Finite-state methods for sub-atomic semantics

3. A finite-state perspective on tense & aspect

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Key phrases:
telic, durative, Aktionsart, imperfective, segmented, whole, incremental change, force and inertia

Could tense & aspect be finite-state?

Were it left to semantics, YES.

At least for Priorean tense logic extended with

**Intervals** (Bennett & Partee 1972, Dowty 1979)

**Temp Parameters** E, S, R (Reichenbach), ... (DRT ...)

**Events**, Panini-Ramsey-Davidson Hypothesis (Parsons 1990)

**Yesterday**
- MSO$\Sigma$ with models in $(2^\Sigma)^+$ & intervals in strings (Allen, RWK)

**Monday**
- from intervals to strings, under Dowty’s aspect hypothesis

$\Sigma$ can always be expanded to a larger finite set
Main challenge: events

Parsons 1990

*the Panini-Ramsey-Davidson hypothesis that English sentences of the simplest sort contain some underlying reference to (quantification over) events or states.*

Davidson 1970

*an ontology of events as unrepeatable particulars* ("concrete individuals")

Finite-state claim
- these events be analyzed, *up to bounded granularity* $\Sigma$, as runs of finite automata
- the semantics of tense & aspect is finite-state approximable
- the finite-state approximations are what count

Events as truthmakers (if not denotations)

Davidson 1967

(7) *Amundsen flew to the North Pole in May 1926.*

(7) ... *does not describe any event at all. But if (7) is true, then there is an event that makes it true.*

$\exists x \text{ Flew(Amundsen, } x) \land \text{To(NorthPole, } x) \land \text{In(May1926, } x)\text{ }$

Aim: encode index as a string $i$ to feed into a binary relation $R[\varphi]$ on strings s.t.

$$i \models \varphi \iff i \in \text{domain}(R[\varphi])$$

without insisting that $R[\varphi]$ be deterministic — i.e., there may be more than one string in the set

$$\{ e \mid i \ R[\varphi] \ e \}$$

described by $\varphi$ at $i$. 
From intervals to strings

Krifka 1998

One and the same event of running can be described by running (i.e. by an atelic predicate) or by running a mile (i.e. a telic, or delimited, predicate).

Searle 1978

The world doesn't come to us already sliced up into objects and experiences ... the world divides the way we divide it.

Segment an interval \( I \) into a string \( I_1 \cdots I_n \) of subintervals with

\[
I_1 \cdots I_n \models \alpha_1 \cdots \alpha_m \quad \text{iff} \quad n = m \quad \text{and for } 1 \leq i \leq n \quad \text{and } \varphi \in \alpha_i, \\
I_i \models \varphi \\
\text{iff} \quad \Delta_\Sigma(I_1 \cdots I_n) \supseteq \alpha_1 \cdots \alpha_m
\]

where \( \alpha_i \subseteq \Sigma \) for all \( 1 \leq i \leq m \).

Aktionsart in strings

Claim. Telicity and durativity concern string representations over and above timelines (\( \models \) on fluents).

\( \alpha_1 \cdots \alpha_n \) is telic if there is some \( \varphi \) in \( \alpha_n \) such that the negation \( \neg \varphi \) of \( \varphi \) appears in \( \alpha_i \) for \( 1 \leq i < n \)

Mary ran to post-office \( \varphi = \text{at(mary,post-office)} \) not quantized (Krifka)

\( \alpha_1 \cdots \alpha_n \) is durative if its length \( n \) is \( \geq 3 \).

<table>
<thead>
<tr>
<th></th>
<th>non-durative</th>
<th>durative</th>
</tr>
</thead>
<tbody>
<tr>
<td>−tel</td>
<td>semelfactive</td>
<td>activity</td>
</tr>
<tr>
<td>telic</td>
<td>achievement</td>
<td>accomplishment</td>
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</table>
Subsumption $\triangleright$ and superposition &

$$\alpha_1 \cdots \alpha_n \triangleright \beta_1 \cdots \beta_m$$ iff $n = m$ and $\alpha_i \supseteq \beta_i$ for $1 \leq i \leq n$

$$s \triangleright L$$ iff $(\exists s' \in L) s \triangleright s'$

so that $s$ is durative iff $s \triangleright \square^+$
and telic iff $s \triangleright \neg \square^+ \varphi$ for some $\varphi$.

$$\alpha_1 \cdots \alpha_n \& \beta_1 \cdots \beta_n = (\alpha_1 \cup \beta_1) \cdots (\alpha_n \cup \beta_n)$$

$L \& L' = \{s \& s' \mid s \in L, s' \in L' \text{ and } \text{length}(s) = \text{length}(s')\}$

durative strings in $L$  
$$\text{dur}(L) = L \& \square^+$$  
$$= \{s \in L \mid s \triangleright \square^+\}$$

cul($L, \varphi$)  
$$= L \& \neg \square^+ \varphi \triangleright \neg \square^+ \varphi$$

Dowty's aspect hypothesis

statives  $+$  DO, BECOME, CAUSE . . .

A rough event approximation from Rothstein 2004

activities  \[\lambda e.(\text{DO}(\varphi))(e)\]

achievements  \[\lambda e.(\text{BECOME}(\varphi))(e)\]

accomplishments  \[\lambda e.\exists e'[(\text{DO}(\varphi))(e') \land e = e' \cup_s \text{Cul}(e)]\]

<table>
<thead>
<tr>
<th>$\text{DO / dur}$</th>
<th>$\text{DO} / \text{dur}$</th>
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<tbody>
<tr>
<td>$\text{BECOME / cul}$</td>
<td>$\text{semelfactive}$</td>
</tr>
<tr>
<td>$\text{achievement}$</td>
<td>$\text{accomplishment}$</td>
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<tr>
<td>$\text{durative}$</td>
<td>$\text{durative}$</td>
</tr>
</tbody>
</table>
A minimal account

state $\varphi$ pointwise fluent

achievement $\neg \varphi \varphi$ $\text{cul}(\emptyset, \varphi)$

semelfactive $L \& \emptyset$ $f r_f$

activity $\text{dur}(L)$ $f f, r_f r_f$

accomplishment $\text{cul}(\text{dur}(L), \varphi)$ $f, \neg \varphi f, r_f, \neg \varphi r_f, \varphi$

(1) $L = \overline{f f, r_f} \overline{r_f} = \text{iter}(\overline{f r_f})$
(2) $s \beta ; \alpha s' := s(\beta \cup \alpha)s'$
(3) $L; L' := \{s; s' | s \in L - \{\epsilon\} \text{ and } s' \in L' - \{\epsilon\}\}$
(4) $\text{iter}(L) := (\text{least } Z \supseteq L) Z; L \subseteq Z$

Statives are segmented

Stative $\varphi$: $I \models \varphi$ iff $(\forall t \in I) \{t\} \models \varphi$

(1) $\varphi \underbrace{\text{Ed slept from 3 to 6}}_{I} \models \varphi \underbrace{\text{Ed slept from 3 to 5}}_{I'}$

for all intervals $I$ and $I'$,

$I \models \varphi$ and $I' \subseteq I$ implies $I' \models \varphi$

(2) $\text{Ed slept from 3 to 5pm, Ed slept from 4 to 6pm}$

$\models \text{Ed slept from 3 to 6pm}$

$\varphi$ is segmented if for all intervals $I$ and $I'$ s.t. $I \cup I'$ is an interval,

$I \models \varphi$ and $I' \models \varphi$ iff $I \cup I' \models \varphi$. 
From segmented to whole fluents

ϕ is whole if for all intervals I and I’ s.t. \( I \cup I' \) is an interval,

\[ I \models \varphi \text{ and } I' \models \varphi \implies I = I'. \]

Useful for an event described by ϕ

\[ I \models \varphi \iff I \text{ is the time of a } \varphi\text{-event} \]

Identify an interval J with the fluent naming it

\[ I \models J \iff I = J \]

contra “ϕ-segment”

\[ I \models \varphi_o \iff (\exists I' \supseteq I) I' \models \varphi \]

**Fact.** ϕo is segmented if ϕ is whole

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**Imperfectives vs perfectives**

<table>
<thead>
<tr>
<th>whole</th>
<th>count</th>
<th>perfective</th>
</tr>
</thead>
<tbody>
<tr>
<td>segmented</td>
<td>mass</td>
<td>imperfective</td>
</tr>
</tbody>
</table>

**perfective:** viewed from outside, completed, closed

\[
\begin{array}{c|c|c}
V_o & E, V_o & V_o \\
\end{array}
\]

**imperfective:** viewed from inside, ongoing, open-ended

\[
\begin{array}{c|c|c}
E_o & V, E_o & E_o \\
\end{array}
\]

\[ I \text{ inside } I' \iff (\exists t \in I') \{t\} < I \text{ and } (\exists t' \in I') I < \{t'\} \]

For intervals E and V,

\[ (\exists I) I \models \begin{array}{c|c|c}
E_o & E_o, V & E_o \\
\end{array} \iff V \text{ inside } E \]
Segmenting the segmented

φ is segmentable as L if for all segs \( I_1 \cdots I_n \),

\[
\bigcup_{i=1}^{n} I_i \models \phi \quad \text{iff} \quad I_1 \cdots I_n \models L
\]

Extend \( \models \) to a language \( L \) (set of strings) disjunctively

\( \| \models L \quad \text{iff} \quad (\exists s \in L) \| \models s. \)

Fact. The following three conditions are equivalent.

(i) \( \phi \) is segmented

(ii) \( \phi \) is segmentable as

\[
\phi^+ = \phi + \phi \phi + \phi \phi \phi + \cdots
\]

(iii) \( \phi \) is segmentable as \( \phi \circ \).

Segmenting the whole

Fact. The following are equivalent.

(i) \( \phi \) is whole

(ii) there is no seg \( \| \) such that \( \| \models \phi \circ + \phi \circ \phi \)

(iii) \( \phi \) is segmentable as

\[
[\phi \circ, \neg\langle m \rangle \phi \circ, \neg\langle m \rangle \phi \circ] + [\phi \circ, \neg\langle m \rangle \phi \circ] \phi \circ + \phi \circ \phi \circ \phi \circ
\]

where \( m \) is meet and \( m_i \) is its inverse

\( l m l' \quad \text{iff} \quad l \cup l' \in \text{lvl} \) and \( l < l' \)

\( l m_i l' \quad \text{iff} \quad l' m l \)

Fact. The map \( \phi \mapsto \phi \circ \) is the right adjoint in an adjunction between a universal grinder & universal packager.

Whole implies quantized (Krifka), but converse fails.
Constraints

Let

\[ s \text{ has-factor } s' \text{ iff } (\exists u, v) \ s = us'v. \]

\[ \langle R \rangle L = \{ s \mid (\exists s' \in L) \ sRs' \} \]

\[ \text{counterEx}(L \Rightarrow L') = \langle \text{has-factor} \rangle (\langle \Rightarrow \rangle L \cap \langle \Rightarrow \rangle L') \]

\[ L \Rightarrow L' = \langle \text{has-factor} \rangle (\langle \Rightarrow \rangle L \cap \langle \Rightarrow \rangle L') \]

E.g. \[ \varphi \Rightarrow \varphi = \{ \alpha_1 \cdots \alpha_n \mid \text{whenever } \varphi \in \alpha_i, \ \varphi \in \alpha_{i+1} \]

\[ \text{for } 1 \leq i < n \}

Inertial statives

Pat stopped the car before it hit the tree.

Statives persist forward and backward unless forced otherwise

\[ \varphi \Rightarrow \varphi + f\neg\varphi \]

\[ \neg\varphi \Rightarrow \varphi + f\varphi \]

Forces succeed unless opposed

\[ f\varphi \Rightarrow \varphi + f\neg\varphi \]

Refine with forces

\[ \text{cul}_f(L, \varphi) = L & \neg\varphi, \neg\varphi, f\varphi \]

\[ \text{dur}^\uparrow(\varphi) = \uparrow\varphi, \uparrow\varphi, \uparrow\varphi \]
Incremental change

Refine bivalent $\varphi$ with degrees $d$

\[
\begin{align*}
    d\varphi & : \quad d \leq \varphi\text{-degree} & \quad \downarrow \varphi & : \quad f\neg d\varphi \quad \text{(same for all } d\text{'s)} \\
    \varphi d & : \quad \varphi\text{-degree} \leq d & \quad \uparrow \varphi & : \quad fd\varphi \quad \text{(same for all } d\text{'s)}
\end{align*}
\]

\[
\begin{align*}
    d\varphi & \Rightarrow \frac{d\varphi}{d\varphi} + \frac{\downarrow \varphi}{\downarrow \varphi} \\
    \frac{d\varphi}{d\varphi} \Rightarrow \frac{d\varphi}{d\varphi} + \frac{\uparrow \varphi}{\uparrow \varphi} \\
    \frac{\uparrow \varphi, d\varphi}{d\varphi} \Rightarrow \frac{\neg d\varphi + \downarrow \varphi}{\neg d\varphi + \downarrow \varphi}
\end{align*}
\]

\[
\begin{align*}
    \varphi d & \Rightarrow \frac{\varphi d}{\varphi d} + \frac{\uparrow \varphi}{\uparrow \varphi} \\
    \frac{\varphi d}{\varphi d} \Rightarrow \frac{\varphi d}{\varphi d} + \frac{\downarrow \varphi}{\downarrow \varphi} \\
    \frac{\downarrow \varphi, \varphi d}{\varphi d} \Rightarrow \frac{\neg d\varphi + \uparrow \varphi}{\neg d\varphi + \uparrow \varphi}
\end{align*}
\]

Refrinements with force

Comrie 1976

With a state, unless something happens to change that state, then the state will continue ... With a dynamic situation, on the other hand, the situation will only continue if it is continually subject to a new input of energy.

[ = force, Copley & Harley 2012]

E.g. rise in $\varphi$-degree, $\varphi:\ (\exists d)\ d\varphi \land \text{Prev } \neg d\varphi$

\[
dur_{\uparrow}(\varphi) = \frac{\uparrow \varphi}{\uparrow \varphi}, \frac{\uparrow \varphi}{\uparrow \varphi} + \frac{\uparrow \varphi}{\uparrow \varphi} \quad \text{(bc length } \geq 3)
\]

force fluent $\uparrow \varphi$

\[
\begin{align*}
    \text{cul}_f(L, \psi) = L \& \neg \psi^* \neg \psi, f\psi \psi
\end{align*}
\]
Continuous change

soup cool in an hour: \[ x, d \leq sDg \quad d \leq sDg \quad \text{hour}(x), sDg < d \]

\[ =_{bc} \quad d \leq sDg \quad sDg < d \quad \& \quad x \quad \text{hour}(x) \]

\[ I \models d \leq sDg \quad \text{iff} \quad (\forall r \in I) \quad d \leq sDg(r) \]

soup cool for an hour: \[ x \quad [\Box]sDg_{\downarrow} \quad \text{hour}(x), [\Box]sDg_{\downarrow} \]

\[ =_{bc} \quad [\Box]sDg_{\downarrow} \quad \& \quad x \quad \text{hour}(x) \]

\[ sDg_{\downarrow} := \exists x (sDg < x \quad \& \quad \text{Prev}(x \leq sDg)) \]

\[ I \models [\Box]\varphi \quad \text{iff} \quad (\forall I' \subseteq I) \quad I' \models \varphi \]

Addendum to: No time without change

No change unless observed
in a fluent \( \varphi \) from a finite set \( A \) fixing granularity \((\rho_A, bc)\)

Add fluents for
- degrees (incremental change)
- forces (inertia)

No change (in inertial fluents) unless forced

Forces as finite automata / frames

Derive world-time pairs from runs of

many automata, only partially known, on different clocks