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Abstract *- Time is gaining consideration in Information Systems as an important variable to be managed either explicitly or implicitly. Applications range from Historical Databases to Time Dependent Reasoning; researchers backgrounds range from theoretical physics to mathematical logic, from database systems to artificial intelligence [BOLO 82, MAPE 89, ROLL 88, SNOD 86].*
This paper aims to be a short guide to the ontological issues of time relevant to the information systems area which appear in the literature.

1. Introduction

Time has always been a major concern in philosophical as well as in physical speculation. The need of some apparently peculiar features of time such as the *"uni-directionality",* the so called "Time Arrow" [VBEN 83, REIC 57] and the dynamics implied by its *"continuous flow"*, always troubled men about the very nature of time in such a way that St. Augustin could say "What then is time? I know well enough what it is provided that nobody asks me about; but if I am asked what it is and I try to explain, I am baffled" [AUGU]. Kant places time as one of the two special "a priori" synthetic categories which underlie scientific reasoning. Minkowsky, on the other hand, with the definition of the four-dimensional space-time continuum, puts the basis of a homogeneous treatment of space and time. In fact, today we can speak of a geometry of time as well as of a geometry of space and define many different *"possible worlds"* by changing the postulates we rely on.

A bridge between philosophy and mathematical-physics has been set by logicians, who are both interested in linguistic and ontological aspects of time. However, even in the logicians' community there is a strong debate on the need of creating a non standard *"temporal logic".* Scholars having mathematical and physical background and interests claim that *times can be designated by terms in a first order theory*, and this is adequate for time modelling. These authors, referred often to as *,"detensers",* comprise Russell, Quine, Allen, McDermott, Kowalski and others. People interested in linguistic aspects of logic, on the other hand, feel that *time is tightly woven into languages under the form of the different tenses of the verb* [GALT 87].These authors, who seek to relate modal to temporal notions, are referred to as *"tensers",* and include Prior and Von Wright.

For the detensers, temporal qualification of anything which exists is the result of its *standing timelessly* in relation with certain times, which belong to a dimension on a par with the three dimensions of space. Tensers feel that such a view leaves out of account *transience*, which is essential in temporal phenomena [GALT 87].

As an example, let us look at how the two schools represent the statement:

Jones is never ill

detensers: $\neg (\exists x)(x \text{ is a time} \wedge \text{"Jones is ill" at } x)$

tensers: $G \neg p$
where: p = *"Jones is ill"* and G means *"it will always be the case that"*

In examining a time ontology in view of reasoning about physical and technological processes such as those considered in engineering systems, we must free ourselves from purely theoretical or metaphysical issues and choose a model of time which is fit for describing the dynamic relations existing among sets of complex objects and processes.

2. Ontological Issues

First of all, let us review the stones out of which a time model is built:

primitive entities

One of the most fundamental questions in the whole ontological issue, which rises a sort of "chicken-and-egg" problem, is the choice of what to consider as primitive concepts of time. Three entities have been proposed by several authors as time primitives:

- *points of time* (instants);
- *segments of time* (intervals);
- *occurrences in time* (events).

Connected to these primitives there are also the concepts of:

- *facts* (sets of states of the universe) [VBEN 83];
- *properties* (holding in *every subinterval* of an interval) [GALT 87];
- *processes* (lasting during *some subinterval* of an interval) [R&UR 71].

From an application point of view, it seems that, while linguists prefer points as primitives in building linguistic structures, computer scientists prefer intervals and events as building blocks for time reasoning. Events, in particular, partition scholars in two sets:

- *absolutists*, for whom a "moment of time" is a content-indifferent container of events. Events are differentiated by time, so *time precedes events*;

- *relativists*, for whom events precede time because *events constitute time*. In his Special Relativity Theory, Einstein defines time measurement as the correlation of two events [EINS 55].

2.1 Ordering

While it is commonly felt that time flows in an orderly way, it seems that a total (linear) ordering is too strong a condition; in many cases connectedness is enough [VBEN 83].

- *linear time*, the most common model, widely used in physics, has been studied by N. Cocchiarella [VBEN 83, R&UR 71] and has been adopted by Allen.

- *branching time* is obtained by releasing the linearity constraint at left (open past), at right (open future) or at both ends. This means that total ordering is replaced by partial ordering. Branching in the future, which seems a good model for program verification techniques, allows for many possible evolutions of the system, while just one will actually take place. McArthur [MCAR 76], Ben Ari [BENA 81] and Emerson & Halpern [EMHA 83] discuss temporal modalities related to branching in the future [GALT 87].Branching in the future allows the modelling of stochastic processes [R&UR 71]; McDermott [MCDE 82] adopts an (open future)-(linear past) model on the ground that future really is indeterminate. More complicated issues of branching in the future are considered in [R&UR 71], but it seems that they are more relevant to theoretical physics than to our kind of problems.

The main difference between the models on this point concerns whether branching is a property of the structure of time itself or it is the course of events which branches in a linearly flowing time [R&UR 71]. However, a relativist point of view clears out the duality since events constitute time.

A branching structure can also be applied to a set of events and the (metric) concept of simultaneity between events belonging to different branches can be introduced as the coincidence of the projections of the events on the linear time axis [VBEN 83].

- *circular time* can be considered a special form of linear time. It can be used to model recurrent events and processes. Since it models periodic time, it can be thought as provided of an ordering relation which, under some hypotheses (see below), can be one of total ordering. This model, as well as all "knotted" time axes (8-shape, epicycloids, etc.), is incompatible with a relativist view, for which each event represents a different time. Whenever a temporal structure is one-dimensional, finite, and closed then any of its possible courses of history can be realised on the line.[R&UR 71].

2.2 Structure

For linear time several different granularities have been defined [R&UR 71]:

- *density*: time primitives can be mapped into $\mathbf{Q}$;
- *continuity*: time primitives can be mapped into $\mathbf{R}$;
- *discreteness*: time primitives can be mapped into $\mathbf{Z}$.

where $\mathbf{Q}$, $\mathbf{R}$, and $\mathbf{Z}$ represent the sets of rational, real, and integer numbers respectively. It seems that the choice of either of these models is not a critical issue, but it strictly depends on the "world" that must be represented. However, it must be noted that dense and continuous times rule out finiteness.

Dense linear time has been studied by A. N. Prior, while R. A. Bull derived results for continuous and discrete linear time. Syntactical completeness has been proved in [VBEN 83] for dense and discrete linear time both for points and intervals.

2.3 Metrics

Metric concepts can be introduced into a temporal system - transforming it into a *chronological system*, - by defining a "*distance function*" over all pairs of time elements which satisfies the following conditions:

a) the null distance between two elements is defined;

b) the distances among three elements obey the triangular inequality.

Thus the set of values over which the temporal variables are to range constitutes a *metric space*.In such a system it is possible to correlate an arbitrary element of time with a unique real number which represents the distance of the element itself from a *reference element*. Usually the reference element is assumed to be the identity element of the additive group formed by the set of the time values together with the (relative) addition operation. In this case the identity element is the zero and distances add up in the usual arithmetic way [R&UR 71].

Such groups have an intrinsic linear ordering relation which is symmetric with respect to past and future, the identity element behaving as the "present time". In branching structures, it is not possible to speak of a strictly metric time by measuring distances on the projections of the elements on the underlying time axis since, as we noticed above, simultaneity can appear thus violating condition a); such systems can be characterised as *quasi-metric*. Moreover, in branching time structures a further problem is constituted by the fact that *we are not assured* that clocks in the different branches behave in the same way, thus granting the comparability of the measures [R&UR 71].

As a last topic, we can observe that the introduction of metrics entails, as a premise, the definition of metric units of time such as years, days, minutes, etc.by which *dates* - such as "February 8th, 1989" - or *pseudo-dates* - such as "the day after tomorrow" - can be stated.

2.4 Boundedness

Boundedness addresses the problem of whether every time has a successor (predecessor) or if there is a last (first) moment, i.e. time begins and ends.

Speaking in terms of intervals, the question is whether they are open (closed) at one or at both ends. If we remain in a classical logic context, symmetric models of the kind closed-closed or open-open must be ruled out in the description of physical systems because it is impossible that $\mathbf{p}$, and $\neg\mathbf{p}$, be both false (tertium non datur principle) or both true (non contradiction principle) at the same instant.

If no beginning or ending times exist, it is possible to introduce a *homogeneous time structure*, where the structure of the local temporal environment of every temporal position is exactly like that of all the others. Time homogeneity allows temporal compression and expansion, so that simulation of a long "real time" can be made in a shorter "synthetic time". Temporal dilatation can occur in continuous linear time as well as in circular time, but it cannot occur in discrete linear or in branching time [R&UR 71].

If a metrics is introduced, it is also possible to consider time finite or infinite in extension. If time is linear and infinite into both the past and future, then time as a whole can be isomorphically modelled by a finite interval that is open at both ends [R&UR 71]. A study of infinite linear time has been made by Dana Scott.

2.5 Other issues

Issues closely related to the ontology of time, but not part of it, are the properties of primitive events such as the *causation* relation between events, and the *persistence* of the effects of an event, which induces a change in the state of a system [MCDE 82]. Causation, in particular, is a millenary source of philosophical debate among scientists who either support or strongly deny the existence of a cause-effect relation [RUSS 45]. A proof that things are not yet settled is given by the work of Shoham [SHOH 88] and by the critical reviews of it which appeared in [CREV 89].

Table 1 summarises the ontological choices of some of the time models which have been proposed in the literature:

Author	**Allen ALLE 83**	**Kowalski KOSE 86**	**McDermott MCDE 82**	**Pernici PEBA 85**	**Dean DEMD 87**
Primitive	interval	event	point	point	point
Abs/Rel	relative	relative	relative	abs/rel	abs/rel
Ordering	linear	linear	L-linear	linear	L-linear
Structure	continuous	discrete	continuous	discrete	discrete
Bounds	[-)	(-)	∞	[-), ∞	?

Tab. 1

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Appendix

The tables which follow are a synthetic and diagrammatic form of part of [R&UR 71], in which the axioms and rules of temporal logic most relevant to the ontology of time are summarised

A SUMMARY OF TEMPORAL LOGIC

by F. A. Schreiber from Rescher & Urquhart

Propositional Logic

$\Downarrow$

$+$

$\boxed{P\alpha}$

proposition P is true at position α

$\Downarrow$

Topological Logic

(2-valued)

AxiomSchemata

P1: $P\alpha(\sim A) \equiv \sim P\alpha(A)$

P2: $P\alpha(A \& B) \equiv [P\alpha(A) \& P\alpha(B)]$

P3: $(\forall\alpha) P\beta[A(\alpha)] \equiv P\beta(\forall\alpha)[A(\alpha)]$

P4: $(\forall\alpha) P\alpha(p) \supset p$

P4′: $A \equiv P\xi(A)$; ξ special position

$\swarrow \quad \searrow$

P5.1: $P\beta[P\alpha(A)] \equiv P\alpha(A)$

fixed-point coordinate scheme with origin α: if P is true at α, then it is true everywhere that P is true at α

P5.2: $P\beta[P\alpha(A)] \equiv P(\beta \oplus \alpha)(A)$

floating-point coordinate scheme: $P\alpha(p)$ is true at β units from here, where $P\alpha(p)$ is true if p is true at α units from here

$\searrow \quad \swarrow$

$\Downarrow$

Temporal Logic

special case of topological logic

$$\begin{cases} \alpha, \beta & \text{positions in time;} \\ \xi & \text{now} \end{cases}$$

$\downarrow$

statements

$\swarrow \quad \searrow$

temporally *definite*

T or F is independent of the time of assertion

temporally *indefinite*

T or F depends on the time of assertion

$\searrow \quad \swarrow$

$\downarrow$

$\boxed{\text{now}}$

now

$\swarrow \quad \searrow$

Mc Taggart *B-series*
before–concurrent with–after
(positional structures)

Mc Taggart *A-series*
past–present–future
(tensed structures)

$\searrow \quad \swarrow$

$\downarrow$

$\swarrow \quad \searrow$

dates
chronologically stable
time specifications
(e. g. August 11, 1987,. . .)

pseudo-dates
chronologically unstable
time specifications
(e. g. today, six weeks ago,. . .)

$\searrow \quad \swarrow$

$R_t(A)$

A is Realized at time t

$\downarrow$

homogeneity

$\swarrow \quad \searrow$

does not admit
beginning, ending, now

allows *temporal*
compression and expansion

$\searrow \quad \swarrow$

AxiomSchemata

T1: $R_t(\sim A) \equiv \sim R_t(A)$
T2: $R_t(A \& B) \equiv [R_t(A) \& R_t(B)]$
T2.1: $[R_t(A) \& R_t(B)] \supset R_t(A \& B)$
T3: $R_n(A) \equiv A$
T4: $R_{t'}[(\forall t)A] \equiv (\forall t)R_{t'}(A)$
T5: $R_{t'}[R_t(A)] \equiv R_t(A)$
T5.1: $R_{t'}[R_t(A)] \supset R_t(A)$
T6: $R_t(n = t') \equiv t = t'$
T7: $R_t(t' = t'') \equiv t' = t''$
T8: $(\forall t)A \supset A^{t/n}$

Rules

R : if $\vdash A$ then $\vdash (\forall t)R_t(A)$
RE: if $\vdash A \equiv B$ then $\vdash (\ldots A \ldots) \equiv (\ldots B \ldots)$

$\Downarrow$

$\Downarrow$

$+$

n privileged present

$+$

temporal precedence

$\boxed{U\,tt'}$

time t is before time t'

$\Downarrow$

<u>*Tense Logic*</u>

Fp	it will be that p	$(\exists t)[U\,nt\,\&\,R_t(p)]$
Pp	it has been that p	$(\exists t)[U\,tn\,\&\,R_t(p)]$
Gp	henceforth always p	$(\forall t)[U\,nt \supset R_t(p)]$
Hp	heretofore always p	$(\forall t)[U\,tn \supset R_t(p)]$

$G = \sim F \sim$
$H = \sim P \sim$

$\Downarrow$

<u>*Minimal Tense Logic K_t*</u>

no specific assumption about the structure of time

$\downarrow$

Axioms(Lemmons)

G1: $G(p \supset q) \supset (Gp \supset Gq)$
H1: $H(p \supset q) \supset (Hp \supset Hq)$
G2: $\sim H \sim Gp \supset p$
H2: $\sim G \sim Hp \supset p$

Rules

RT: if A then $\vdash A$
RH: if $\vdash A$ then $\vdash HA$
RG: if $\vdash A$ then $\vdash GA$
RD: if $\vdash A$ and $\vdash A \supset B$ then B

$\Downarrow$

<u>*Time ordering K_b*</u>

transitivity

$\downarrow$

G3: $Gp \supset GGp$
H3: $Hp \supset HHp$

$\swarrow \quad \searrow$

backward (left) linear

H4: $[H(p \vee q) \& H(p \vee Hq) \& H(Hp \vee q)] \supset$
$\supset (Hp \vee Hq)$

equivalent to

$(Pp\&Pq) \supset [P(p\&Pq) \vee P(p\&q) \vee P(Pp\&q)]$

forward (right) linear

G4: $[G(p \vee q) \& G(p \vee Gq) \& G(Gp \vee q)] \supset$
$\supset (Gp \vee Gq)$

equivalent to

$(Fp\&Fq) \supset [F(p\&Fq) \vee F(p\&q) \vee F(Fp\&q)]$

$\searrow \quad \swarrow$

$\downarrow$

$\downarrow$

<u>*Linear Ordering K_l*</u>

mirror image rule

RM: if $\vdash A$ then $\vdash A'$

(A' results from replacing every G by H and viceversa)

$\swarrow$ $\searrow$

finite (with max. and min.)
$Gp \vee FGp$ (time stops)
$Hp \vee PHp$ (time begins)

infinite
G5: $Gp \supset Fp$ (∞ in the future $K_l^{\infty+}$)
H5: $Hp \supset Pp$ (∞ in the past $K_l^{\infty-}$)

$\searrow$ $\swarrow$

$\downarrow$

$\swarrow$ $\downarrow$ $\searrow$

dense ($\longrightarrow$ rationals)
G6: $GGp \supset Gp$
equivalent $(Fp \supset FFp)$
H6: $HHp \supset Hp$

discrete ($\longrightarrow$ integers)
G7: $\Box[Gp \supset p] \supset [Gp \supset Hp]$
H7: apply RM

continuous ($\longrightarrow$ reals)
G8: $\Box(Gp \supset PGp) \supset (Gp \supset Hp)$
H8: apply RM