Qualitative Spatio-Temporal Knowledge Graphs

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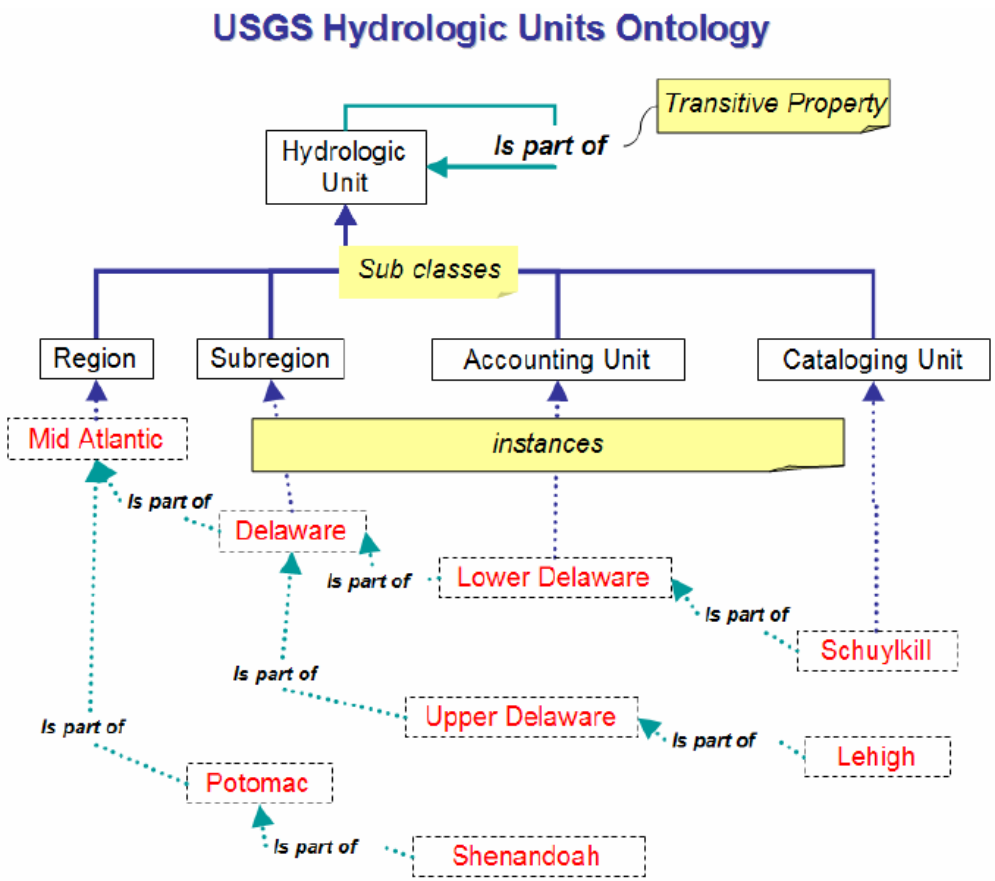
Two "flavors" of Artificial Intelligence: Subsymbolic versus Symbolic Representations

- Subsymbolic: Machine Learning, Neural Networks, Foundation Models
  - Very popular with non-experts, journalists, social media in general right now
  - Currently high economic relevance
  - Big progress in the last 15 years
  - Excellent, amazing performance BUT
  - Black box with behaviour hard to predict
  - Weak in longer reasoning chains, frequent incorrect reasoning results
- Symbolic: Logical Calculi, Ontologies, Formal Models of Commensense Knowledge, QSTR
  - very long and correct reasoning chains: but often exponential resource demand
  - Strong success about formalising science (e.g. life-science) and mathematics.
  - Recent good progress known only to experts

Ontologies for Semantic Integration of Data Bases

- Ontologies are shared conceptualisations.
- Formal ontologies can guide data integration.
- Semantic Web for Earth and Environmental Terminology (SWEET)
- A new term for Ontologies is Knowledge Graphs
- Knowledge Graphs will play a key role in making LLMs more usable



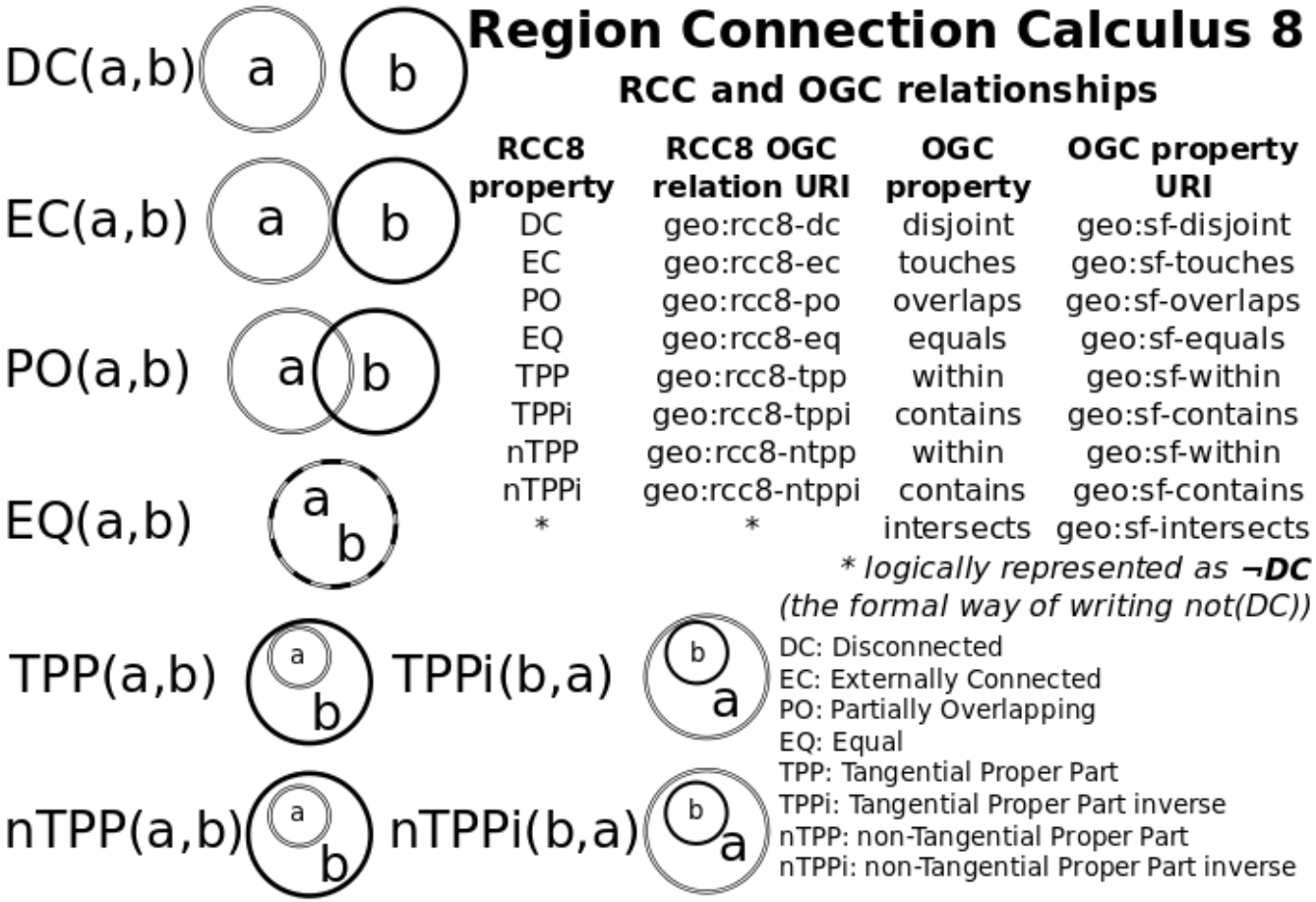
Adding spatial relations to an ontology

A formal ontology uses a logic-based representation language. The following example uses description logic which is functionally equivalent to the Web Ontology Language (OWL):

$$
\begin{aligned}
\mathit{River} &\sqsubseteq \exists \mathit{flowsInto}.(\mathit{River} \sqcup \mathit{Sea} \sqcup \mathit{Lake}) \\
\mathit{River} &\sqsubseteq \exists \mathit{spatiallyAdjacentTo}.\mathit{RiverBank} \\
\mathit{RiverStrech} &\sqsubseteq \exists \mathit{spatiallyOverlaps}.\mathit{RiverMouth}
\end{aligned}
$$

My research focus at the University of Maine was to make spatial relations available for such logic-based representations.

RCC-8 relations



Region Connection Calculus 8

RCC and OGC relationships

RCC8 property	RCC8 OGC relation URI	OGC property	OGC property URI
DC	geo:rcc8-dc	disjoint	geo:sf-disjoint
EC	geo:rcc8-ec	touches	geo:sf-touches
PO	geo:rcc8-po	overlaps	geo:sf-overlaps
EQ	geo:rcc8-eq	equals	geo:sf-equals
TPP	geo:rcc8-tpp	within	geo:sf-within
TPPi	geo:rcc8-tppi	contains	geo:sf-contains
nTPP	geo:rcc8-ntpp	within	geo:sf-within
nTPPi	geo:rcc8-ntppi	contains	geo:sf-contains
*	*	intersects	geo:sf-intersects

** logically represented as **¬DC***
(the formal way of writing not(DC))

DC: Disconnected
EC: Externally Connected
PO: Partially Overlapping
EQ: Equal
TPP: Tangential Proper Part
TPPi: Tangential Proper Part inverse
nTPP: non-Tangential Proper Part
nTPPi: non-Tangential Proper Part inverse

From the river example **spatiallyAdjacentTo**, **spatiallyOverlaps** can be expressed with RCC-8.

QSR: Qualitative Spatial Representations (and Reasoning)

- abstract descriptions
- describing concepts and their relations not just instance-based
- topology alone is not sufficent
- adding direction, distance, qualitative shape, time
- able to express underdetermined knowledge

Reasoning: RCC-8 and Consistency

It is relatively easy to construct examples of ontologies based on the RCC-8 relations that are consistent according to OWL semantics, but inconsistent according to RCC-8, for example:

$$
\begin{aligned}
A &\sqsubseteq \exists \mathit{spatiallyDisjoint}.B \\
C &\sqsubseteq \exists \mathit{spatiallyPartOf}.A \\
C &\sqsubseteq \exists \mathit{spatiallyOverLaps}.B
\end{aligned}
$$

Spatial reasoning decides consistency of a set of statements. Also implicit knowledge can be made explicit by deductive reasoning.

Spatial Reasoning with Composition Table and Algebraic Closure

$R1(a,b)$ \ $R2(b,c)$	DC	EC	PO	TPP	NTPP	TPPi	NTPPi	EQ
DC	no.info	DR,PO,PP	DR,PO,PP	DR,PO,PP	DR,PO,PP	DC	DC	DC
EC	DR,PO,PPi	DR,PO TPP,TPi	DR,PO,PP	EC,PO,PP	PO,PP	DR	DC	EC
PO	DR,PO,PPi	DR,PO,PPi	no.info	PO,PP	PO,PP	DR,PO,PPi	DR,PO PPi	PO
TPP	DC	DR	DR,PO,PP	PP	NTPP	DR,PO TPP,TPi	DR,PO PPi	TPP
NTPP	DC	DC	DR,PO,PP	NTPP	NTPP	DR,PO,PP	no.info	NTPP
TPPi	DR,PO,PPi	EC,PO,PPi	PO,PPi	PO,TPP,TPi	PO,PP	PPi	NTPPi	TPPi
NTPPi	DR,PO,PPi	PO,PPi	PO,PPi	PO,PPi	O	NTPPi	NTPPi	NTPPi
EQ	DC	EC	PO	TPP	NTPP	TPPi	NTPPi	EQ

The algebraic closure algorithm applies the information from the composition table to the relations between three enities recursively over all triples until a fixpoint is reached.

Spatial and Temporal Reasoning Calculi

- Time: Allens Interval Calculus, INDU, Point Algebra
- Mereotopology: RCC5, RCC8, RCC23, 4-intersection, 9-intersection, Closed Disk Algebra, MC-4,
- Absolute orientation: Cardinal direction calculus, Star Algebra, rectangle calculus, RCD,
- Relative Orientation - intrinsic reference system: FlipFlop, LR, DRAfp, OPRAm,
- Relative Orientierung - extrinsic reference system: Single Cross, Double Cross, TPCC, CYC-t,
- Trajektories: QTC-B11, QTC-B21, QTC-B12, QTC-B22, QTC-C21, QTC-C22, QTC-N

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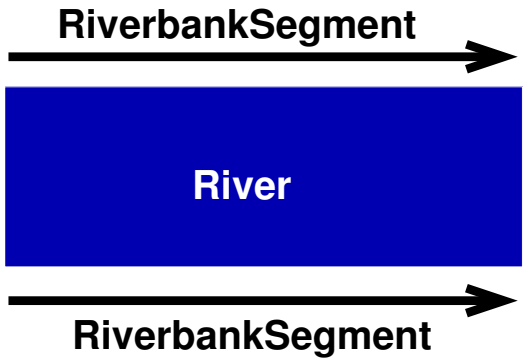
Let's have a look at DRAfp [Moratz et. al. 2000], [Moratz et. al. 2011]

Oriented Straight Line Segments (Dipoles)

Natural objects

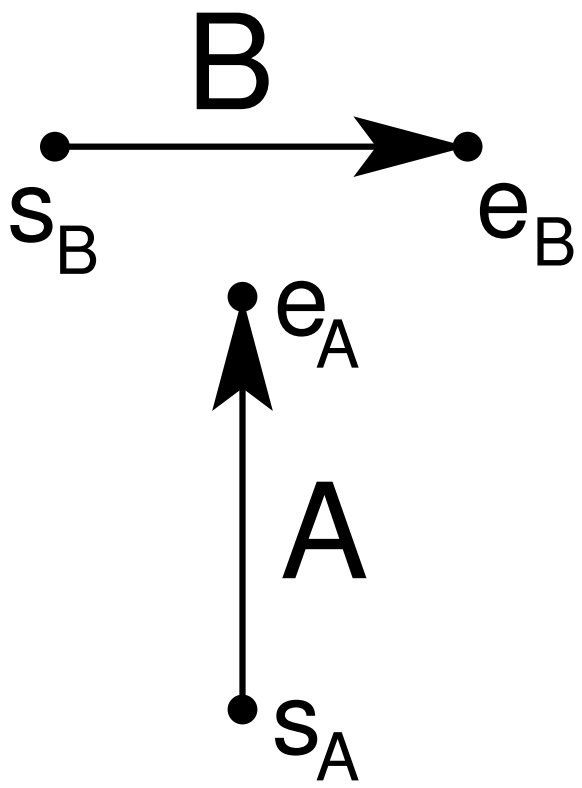
- are extended.
- often have an intrinsic direction.

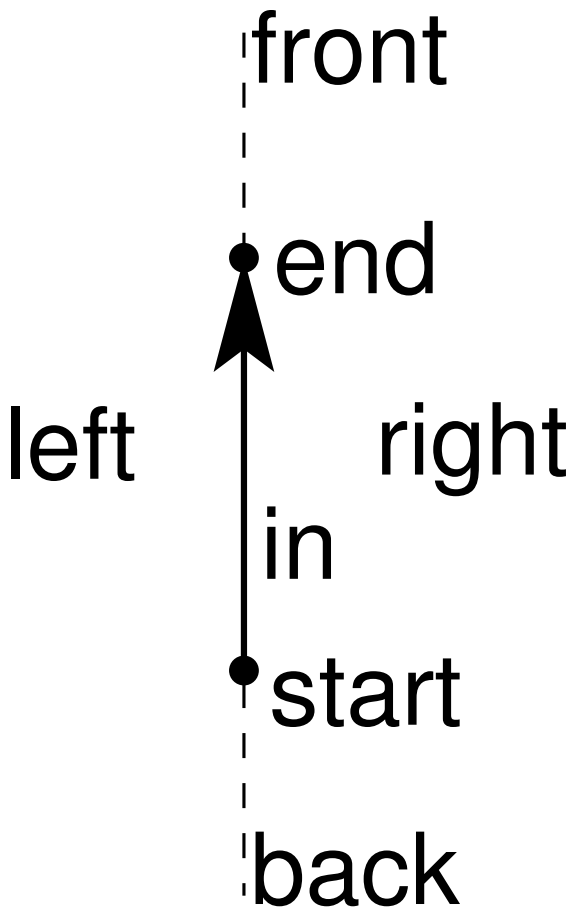
Oriented line segments are the simplest objects with these properties.



$$\mathit{RiverbankSegment} \sqsubseteq \exists \mathit{spatiallyParallelTo}.\mathit{RiverbankSegment}$$

Qualitatve Spatial Relations between two Dipoles





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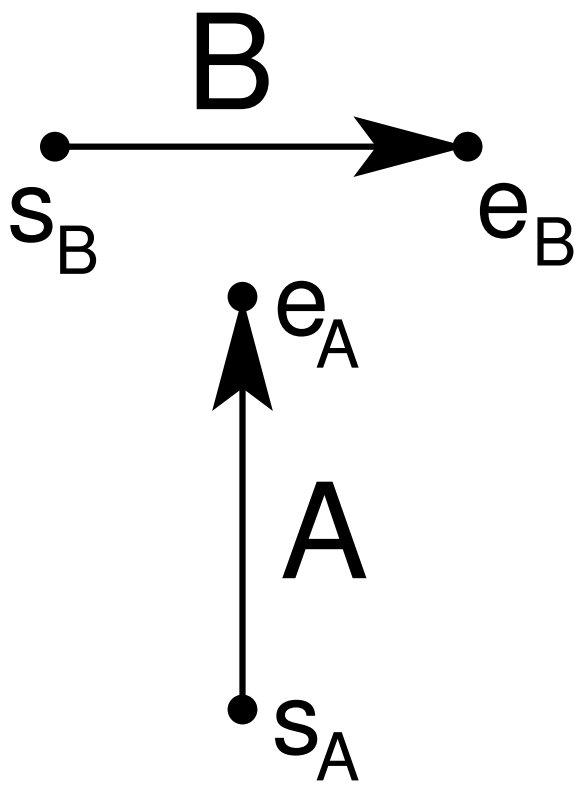

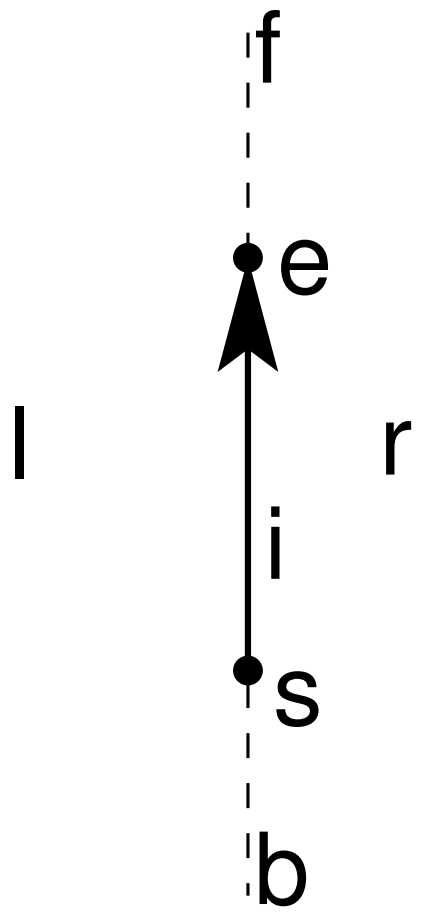

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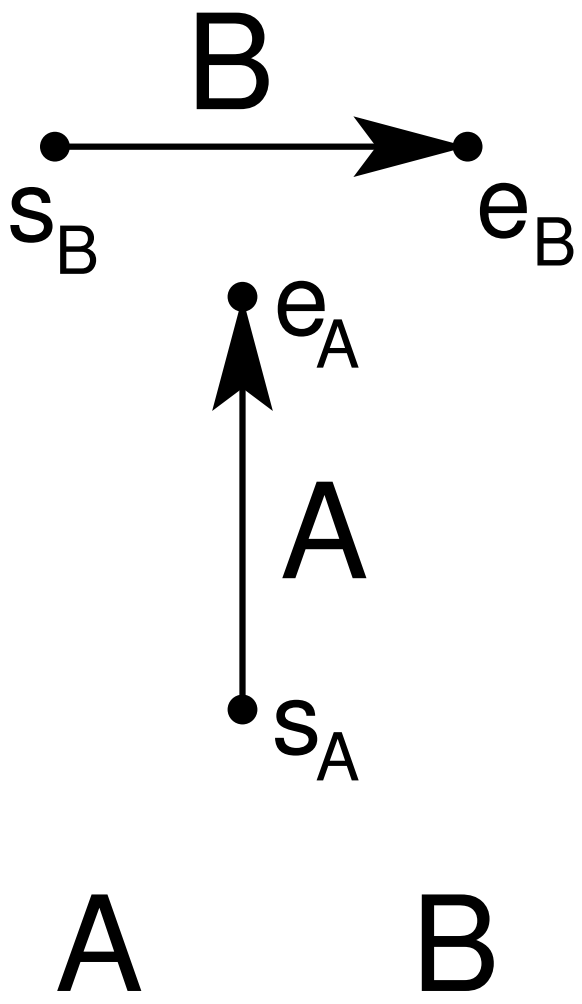

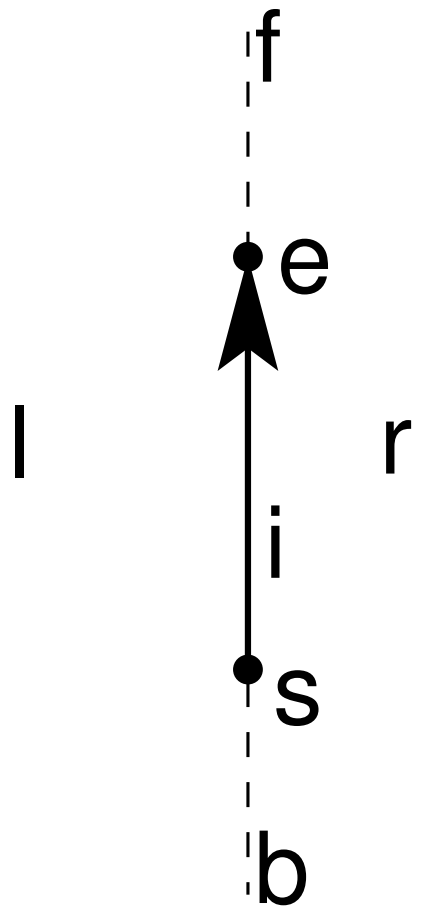

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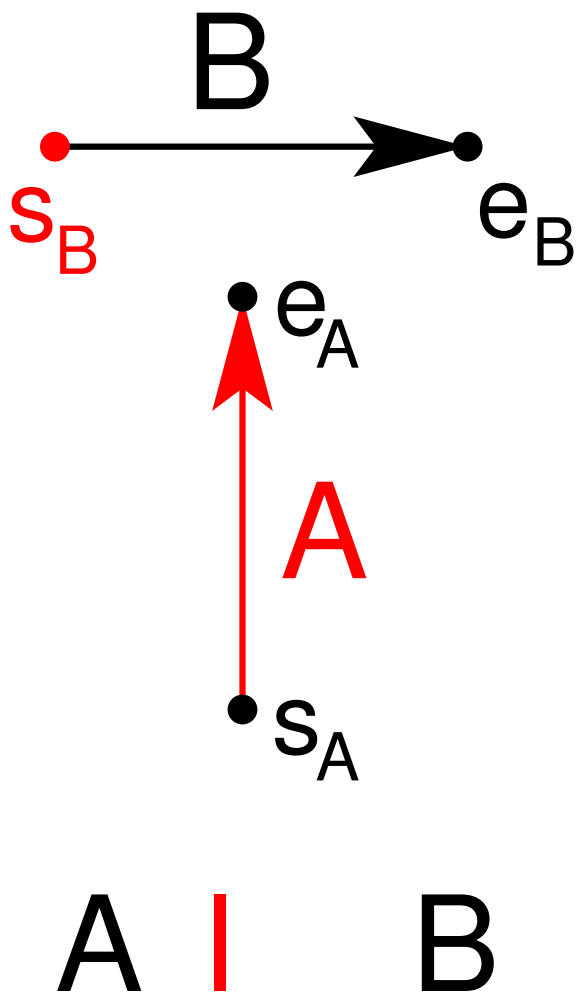

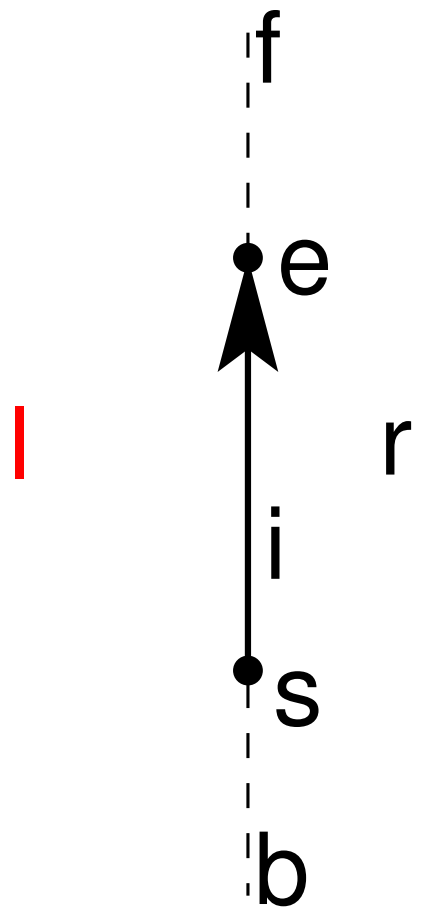

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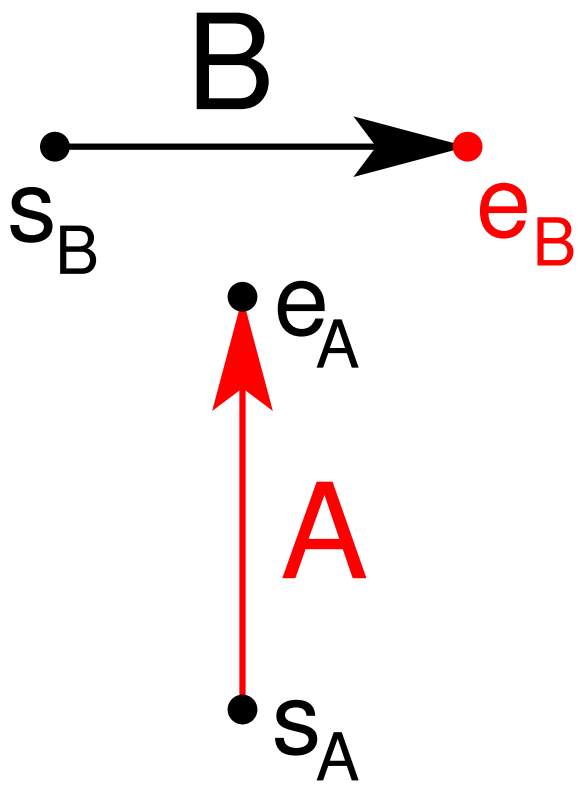
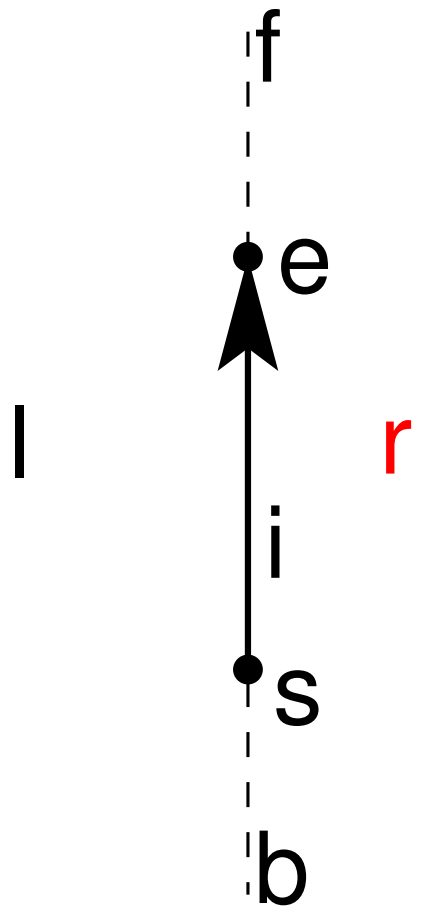


A l r B



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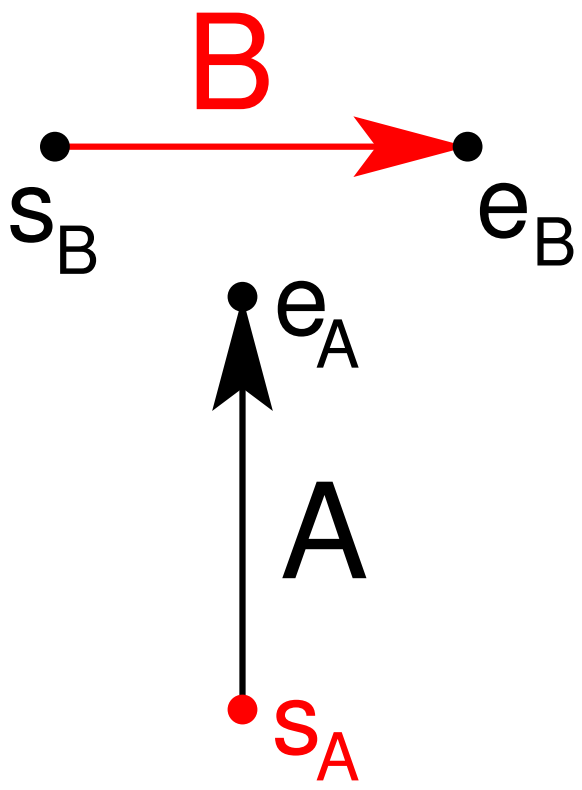
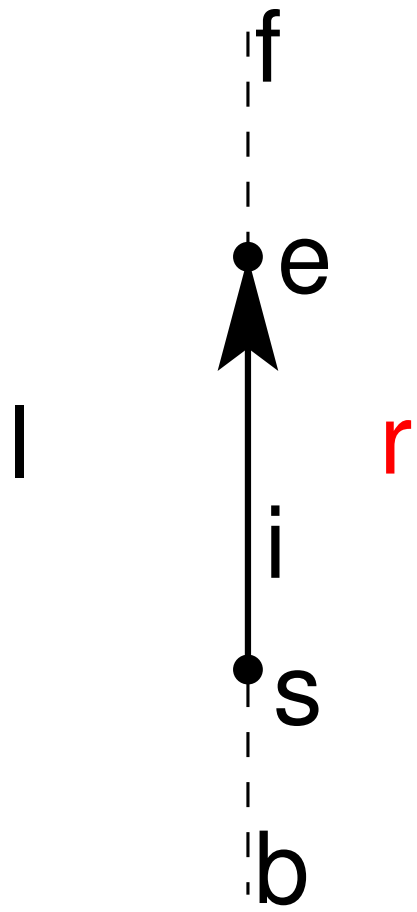


A Irr B



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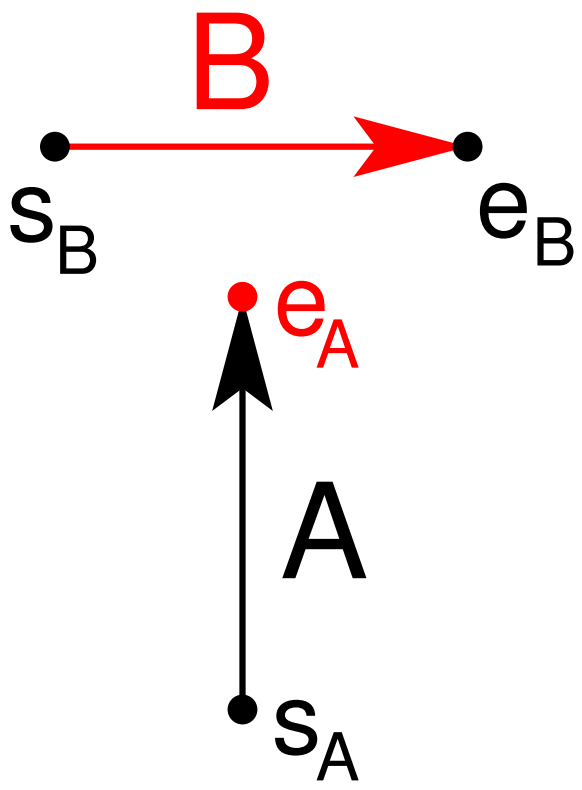
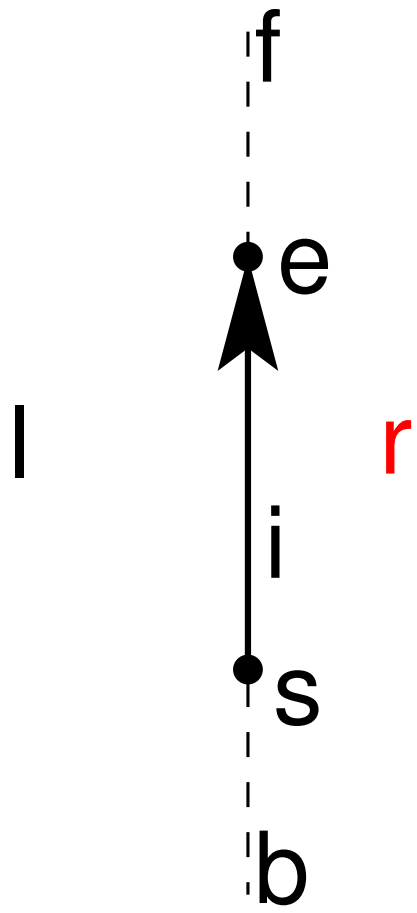


A Irr**r** B



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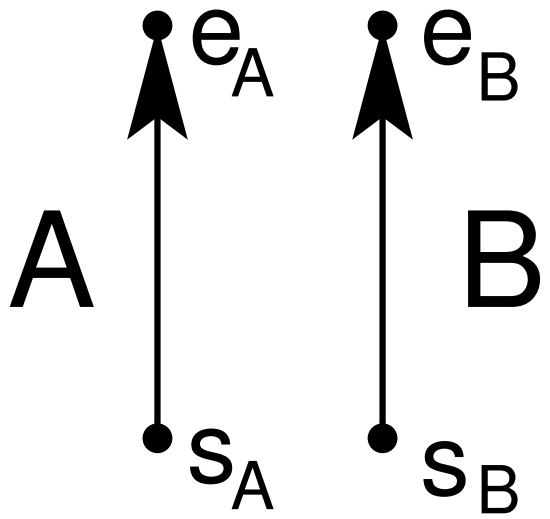
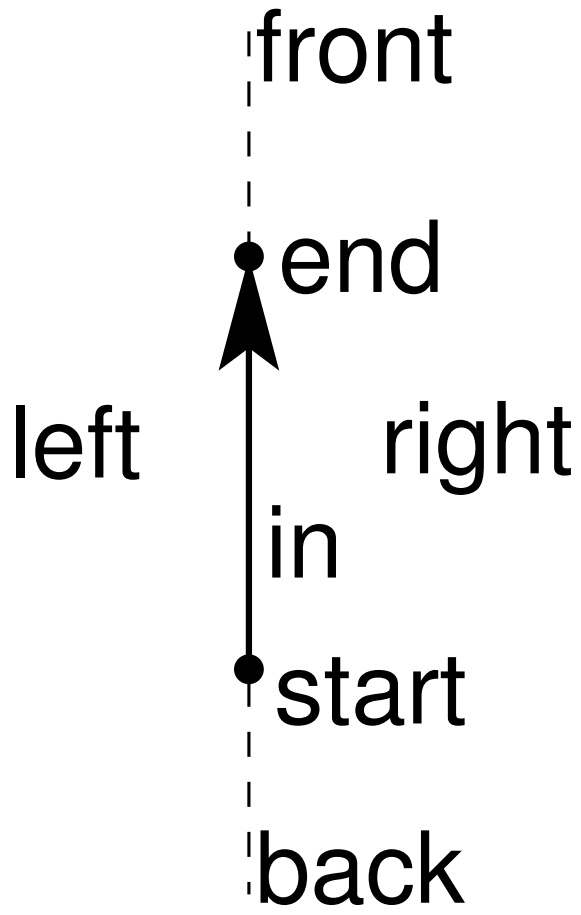
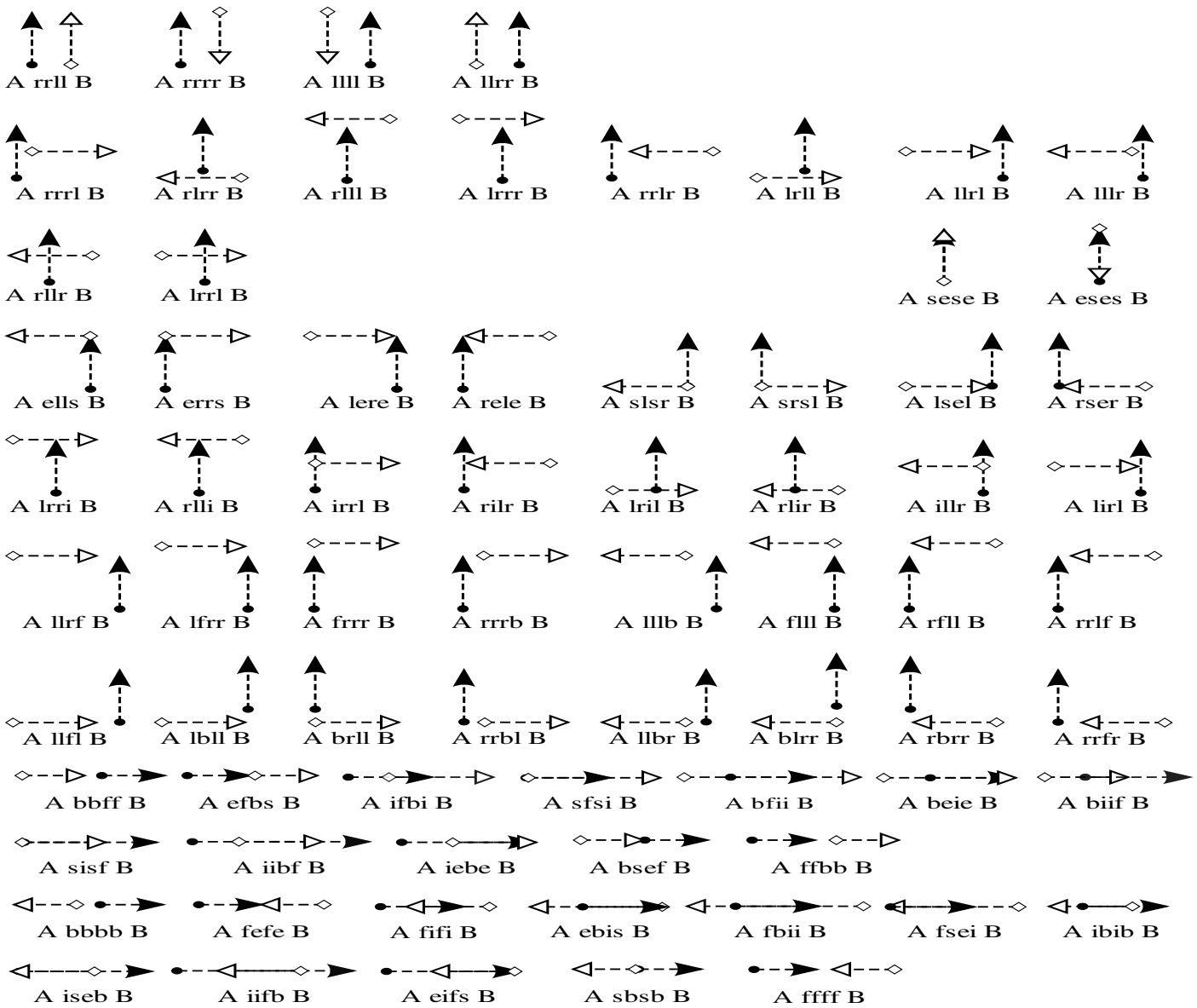


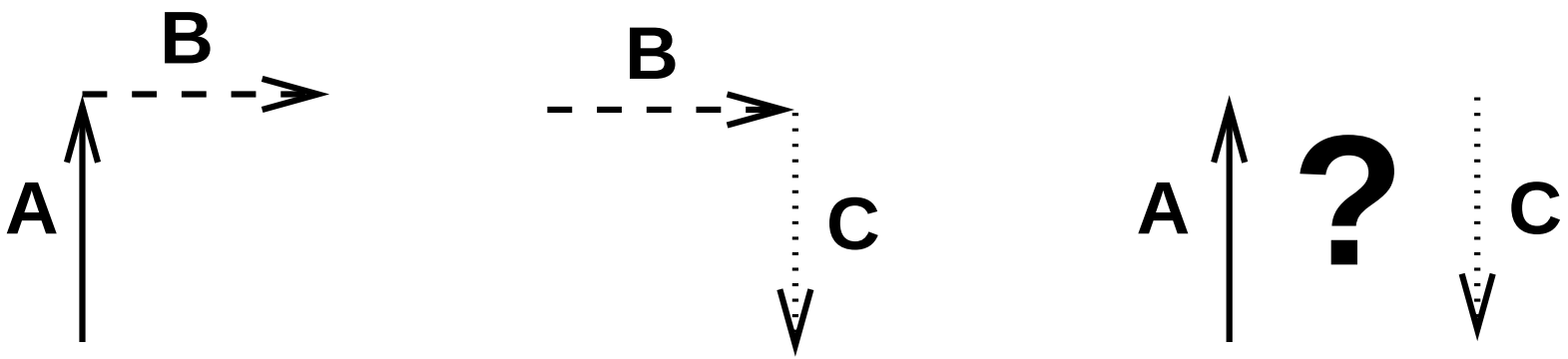
A rrll B



The 72 atomic relations of the DRA_f calculus

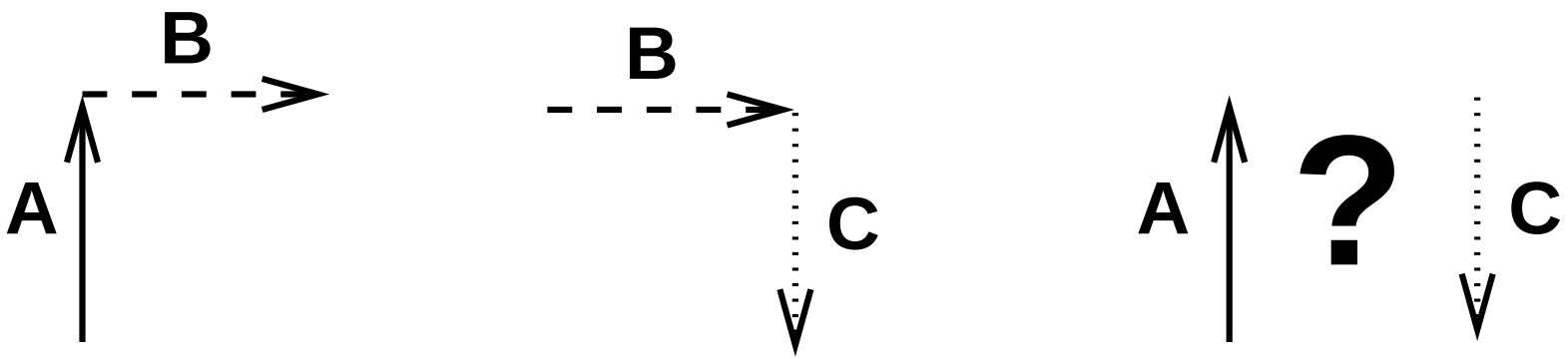


Composition of qualitative relations



- A errs B
- B errs C
- A ? C

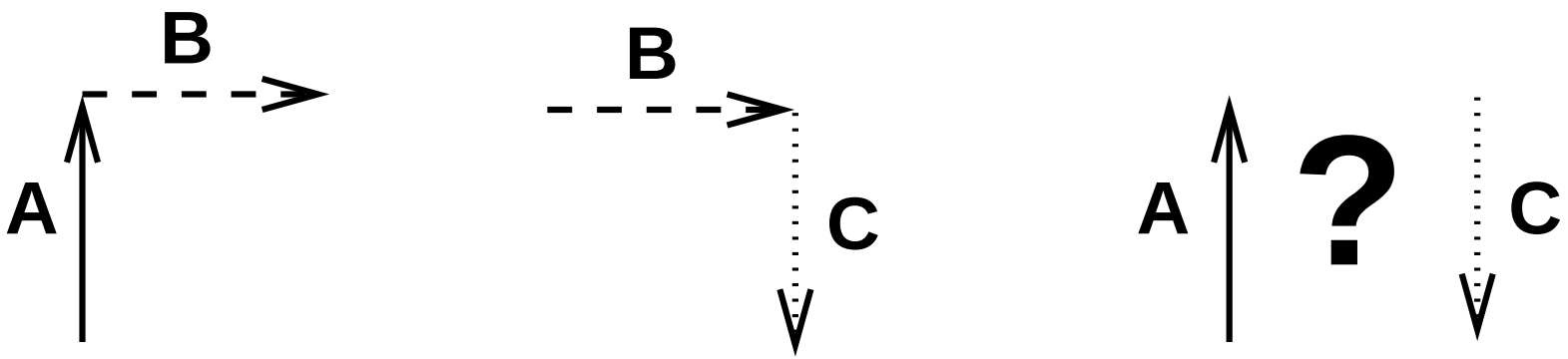
Composition of qualitative relations



- A errs B
- B errs C
- A ? C

A (rser, rrrr, rrlr, rlrr, rllr, rilr, rfer, rrfr, rlir) C

Composition of qualitative relations



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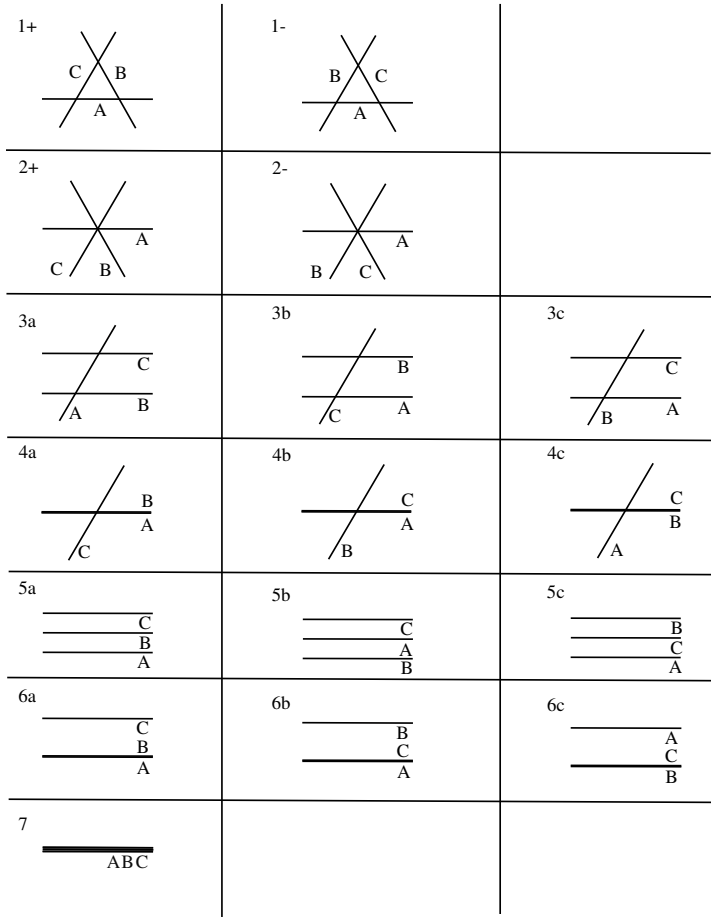
A (rser, rrrr, rrlr, rlrr, rllr, rilr, rfer, rrfr, rlir) C

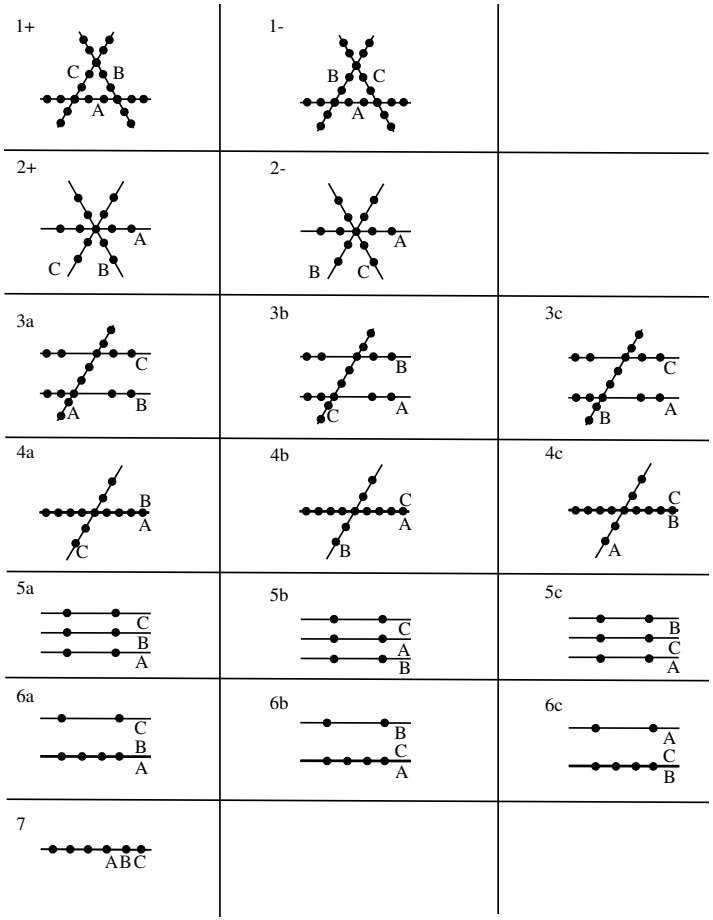
How can we get the full 72×72 composition table?

The condensed semantics method



The 17 qualitatively different straight line configurations. And generating exhaustively all the configurations with potential dipole start/end points.

The condensed semantics method



The 17 qualitatively different straight line configurations. And generating exhaustively all the configurations with potential dipole start/end points.

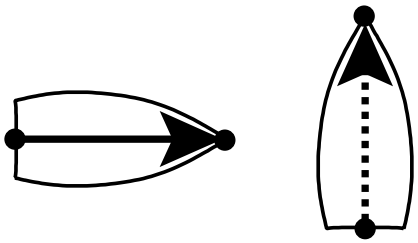
Granularity

Granularity plays a key role in human strategies to deal with the complexity of the spatial features of the real world.

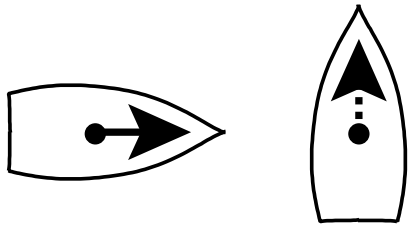
An example from Hobbs:

- Humans conceptualize streets as one-dimensional entities when they plan a trip.
- They use a two-dimensional conception when they cross a street.
- In contexts where the pavement has to be dug up the street becomes a three-dimensional volume.

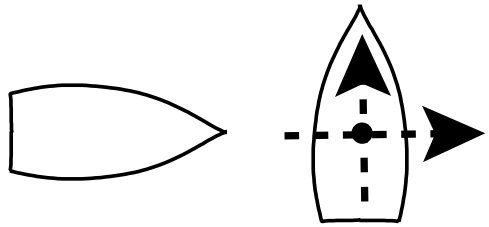
Modelling relative ship directions on different levels of granularity



abstraction from shape

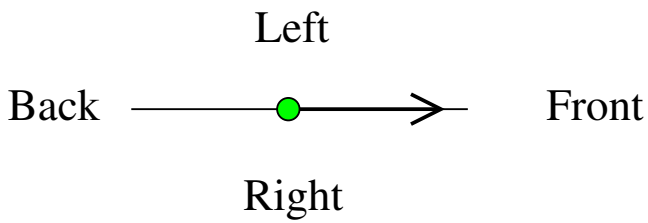


abstraction from length

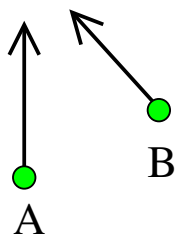


abstraction from location

OPRA orientation calculus

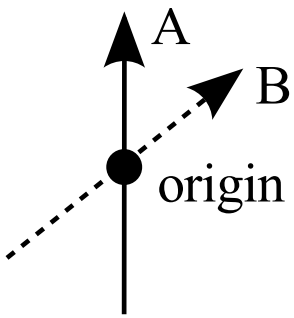


An oriented point and its qualitative spatial relative directions

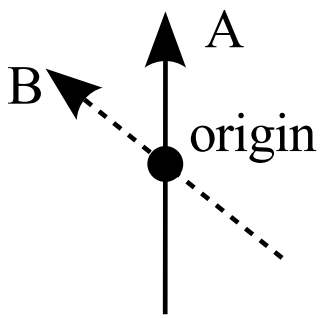


Qualitative spatial relation between two oriented points at different positions. The qualitative spatial relation depicted here is A RightLeft B.

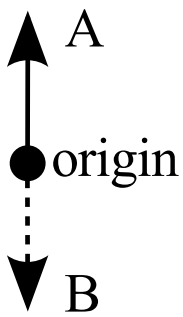
CYC orientation calculus



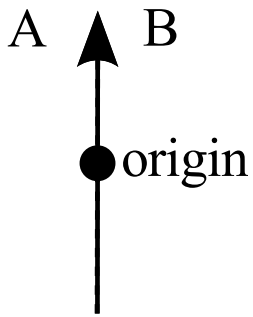
A r B



A l B

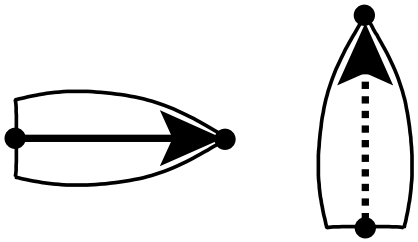


A o B

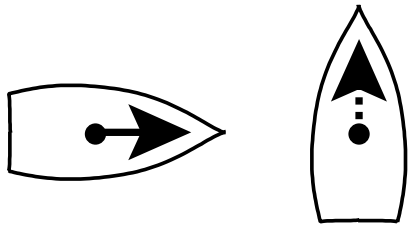


A e B

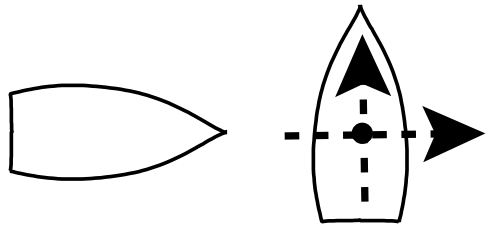
Relations Among Calculi



abstraction from shape



abstraction from length



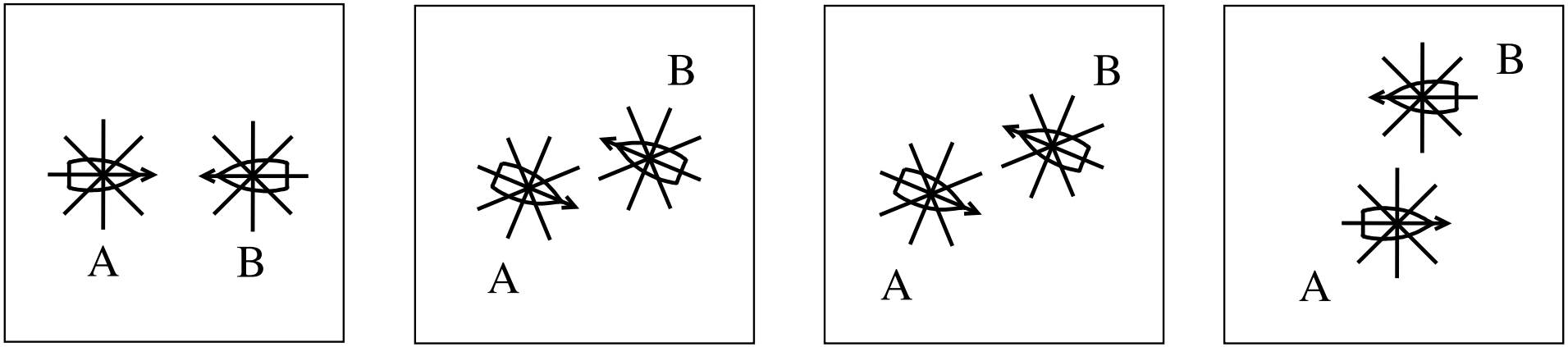
abstraction from location

Theorem

Composition tables can be transferred along full quotient homomorphisms.

T. Mossakowski, R. Moratz: Relations Between Spatial Calculi About Directions and Orientations. *Journal of Artificial Intelligence Research, 2015, extended abstract in: Proceedings International Joint Conference on AI 2017*

Qualitative Spatio-Temporal Simulation with OPoints



Representation of vessel navigation in $OPRA_4$. This conceptual neighborhood transition diagram represents the relative trajectories of two rule following vessels. The depicted sequence between two vessels A and B is: $A\ {}_4\angle_0^0\ B \rightarrow A\ {}_4\angle_1^1\ B \rightarrow A\ {}_4\angle_2^2\ B \rightarrow A\ {}_4\angle_3^3\ B$.

Summary/Results

- Ontological (terminological) reasoning can be complemented with spatial reasoning
- Qualitative spatial reasoning abstracts from metrical details
- Qualitative spatio-temporal simulation enables exhaustive search of design spaces