Predication via Finite-State Methods

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_Σ with models in $(2^\Sigma)^+$ & intervals in strings (Allen, RWK)

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

Σ 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* Σ, 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.*

$$\exists x\ \mathsf{Flew}(\mathsf{Amundsen}, x) \wedge \mathsf{To}(\mathsf{NorthPole}, x) \wedge \mathsf{In}(\mathsf{May1926}, x)$$

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

$$i \models \varphi \quad \Longleftrightarrow \quad i \in dom(\mathcal{R}[\varphi])$$

with*out* insisting that $\mathcal{R}[\varphi]$ be deterministic — i.e., there may be more than one string in the set

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

described by φ 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

$$\begin{aligned} I_1 \cdots I_n \models \alpha_1 \cdots \alpha_m \quad &\iff \quad n = m \text{ and for } 1 \leq i \leq n \text{ and } \varphi \in \alpha_i, \\ &\qquad\qquad\qquad\qquad I_i \models \varphi \\ &\iff \quad \Delta_\Sigma(I_1 \cdots I_n) \trianglerighteq \alpha_1 \cdots \alpha_m \end{aligned}$$

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

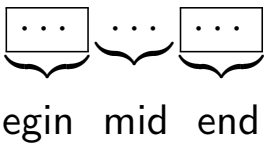
Aktionsart in strings

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 φ in α_n such that the negation $\neg\varphi$ of φ appears in α_i for $1 \leq i < n$

Mary ran to post-office $\quad \varphi =$at(mary,post-office)
not quantized (Krifka)

$\alpha_1 \cdots \alpha_n$ is *durative* if its length n is ≥ 3.



	non-durative	durative
−tel	semelfactive	activity
telic	achievement	accomplishment

Subsumption $\trianglerighteq$ and superposition &

$$\alpha_1 \cdots \alpha_n \trianglerighteq \beta_1 \cdots \beta_m \iff n = m \text{ and } \alpha_i \supseteq \beta_i \text{ for } 1 \leq i \leq n$$
$$s \trianglerighteq L \iff (\exists s' \in L)\ s \trianglerighteq s'$$

so that s is durative iff $s \trianglerighteq \boxed{}\boxed{}\boxed{}^{+}$
and telic iff $s \trianglerighteq \boxed{\neg\varphi}^{+}\boxed{\varphi}$ for some φ.

$$\alpha_1 \cdots \alpha_n \ \&\ \beta_1 \cdots \beta_n = (\alpha_1 \cup \beta_1) \cdots (\alpha_n \cup \beta_n)$$
$$L \ \&\ L' = \{s \ \&\ s' \mid s \in L,\ s' \in L' \text{ and length}(s)\text{=length}(s')\}$$

$$\text{durative strings in } L \quad \text{dur}(L) = L\& \boxed{}\boxed{}\boxed{}^{+} = \{s \in L \mid s \trianglerighteq \boxed{}\boxed{}\boxed{}^{+}\}$$

$$\text{cul}(L, \varphi) = L\& \boxed{\neg\varphi}^{+}\boxed{\varphi} \trianglerighteq \boxed{\neg\varphi}^{+}\boxed{\varphi}$$

Dowty 1979 with events

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	$\lambda e.\exists e'[(\text{DO}(\varphi))(e') \wedge e = e' \sqcup_S \text{Cul}(e)]$

		DO / dur	
BECOME / cul	semelfactive achievement	activity accomplishment	−telic +telic
	−durative	+durative	

A minimal account

state	φ	pointwise fluent
achievement	$\boxed{\neg\varphi}\boxed{\varphi}$	$\mathrm{cul}(\boxed{}\boxed{}, \varphi)$
semelfactive	$L\&\boxed{}\boxed{}$	$\boxed{f}\boxed{r_f}$
activity	$\mathrm{dur}(L)$	$\boxed{f}\boxed{f, r_f}\boxed{r_f}$
accomplishment	$\mathrm{cul}(\mathrm{dur}(L), \varphi)$	$\boxed{f, \neg\varphi}\boxed{f, r_f, \neg\varphi}\boxed{r_f, \varphi}$

(1) $L \;=\; \boxed{f}\boxed{f, r_f}^{*}\boxed{r_f} \;=\; \mathrm{iter}(\boxed{f}\boxed{r_f})$

(2) $s\beta \;;\; \alpha s' \;:=\; s(\beta \cup \alpha)s'$

(3) $L; L' \;:=\; \{s; s' \mid s \in L - \{\epsilon\} \text{ and } s' \in L' - \{\epsilon\}\}$

(4) $\mathrm{iter}(L) \;:=\; (\text{least } Z \supseteq L)\; Z; L \subseteq Z$

Statives are segmented

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

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

for all intervals I and I',

$$I \models \varphi \text{ and } I' \subseteq I \quad \text{implies} \quad I' \models \varphi$$

(2) Ed slept from 3 to 5pm, Ed slept from 4 to 6pm
$\vdash$ Ed slept from 3 to 6pm

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

$$I \models \varphi \text{ and } I' \models \varphi \iff I \cup I' \models \varphi.$$

From segmented to whole fluents

φ is *whole* if for all intervals I and I' s.t. $I \cup I'$ is an interval,

$$I \models \varphi \text{ and } I' \models \varphi \quad \text{implies} \quad I = I'.$$

Useful for an event described by φ

$$I \models \varphi \quad \Longleftrightarrow \quad I \text{ is the time of a } \varphi\text{-event}$$

Identify an interval J with the fluent naming it

$$I \models J \quad \Longleftrightarrow \quad I = J$$

contra "φ-segment"

$$I \models \varphi_\circ \quad \Longleftrightarrow \quad (\exists I' \supseteq I)\ I' \models \varphi$$

Fact. $\varphi_\circ$ is segmented if φ is whole

Imperfectives vs perfectives

$$\frac{\text{whole}}{\text{segmented}} \approx \frac{\text{count}}{\text{mass}} \approx \frac{\text{perfective}}{\text{imperfective}}$$

perfective: viewed from outside, completed, closed

$V_\circ$	$E,V_\circ$	$V_\circ$

imperfective: viewed from inside, ongoing, open-ended

$E_\circ$	$V,E_\circ$	$E_\circ$

$$I \text{ inside } I' \quad \Longleftrightarrow \quad (\exists t \in I')\ \{t\} < I \text{ and } (\exists t' \in I')\ I < \{t'\}$$

For intervals E and V,

$$(\exists \mathbb{I})\ \mathbb{I} \models \begin{array}{|c|c|c|}\hline E_\circ & E_\circ,V & E_\circ \\ \hline \end{array} \quad \Longleftrightarrow \quad V \text{ inside } E$$

Segmenting the segmented

φ is *segmentable as* L if for all segs $I_1 \cdots I_n$,

$$\bigcup_{i=1}^{n} I_i \models \varphi \quad \Longleftrightarrow \quad I_1 \cdots I_n \models L$$

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

$$\mathbb{I} \models L \quad \Longleftrightarrow \quad (\exists s \in L)\ \mathbb{I} \models s.$$

Fact. *The following three conditions are equivalent.*

(i) φ *is segmented*

(ii) φ *is segmentable as*

$$\boxed{\varphi}^{+} = \boxed{\varphi} + \boxed{\varphi}\boxed{\varphi} + \boxed{\varphi}\boxed{\varphi}\boxed{\varphi} + \cdots$$

(iii) φ *is segmentable as* $\boxed{\varphi_\circ}^{+}$.

Segmenting the whole

Fact. *The following are equivalent.*

(i) φ *is whole*

(ii) *there is no seg* $\mathbb{I}$ *such that* $\mathbb{I} \models \boxed{\varphi}\boxed{\varphi_\circ} + \boxed{\varphi_\circ}\boxed{\varphi}$

(iii) φ *is segmentable as*

$$\boxed{\varphi_\circ, \neg\langle \mathtt{mi} \rangle \varphi_\circ, \neg\langle \mathtt{m} \rangle \varphi_\circ} + \boxed{\varphi_\circ, \neg\langle \mathtt{mi} \rangle \varphi_\circ}\boxed{\varphi_\circ}^{*}\boxed{\varphi_\circ, \neg\langle \mathtt{m} \rangle \varphi_\circ}$$

where $\mathtt{m}$ *is* meet *and* $\mathtt{mi}$ *is its inverse*

$$I \ \mathtt{m}\ I' \quad \Longleftrightarrow \quad I \cup I' \in \mathbf{lvl} \text{ and } I < I'$$
$$I \ \mathtt{mi}\ I' \quad \Longleftrightarrow \quad I' \ \mathtt{m}\ I$$

Fact. The map $\varphi \mapsto \varphi_\circ$ is the right adjoint in an adjunction between a universal grinder & universal packager.

Whole implies quantized (Krifka), but converse fails.

Constraints

Let

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

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

$$\begin{aligned} \text{counterEx}(L \Rightarrow L') &= \langle \text{has-factor} \rangle (\langle \trianglerighteq \rangle L \cap \overline{\langle \trianglerighteq \rangle L'}) \\ L \Rightarrow L' &= \overline{\langle \text{has-factor} \rangle (\langle \trianglerighteq \rangle L \cap \overline{\langle \trianglerighteq \rangle L'})} \end{aligned}$$

E.g. $\boxed{\varphi}\boxed{} \Rightarrow \boxed{}\boxed{\varphi} = \{\alpha_1 \cdots \alpha_n \mid \text{whenever } \varphi \in \alpha_i,\ \varphi \in \alpha_{i+1}$ for $1 \leq i < n\}$

Inertial statives

`Pat stopped the car before it hit the tree.`

Statives persist forward and backward unless forced otherwise

$$\boxed{\varphi}\boxed{} \Rightarrow \boxed{}\boxed{\varphi} + \boxed{\mathsf{f}\neg\varphi}\boxed{}$$

$$\boxed{}\boxed{\varphi} \Rightarrow \boxed{\varphi}\boxed{} + \boxed{\mathsf{f}\varphi}\boxed{}$$

Forces succeed unless opposed

$$\boxed{\mathsf{f}\varphi}\boxed{} \Rightarrow \boxed{}\boxed{\varphi} + \boxed{\mathsf{f}\neg\varphi}\boxed{}$$

Refine with forces

$$\begin{aligned} \text{cul}_{\mathrm{f}}(L, \varphi) &= L \,\&\, \boxed{\neg\varphi}^{*}\boxed{\neg\varphi, \mathrm{f}\varphi}\boxed{\varphi} \\ \text{dur}_{\uparrow}(\varphi) &= \boxed{\uparrow\varphi}\boxed{\uparrow\varphi, \varphi\uparrow}^{+}\boxed{\varphi\uparrow} \end{aligned}$$

Dowty 1986: Semantics or pragmatics?

> *This principle of "inertia" in the interpretation of statives in discourse applies to many kinds of statives but of course not to all of them . . . there must be a graded hierarchy of the likelihood that various statives will have this kind of implicature, depending on the nature of the state, the agent, and our knowledge of which states are long-lasting and which decay or reappear rapidly.*
> *Clearly, an enormous amount of real-world knowledge and expectation must be built into any system which mimics the understanding that humans bring to the temporal interpretations of statives in discourse, so no simple non-pragmatic theory of discourse interpretation is going to handle them very effectively.*

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Inertia and force constraints above are non-defeasible.

Left open: forces at play and which win out ... PRAGMATICS

Incremental change

Refine bivalent φ with degrees d

$d\varphi$:	$d \leq \varphi$-degree	$\downarrow\varphi$:	f$\neg d\varphi$	(same for all d's)
φd :	φ-degree $\leq d$	$\uparrow\varphi$:	f$d\varphi$	(same for all d's)

$$\boxed{d\varphi\,|\,} \Rightarrow \boxed{\,|\,d\varphi} + \boxed{\downarrow\varphi\,|\,}$$

$$\boxed{\,|\,d\varphi} \Rightarrow \boxed{d\varphi\,|\,} + \boxed{\uparrow\varphi\,|\,}$$

$$\boxed{\uparrow\varphi, d\varphi\,|\,} \Rightarrow \boxed{\,|\,\neg\varphi d} + \boxed{\downarrow\varphi\,|\,}$$

$$\boxed{\varphi d\,|\,} \Rightarrow \boxed{\,|\,\varphi d} + \boxed{\uparrow\varphi\,|\,}$$

$$\boxed{\,|\,\varphi d} \Rightarrow \boxed{\varphi d\,|\,} + \boxed{\downarrow\varphi\,|\,}$$

$$\boxed{\downarrow\varphi, \varphi d\,|\,} \Rightarrow \boxed{\,|\,\neg d\varphi} + \boxed{\uparrow\varphi\,|\,}$$

Refinements 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 φ-degree, $\varphi_{\uparrow}$: $(\exists d)\ d\varphi \wedge \mathrm{Prev}\ \neg d\varphi$

$$\mathrm{dur}_{\uparrow}(\varphi) \quad = \quad \boxed{\uparrow\varphi}\boxed{\uparrow\varphi, \varphi_{\uparrow}}^{+}\boxed{\varphi_{\uparrow}} \qquad (bc \text{ length } \geq 3)$$

force fluent $\uparrow\varphi$

$$\mathrm{cul}_{\mathrm{f}}(L, \psi) \quad = \quad L\&\ \boxed{\neg\psi}^{*}\boxed{\neg\psi, \mathrm{f}\psi}\boxed{\psi}$$

Continuous change

$$\texttt{soup cool in an hour}\ \boxed{x, d \leq sDg}\boxed{d \leq sDg}\boxed{\mathrm{hour}(x), sDg < d}$$

$$=_{bc}\ \boxed{d \leq sDg}^{+}\boxed{sDg < d}\ \&\ \boxed{x}\boxed{}^{+}\boxed{\mathrm{hour}(x)}$$

$$I \models d \leq sDg \iff (\forall r \in I)\ d \leq sDg(r)$$

$$\texttt{soup cool for an hour}\ \boxed{x}\boxed{[\sqsupseteq]sDg_{\downarrow}}\boxed{\mathrm{hour}(x), [\sqsupseteq]sDg_{\downarrow}}$$

$$=_{bc}\ \boxed{}\boxed{[\sqsupseteq]sDg_{\downarrow}}^{+}\ \&\ \boxed{x}\boxed{}^{+}\boxed{\mathrm{hour}(x)}$$

$$sDg_{\downarrow} \quad := \quad \exists x(sDg < x \wedge \mathrm{Prev}(x \leq sDg))$$

$$I \models [\sqsupseteq]\varphi \iff (\forall I' \sqsubseteq I)\ I' \models \varphi$$

Addendum to: *No time without change*

No change unless observed
in a fluent φ from a finite set A fixing granularity (ρ_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