Spatial Relations in Motion Predicates

- Topological Path Expressions
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- Topo-metric orientation Expressions
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Language Data

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  English, German, Russian, Swedish, Chinese
- Path construction languages
  Path information is encoded in matrix verb, while adjuncts specify manner of motion
  Modern Greek, Spanish, Japanese, Turkish, Hindi

Defining Motion (Talmy 1985)

(57) a. The *event* or situation involved in the change of location ;

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b. The object (construed as a point or region) that is undergoing movement (the *figure*);

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c. The region (or *path*) traversed through the motion;

Defining Motion (Talmy 1985)

(60) a. The *event* or situation involved in the change of location ;
b. The object (construed as a point or region) that is undergoing movement (the *figure*);
c. The region (or *path*) traversed through the motion;
d. A distinguished point or region of the path (the *ground*);

Defining Motion (Talmy 1985)

(61) a. The *event* or situation involved in the change of location ;
b. The object (construed as a point or region) that is undergoing movement (the *figure*);
c. The region (or *path*) traversed through the motion;
d. A distinguished point or region of the path (the *ground*);
e. The *manner* in which the change of location is carried out;

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(62) a. The *event* or situation involved in the change of location ;
b. The object (construed as a point or region) that is undergoing movement (the *figure*);
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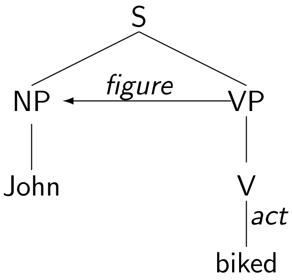
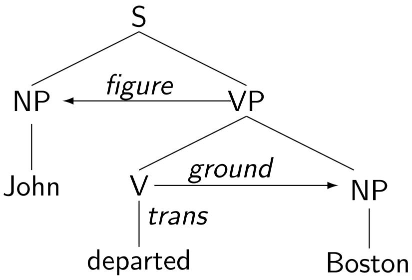
d. A distinguished point or region of the path (the *ground*);
e. The *manner* in which the change of location is carried out;
f. The *medium* through which the motion takes place.

(63)



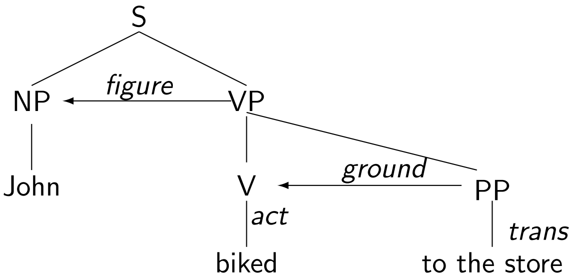
Path Predicates

(64)



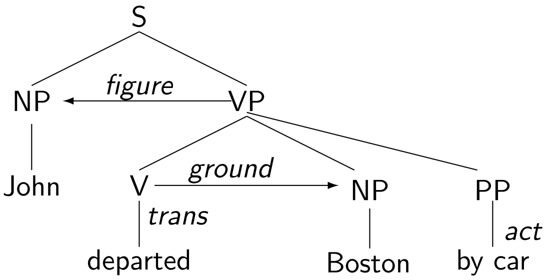
Manner with Path Adjunction

(65)



Path with Manner Adjunction

(66)



Path+manner Predicates (Talmy 2000) 1/2

(67) a. Isabel climbed for 15 minutes.

Path+manner Predicates (Talmy 2000) 1/2

(69) a. Isabel climbed for 15 minutes.
     b. Nicholas fell 100 meters.

Path+manner Predicates (Talmy 2000) 1/2

(71) a. Isabel climbed for 15 minutes.
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(72) a. There is an action (e) bringing about an iterated non-distinguished change of location;

Path+manner Predicates (Talmy 2000) 1/2

(73) a. Isabel climbed for 15 minutes.
b. Nicholas fell 100 meters.

(74) a. There is an action (e) bringing about an iterated non-distinguished change of location;
b. The figure undergoes this non-distinguished change of location;

Path+manner Predicates (Talmy 2000) 1/2

(75) a. Isabel climbed for 15 minutes.
b. Nicholas fell 100 meters.

(76) a. There is an action (e) bringing about an iterated non-distinguished change of location;
b. The figure undergoes this non-distinguished change of location;
c. The figure creates (leaves) a path by virtue of the motion.

Path+manner Predicates (Talmy 2000) 1/2

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d. The action (e) is performed in a certain manner.

Path+manner Predicates (Talmy 2000) 1/2

(79) a. Isabel climbed for 15 minutes.
b. Nicholas fell 100 meters.

(80) a. There is an action (e) bringing about an iterated non-distinguished change of location;
b. The figure undergoes this non-distinguished change of location;
c. The figure creates (leaves) a path by virtue of the motion.
d. The action (e) is performed in a certain manner.
e. The path is oriented in an identified or distinguished way.

Path+manner Predicates (Talmy 2000) 2/2

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John climbed to the summit.

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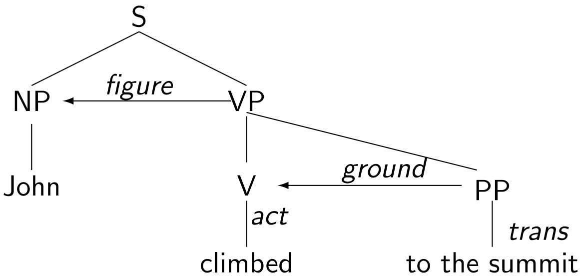
(85) **Manner of motion verb with path adjunct;**
John climbed to the summit.

(86) **Manner of motion verb with path argument;**
John climbed the mountain.

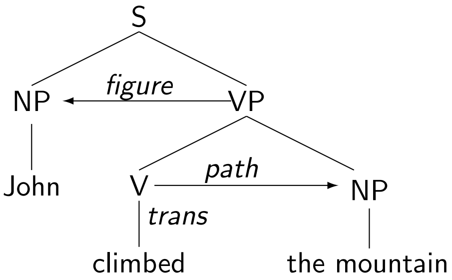
With Path Adjunct

(87)

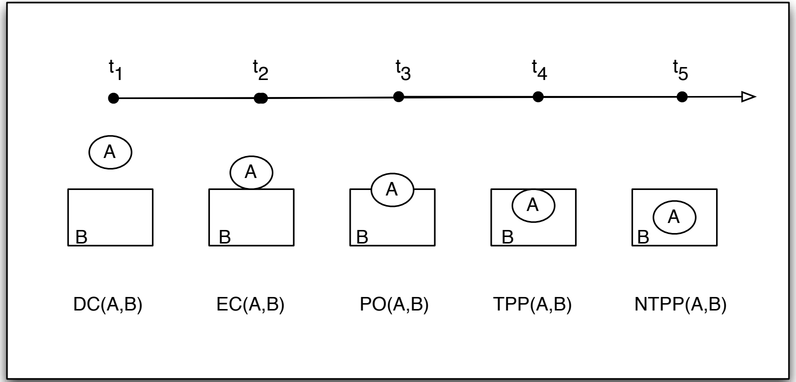


With Path Argument

(88)



Tracking Motion with RCC8: example of enter



Dynamic Interval Temporal Logic

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Capturing Motion as Change in Spatial Relations

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Capturing Motion as Change in Spatial Relations

Dynamic Interval Temporal Logic

- Path verbs designate a distinguished value in the change of location, from one state to another.
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- Manner of motion verbs iterate a change in location from state to state.
  The value is assigned and reassigned.

Directed Motion

(89) $\overset{x \neq y?}{\curvearrowleft}$ $\boxed{loc(z) = x}_{e_1} \xrightarrow{\nu} \boxed{loc(z) = y}_{e_2}$

Directed Motion

$$(91)\quad \boxed{loc(z) = x}_{e_1} \xrightarrow{\nu} \boxed{loc(z) = y}_{e_2}$$

$x{\neq}y?$

When this test references the ordinal values on a scale, C, this becomes a *directed* ν*-transition* ($\vec{\nu}$), e.g., $x \preccurlyeq y$, $x \succcurlyeq y$.

Directed Motion

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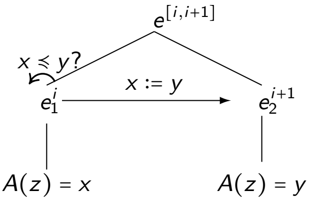
When this test references the ordinal values on a scale, C, this becomes a *directed ν-transition ($\vec{\nu}$)*, e.g., $x \preccurlyeq y$, $x \succcurlyeq y$.

(94) $\vec{\nu} =_{df} \overset{\overset{C?}{\curvearrowleft}}{e_i} \xrightarrow{\nu} e_{i+1}$

Directed Motion

(95)



Change and Directed Motion

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  $loc(x) := y; y := z$

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  $loc(x) := y; y := z$
- Directed motion introduces a dimension that is measured against:
  $d(b, y) < d(b, z)$
- Path verbs introduce a pair of tests:
  $\neg\phi? \ldots \phi?$

Change and the Trail it Leaves

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- For motion, this trail is the created object of the path p which the mover travels on;
- For creation predicates, this trail is the created object brought about by order-preserving transformations as executed in the directed process above.

Motion Leaving a Trail

(96) MOTION LEAVING A TRAIL:

a. Assign a value, y, to the location of the moving object, x.

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d. Then, reassign the value of y to z, where $y \neq z$

$$y := z, y \neq z$$

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$b := y$

c. Initiate a path p that is a list, starting at b;

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e. Add the reassigned value of y to path p;

$p := (p, z)$

f. Kleene iterate steps (d) and (e).

Quantifying the Resulting Trail

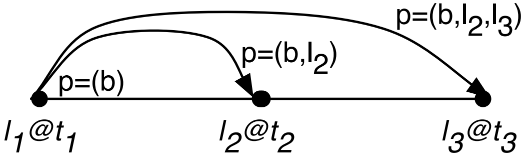

Figure: Directed Motion leaving a Trail

Quantifying the Resulting Trail

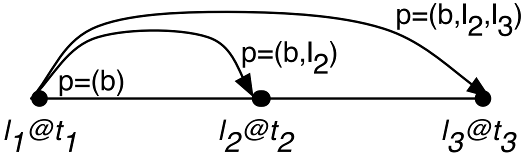

Figure: Directed Motion leaving a Trail

(103) a. The ball rolled 20 feet.
$\exists p \exists x[[roll(x,p) \wedge ball(x) \wedge length(p) = [20, foot]]$

Quantifying the Resulting Trail

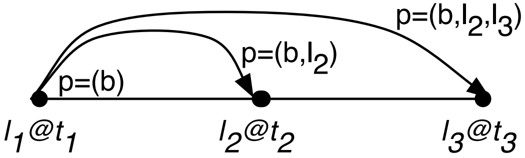

Figure: Directed Motion leaving a Trail

(104) a. The ball rolled 20 feet.

$\exists p \exists x[[roll(x,p) \wedge ball(x) \wedge length(p) = [20, foot]]$

b. John biked for 5 miles.

$\exists p[[bike(j,p) \wedge length(p) = [5, mile]]$

Generalizing the Path Metaphor

- We generalize the Path Metaphor to the analysis of the creation predicates.

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- We analyze creation predicates as predicates referencing two types of scales.

Type of Creation Verbs

(105) a. John wrote a letter.

Type of Creation Verbs

(107) a. John wrote a letter.
b. Sophie wrote for hours.

Type of Creation Verbs

(109) a. John wrote a letter.
b. Sophie wrote for hours.
c. Sophie wrote for an hour.

(110) a. John built a wooden bookcase.
b. *John built for weeks.

Linguistic View on Scales

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- For example, Rappaport Hovav 2008, Kennedy 2009 claim that "the scale which occurs with incremental theme verbs (extent scale) is not directly encoded in the verb, but rather provided by the referent of the direct object".
- This has lead them to the assumption that when nominal reference plays a role in measuring the change, V is not associated with a scale (denoting a non-scalar change).

Challenge for Scalar Models

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- What is the role of nominal reference in aspectual composition?

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How Language Encodes Scalar Information

Pustejovsky and Jezek 2012

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- Verbs may reference multiple scales.

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- Ratio scales: have equal distances between scale units as well as a zero value. Most measures encountered in daily discourse are based on a ratio scale.

Generalizing the Path Metaphor to Creation Predicates

Pustejovsky and Jezek 2012

- Use multiple scalar domains and the "change as program" metaphor proposed in Dynamic Interval Temporal Logic (DITL, Pustejovsky 2011, Pustejovsky & Moszkowicz 2011).

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- If the program is "change by assignment", Result refers to the record or trail of the change (e.g., the path of a walking, the stuff written in writing, etc.).

Scale shifting

Pustejovsky and Jezek 2012

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- Arguments (selected vs. non-selected, semantic typing, quantification).

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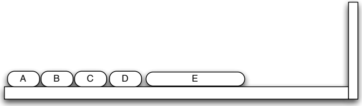
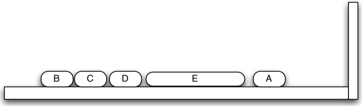
- An ordinal scale drives the incremental creation forward
- A nominal scale acts as a test for completion (telicity)

Incremental Theme and Parallel Scales



- Mary is building a table.
- Change is measured over an **ordinal scale**.
- Trail, τ is null.

Incremental Theme and Parallel Scales



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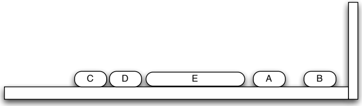
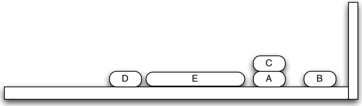
- Trail, $\tau = [A]$.

Incremental Theme and Parallel Scales



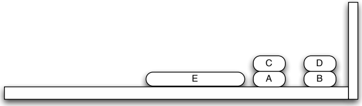
- Mary is building a table.
- Change is measured over an **ordinal scale**.
- Trail, $\tau = [A, B]$

Incremental Theme and Parallel Scales



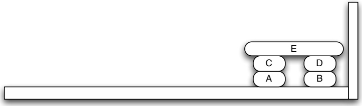
- Mary is building a table.
- Change is measured over an **ordinal scale**.
- Trail, $\tau = [A, B, C]$

Incremental Theme and Parallel Scales



- Mary is building a table.
- Change is measured over an **ordinal scale**.
- Trail, $\tau = [A, B, C, D]$

Incremental Theme and Parallel Scales



- Mary built a table.
- Change is measured over a **nominal scale**.
- Trail, $\tau = [A, B, C, D, E]$; $table(\tau)$.

(111) a. John built a table.
b. Mary walked to the store.

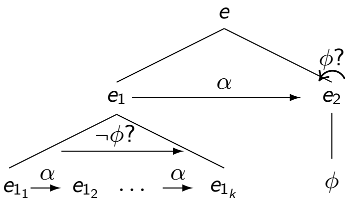
$build(x,z,y)$	$build(x,z,y)^+$	$build(x,z,y), y = v$
$\neg table(v)$		$table(v)$

$\langle i,j \rangle$

Table: Accomplishment: parallel tracks of changes

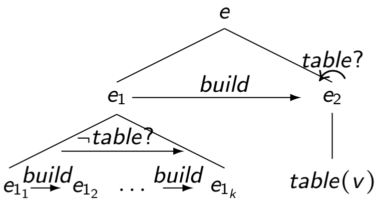
Dynamic Event Structure

(112)



Parallel Scales define an Accomplishment

(113)



Motivation

- We need to move beyond shallow semantic parsing to deeper semantic analysis of text;
- Understanding sentences requires more than identifying events and participants and giving them semantic role labels;
- It is essential to recognize temporal sequencing within the event and any changes in state that might have occurred.

VerbNet 1/2

Kipper et al. (2006)

- A hierarchical, domain-independent verb lexicon that groups verbs into classes based on similarities in their syntactic and semantic behavior (Schuler, 2005);
- Each class in VerbNet defines:
  - a set of member verbs;
  - semantic roles for the predicate-argument structure of these verbs;
  - selectional restrictions on the arguments; and
  - frames consisting of a syntactic description and a corresponding semantic representation.

VerbNet 2/2

Used extensively in:

- Linking lexical resources to ontologies (Brown et al. (2017));
- Semantic role labeling tasks (Shi and Mihalcea, 2005);
- Word sense disambiguation for verbs (Abend et al., 2008; Brown et al., 2014; Kawahara and Palmer, 2014);
- Inference-enabling tasks (Giuglea and Moschitti, 2006; Loper et al., 2007).

- But ...

VerbNet 2/2

Used extensively in:

- Linking lexical resources to ontologies (Brown et al. (2017));
- Semantic role labeling tasks (Shi and Mihalcea, 2005);
- Word sense disambiguation for verbs (Abend et al., 2008; Brown et al., 2014; Kawahara and Palmer, 2014);
- Inference-enabling tasks (Giuglea and Moschitti, 2006; Loper et al., 2007).

- But ... Semantic representations can be improved for consistency and greater expressiveness, e.g., linking semantic roles to predicative changes within the verb's subevents (Zaenen et al., 2008), typing over frames (Danlos et al. 2016);
- Generative Lexicon has long focused on articulating the semantics of event structure in language; more recent work identifies dynamic change associated with subevents (Pustejovsky, 1995, 2013).

VerbNet Classes - Run-51.3.2

MEMBERS

AMBLE (FN 1; WN 1; G 1)	GOOSE_STEP (WN 1)
AMBULATE (WN 1; G 1)	HIKE (FN 1; WN 2; G 1)
BACKPACK (WN 1)	HITCHHIKE (WN 1)
BOLT (FN 1, 2, 3, 4; WN 4; G 1)	HOPSCOTCH
BOUND (FN 1; WN 1; G 1)	JOUNCE
BREEZE	LIMP (FN 1; WN 1, 2)
BUSTLE (WN 1)	LOLLOP (WN 1)

ROLES

- AGENT [+ANIMATE]
- THEME [+ANIMATE | +MACHINE]
- LOCATION [+CONCRETE]

FRAMES

NP V

EXAMPLE	"The horse jumped."
SYNTAX	THEME V
SEMANTICS	MOTION(DURING(E), THEME)

NP V PP.LOCATION

EXAMPLE	"The horse jumped over the fence."
SYNTAX	THEME V {{+SPATIAL}} LOCATION
SEMANTICS	MOTION(DURING(E), THEME) PREP(E, THEME, LOCATION)

VerbNet Representations for Events

- Each VerbNet class contains semantic representations compatible with the members and syntactic frames of class;
- Representation makes use of semantic predicates:
    - **motion**
    - **perceive**
    - **cause**
- References semantic role participants and an event variable **E**.
- Some of these are meant to describe the participants during various stages of the event evoked by the syntactic frame.

(114) *The horse ran into the barn.*

NP V PP

Theme V Destination

motion(during(E), Theme)

path_rel(start(E), Theme, Initial_location, ch_of_loc, prep)

path_rel(during(E), Theme, Trajectory, ch_of_loc, prep)

path_rel(end(E), Theme, Destination, ch_of_loc, prep)

VerbNet Representations for Events: *run* 2/2

- The arguments of each predicate are represented using the semantic roles for the class;
- Participants mentioned in the syntax as well as those not expressed are accounted for in the semantics;
- The second component of the first **path_rel** semantic predicate above includes an unidentified Initial_location;
- Temporal sequencing is indicated with the second-order predicates **start**, **during**, and **end**;

(115) *John herded the sheep into the barn.*

NP V NP PP

cause(Agent, E)

Agent V Theme Destination

motion(during(E), Theme)

path_rel(start(E), Theme, Initial_location, ch_of_loc, prep)

path_rel(during(E), Theme, Trajectory, ch_of_loc, prep)

path_rel(end(E), Theme, Destination, ch_of_loc, prep)

Class-Internal Semantic Coherence 1/2

- Semantic representations capture generalizations about the semantic behavior of the class member as a group;
- For some classes (e.g., Battle-36.4), verbs are semantically coherent, *battle, skirmish, war*;

(116) *Sparta warred with Athens.*

NP V PP

Agent V {with} Co-Agent

social_interaction(during(E), Agent, Co-Agent)

conflict(during(E), Agent, Co-Agent)

possible_contact(during(E), Agent, Co-Agent)

manner(Hostile, Agent, Co-Agent)

Class-Internal Semantic Coherence 2/2

- Other classes (e.g., Other Change of State-45.4) contain widely diverse member verbs, *dry, gentrify, renew, whiten*;
- Semantics for this class ignores specific type of state change in order to be general enough for any verb in the class when used in a basic transitive sentence;

(117) *John dried the clothes.*

NP V NP

Agent V Patient

path_rel(start(E), Initial state, Patient, ch_of_state, prep)

path_rel(result(E), Result, Patient, ch_of_state, prep)

cause(Agent, E)

Impetus for Change 1/2

- VerbNet has expanded its coverage (Kipper et al., 2008);
- Class and verb components have improved in clarity and consistency (Bonial et al., 2011; Hwang, 2014);
- Zaenen et al. (2008) show VerbNet is unable to support some temporal and spatial inferencing tasks;
  - From *The diplomat left Bhagdad* you can't infer *The diplomat was in Bhagdad*;
  - For several motion classes, End(E) was given but not Start(E);
  - Some classes involving change of location of participants (e.g., gather, mix) did not include a motion predicate at all.

Impetus for Change 1/2

- Efforts to use VerbNet in human-computer interaction found that an enriched event representation would facilitate the interaction between the language parsing and the planning components of the system (Narayan-Chen et al., 2017);
- Attempts to use VerbNet in robotics show the need for:
  - a first-order representation;
  - more specific event causal relation, instead of **cause**(Agent,E);
  - more explicit temporal relations, over reified events rather than functional expressions over the matrix event, E.

(118) *Mary threw the ball.*

NP V NP

Agent V Theme

exert_force(during(E_0), Agent, Theme)

contact(end(E_0), Agent, Theme)

$\neg$ **contact**(during(E_1), Agent, Theme)

motion(during(E_1), Theme)

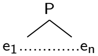
cause(Agent, E_1)

Classic GL Event Structure

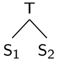
Pustejovsky (1995)

(119) a. STATE: a simple event, evaluated without referring to other events: *be sick*, *love*, *know*

b. PROCESS: a sequence of events identifying the same semantic expression: *run*, *push*, *drag*



c. TRANSITION: an event identifying a semantic expression evaluated with respect to its opposition: *give*, *open*; *build*:
Binary transition (achievement): $\neg\phi \in S_1$, and $\phi \in S_2$



Complex transition (accomplishment): $\neg\phi \in P$, and $\phi \in S$

First-Order Subevent Representations

(120) a. The destroyer is sinking a boat.
$\exists e_1 \exists y[\text{sink\_act}(e_1, \iota x(\text{destroyer}(x), y) \wedge \text{boat}(y)]$

b. The destroyer sank a boat.
$\exists e_1, e_2 \exists y[\text{sink\_act}(e_1, \iota x(\text{destroyer}(x), y) \wedge \text{boat}(y) \wedge$
$\text{sink\_result}(e_2, y) \wedge e_1 < e_2]$

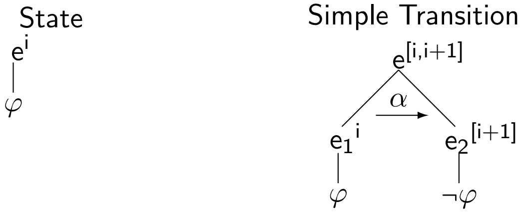
c. A boat sank.
$\exists e_2, e_1 \exists x, y[\text{sink\_result}(e_2, y) \wedge \text{boat}(y)$
$\wedge \text{sink\_act}(e_1, x, y) \wedge e_1 < e_2]$

- Event structure is integrated with first-order dynamic logic;
- Represents the attribute modified in the course of the event (the location of the moving entity, the extent of a created or destroyed entity, etc.);
- A complex event can be modeled as a sequence of frames;
- To adequately model events, the representation should track the change in the assignment of values to attributes in the course of the event.
- This includes making explicit any *predicative opposition* denoted by the verb:
  - *die* encodes going from $\neg dead(e_1, x)$ to $dead(e_2, x)$;
  - *arrive* encodes going from $\neg loc\_at(e_1, x, y)$ to $loc\_at(e_2, x, y)$.

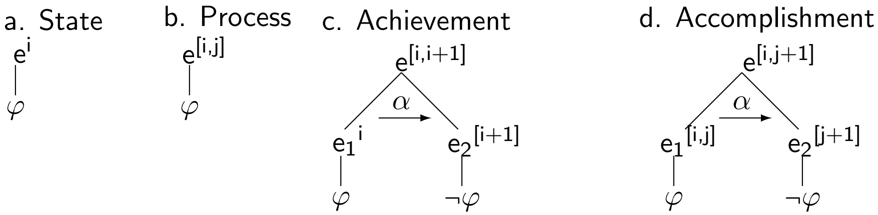
Dynamic Event Structure

Pustejovsky and Moszkowicz (2011)

Two Primitive Event Types



Derived Vendler Event Types



VN-GL - VerbNet with GL Event Structure

- Elimination of tripartite division of temporal span of the event, i.e., **Start**, **During**, **End**;
- Subevents introduced as first-order quantified individuals, $e_1, e_2, \ldots$;
- Temporal (Allen-like) relations can be employed for verb-class specific semantics:
  - **before**(e_2, e_3)
  - **meets**(e_2, e_3)
  - **while**(e_2, e_3)
- Causation is an event-relation: **cause**(e_1, e_2)

Before/After VerbNet Event Semantics - *jump*

VerbNet 3.3

(121) *The lion tamer jumped the lion through the hoop.*
NP V NP PP
Agent V Theme Trajectory
motion(during(E), Theme)
path_rel(start(E), Theme, ?Initial_location, ch_of_loc, prep)
path_rel(during(E), Theme, Trajectory, ch_of_loc, prep)
path_rel(end(E), Theme, ?Destination, ch_of_loc, prep)
cause(Agent, E)

VN-GL

(122) *The lion tamer jumped the lion through the hoop.*
has_location(e_1, Theme, ?Initial_Location)
do(e_2, Agent)
motion(e_3, Theme, Trajectory)
cause(e_2, e_3)
has_location(e_4, Theme, ?Destination)

VN-GL - Change of Location

- State predicate **has_location**, with event argument e_1; Theme argument for the object in motion; and an Initial_location argument;
- The motion predicate is underspecified as to the manner of motion in order to be applicable to all 97 verbs in the class;
- A final **has_location** predicate indicates the Destination of the Theme at the end of the event;
- Any uninstantiated roles in a frame are preceded by ?, such as Initial_location and Trajectory.

(123) *The rabbit hopped across the lawn.*

motion(during(E), Theme)

path_rel(start(E), Theme, ?Initial_location, ch_of_loc, prep)

path_rel(during(E), Theme, Trajectory, ch_of_loc, prep)

path_rel(end(E), Theme, ?Destination, ch_of_loc, prep)

(124) *The rabbit hopped across the lawn.*

has_location(e_1, Theme, ?Initial_Location)

motion(e_2, Theme, Trajectory)

has_location(e_3, Theme, ?Destination)

Causation in VN-GL 1/2

- Specifying causation: **cause**(e_1, e_2);
- Adding underspecified action: **do**.

(125) *The farmer herded the sheep into the meadow.*

has_location(e_1, Theme, ?Initial_Location)

do(e_2, Agent)

motion(e_3, Theme, ?Trajectory)

cause(e_2, e_3)

has_location(e_4, Theme, Destination)

Causation in VN-GL 2/2

- Specifying subtypes of causation: **exert_force** $\sqsubseteq$ **cause**;
- Adding new constraints: **contact**.

(126) *John pushed the plate to the edge of the table.*

has_location(e_1, Theme, ?Initial_Location)
cause(e_2, e_3)
contact(e_2, Agent, Theme)
exert_force(e_2, Agent, Theme)
motion(e_3, Theme, ?Trajectory)
has_location(e_4, Theme, Destination)

Comparing to VerbNet 3.3

(127) *John pushed the plate to the edge of the table.*

cause(Agent, E)

contact(during(E), Agent, Theme)

exert_force(during(E), Agent, Theme)

path_rel(start(E), Theme, ?Initial_location, ch_of_loc, prep)

path_rel(during(E), Theme, Trajectory, ch_of_loc, prep)

path_rel(end(E), Theme, ?Destination, ch_of_loc, prep)

motion(during(E), Theme)

Accompanied Motion - *guide*

(128) *Elena guided Frank through the building.*

has_location(e_1, Theme, ?Initial_Location)
has_location(e_2, Agent, ?Initial_Location)
motion(e_3, Agent, Trajectory)
motion(e_4, Theme, Trajectory)
has_location(e_5, Agent, ?Destination)
has_location(e_6, Theme, ?Destination)
while(e_3, e_4)

Change of State

Explicit Opposition Structure

(129) *John died.*

alive(e_1, Patient)

¬**alive**(e_2, Patient)

(130) *The balloon burst.*

has_state(e_1, Patient, Initial_State)

opposition(Initial_State, V_Result)

has_state(e_2, Patient, V_Result)

Result Verbs - *dry*

(131) *The clothes dried wrinkled.*

NP V AP

Theme V Result

has_state(e_1, Patient, Initial_State)

has_state(e_2, Patient, V_Result)

has_state(e_2, Patient, Result)

opposition(Initial_State, V_Result)

opposition(Initial_State, Result)

- Members have verb-specific features, either increase (e.g., *rise*), decrease (e.g., *fall*) or fluctuate (e.g., *vary*).
- Direction is a variable whose value can be found in context from the particular verb's verb-specific feature.

(132) *The price of oil rose by 500% from $5 to $25.*

has_val(e_1, Patient, Initial_State)

change_value(e_2, Direction, Extent, Attribute, Patient)

has_val(e_3, Patient, Result)

Results

- VerbNet is becoming one of the most important lexical resources in the community, providing syntactic behavior clustering, argument structure listing, semantic role labels, and linkages between these levels;
- The semantic representations for VerbNet classes are formally and expressively lacking in several respects, relating to the applicability of VerbNet resources to inferencing, HCI, human-robot communication, etc.;
- Generative Lexicon Event Structure can be easily integrated into the representation associated with verb classes, addressing these issues;
- Changes have been made automatically to 65 classes and manually checked for 41;
- Future work includes semantics for verbs of **creation**, **transformation**, **perception**, and **experience**.