James Allen (1984) argued that instants have no empirical reality and that all reasoning about temporal phenomena should be based on a model of time in which intervals are primitive elements, not constructed as aggregates of instants.

He devised a set of 13 basic qualitative relations between intervals, forming a jointly exhaustive and pairwise disjoint (JEPD) set.

These can all be defined in terms of a single primitive relation, meets, denoted |(or sometimes m), where $a \mid b$ means that interval $a$ ends exactly as interval $b$ begins.

Reference:
James F. Allen, 'Towards a general theory of action and time', Artificial Intelligence, 23 (1984) 123-154.

The following is a commonly-used set of axioms for the 'meets' relation |:
(M1) $u|v \wedge u| w \wedge x|v \rightarrow x| w$
(M2) $u|v \wedge w| x \rightarrow u \mid x \vee \exists y(u|y| x) \vee \exists z(w|z| v)$
(M3) $\exists v \exists w(v|u| w)$
(M4) $u|v| x \wedge u|w| x \rightarrow v=w$
(M5) $u \mid v \rightarrow \exists w \forall x \forall y(x|u \wedge v| y \rightarrow x|w| y)$

The 13 interval-interval relations are illustrated schematically here:


| Name | Symbol | Definition |
| :---: | :---: | :---: |
| is before | < | $a<b \equiv \exists j(a\|j\| b)$ |
| meets | \| | Primitive |
| overlaps | o | $\begin{array}{r} a \circ b \equiv \exists i \exists j \exists k \exists / \exists m(i\|j\| k\|I\| m \wedge \\ i\|a\| l \wedge j\|b\| m) \end{array}$ |
| starts | s | $a s b \equiv \exists i \exists j \exists k(i\|a\| j\|k \wedge i\| b \mid k)$ |
| finishes | f | $a \mathrm{f} b \equiv \exists i \exists j \exists k(i\|j\| a\|k \wedge i\| b \mid k)$ |
| is during | d | $a \mathrm{~d} b \equiv \exists i \exists j \exists k \exists l(i\|j\| a\|k\| l \wedge$ |
|  |  | $i\|b\| I)$ |
| equals | $=$ | $a=b \equiv \exists i \exists j(i\|a\| j \wedge i\|b\| j)$ |
| is after | > | $a>b \equiv b<a$ |
| is met by | mi | $a \mathrm{mi} b \equiv b \mid a$ |
| is overlapped by | oi | $a$ oi $b \equiv b \circ a$ |
| is started by | si | $a$ si $b \equiv b$ sa |
| is finished by | fi | $a \mathrm{fi} b \equiv b \mathrm{f} a$ |
| contains | di | $a \mathrm{di} b \equiv b \mathrm{~d} a$ |

The following diagram illustrates the definition

$$
a \circ b \equiv \exists i \exists j \exists k \exists / \exists m(i|j| k|I| m \wedge i|a| I \wedge j|b| m)
$$



## Given that

The time of the earthquake overlaps the time of the landslide The time of the landslide overlaps the collapse of the dam what is the relation between the time of the earthquake and the collapse of the dam?


Conclusion: The time of the earthquake overlaps, meets or precedes the collapse of the dam.

The example on the preceding slide is an example of a composition rule.

Composition rules for relations take the form:

- If $a$ stands in relation $R$ to $b$ and $b$ stands in relation $S$ to $c$, then $a$ stands in one of the relations $T_{1}, T_{2}, \ldots, T_{n}$ to $c$.

Our example can be written as

$$
a \circ b \wedge b \circ c \rightarrow a \circ c \vee a \mid c \vee a<c
$$

The Composition Table for a set $\mathcal{R}$ of JEPD relations gives the composition rule for every pair of relations $\langle R, S\rangle \in \mathcal{R} \times \mathcal{R}$.

|  | < | m | 0 | d |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| < | < | $<$ | $<$ | $<$ |  |
| m | $<$ | $<$ | $<$ | odm |  |
| 0 | < | $<$ | < 0 m | od |  |
| d | $<$ | < m | <odm | d |  |

## Events in TimeML

Pustejovsky et al. (2017)
(23) a. to examine how to formally recognize events and their temporal anchoring in text (news articles); and
b. to develop and evaluate algorithms for identifying and extracting events and temporal expressions from texts.
c. Order events with respect to each other (relating more than one event in terms of precedence, overlap, and inclusion);
d. Reason about the ramifications of an event (what is changed by virtue of an event);
e. Reason about the persistence of an event (how long an event or the outcome of an event persists);
f. Determine whether an event actually happened, according to the text, or whether it was merely an intention, or even something that had been avoided or prevented.

## TimeML Adopts Neo-Davidsonian Event Structure

(24) a. Mary ate an apple.
b. Mary ate an apple in the kitchen.
d. Mary ate an apple at 3:00pm.
e. Mary ate in the kitchen at 3:00pm..
(25) a. $\exists e \exists x[\operatorname{eat}(e, m, x) \wedge \operatorname{apple}(x)]$
b. $\exists e \exists x[\operatorname{eat}(e, m, x) \wedge$ apple $(x) \wedge$ in $(e$, the_kitchen $)]$
c. $\exists e \exists x[\operatorname{eat}(e, m, x) \wedge \operatorname{apple}(x) \wedge$ at $(e, 3: 00 \mathrm{pm})]$
d. $\exists e \exists x[\operatorname{eat}(e, m, x) \wedge \operatorname{apple}(x) \wedge$ in $(e$, the_kitchen $) \wedge$
at $(e, 3: 00 \mathrm{pm})]$

## Temporal Expressions

(26) a. Times: June 11, 1989, July 4;
b. Durations: three months, several days;
c. Frequencies: weekly, every year.
(27) a. Monday works better than Tuesday for the meeting.
b. Mary likes the morning, since she is more awake.
c. The 1960s was a turbulent decade.

In its more typical use, time functions as a modifying phrase, e.g., an Adjectival, Adverbial, or a Prepositional Phrase (or bare temporal NP).
(28) a. Our previous meal was much cheaper.
b. The plane arrived late.
c. Our dinner is at 8:00 pm.
d. Max teaches Tuesdays.

## Temporal Relations in TimeML

(29) a. event-event relations:

John left before Mary arrived.
b. time-time relations:

Mary left on Tuesday last week.
c. event-time relations:

The plane landed at noon.
Recall the options for temporal ordering:
(30) a. Add a modal operator over the proposition, where temporal order is interpreted from the syntactic combination of an operator over an expression;
b. Denote events and times as intervals with explicit ordering relations over them.

## Minimal Tense Logic $\left(K_{t}\right)$ - Prior (1967)

For $K_{t}$, four axioms form the core knowledge about temporal relations:
(31) a. $\phi \rightarrow \mathbf{H} \mathbf{F} \phi$ : What is, has always been going to be;
b. $\phi \rightarrow \mathbf{G} \mathbf{P} \phi$ : What is, will always have been;
c. $\mathbf{H}(\phi \rightarrow \psi) \rightarrow(\mathbf{H} \phi \rightarrow \mathbf{H} \psi)$ : Whatever always follows from what always has been, always has been;
d. $\mathbf{G}(\phi \rightarrow \psi) \rightarrow(\mathbf{G} \phi \rightarrow \mathbf{G} \psi)$ : Whatever always follows from what always will be, always will be.

## TimeML adopts Allen's Interval Calculus

The 13 interval-interval relations are illustrated schematically here:


## Event Interval Relations in Language: before/after

The ordinal relation of before (b) along with its inverse after (bi) is defined as follows:
(32) a. before $(x, y)$ : the interval $x$ completely precedes the interval $y$ with no contact or connection between $x$ and $y$. b. after $(x, y)$ : the interval $x$ completely follows the interval $y$ with no contact or connection between $x$ and $y$.

These are illustrated by the examples in (33).
(33) a. The rains destroyed the house. The owners are filing for flood insurance.
b. The Senate rejected the judge after learning of his past criminal activities.

## Event Interval Relations in Language: meets

When an ordinal relation of before exists, $b(x, y)$, and there is no interval between $x$ and $y$, we say that $x$ meets $y$.
(34) a. meet $(x, y)$ : the interval $x$ precedes the interval $y$ where the final point of $x$ touches the initial point of $y$.
b. metBy $(x, y)$ : the interval $x$ follows the interval $y$ where the final point of $y$ touches the initial point of $x$.

This is illustrated below in (35).
(35) The book fell to the floor. It sat there for days.

## Event Interval Relations in Language: overlap

If the before relation holds for only the initial part of interval $x$ relative to interval $y$, we have an overlap relation.
(36) a. overlap $(x, y)$ : the interval $x$ partially precedes and partially intersects the interval $y$.
b. overlappedBy $(x, y)$ : the interval $x$ partially intersects and partially follows the interval $y$.
The example in (37) illustrates this.
(37) Bill ate a big breakfast. He was full before he was done.

## Event Interval Relations in Language: start

When $x$ and $y$ have the same begin point but different end points, where $x$ stops earlier than $y$, we have a start relation, defined below and illustrated in (39).
(38) a. start $(x, y)$ : the interval $x$ begins at the same moment as interval $y$ and ends before $y$ terminates.
b. startedBy $(x, y)$ : the interval $x$ begins at the same moment as interval $y$ and continues on after $x$ has terminated.
(39) The sunrise occurred at 6:30 am this morning.

## Event Interval Relations in Language: finish

When $x$ and $y$ have the same end point but different begin points, where $x$ ends earlier than $y$, we have a finish relation, defined below with an example in (41).
(40) a. finish $(x, y)$ : the interval $x$ begins at the same moment as interval $y$ and ends before $y$ terminates.
b. finishedBy $(x, y)$ : the interval $x$ begins at the same moment as interval $y$ and continues on after $x$ has terminated.
(41) They reached the summit of the mountain at noon. The hike took four hours.

## Event Interval Relations in Language: during

Finally, consider the relation of complete temporal containment and its inverse, during.
(42) a. during $(x, y)$ : the interval $x$ completely precedes the interval $y$ with no contact or connection between $x$ and $y$. b. contains $(x, y)$ : the interval $x$ completely follows the interval $y$ with no contact or connection between $x$ and $y$.

The example in (43) illustrates the during relation.
(43) A baby cried during the concert.

The TLINK relation specifies the particular temporal ordering or anchoring of event predicates interpreted as intervals.
(44) John [taught] $]_{e 1}$ before Mary [arrived] ${ }_{e 2}$.
(45) <TLINK evID="e1" relToEvent=e2" sigID="s1" relType="BEFORE" />
(46) a. teach $=e_{1}$, arrive $=e_{2}$
b. $\exists e_{1} \exists e_{2}\left[\right.$ teach $\left.\left(e_{1}\right) \wedge \operatorname{arrive}\left(e_{2}\right) \wedge \tau\left(e_{1}\right)<\tau\left(e_{2}\right)\right]$

## Measuring Events in ISO-TimeML

(47) a. John slept for 2 hours.
b. a three-day vacation
(48) John taught for three hours on Tuesday.
(49) a. teach $=e_{1}$, tuesday $=t_{2}, m=3$ hour
b. $\exists e_{1} \exists t_{2}\left[\right.$ teach $\left(e_{1}\right) \wedge \mu\left(\tau\left(e_{1}\right)\right)=v \wedge v=$ 3_hour $\wedge$ tuesday $\left(t_{2}\right) \wedge \tau\left(e_{1}\right) \subseteq t_{2}$ ]

## Quantifying Events in TimeML

(50) John taught on Tuesday.

In TimeML, the translation of the distinct XML elements is given below:
(51) a. EVENT tag introduces a quantified event expression $\Longrightarrow$ $\exists e_{1}\left[\right.$ teach $\left.\left(e_{1}\right)\right]$;
b. TIMEX3 tag introduces the temporal expression $\Longrightarrow$ $\exists t_{2}\left[\right.$ tuesday $\left.\left(t_{2}\right)\right]$;
c. TLINK introduces the ordering relation $\Longrightarrow$ $\lambda y \lambda x[\tau(x) \subseteq y]$.
(52) $\exists e_{1} \exists t_{2}\left[\right.$ teach $\left(e_{1}\right) \wedge$ tuesday $\left.\left(t_{2}\right) \wedge \tau\left(e_{1}\right) \subseteq t_{2}\right]$

## Quantifying Events in TimeML

(53) John taught every Tuesday in November.
(54) $\forall t_{1} \exists e_{1} \exists t_{2}\left[\left(\right.\right.$ Tuesday $\left(t_{1}\right) \wedge$ November $\left.\left(t_{2}\right) \wedge t_{1} \subseteq t_{2}\right) \rightarrow$ $\left(\right.$ teach $\left.\left.\left(e_{1}\right) \wedge \tau\left(e_{1}\right) \subseteq t_{1}\right)\right]$
(55) Mary read during every lecture.
(56) $\forall e_{2} \exists e_{1}\left[\right.$ lecture $\left.\left(e_{2}\right) \rightarrow\left[\operatorname{read}\left(e_{1}\right) \wedge \tau\left(e_{1}\right) \subseteq \tau\left(e_{2}\right)\right]\right]$

