Computational Models of Events

Lecture 4: Situational Grounding of Events

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Today's Outline

- Event Localization and Habitat Theory
- Event and object Embodiment: affordances, qualia
- Narratives for Objects: latent event structure

Putting Space in Language

- Space as Modality: "add an operator"
  $P_\alpha(meet(john, mary))$
  (Rescher and Garson, 1968, von Wright, 1979, Bennett, 1995, etc.)
- Method of Spatial Arguments: "add an l in a relation"
  $\exists l[meet(john, mary, l) \wedge in(l, \text{Boston})]$
  (Whitehead, 1929, Randell et al, 1992, Cohn et al, 1997, etc.)

"To each their own" (Vendler, 1967)

- Events are temporal entities:
  modified by temporal predicates
- Objects are spatial entities:
  modified by spatial predicates
- Temporal properties of objects are derivative
- Spatial properties of events are derivative

Locating Events (Davidson, 1967)

- An event is a first-order individual, e:

$$P(x_1, \ldots, x_n, e)$$

- We can identify the location of an event by a relation:

$$loc(e, l)$$

- $\exists e \exists x[smoke(j, e) \wedge in(e, x) \wedge bathroom(x)]$

(1) a. John sang in a field.
$\exists e \exists l[sing(j, e) \wedge in(e, l) \wedge field(l)]$
b. Mary ate her lunch under a bridge.
$\exists e \exists l[eat\_lunch(m, e) \wedge under(e, l) \wedge bridge(l)]$
c. The robbery happened behind a building.
$\exists e \exists l[robbery(e) \wedge behind(e, l) \wedge building(l)]$

Locating Events (Kim, 1973, 1975) 1/2

- An event is a structured object exemplifying a property (or *n*-adic relation), at a time, t:

$$[(x_1, \ldots, x_n, t), P^n]$$

- We can identify the location of an object in the event:

$$loc(x, t) = r_x$$

- For purposes of event identity, we can construe an event as:

$$[(x_1, \ldots, x_n, r_{x_1}, \ldots, r_{x_n}, t), P^n]$$

$$= [([x_i], [r_{x_i}], t), P^i]$$

Locating Events (Kim, 1973, 1975) 2/2

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- The event location, l_e, is supervenient on the object locations, $r_{x_1}, \ldots, r_{x_n}$.

Linguistic Approaches to Defining Paths

- Talmy (1985): Path as part of the Motion Event Frame
- Jackendoff (1983,1996): GO-function
- Langacker (1987): COS verbs as paths
- Goldberg (1995): way-construction introduces path
- Krifka (1998): Temporal Trace function
- Zwarts (2006): event shape: The trajectory associated with an event in space represented by a path.

Computing the Location of Motion Events

- Language encodes motion in Path and Manner constructions
- Path: change with distinguished location
- Manner: motion with no distinguished locations
- Manner and paths may compose.

Change and the Trail it Leaves

- The execution of a change in the value to an attribute $\mathcal{A}$ for an object x leaves a trail, τ.
- 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.

Formal Foundations for Spatial Representation

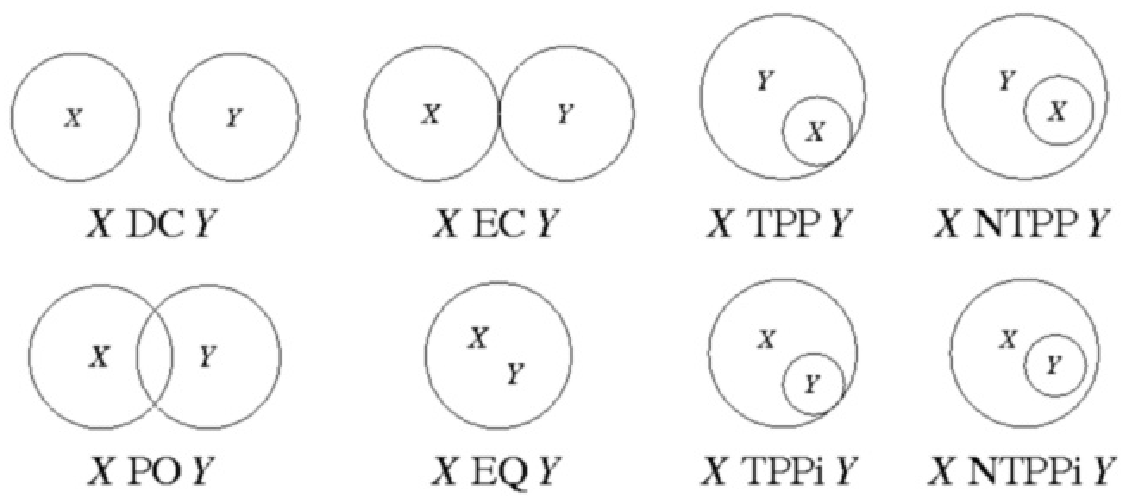
- Egenhofer (1991)
- Randell, Cui and Cohn (1992)
- Ligozat (1992)
- Freksa (1992)
- Galton (1993)
- Asher and Vieu (1995), Asher and Sablayrolles (1995)
- Gooday and Galton (1997)
- Muller (1998)

(Randell, Cui and Cohn, 1992)

RCC-8 Meretopology

1. DC(x, y) $\stackrel{def}{=}$ ∽ Connect(x, y).
2. Part(x, y) $\stackrel{def}{=}$ ∀z Connect(z, x) → Connect(z, y).
3. EQ(x, y) $\stackrel{def}{=}$ Part(x, y) ∧ Part(y, x).
4. Overlap(x, y) $\stackrel{def}{=}$ ∃z Part(z, x) ∧ Part(z, y).
5. EC(x, y) $\stackrel{def}{=}$ Connect(x, y) ∧ ∽ Overlap(x, y).
6. PO(x, y) $\stackrel{def}{=}$ Overlap(x, y) ∧ ∽ Part(x, y) ∧ ∽ Part(y, x).
7. PP(x, y) $\stackrel{def}{=}$ Part(x, y) ∧ not Part(y, x).
8. TPP(x, y) $\stackrel{def}{=}$ PP(x, y) ∧ ∃z[EC(z, x) ∧ EC(z, y)]
9. NTPP(x, y) $\stackrel{def}{=}$ PP(x, y) ∧ ∽ ∃z[EC(z, x) ∧ EC(z, y)].

Disconnected (DC): A and B do not touch each other.
Externally Connected (EC): A and B touch each other at their boundaries.
Partial Overlap (PO): A and B overlap each other in Euclidean space.
Equal (EQ): A and B occupy the exact same Euclidean space.
Tangential Proper Part (TPP): A is inside B and touches the boundary of B.
Non-tangential Proper Part (NTPP): A is inside B and does not touch the boundary of B.



Topological Meaning in RCC-8

a city <u>in</u> Sweden	$TPP(x, y) \vee NTPP(x, y)$
the coffee <u>in</u> the cup	$TPP(x, y)$
the spoon <u>in</u> the cup	$TPP(x', x) \wedge TPP(x', y)$
the bulb <u>in</u> the socket	$TPP(x', x) \wedge EC(x', y)$
the lamp <u>on</u> the table	$EC(x, y) \vee (EC(x, z) \wedge EC(z, y))$
the wrinkles <u>on</u> his forehead	$TPP(x, y)$
the house <u>on</u> the river	$EC(x, y)$
the boat <u>on</u> the river	$NTPP(x, y)$
the boy jumped <u>over</u> the wall	$DC(x, y)$
Joan nailed a board <u>over</u> the hole in the ceiling	$EC(x, y)$
he walked <u>around</u> the pool	$DC(x, y)$
he swam <u>around</u> the pool	$TPP(x, y)$

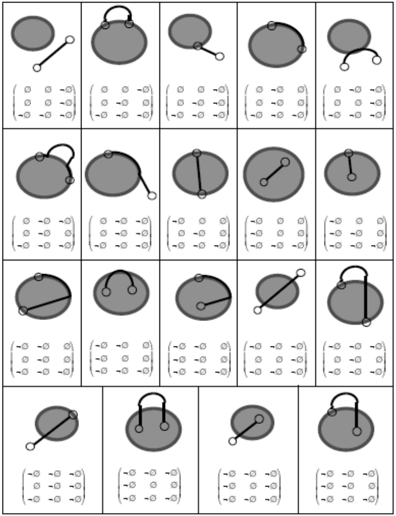
9-Intersection Model for Line-Region Relations Egenhofer and Herring (1991)

Characterized by the topological relations between two point sets, A and B, and the set intersections of their interior, boundary, and exterior:

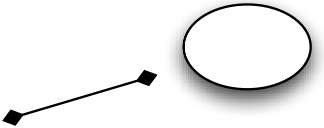
(i) Region interior: R^o
(ii) Region boundary: ∂R
(iii) Region exterior: R^-

$$I(A,B) = \begin{pmatrix} A^o \cap B^o & A^o \cap \partial B & A^o \cap B^- \\ \partial A \cap B^o & \partial A \cap \partial B & \partial A \cap B^- \\ A^- \cap B^o & A^- \cap \partial B & A^- \cap B^- \end{pmatrix}$$

Line-Region Intersection in 9IC

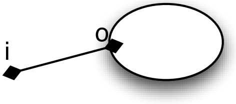


Line-Region Intersection



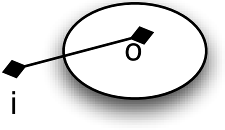
$$\begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 1 \\ 1 & 1 & 1 \end{pmatrix}^{(LR11)}$$

Line-Region Intersection



$$\begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}^{(LR13)}$$

Line-Region Intersection



$$\begin{pmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 1 \end{pmatrix}^{(LR75)}$$

Dynamic LR-Intersection Model

cf. Kurata and Egenhofer (2007): Directed Line-Region Intersection

Assume the intersection relations for a region, R, and a line, L, with two distinguished boundaries instead of one:

- left-boundary: $\partial_L L$,
- right-boundary: $\partial_R L$

Let the relation, I^e (e.g., intersection with distinguished endpoints) be defined as the intersection of a region, R, and a two-boundaried line, L, where :

$$I^e(L,R) = \begin{pmatrix} L^o \cap R^o & L^o \cap \partial R & L^o \cap R^- \\ \partial_L L \cap R^o & \partial_L L \cap \partial R & \partial_L L \cap R^- \\ \partial_R L \cap R^o & \partial_R L \cap \partial R & \partial_R L \cap R^- \\ L^- \cap R^o & L^- \cap \partial R & L^- \cap R^- \end{pmatrix}$$

Dynamic LR-Intersection Model

So $LR13$ has an I^e value represented as the following:

$$\begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 1 & 1 \end{pmatrix}^{(LR13^e)}$$

Direct LR Relations: Egenhofer and Herring (1991)

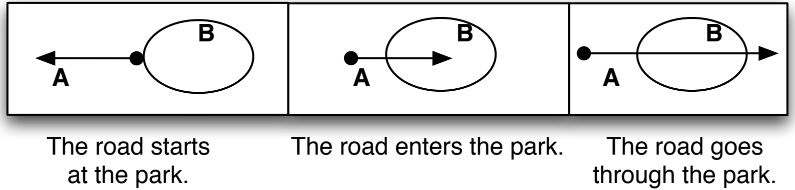


Figure: Directed Line-region examples

Interpreting Motion in the LR-Intersection Model

A specific matrix can be viewed as encoding the value of intersective relations from multiple states. These state values are overlays on top of each other.

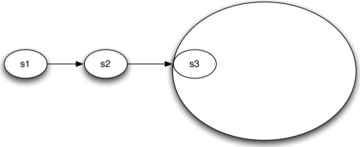
Motion can now be read off of the matrix as a Temporal Trace (e.g., ordering) of LR Intersection cell values:

We will model the "object in motion" as the topological transformations over the line, indexed through a temporal trace.

For example, $LR13^e$ encodes two path predicates:

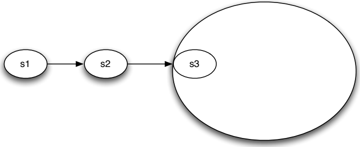
- $[\![land]\!]_{LR13^e}$:
  $\langle [\partial_L L \cap \partial R = 0]@s_1, [L^o \cap \partial R = 0]@s_2, [\partial_R L \cap \partial R = 1]@s_3 \rangle$;
- $[\![take\ off]\!]_{LR13^e}$:
  $\langle [\partial_R L \cap \partial R = 1]@s_1, [L^o \cap \partial R = 0]@s_2, [\partial_L L \cap \partial R = 0]@s_3 \rangle$;

Dynamic LR-Intersection Model: land



$$I^e(L,R) = \begin{pmatrix} L^o \cap R^o = 0 & L^o \cap \partial R = 0 & L^o \cap R^- = 1 \\ \partial_L L \cap R^o = 0 & \partial_L L \cap \partial R = 0 & \partial_L L \cap R^- = 1 \\ \partial_R L \cap R^o = 0 & \partial_R L \cap \partial R = 1 & \partial_R L \cap R^- = 0 \\ L^- \cap R^o = 1 & L^- \cap \partial R = 1 & L^- \cap R^- = 1 \end{pmatrix} \quad (LR13^e)$$

Dynamic LR-Intersection Model: land



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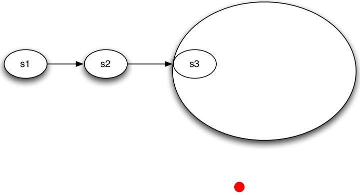
Dynamic LR-Intersection Model: land



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Dynamic LR-Intersection Model

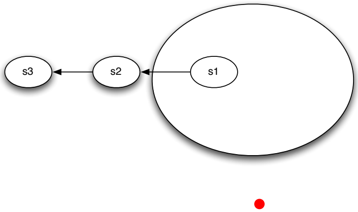
$LR75$ has an I^e value represented as the following:

$$\begin{pmatrix} 1 & 1 & 1 \\ 0 & 0 & 1 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{pmatrix}^{(LR75^e)}$$

$LR75^e$ encodes several path predicates:

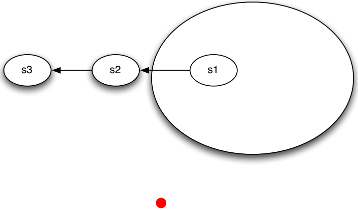
- $[[arrive]]_{LR13^e}$:
  $\langle [\partial_L L \cap \partial R = 0]@s_1, [L^o \cap \partial R = 0]@s_2, [\partial_R L \cap \partial R = 1]@s_3 \rangle$;
- $[[exit]]_{LR13^e}$:
  $\langle [\partial_R L \cap \partial R = 1]@s_1, [L^o \cap \partial R = 0]@s_2, [\partial_L L \cap \partial R = 0]@s_3 \rangle$;

Dynamic LR-Intersection Model: leave



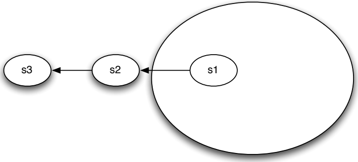
$$\begin{pmatrix} 1 & 1 & 1 \\ 0 & 0 & 1 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{pmatrix}^{(LR75^e)}$$

Dynamic LR-Intersection Model: leave



$$\begin{pmatrix} 1 & 1 & 1 \\ 0 & 0 & 1 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{pmatrix}^{(LR75^e)}$$

Dynamic LR-Intersection Model: leave



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$$\begin{pmatrix} 1 & 1 & 1 \\ 0 & 0 & 1 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{pmatrix}^{(LR75^e)}$$

Metric Extensions to Dynamic LR-Intersection Model

- Splitting: determines how the R and L boundaries, interiors, and exteriors are cut.

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- Metric relations capture predicates such as *approach*, *pull away from*.

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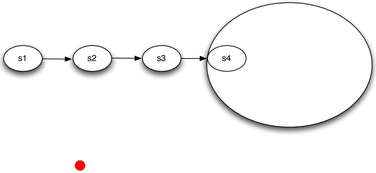
- Closeness: determines how far apart the region's boundary is from the line.
- Metric relations capture predicates such as *approach*, *pull away from*.

  a. The car approached the building.

  b. The car pulled away from the sidewalk.

Dynamic LR-Intersection Model: approach



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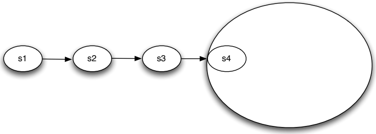
Dynamic LR-Intersection Model: approach



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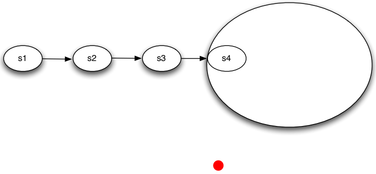
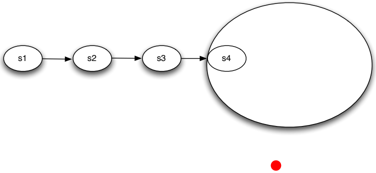
$$I^e(L,R) = \begin{pmatrix} L^o \cap R^o = 0 & L^o \cap \partial R = .3 & L^o \cap R^- = 1 \\ \partial_L L \cap R^o = 0 & \partial_L L \cap \partial R = 0 & \partial_L L \cap R^- = 1 \\ \partial_R L \cap R^o = 0 & \partial_R L \cap \partial R = 1 & \partial_R L \cap R^- = 0 \\ L^- \cap R^o = 1 & L^- \cap \partial R = 1 & L^- \cap R^- = 1 \end{pmatrix}^{(LR13^e)}$$

Dynamic LR-Intersection Model: approach



$$I^e(L,R) = \begin{pmatrix} L^o \cap R^o = 0 & L^o \cap \partial R = .6 & L^o \cap R^- = 1 \\ \partial_L L \cap R^o = 0 & \partial_L L \cap \partial R = 0 & \partial_L L \cap R^- = 1 \\ \partial_R L \cap R^o = 0 & \partial_R L \cap \partial R = 1 & \partial_R L \cap R^- = 0 \\ L^- \cap R^o = 1 & L^- \cap \partial R = 1 & L^- \cap R^- = 1 \end{pmatrix}^{(LR13^e)}$$



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Region Connection Calculus (RCC8)

(2) a. Disconnected (DC): A and B do not touch each other.
b. Externally Connected (EC): A and B touch each other at their boundaries.
c. Partial Overlap (PO): A and B overlap each other in Euclidean space.
d. Equal (EQ): A and B occupy the exact same Euclidean space.
e. Tangential Proper Part (TPP): A is inside B and touches the boundary of B.
f. Non-tangential Proper Part (NTPP): A is inside B and does not touch the boundary of B.
g. Tangential Proper Part (TPPi): B is inside A and touches the boundary of A.
h. Non-tangential Proper Part Inverse (NTPPi): B is inside A and does not touch the boundary of A.

Region Connection Calculus (RCC8)

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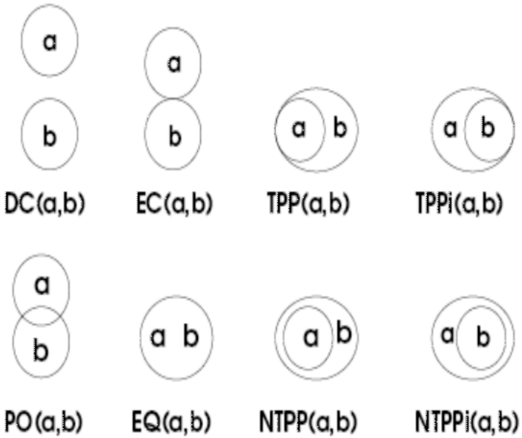

- These 8 JEPD relations describe topological relationships.

Examples of RCC8 Relations

(3) a. A touches B.
$EC(A, B)$
b. A does not touch B. /A is separated from B.
$DC(A, B)$

(4) a. The glass is on the table.
$[glass(G) \wedge table(T) \wedge EC(G, T)]$
b. The glass is not on the table.
$[glass(G) \wedge table(T) \wedge DC(G, T)]$

Problems with QSR Treatments

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- No compositional behavior for the semantics of language.
- Expressive coverage is weakly sufficient at best.
- Spatial relations in language are rarely just spatial.

Problems with RCC8 Relations

(5) a. The glass is on the table.
$[glass(G) \wedge table(T) \wedge EC(G,T) \wedge OVER(G,T)]$
b. The smoke alarm is on the ceiling.
$[alarm(A) \wedge ceiling(C) \wedge EC(A,C) \wedge UNDER(A,C)]$
c. The picture is on the wall.
$[picture(P) \wedge wall(W) \wedge EC(P,W) \wedge NEXT\_TO(P,W)]$

(6) a. The price tag is on the table (on the leg).
b. There's blue paint on the table (on the edge).

(7) a. The box is in the middle of the room.
$[box(B) \wedge room(R) \wedge NTPP(B,R)]$
b. Milk is the glass.
$[milk(M) \wedge glass(G) \wedge TPP(M,G)]$

Spatial Relations in Motion Predicates

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- Topological Path Expressions

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  arrive, leave, exit, land, take off

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  climb, descend

Spatial Relations in Motion Predicates

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  arrive, leave, exit, land, take off
- Orientation Path Expressions
  climb, descend
- Topo-metric Path Expressions

Spatial Relations in Motion Predicates

- Topological Path Expressions
  arrive, leave, exit, land, take off
- Orientation Path Expressions
  climb, descend
- Topo-metric Path Expressions
  approach, near, distance oneself

Spatial Relations in Motion Predicates

- Topological Path Expressions
  arrive, leave, exit, land, take off
- Orientation Path Expressions
  climb, descend
- Topo-metric Path Expressions
  approach, near, distance oneself
- Topo-metric orientation Expressions

Spatial Relations in Motion Predicates

- Topological Path Expressions
  arrive, leave, exit, land, take off
- Orientation Path Expressions
  climb, descend
- Topo-metric Path Expressions
  approach, near, distance oneself
- Topo-metric orientation Expressions
  just below, just above

RCC8 Decomposition of enter (Galton, 2000)

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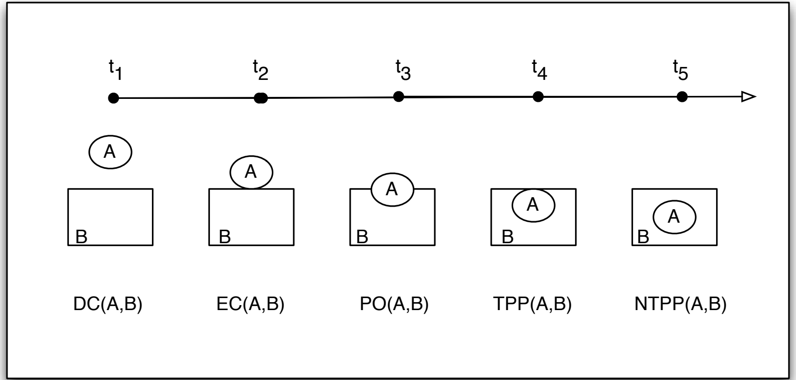

Generalizing the Path Metaphor to Locate Events

- Pustejovsky and Moszkowicz (2011): Manner verbs assume a change of location while making no explicit mention of a distinguished place. Path verbs can be identified as transitions, while manner-of-motion verbs can be seen as processes.
- a process "leaves a trail" as it is executed.
- verbs such as *walk* or *run*, this trail is the created object of the path which the mover traverses.
- the path is a program variable, $\hat{p}$, to the motion verb, dynamically creating the trail as an 'initiated" object from the resource locations, z.
- **move**: $e_N \rightarrow (e_A \rightharpoonup (e_N \rightarrow s \times s))$
- $\lambda z \lambda_{\rightharpoonup} \hat{p} \lambda x[walk(x, z, \hat{p})]$

Event Locus and Spatial Aspect 1/4

- Encoding locations is generally not part of the grammatical system of a language (cf. Ritter and Wiltschko, 2005, Deal, 2008)
- Locating an event in the spatial domain is referential (except for deictic spatial morphology).
- We will distinguish between an event locus and its spatial aspect.

Event Locus and Spatial Aspect 2/4

- l_e: Event Locus: similar to Event Time in Reichenbach.
  it is a referential partition over the Spatial Domain, $\mathcal{D}_{\mathcal{S}}$.
  John walked.
- l_r: Spatial Aspect: a binary partitioning relative to this first partition. Similar to Reference Time.

Event Locus and Spatial Aspect 3/4

Sources of Spatial Aspect in Motion Verbs:

- ANALYTIC ASPECT: verb selects a spatial argument;
  Mary left *the room*.
  John entered *the hall*.
- SYNTHETIC ASPECT: verb is modified through PP adjunction;
  Mary swam *in the pool*.
  John walked *to the corner*.

Event Locus and Spatial Aspect 4/4

- Simple Locus: $l_e = l_r$.
  John **walked**$_{l_e, l_r}$.
- Relative Aspect: $l_e <_d l_r$.
  John **walked**$_{l_e}$ under the tree$_{l_r}$.
- Embedded Aspect: $l_e \subseteq l_r$.
  John **walked**$_{l_e}$ in the building$_{l_r}$.
- Completive Aspect: $\mathbf{EC}(l_e, l_r)$, $\mathbf{end}(l_r, \hat{p})$.
  John **arrived**$_{l_e}$ home$_{l_r}$.
  John **walked**$_{l_e}$ to the park$_{l_r}$
- Ingressive Aspect: $\mathbf{EC}(l_r, l_e)$, $\mathbf{begin}(l_r, \hat{p})$.
  John **walked**$_{l_e}$ from the park$_{l_r}$.

Event Localization

- the dynamic structure of the event
- its semantic type; and
- the specific role that the participants play in the event.

Event Model Constituents

- Object Model: that aspect of the event involving change
- Action Model: that aspect of the event involving causation

Event Localization

- r_{x_i}: The Kimian spatial extent of an object, x_i;
- $\hat{p}$: The path created by the motion in e;
- R_e: an embedding space (ES) for e, defined as a region containing $\hat{p}$ and r_{x_i} in a specific configuration, the convex hull of r_{x_i} through $\hat{p}$, $Conv(\hat{p} \otimes r_{x_i})$
- l_e, the event locus: the minimum embedding space for e.
- Where μ can be defined as: $\forall e \forall R_e \forall \mu [[ES(R_e, e) \wedge Min(\mu, R_e)] \leftrightarrow [\mu \subseteq R_e \wedge \forall y[y \subseteq R_e \rightarrow \mu \subseteq y]]]$.
- l_a, spatial aspect: a region r, $r \subseteq R_e$, identified relative to l_e.

Constructing the Convex Hull in Space

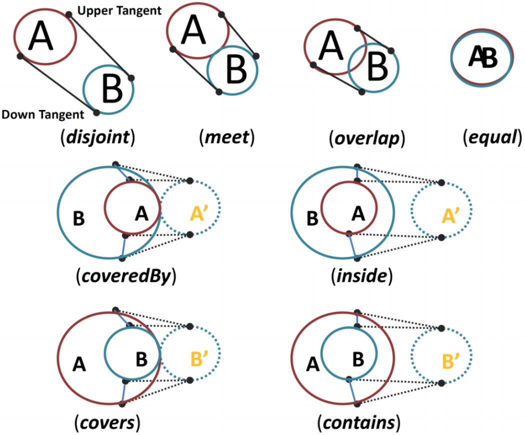

Figure 2. The eight topological relations between two regions in $\mathbb{R}^2$ with their merged convex hull representations.

Causatives and where they are located 1/2

- Atelic Relative Aspect: $l_e <_d l_r$.
  The storm **approached**$_{l_e}$ the shore$_{l_r}$.
- Embedded Aspect with event agent: $l_e \subseteq l_r$.
  The storm **destroyed**$_{l_e}$ the boat in the harbor$_{l_r}$.

The locus is not supervenient on the entire object localization of the causing argument (the storm), but of the local effects of this event as defined in the object model: further, the locus is restricted to within the harbor, $l_e \subseteq l_r$, where l_r is the harbor.

Causatives and where they are located 2/2

- The sun killed the grass on the lawn.
- The wind broke the glass.

It appears that the effects of distal causation are computed locally (through a sort of transitivity operation), leaving the locus of the event to be proximate to the resulting state.

Perception Predicates

- John saw an eagle in his backyard.
- Mary heard an alarm down the street.

Following Higginbotham 1983, Pustejovsky 1995, such verbs select for event complements. This introduces the problem of identifying two event distinct loci in a perception report.

Latent Event Structure

- Atomic Object Structure:
  Formal Quale (objects expressed as basic nominal types)
- Subatomic Object Structure:
  Constitutive Quale (mereotopological structure of objects)
- Object Event Structure:
  Telic and Agentive Qualia structure (origin and functions associated with an object)
- Macro Object Structure:
  habitats, object frames, embedding object structures