Predication via Finite-State Methods

3. A finite-state perspective on tense & aspect

Tim Fernando
ESSLLI 2017, Toulouse

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
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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
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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.

\[ \exists x \text{ Flew}(\text{Amundsen}, x) \land \text{To}(\text{North Pole}, x) \land \text{In}(\text{May 1926}, x) \]

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

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

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

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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 $l_1 \cdots l_n$ of subintervals with

\[
l_1 \cdots l_n \models \alpha_1 \cdots \alpha_m \iff n = m \text{ and for } 1 \leq i \leq n \text{ and } \varphi \in \alpha_i, \\
l_i \models \varphi \\
\Delta_\Sigma(l_1 \cdots l_n) \succeq \alpha_1 \cdots \alpha_m
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where $\alpha_i \subseteq \Sigma$ for all $1 \leq i \leq m$. 
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$l_1 \cdots l_n \models \alpha_1 \cdots \alpha_m \iff n = m$ and for $1 \leq i \leq n$ and $\varphi \in \alpha_i$,

$l_i \models \varphi \iff \Delta_\Sigma(l_1 \cdots l_n) \supseteq \alpha_1 \cdots \alpha_m$

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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* \(\varphi = \text{at}(\text{mary,post-office})\)

not quantized (Krifka)

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

\[\cdots \cdots \cdots\]

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<tr>
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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 $s \triangleright \text{true}^+$

and telic iff $s \triangleright \neg \varphi^+ \varphi$ for some $\varphi$.

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

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

durative strings in $L$ \quad $\text{dur}(L) = L\& \text{true}^+$

\[= \{s \in L \mid s \triangleright \text{true}^+\}\]

$\text{cul}(L, \varphi) = L\& \neg \varphi^+ \varphi \triangleright \neg \varphi^+ \varphi$
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cul($L, \varphi$) = $L \& [\neg \varphi \ | + \varphi] \triangleright [\neg \varphi \ | + \varphi]$
Dowty’s aspect hypothesis

\[
\text{statives} + \ DO, \ BECOME, \ CAUSE \ldots
\]

A rough event approximation from Rothstein 2004

- activities: \( \lambda e. (DO(\varphi))(e) \)
- achievements: \( \lambda e. (BECOME(\varphi))(e) \)
- accomplishments: \( \lambda e. \exists e'[ (DO(\varphi))(e') \land e = e' \sqcup S \ Cul(e)] \)

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statives + DO, BECOME, CAUSE . . .

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

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

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accomplishments $\lambda e. \exists e' [(DO(\varphi))(e') \land e = e' \sqcup S Cul(e)]$

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<tr>
<td>BECOME / cul</td>
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</tr>
<tr>
<td></td>
<td>−durative</td>
</tr>
<tr>
<td></td>
<td></td>
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</table>
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 $\lambda e. \exists e'[(\text{DO}(\varphi))(e') \land e = e' \sqcup S \text{Cul}(e)]$

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A minimal account

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<th>( \varphi )</th>
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</tr>
<tr>
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(1) \[ L = f f, r_f^* r_f = \text{iter}(f r_f) \]

(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) \[ \text{iter}(L) := (\text{least } Z \supseteq L) \ Z; L \subseteq Z \]
## A minimal account

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<tr>
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<td>$\text{dur}(L)$</td>
<td>$[f, f, r_f, r_f]$</td>
</tr>
<tr>
<td>Accomplishment</td>
<td>$\text{cul}(\text{dur}(L), \varphi)$</td>
<td>$[f, \neg \varphi, f, r_f, \neg \varphi, r_f, \varphi]$</td>
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(1) $L = [f, f, r_f]^* r_f = \text{iter}(f r_f)$

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

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(1) $L = f \mid f, r_f^* \mid r_f = \text{iter}(f \mid r_f)$

(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) $\text{iter}(L) := (\text{least } Z \supseteq L) \ Z; L \subseteq Z$
A minimal account

- **state** \( \varphi \)  
- **pointwise fluent achievement** \( \neg \varphi \) \( \varphi \)  
- **semelfactive activity** \( L \& \)  
- **accomplishment** \( \text{cul}(\text{dur}(L), \varphi) \)

\[
\begin{align*}
(1) \quad & L = \begin{array}{c|c|c}
\text{\( f \)} & \text{\( f, r_f \)} & \text{\( r_f \)} \\
\end{array} = \text{iter}(\begin{array}{c|c}
\text{\( f \)} & \text{\( r_f \)} \\
\end{array}) \\
(2) \quad & s\beta ; \alpha s' := s(\beta \cup \alpha)s' \\
(3) \quad & L; L' := \{s; s' \mid s \in L - \{\epsilon\} \text{ and } s' \in L' - \{\epsilon\}\} \\
(4) \quad & \text{iter}(L) := \text{(least } Z \supseteq L \text{) } Z; L \subseteq Z
\end{align*}
\]
A minimal account

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(1) $L = f \upharpoonright f, r_f \ast r_f = \text{iter}(f \upharpoonright r_f)$

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A minimal account

state \( \varphi \)

pointwise fluent

achievement \( \neg \varphi \) \( \varphi \)

\( \text{cul}(\square, \varphi) \)

semelfactive \( L \& \)

\( \text{f} \) \( \text{r}_f \)

activity \( \text{dur}(L) \)

\( \text{f} \) \( \text{f, r}_f \) \( \text{r}_f \)

accomplishment \( \text{cul}(\text{dur}(L), \varphi) \)

\( \text{f, } \neg \varphi \) \( \text{f, } \text{r}_f, \neg \varphi \) \( \text{r}_f, \varphi \)

1. \( L = \text{f} \) \( \text{f, r}_f \)^* \( \text{r}_f \) = \( \text{iter}(\text{f} \) \( \text{r}_f) \)

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. \( \text{iter}(L) := (\text{least } Z \supseteq L) \) \( Z; L \subseteq Z \)
Statives are segmented

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

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

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 $I' \models \varphi \iff I \cup I' \models \varphi$. 
Statives are segmented

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

(1)  
\[ \underbrace{\text{Ed slept \ from 3 to 6}}_{\varphi} \models \underbrace{\text{Ed slept \ from 3 to 5}}_{\varphi} \]

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

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

(2)  
\[ \text{Ed slept from 3 to 5pm, } \quad \text{Ed slept from 4 to 6pm} \]
\[ \models \text{Ed slept from 3 to 6pm} \]

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\[ I \models \varphi \text{ and } I' \models \varphi \iff I \cup I' \models \varphi. \]
Statives are segmented

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

(1) Ed slept from 3 to 6 \( \models \) Ed slept from 3 to 5

\( \varphi \)
\( I \)
\( \varphi \)
\( I' \)

for all intervals \( I \) and \( I' \),

\( I \models \varphi \) and \( I' \subseteq I \) implies \( I' \models \varphi \)

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

\( \models \) Ed slept from 3 to 6pm

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

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$\varphi$ 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,

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

Useful for an event described by \( \varphi \)

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

Identify an interval \( J \) with the fluent naming it

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

ccontra “φ-segment”

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

Fact. \( \varphi \circ \) is segmented if \( \varphi \) is whole
From segmented to whole fluents

\( \varphi \) is \textit{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 \( \varphi \)

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

Identify an interval \( J \) with the fluent naming it

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

contra “\( \varphi \)-segment”

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

\textbf{Fact.} \( \varphi_\circ \) is segmented if \( \varphi \) is whole
From segmented to whole fluents

\( \varphi \) is \textit{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 \( \varphi \)

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

Identify an interval \( J \) with the fluent naming it

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

contra “\( \varphi \)-segment”

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

\textbf{Fact.} \( \varphi \) is segmented if \( \varphi \) is whole
From segmented to whole fluents

\( \varphi \) 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 \( \varphi \)

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I \models \varphi \iff I \text{ is the time of a } \varphi\text{-event}
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contra "\( \varphi \)-segment"

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

**Fact.** \( \varphi_\circ \) is segmented if \( \varphi \) is whole
Imperfectives vs perfectives

\[
\begin{array}{ccc}
\text{whole} & \approx & \text{count} \\
\text{segmented} & \approx & \text{mass} \\
& & \approx \text{perfective} \\
& & \text{imperfective}
\end{array}
\]

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

\[
V \circ E, V \circ V
\]

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

\[
E \circ V, E \circ E
\]

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

For intervals \(E\) and \(V\),

\[
(\exists II) II \models E \circ E, V \circ E \iff V \text{ inside } E
\]
Imperfectives vs perfectives

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

\[ V_\circ | E, V_\circ | V_\circ \]

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

\[ E_\circ | V, E_\circ | E_\circ \]

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

For intervals \( E \) and \( V \),

\[ (\exists II) II \models E_\circ | E_\circ, V | E_\circ \iff V \text{ inside } E \]
Imperfectives vs perfectives

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

\[
V_0 \times E, V_0 \times V_0
\]

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

\[
E_0 \times V, E_0 \times E_0
\]

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

For intervals $E$ and $V$,

\[
(\exists \Pi) \Pi \models E_0 \times E_0, V \times E_0 \iff V \text{ inside } E
\]
Imperfectives vs perfectives

Whole \approx \text{count} \approx \text{perfective}

Segmented \approx \text{mass} \approx \text{imperfective}

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

\[
\begin{array}{c}
\text{V}_o & \text{E}, \text{V}_o & \text{V}_o \\
\end{array}
\]

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

\[
\begin{array}{c}
\text{E}_o & \text{V}, \text{E}_o & \text{E}_o \\
\end{array}
\]

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

For intervals E and V,

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

\( \varphi \) is *segmentable as* \( L \) if for all segs \( l_1 \cdots l_n \),

\[
\bigcup_{i=1}^{n} l_i \models \varphi \iff l_1 \cdots l_n \models L
\]

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

\[
\Pi \models L \iff (\exists s \in L) \ \Pi \models s.
\]

**Fact.** The following three conditions are equivalent.

(i) \( \varphi \) is segmented

(ii) \( \varphi \) is segmentable as

\[
\varphi^+ = \varphi + \varphi \varphi + \varphi \varphi \varphi + \cdots
\]

(iii) \( \varphi \) is segmentable as \( \varphi^+_0 \).
Segmenting the segmented

φ is segmentable as L if for all segs $l_1 \cdots l_n$,

$$\bigcup_{i=1}^{n} l_i \models \varphi \iff l_1 \cdots l_n \models L$$

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

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

**Fact.** The following three conditions are equivalent.

(i) φ is segmented

(ii) φ is segmentable as

$$\varphi^+ = \varphi + \varphi\varphi + \varphi\varphi\varphi + \cdots$$

(iii) φ is segmentable as $\varphi^+_o$. 
Segmenting the segmented

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

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

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

$$\models \models L \iff (\exists s \in L) \models s.$$  

**Fact.** The following three conditions are equivalent.

(i) $\varphi$ is segmented

(ii) $\varphi$ is segmentable as

$$\varphi^+ = \varphi + \varphi \varphi + \varphi \varphi \varphi + \cdots$$

(iii) $\varphi$ is segmentable as $\varphi_0^+$. 
Segmenting the segmented

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

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

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

$$\exists \models L \iff (\exists s \in L) \exists \models s.$$

**Fact.** The following three conditions are equivalent.

(i) $\varphi$ is segmented

(ii) $\varphi$ is segmentable as

$$\varphi^+ = \varphi + \varphi \varphi + \varphi \varphi \varphi + \cdots$$

(iii) $\varphi$ is segmentable as $\varphi^+$. 
Segmenting the segmented

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

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

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

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

**Fact.** The following three conditions are equivalent.

(i) $\varphi$ is segmented

(ii) $\varphi$ is segmentable as

$$\varphi^+ = \varphi + \varphi \varphi + \varphi \varphi \varphi + \cdots$$

(iii) $\varphi$ is segmentable as $\varphi_0^+$. 
Segmenting the whole

Fact. The following are equivalent.

(i) \( \varphi \) is whole
(ii) there is no seg \( \mathbb{I} \) such that \( \mathbb{I} \models \varphi \circ \varphi + \varphi \circ \varphi \)
(iii) \( \varphi \) is segmentable as

\[
\varphi, \neg\langle m \rangle \varphi, \neg\langle m \rangle \varphi + \varphi, \neg\langle m \rangle \varphi \varphi^* \varphi, \neg\langle m \rangle \varphi
\]

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

\[
\mathbb{I} m \mathbb{I}' \iff \mathbb{I} \cup \mathbb{I}' \in \text{lvI} \text{ and } \mathbb{I} < \mathbb{I}'
\]

\[
\mathbb{I} m_i \mathbb{I}' \iff \mathbb{I}' m \mathbb{I}
\]

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.
Segmenting the whole

**Fact.** The following are equivalent.

(i) \( \varphi \) is whole

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

(iii) \( \varphi \) is segmentable as

\[
\varphi_{\circ}, \neg\langle \text{mi} \rangle \varphi_{\circ}, \neg\langle \text{m} \rangle \varphi_{\circ} \quad + \quad \varphi_{\circ}, \neg\langle \text{mi} \rangle \varphi_{\circ} \quad \varphi_{\circ} \quad \ast \quad \varphi_{\circ}, \neg\langle \text{m} \rangle \varphi_{\circ}
\]

where \( \text{m} \) is meet and \( \text{mi} \) is its inverse

\[
\begin{align*}
I \text{ m } I' & \iff I \cup I' \in \text{lv} \text{ l and } I < I' \\
I \text{ mi } I' & \iff I' \text{ m } I
\end{align*}
\]

**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.
Fact. The following are equivalent.

(i) \( \varphi \) is whole

(ii) there is no seg \( I \) such that \( I \models \varphi \circ \varphi + \varphi \circ \varphi \)

(iii) \( \varphi \) is segmentable as

\[
\begin{align*}
\varphi, \neg\langle \text{mi} \rangle \varphi, \neg\langle \text{m} \rangle \varphi & \quad + \quad \varphi, \neg\langle \text{mi} \rangle \varphi \quad \varphi & \quad \ast \quad \varphi, \neg\langle \text{m} \rangle \varphi \\
\end{align*}
\]

where \( m \) is meet and \( \text{mi} \) is its inverse

\[
\begin{align*}
I \land m \land I' & \iff I \cup I' \in \text{lvI} \text{ and } I < I' \\
I \land \text{mi} \land I' & \iff I' \land m \land I \\
\end{align*}
\]

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.
Fact. The following are equivalent.

(i) $\varphi$ is whole
(ii) there is no seg $I$ such that $I \models \varphi \circ \varphi + \varphi \circ \varphi$
(iii) $\varphi$ is segmentable as $\varphi, \neg \langle mi \rangle \varphi, \neg \langle m \rangle \varphi$

where $m$ is meet and $mi$ is its inverse

\[
\begin{align*}
\varphi, \neg \langle mi \rangle \varphi, \neg \langle m \rangle \varphi & + \varphi, \neg \langle mi \rangle \varphi \varphi^* \varphi, \neg \langle m \rangle \varphi \\
\end{align*}
\]

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

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

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

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

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

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

Let

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

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

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

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

E.g. \[
\begin{array}{c}
\varphi \quad \Rightarrow \quad \varphi \\
\end{array}
= \{ \alpha_1 \cdots \alpha_n \mid \text{whenever } \varphi \in \alpha_i, \ \varphi \in \alpha_{i+1} \text{ for } 1 \leq i < n \} \]
Let

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

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

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

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

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

Let

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

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

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

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

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

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

Forces succeed unless opposed

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

Refine with forces

\[ \mathrm{cul}_f(L, \varphi) = L \& \neg \varphi^* \neg \varphi, f\varphi \varphi \]
\[ \mathrm{dur}_\uparrow(\varphi) = \uparrow \varphi, \uparrow \varphi, \uparrow \varphi \]
Pat stopped the car before it hit the tree.

Statives persist forward and backward unless forced otherwise

\[
\begin{align*}
\varphi & \Rightarrow \varphi + f\neg \varphi \\
\varphi & \Rightarrow \varphi + f\varphi
\end{align*}
\]

Forces succeed unless opposed

\[
\begin{align*}
f\varphi & \Rightarrow \varphi + f\neg \varphi
\end{align*}
\]

Refine with forces

\[
\begin{align*}
cul_f(L, \varphi) & = L\& \neg \varphi^* \neg \varphi, f\varphi | \varphi \\
dur_{\uparrow}(\varphi) & = \uparrow \varphi, \uparrow \varphi, \uparrow | \varphi
\end{align*}
\]
Pat stopped the car before it hit the tree.

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

Forces succeed unless opposed

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

Refine with forces

\[ \text{cul}_f(L, \varphi) = L \& (\neg \varphi \ast \neg \varphi, f\varphi | \varphi) \]
\[ \text{dur}_\uparrow(\varphi) = \uparrow \varphi | \uparrow \varphi, \varphi \uparrow | \varphi \uparrow \]
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.

Inertia and force constraints above are non-de defeasible.

Left open: forces at play and which win out ...
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 ...
Incremental change

Refine bivalent $\varphi$ with degrees $d$

$d\varphi : d \leq \varphi$-degree
$\varphi d : \varphi$-degree $\leq d$

$\downarrow \varphi : f \neg d\varphi$ (same for all $d$’s)

$\uparrow \varphi : fd\varphi$ (same for all $d$’s)

\[
\begin{align*}
\begin{array}{c|c|c|}
d\varphi & \Rightarrow & d\varphi + \downarrow \varphi \\
\hline
\end{array} \\
\begin{array}{c|c|c|}
d\varphi & \Rightarrow & d\varphi + \uparrow \varphi \\
\hline
\end{array} \\
\begin{array}{c|c|c|}
\uparrow \varphi, d\varphi & \Rightarrow & \neg \varphi d + \downarrow \varphi \\
\hline
\end{array} \\
\begin{array}{c|c|c|}
\varphi d & \Rightarrow & \varphi d + \uparrow \varphi \\
\hline
\end{array} \\
\begin{array}{c|c|c|}
\varphi d & \Rightarrow & \varphi d + \downarrow \varphi \\
\hline
\end{array} \\
\begin{array}{c|c|c|}
\downarrow \varphi, \varphi d & \Rightarrow & \neg d\varphi + \uparrow \varphi \\
\hline
\end{array}
\]
Incremental change

Refine bivalent $\varphi$ with degrees $d$

$d\varphi : \quad d \leq \varphi$-degree
$\varphi d : \quad \varphi$-degree $\leq d$

$\downarrow \varphi : \quad \neg d\varphi$ (same for all $d$’s)
$\uparrow \varphi : \quad f d\varphi$ (same for all $d$’s)

$$
\begin{array}{c}
\begin{array}{c}
d\varphi \\
\downarrow \varphi
\end{array}
\Rightarrow
\begin{array}{c}
d\varphi \\
\varphi d
\end{array}
\Rightarrow
\begin{array}{c}
\varphi d \\
\neg \varphi d
\end{array}
\Rightarrow
\begin{array}{c}
\uparrow \varphi, d\varphi \\
\uparrow \varphi, \varphi d
\end{array}
\Rightarrow
\begin{array}{c}
\neg \varphi d \\
\neg d\varphi
\end{array}
\Rightarrow
\begin{array}{c}
\neg \varphi d \\
\neg d\varphi
\end{array}
\end{array}
$$
Incremental change

Refine bivalent $\varphi$ with degrees $d$

\[
\begin{align*}
    d\varphi : & \quad d \leq \varphi\text{-degree} \\
    \varphi d : & \quad \varphi\text{-degree} \leq d \\
\end{align*}
\]

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

\[
\begin{align*}
    d\varphi & \implies d\varphi + \downarrow \varphi \\
    d\varphi & \implies d\varphi + \uparrow \varphi \\
    \uparrow \varphi, d\varphi & \implies \neg \varphi d + \downarrow \varphi \\
\end{align*}
\]
Incremental change

Refine bivalent \( \varphi \) with degrees \( d \)

\[
\begin{align*}
\text{d} \varphi : & \quad d \leq \varphi \text{-degree} \\
\varphi d : & \quad \varphi \text{-degree} \leq d
\end{align*}
\]

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

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

\[
\begin{align*}
\varphi \text{d} & \Rightarrow \quad \varphi \text{d} \uparrow \\
\varphi \text{d} & \Rightarrow \quad \varphi \text{d} \downarrow \\
\downarrow \varphi, \varphi \text{d} & \Rightarrow \quad \neg \varphi \text{d} \uparrow
\end{align*}
\]
Incremental change

Refine bivalent $\varphi$ with degrees $d$

- $d \varphi : d \leq \varphi$-degree
- $\varphi d : \varphi$-degree $\leq d$

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

\[\begin{align*}
  \varphi d & \quad \Rightarrow \quad \varphi d + \uparrow \varphi \\
  \varphi d & \quad \Rightarrow \quad \varphi d + \downarrow \varphi \\
  \downarrow \varphi, \varphi d & \quad \Rightarrow \quad \neg d \varphi + \uparrow \varphi
\end{align*}\]
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 $\varphi$-degree, $\varphi_{\uparrow} : (\exists d) \ d\varphi \land \text{Prev} \neg d\varphi$

\[
\text{dur}_{\uparrow}(\varphi) = \uparrow\varphi, \varphi_{\uparrow} + \varphi_{\uparrow} \quad (\text{bc length } \geq 3)
\]

force fluent $\uparrow\varphi$

\[
\text{cul}_f(L, \psi) = L \& \neg \psi^* \neg \psi, f\psi \psi
\]
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 \( \varphi \)-degree, \( \varphi_{↑} : (\exists d) \, d\varphi \land \text{Prev} \neg d\varphi \)

\[
\text{dur}_{↑}(\varphi) = \begin{array}{c}
\uparrow \varphi \\
\uparrow \varphi, \varphi_{↑} \\
\varphi_{↑}
\end{array} \quad (bc \text{ length } \geq 3)
\]

force fluent \( \uparrow \varphi \)

\[
\text{cul}_{f}(L, \psi) = L \& \begin{array}{c}
\neg \psi \\
\neg \psi, f\psi \\
\psi
\end{array}^{*}
\]
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 $\varphi$-degree, $\varphi \uparrow: (\exists d) \ d\varphi \land \text{Prev } \neg d\varphi$

$$\text{dur}_{\uparrow}(\varphi) = \begin{array}{c}
\uparrow\varphi
\end{array} \begin{array}{c}
\uparrow\varphi, \varphi_{\uparrow}
\end{array} \begin{array}{c}
\varphi_{\uparrow}
\end{array} \quad (bc \text{ length } \geq 3)$$

force fluent $\uparrow\varphi$

$$\text{cul}_{f}(L, \psi) = L \& \begin{array}{c}
\neg\psi
\end{array}^{*} \begin{array}{c}
\neg\psi, f\psi
\end{array} \begin{array}{c}
\psi
\end{array}$$
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.

\[ \text{[ = force, Copley & Harley 2012]} \]

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

$$\text{dur}_{\uparrow}(\varphi) = \uparrow \varphi \uparrow \varphi, \varphi \uparrow \varphi \uparrow \quad \text{(bc length } \geq 3)$$

force fluent $\uparrow \varphi$

\[ \text{cul}_{f}(L, \psi) = L \& \neg \psi \ast \neg \psi, f \psi \psi \]

\[ \]
Continuous change

soup cool in an hour

\[ x, d \leq sDg \quad d \leq sDg \quad \text{hour}(x), sDg < d \]

\[ \equiv_{bc} \quad \begin{array}{c}
\begin{array}{c}
d \leq sDg \\
sDg < d \\
\text{hour}(x)
\end{array}
\end{array} \]

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

soup cool for an hour

\[ x \begin{array}{c}
\begin{array}{c}
[\Box]sDg \downarrow \\
\text{hour}(x), [\Box]sDg \downarrow
\end{array}
\end{array} \]

\[ \equiv_{bc} \quad \begin{array}{c}
\begin{array}{c}
[\Box]sDg \downarrow \\
\text{hour}(x)
\end{array}
\end{array} \]

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

\[ I \models [\Box]\varphi \iff (\forall I' \subseteq I) \ I' \models \varphi \]
Continuous change

soup cool in an hour

\[ x, d \leq sDg \quad d \leq sDg \quad \text{hour}(x), sDg < d \]

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

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

soup cool for an hour

\[ x \ [\square]sDg \quad \text{hour}(x), [\square]sDg \]

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

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

\[ I \models [\square] \varphi \iff (\forall I' \subseteq I) \ I' \models \varphi \]
Continuous change

soup cool in an hour

\[ x, d \leq sDg \quad d \leq sDg \quad \text{hour}(x), sDg < d \]

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

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

soup cool for an hour

\[ x \quad [\square]sDg \quad \text{hour}(x), [\square]sDg \]

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

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

\[ I \models [\square] \varphi \iff (\forall I' \subseteq I) \ I' \models \varphi \]
Continuous change

soup cool in an hour

\[ x, d \leq sDg \quad d \leq sDg \quad \text{hour}(x), sDg < d \]

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

\[ l \models d \leq sDg \iff (\forall r \in l) \ d \leq sDg(r) \]

soup cool for an hour

\[ x \quad \square\lceil sDg \rceil \quad \text{hour}(x), \square\lceil sDg \rceil \]

\[ =_{bc} \quad \square\lceil sDg \rceil \quad \& \quad x \quad \uparrow \quad \text{hour}(x) \]

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

\[ l \models \square \varphi \iff (\forall l' \subseteq l) \ l' \models \varphi \]
Continuous change

soup cool in an hour

\[
\begin{array}{c|c|c}
    x, d \leq sDg & d \leq sDg & \text{hour}(x), sDg < d \\
\end{array}
\]

\[=_{bc}
\begin{array}{c|c}
    d \leq sDg & sDg < d \\
\end{array}
\]

\[\begin{array}{c}
x \quad \vdash \quad [\Downarrow]sDg \quad \text{hour}(x), [\Downarrow]sDg \\
\end{array}
\]

\[=_{bc}
\begin{array}{c}
[\Downarrow]sDg \quad \text{hour}(x) \\
\end{array}
\]

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

\[\vdash \Downarrow \varphi \iff (\forall I' \subseteq I) I' \vdash \varphi
\]
Continuous change

soup cool in an hour

\[ x, d \leq sDg \quad d \leq sDg \quad \text{hour}(x), sDg < d \]

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

\[ l \models d \leq sDg \iff (\forall r \in l) \ d \leq sDg(r) \]

soup cool for an hour

\[ x \ [\square]sDg_{\downarrow} \quad \text{hour}(x), [\square]sDg_{\downarrow} \]

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

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

\[ l \models [\square]\varphi \iff (\forall l' \subseteq l) \ l' \models \varphi \]
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
Addendum to: *No time without change*

No change unless observed

in a fluent $\varphi$ from a finite set $A$ fixing granularity $(\rho_A, b\mathcal{C})$

Add fluents for

- degrees (incremental change)
- forces (inertia)

No change (in inertial fluents) unless forced

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