Based on Temporal Intervals

The temporal hierarchy can be evaluated for the purpose of identifying the exact deadlines for playout of all objects by applying Theorem 1 for any object or start point of a temporal interval using either forward or reverse parameters. The expression in Theorem 1 can be evaluated in  $n$  steps where  $n$  is the number of elements indicated by the temporal relation. This is a very important consideration for real-time deadline evaluation when expenditure of time is critical.

Alternatively, the original OCPN model, used to describe a composite multimedia object, can be simulated directly [18]. The following algorithm, based on Theorem 1, finds the playout time, or deadline, for any object or start time of a temporal interval using either forward or reverse parameters. This algorithm uses as input a parameter  $t_{elapsed}$  to indicate the current elapsed time throughout its processing, and is initially set to zero.

#### Playout Deadline Algorithm

1. For object *Object*, identify attributes, get elapsed time offset,  $t_{elapsed}$ .
2. If *Object* is not a terminal then evaluate its subnodes:
  - a) For each subnode with increasing node index  $i$ :
    - i. Recursively invoke algorithm on the  $i$ th subnode with  $t_{elapsed}$ .
    - ii.  $t_{elapsed} = t_{elapsed} + \tau_i^i$ .
3. If *Object* is a terminal then its deadline,  $\pi_{Object}$ , is equal to  $t_{elapsed}$ .

Basically, an object's subnodes are identified in a recursive tree-traversal. As each subnode is identified, its temporal parameters are evaluated via Theorem 1 to generate a set of playout times. It is important to note that for such evaluation, the parallel and sequential information (used in later algorithms presented here) has no significance because deadlines are generated for each interval and a real-time scheduling approach can interpret the deadlines uniformly [19]. Furthermore, the  $n$ th occurrence of each  $\tau_i$  (forward and reverse) is ignored since it has no interpretation without a subsequent object to which it can relate.

Consider the *multimedia slide presentation* as an example. Applying the deadline generation algorithm initially to node 13 results in the identification of a *nonterminal* element. Therefore, its subnodes are evaluated in increasing order of their indices. Node 9 yields yet another subnode which then leads to two terminal nodes. For node 1,  $\pi_1 = t_{elapsed} = 0$ . The return of the recursive call on subnode 1 causes  $t_{elapsed}$  to be set to 0, and  $\pi_2 = 0$  for node 2. The subsequent return of the recursive call on node 9 causes  $t_{elapsed}$  to be set to 10, prior to recursively descending the hierarchy for the second set of audio-image pairs. Evaluation continues in this manner resulting in the following set of playout deadlines:  $\Pi = \{\pi_i\} = \{0, 0, 10, 10, 15, 15, 30, 30\}$ . These deadlines

can be generated in either the forward or reverse direction or beginning at an arbitrary point in the temporal hierarchy.

### 5.3. Retrieval Algorithm for Reverse Payout

To support reverse payout of an object represented by our temporal data model we merely require evaluation of the reverse direction indices. These can be derived from either existing forward temporal parameters or from the temporal relations themselves. Rather than storing identical object durations, indices can be used to establish the payout ordering in the forward and reverse directions, hence the need for the position indices in the relational model. The modification to the original presentation algorithm [17] to support forward and reverse payout is shown as a program fragment as follows (shown later as part of the complete payout algorithm):

1. For each subnode in increasing order of index  $i_d$ :  
where  $i_d$  is either the forward or reverse position index. In the general case, we would like to be able to stop at any point in the temporal hierarchy and restart in either the forward or reverse direction. This functionality is provided through partial-interval evaluation.

### 5.4. Partial-Interval Evaluation

A further enhancement required for multimedia presentation is the ability to payout partial objects. Partial interval evaluation allows us to stop in the middle of presentation and resume in either the forward or reverse direction.

For the fractional part, we must consider both nondecomposable (atomic) and decomposable intervals. A nondecomposable interval indicates the actual payout of a multimedia data element. When this is the case, partial evaluation implies that the data element has already been presented and need only be terminated upon expiration of the temporal interval. For a decomposable interval, the problem is to determine where to begin evaluation of the subintervals. To stop and then restart during presentation of a decomposable interval, we can save the elapsed payout time,  $offset_f$  since starting presentation. For the reverse direction, the reverse elapsed payout time,  $offset_r$ , can be computed by subtracting the forward elapsed payout time from the overall duration of the object under consideration, i.e.,

$$offset_r = \tau_{object} - offset_f$$

Based on Theorems 4 and 5, we describe the modifications necessary to support partial interval evaluation. These modification require as input a parameter  $offset$  indicating the relative time offset from the start of the indicated object (generalized for both forward and reverse payout in the complete algorithm).

#### For the Sequential Cases

1. For each subnode in increasing order of index  $i$ :
  - (a) If  $0 \leq offset < \tau^i$  then (time left in this node)
    - i. Recursively invoke algorithm on the  $i$ th subnode with  $offset$ .
    - ii. Delay by  $\tau_\delta^i - \tau^i$ ,  $offset := 0$ .

- (b) Elseif  $\tau^i \leq offset < \tau_\delta^i$  then (some delay left)
  - i. Delay by  $\tau_\delta^i - offset$ ,  $offset := 0$ .
- (c) Else  $offset \geq \tau_\delta^i$  (no delay left)
  - i.  $offset = offset - \tau_\delta^i$  (try next subnode)

#### For the Parallel Cases

1. For each subnode in increasing order of index  $i$ :
  - (a) If  $0 \leq offset < \tau^i$  then (time left in this node)
    - i. Fork a new process and recursively invoke algorithm on the  $i$ th subnode with  $offset$
  - (b) Else  $offset \geq \tau^i$  (no time left in this node)
  - (c) If  $0 \leq offset < \tau_\delta^i$  then (some delay left)
    - i. Delay by  $\tau_\delta^i - offset$ ,  $offset := 0$ .
  - (d) Else  $offset \geq \tau_\delta^i$  (no delay left)
    - i.  $offset = offset - \tau_\delta^i$  (try next subnode)

With these modifications the payout of an object can be initiated at an arbitrary time within the duration  $\tau_{TR}$  of an object.

### 5.5. Complete Payout Algorithm

The complete algorithm is shown below, considering all of the proposed modifications to our original presentation algorithm to support TAC functionality. In this algorithm  $offset$  indicates either the forward or reverse elapsed time depending on the direction  $d$  of payout.

#### Complete Payout Algorithm

1. For object *Object* identify subnodes, and direction  $d$ .
2. If *Object* is not a terminal then evaluate its temporal relation:
  - (a) If temporal relation is sequential then:
    - i. For each subnode in increasing order of index  $i_d$ :
      - A. If  $0 \leq offset < \tau^i$  then
        - Recursively invoke algorithm on the  $i_d$ th subnode with  $offset$ .
        - Delay by  $\tau_\delta^i - \tau^i$ ,  $offset := 0$ .
      - B. Elseif  $\tau^i \leq offset < \tau_\delta^i$  then
        - Delay by  $\tau_\delta^i - offset$ ,  $offset := 0$ .
      - C. Else  $offset \geq \tau_\delta^i$ 
        - $offset = offset - \tau_\delta^i$

(b) If temporal relation is parallel then:

i. For each subnode in increasing order of index  $i_d$ :

A. If  $0 \leq \text{offset} < \tau^i$  then

- Fork a new process and recursively invoke algorithm on the  $i_d$ th subnode with  $\text{offset}$ .

B. Else  $\text{offset} \geq \tau^i$

C. If  $0 \leq \text{offset} < \tau_\delta^i$  then

- Delay by  $\tau_\delta^i - \text{offset}$ ,  $\text{offset} := 0$ .

D. Else  $\text{offset} \geq \tau_\delta^i$

- $\text{offset} = \text{offset} - \tau_\delta^i$

3. If *Object* is a terminal then present data on the appropriate I/O device for its specified duration.

4. Terminate when all recursive invocations have completed.

## VI. DISCUSSION

The proposed  $n$ -ary temporal relations offer a more elegant means of representing timing information than our previous binary models. In particular, the  $n$ -ary model captures an arbitrary number of component objects with a common temporal relationship without requiring many levels of hierarchy.

We presented a number of consistency formulas in Theorem 2. These formulae can be used at the time of object creation to establish a consistent database of temporal parameters by using a tree traversal procedure akin to the playout algorithms (not shown here). Alternatively, a timing coercion technique can be applied to incompletely specified timing hierarchies to achieve a cohesive presentation as has been applied by Buchanan and Zellweger [4].

In a similar manner, reverse timing parameters can be computed at object creation time and stored in the temporal database or can be computed dynamically at the time of sequence reversal by using the conversions of Table IV. This process can also rearrange the ordering of intervals that are incorrectly arranged (by the author) for sequence reversal (e.g., arbitrarily ordered intervals with the *starts* relation). The penalty for this computation depends on the complexity of the represented objects and their frequency of reversal. Frequent sequence reversal suggests the use of stored reverse parameters whereas infrequent reversal can be adequately provided by dynamic parameter computation.

We have implemented the aforementioned algorithms of Section V using the C programming language and process forking as part of our development of a general purpose distributed multimedia information system in the Multimedia Communications Laboratory at Boston University. The temporal model has also been incorporated into an interactive motion picture database application called the Virtual Video Browser [16]. In this system the relational data structures supporting object timing complement an application-specific schema for

a database of motion pictures. The result is a database that supports both TAC functionality as well as content-based retrieval of motion picture components.

## VII. CONCLUSION

In this paper we have proposed two new temporal models for time-dependent data retrieval in a multimedia database management system. These models, the  $n$ -ary and *reverse* temporal relations, are shown to be useful for facilitating storage and retrieval of time-dependent multimedia data by applying a temporal hierarchy supported by a relational data model.

Because the proposed models are restricted to having the property of monotonically increasing playout deadlines for represented objects, algorithms for synchronous data retrieval are greatly simplified, both for identification of deadlines necessary for real-time scheduling of playout, or for optimistic process playout synchronization. Furthermore, algorithms are shown that allow traversal of the temporal hierarchy in a manner that provides forward, reverse, or partial interval evaluation.

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