Universität Bamberg

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Qualitative Spatial Reasoning: From Calculi to Applications

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Abstract

The qualitative spatial reasoning community investigates abstract representations of spatial knowledge. Research in this area draws motivation from several general aims, for example to gain an understanding of fundamental computational principles, to capture the catalog of cognitive concepts in a computational framework, or to provide useful techniques to applications. So far, research has lead to the development of well over 40 formalisms, widely called qualitative spatial calculi. This wealth results from the diversity of potentially useful spatial concepts and computational challenges faced – designing expressive yet computationally feasible formalisms is a delicate balancing act that often requires some trade-offs. While we have reached a good level of understanding computational aspects of spatial reasoning, how far have we come with respect to our other aims?

In this talk I adopt an application-oriented perspective and examine the contribution of qualitative spatial reasoning techniques. Looking at selected applications broadly related to intelligent service robots, I review the beneficiaries of employing qualitative spatial representation and reasoning. I argue that employing qualitative concepts requires reasoning to implement semantics. However, not all required reasoning techniques are available so far. In this talk I present some case studies which already demonstrate the utility of qualitative spatial reasoning. Additionally, I identify important challenges on the way to qualitative spatial reasoning becoming an integral part of any intelligent service robot.

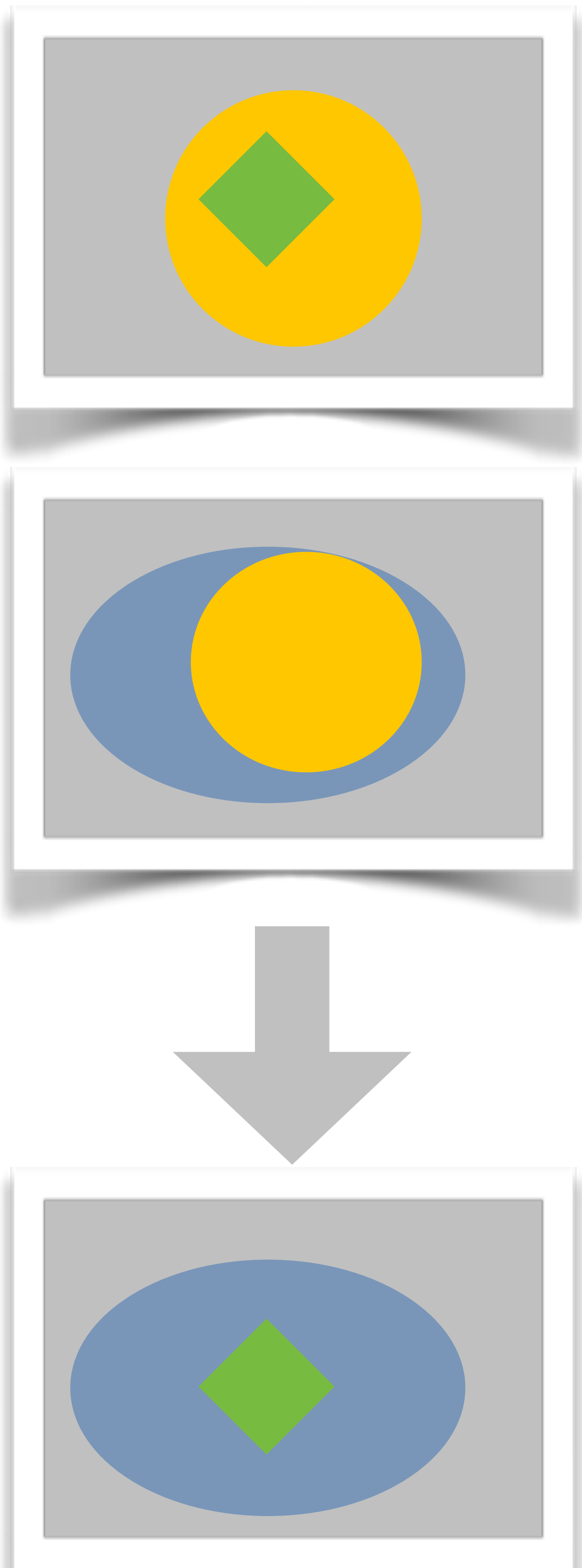
Outline

- **background**
  - general motivation
  - basic QSR notions and reasoning tasks
- **case studies in intelligent service robots**
- **résumé**
  - Are we ready for applications?
  - proposal for future research agenda

Background

- **qualitative reasoning**
  "reaching good conclusions without being precise" (AAAI)
- **motivated by human cognition**
  - formal approach to common-sense
  - foundation for human-machine interaction: align human and machine thinking
  - comprehensible knowledge representation
- **focus on spatial and temporal domains**
  - rich structures to exploit!
  - important for many applications

Background



- **qualitative spatial representation**
  - rather compare than measure
  - abstract from irrelevant details
  - constraint language – **qualitative calculi**

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inside(Bamberg, Franconia),
inside(Franconia, Europe)
⇒ inside(Bamberg, Europe)
```

- **in short:**
  - quantifier-free spatial logic with fixed relation semantics
  - decidable (≤ ∃R-complete), yet often efficient

Qualitative Calculus

- theoretical and computational basis concept (Nebel & Scivos '04, Ligozat & Renz '04, Condotta '06, Dylla et al., 13)
  - several limitations, still popular though (cp. Westphal '15)
- JEPD set of base relations $\mathcal{R}$ provides partition scheme on $\mathcal{U}$

$$(\mathcal{U}, \mathcal{R}) \qquad \mathcal{U}^n = \bigcup_{r \in \mathcal{R}} r \qquad \forall r, r' \in \mathcal{R} : r \neq r' \rightarrow r \cap r' = \emptyset$$

  - universe $\mathcal{U}$ non-empty, typically infinite
  - relations provide semantics and symbols for representations
- knowledge representation using constraints, e.g., $r(x, y) \equiv (x\ r\ y)$

▶ finite vocabulary of concepts, often binary relations

Qualitative Calculus

- symbolic operations induce algebraic structure
- relations are sets → set-theoretic operations

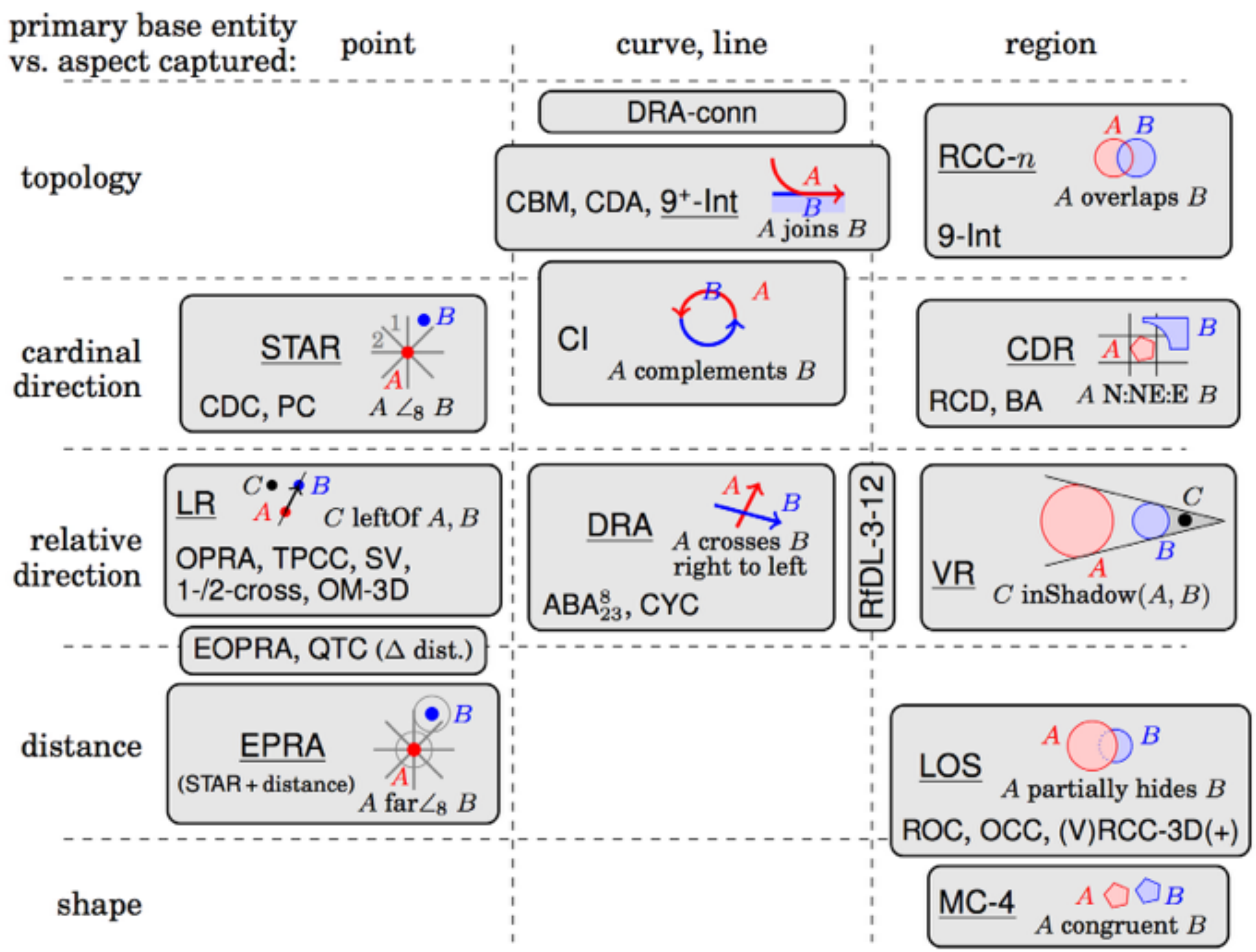
$$\boxed{(x\ (r \cup r' \cup r'')\ y) \equiv (x\ \{r, r', r''\}\ y)}$$

  - Boolean set algebra of relations
- converse and composition operations on relations
  - calculi closed under operations, defined extensionally
  - provide simple inference rules

$$(x\ r\ y) \vdash (y\ r^{\smile}\ x) \qquad \{(x\ r\ y), (y\ s\ z)\} \vdash (x\ (r \diamond s)\ y)$$

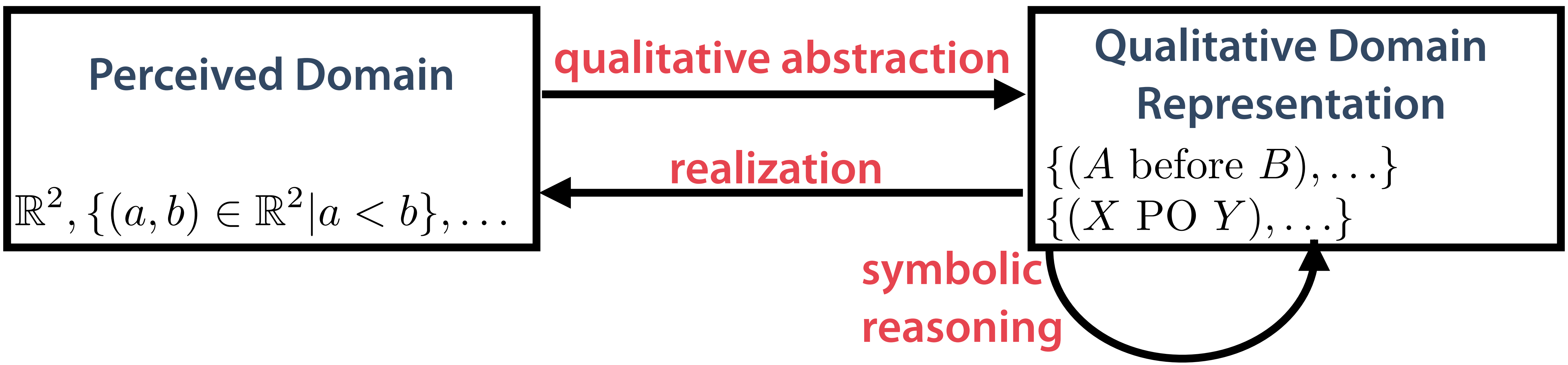
▸ algebraic structure of qualitative calculi grants symbolic knowledge manipulation rules

Some Spatial Calculi



- wealth of representations, not all formal properties known so far

Reasoning Tasks in QSR



- perceived domain already abstract, not close to perception
- qualitative spatial **reasoning** mostly studies **symbolic reasoning**
  - focus on constraint-based reasoning
- qualitative abstraction and realization not easy

▶ QSR often concerned with deciding consistency of constraints

Applications

- survey of papers employing qualitative spatio-temporal relations
  - sometimes, only sheer representation
  - yet reasoning increasingly important!

survey by J. Lee et al. (2014, unpublished)

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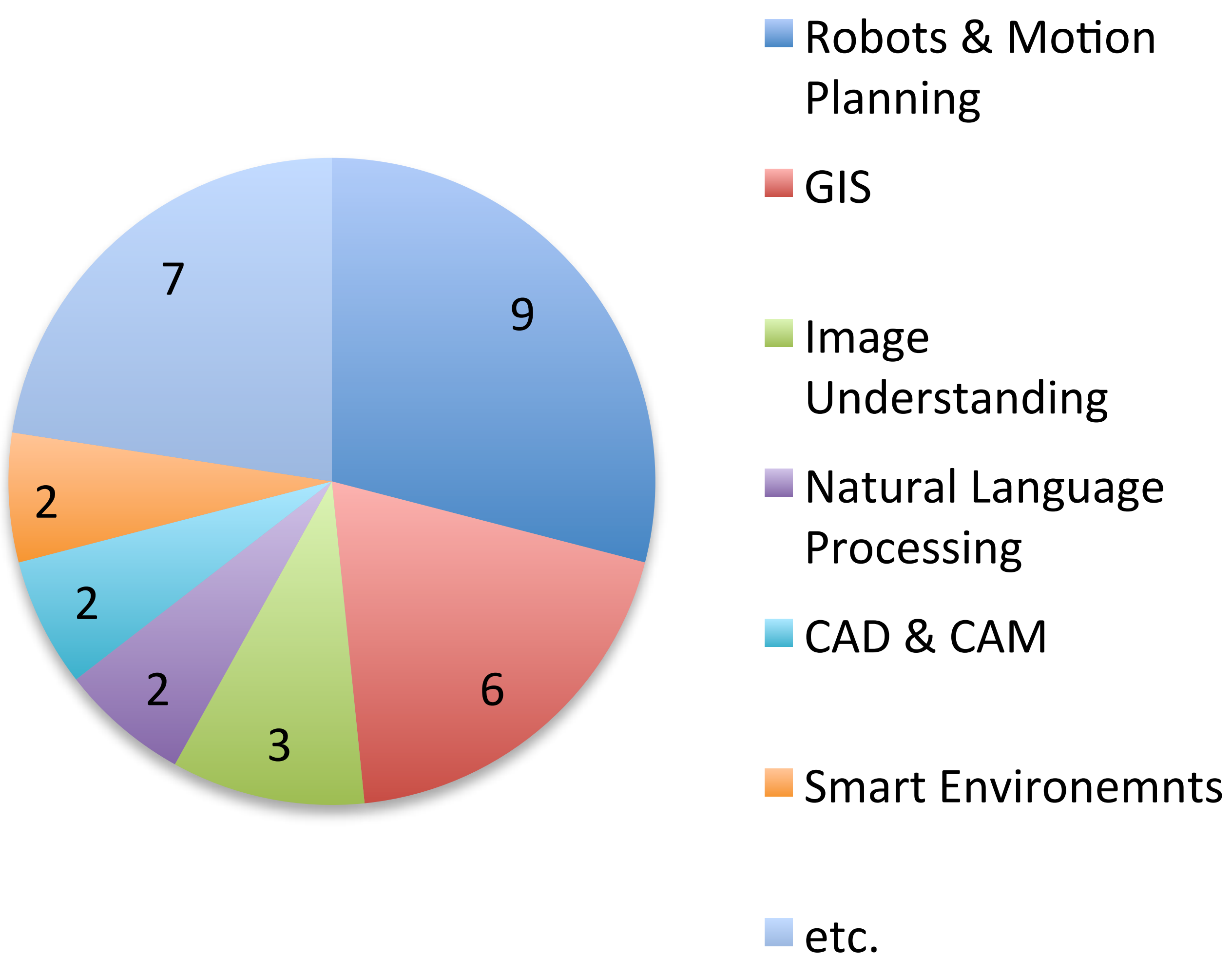

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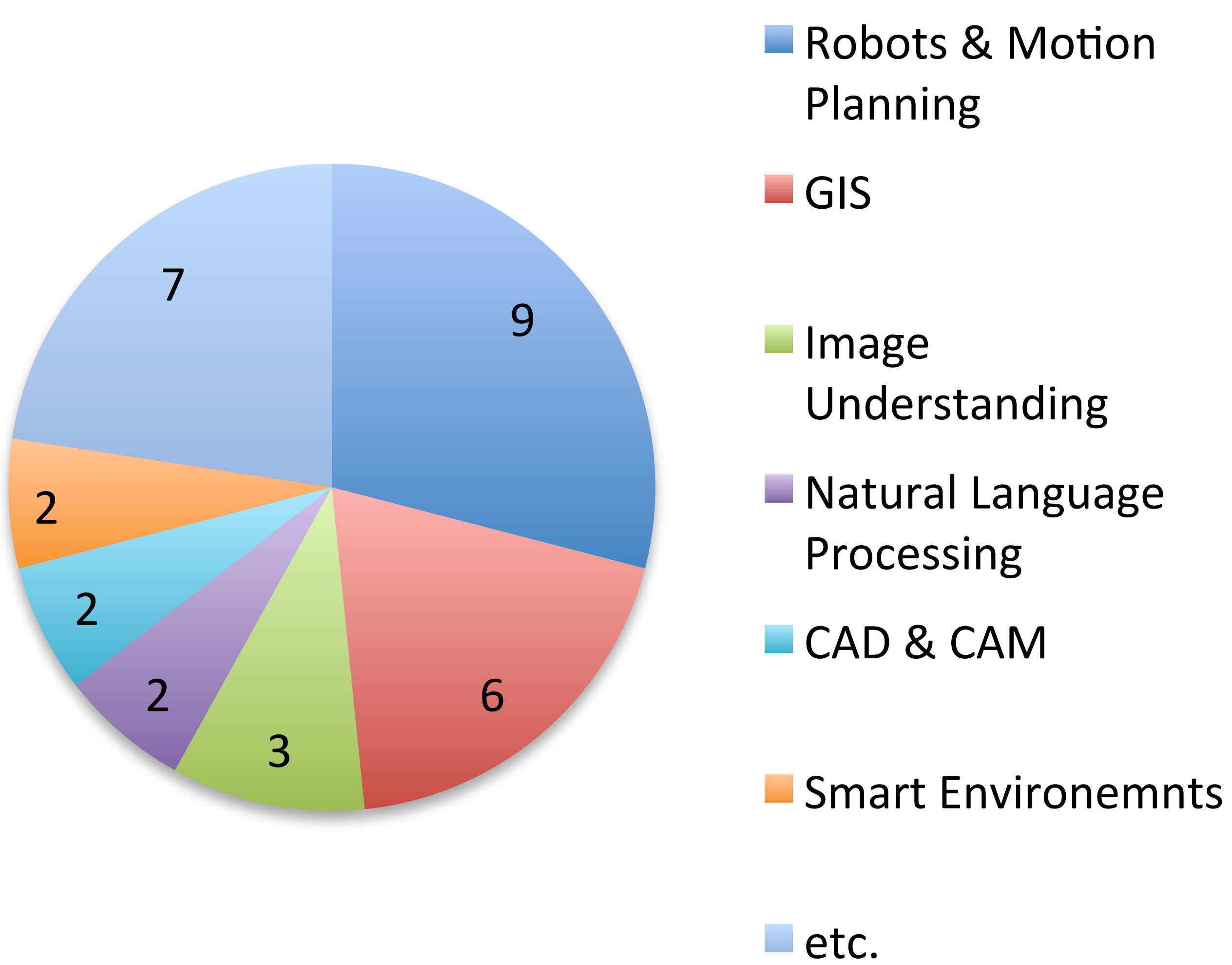

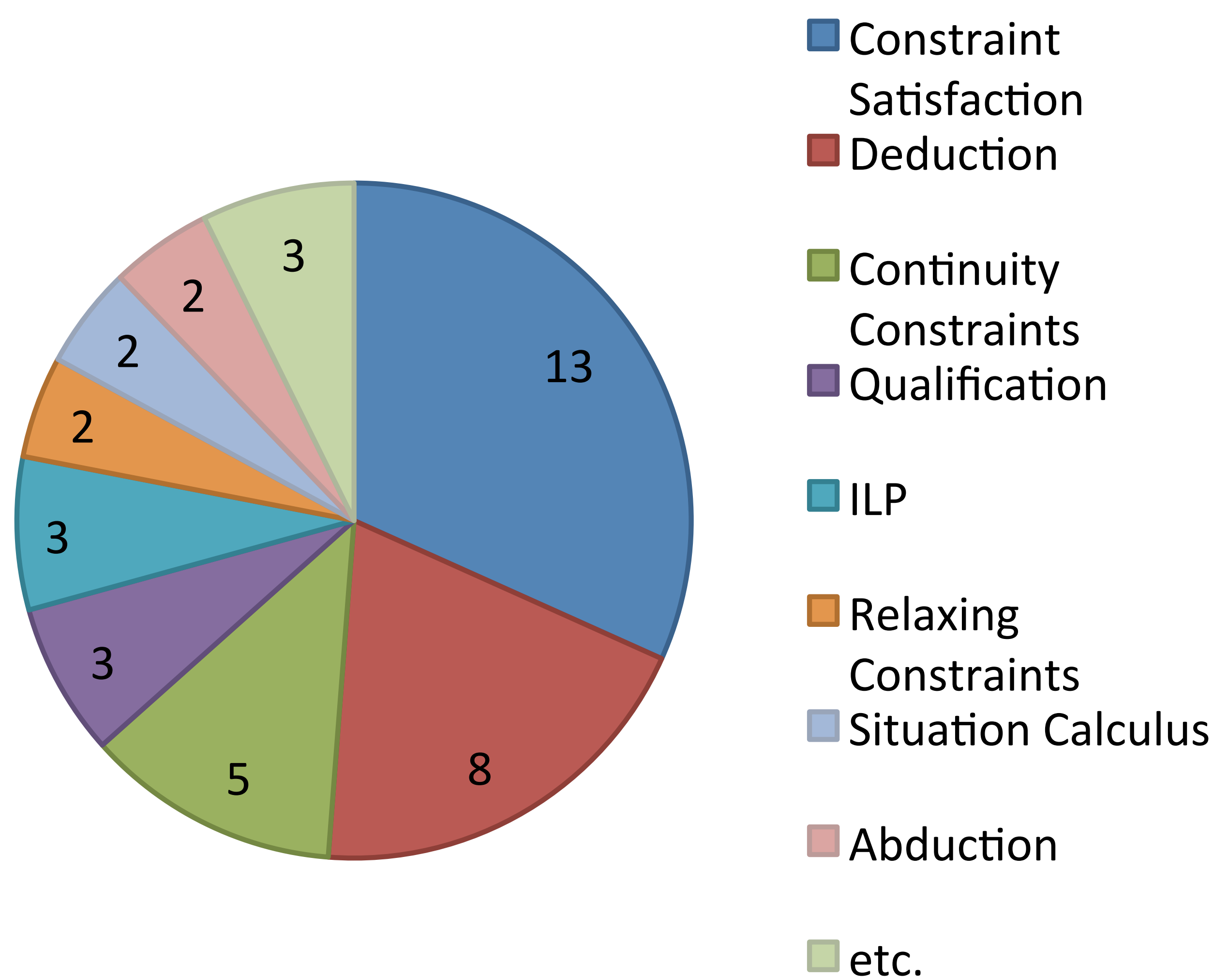

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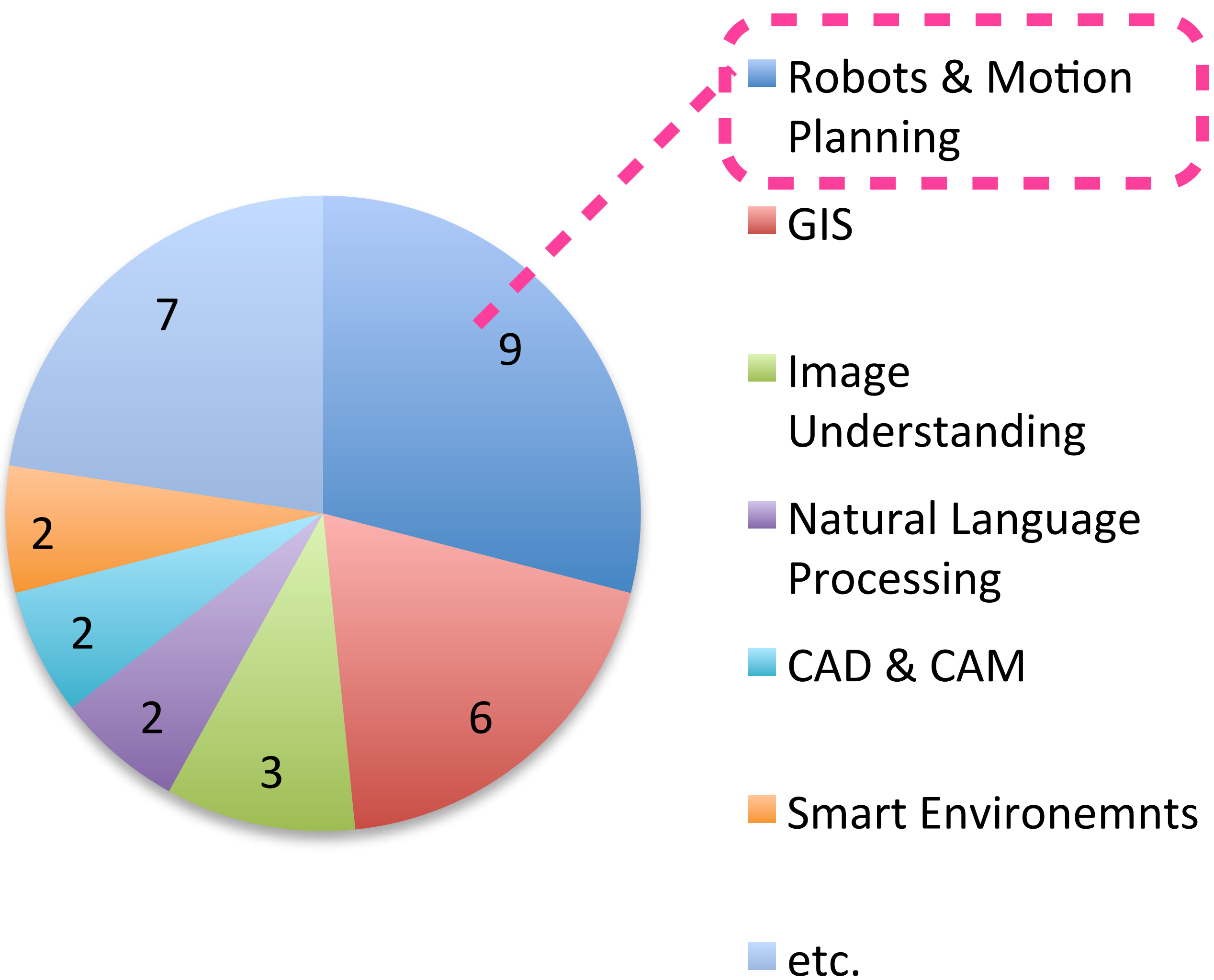

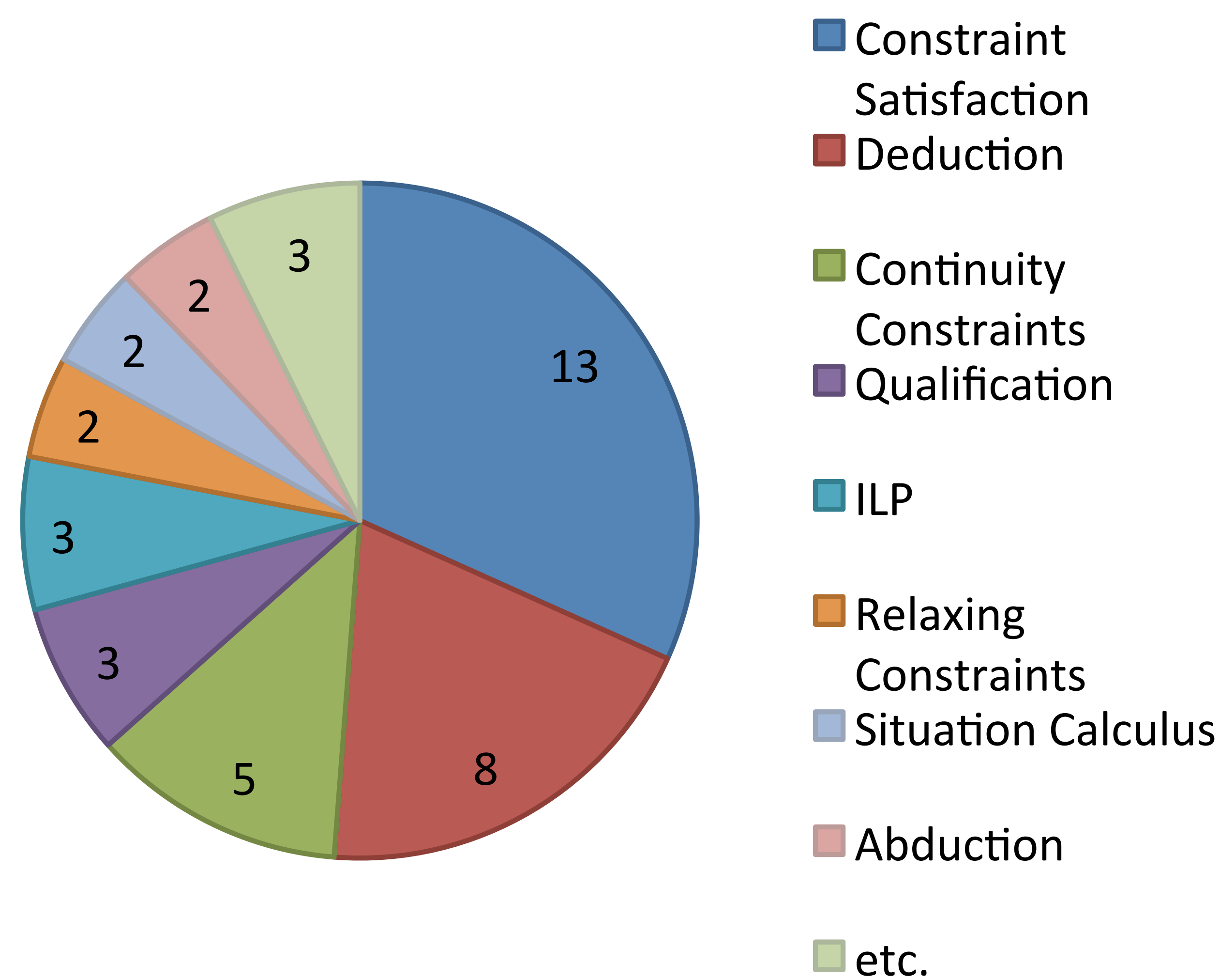

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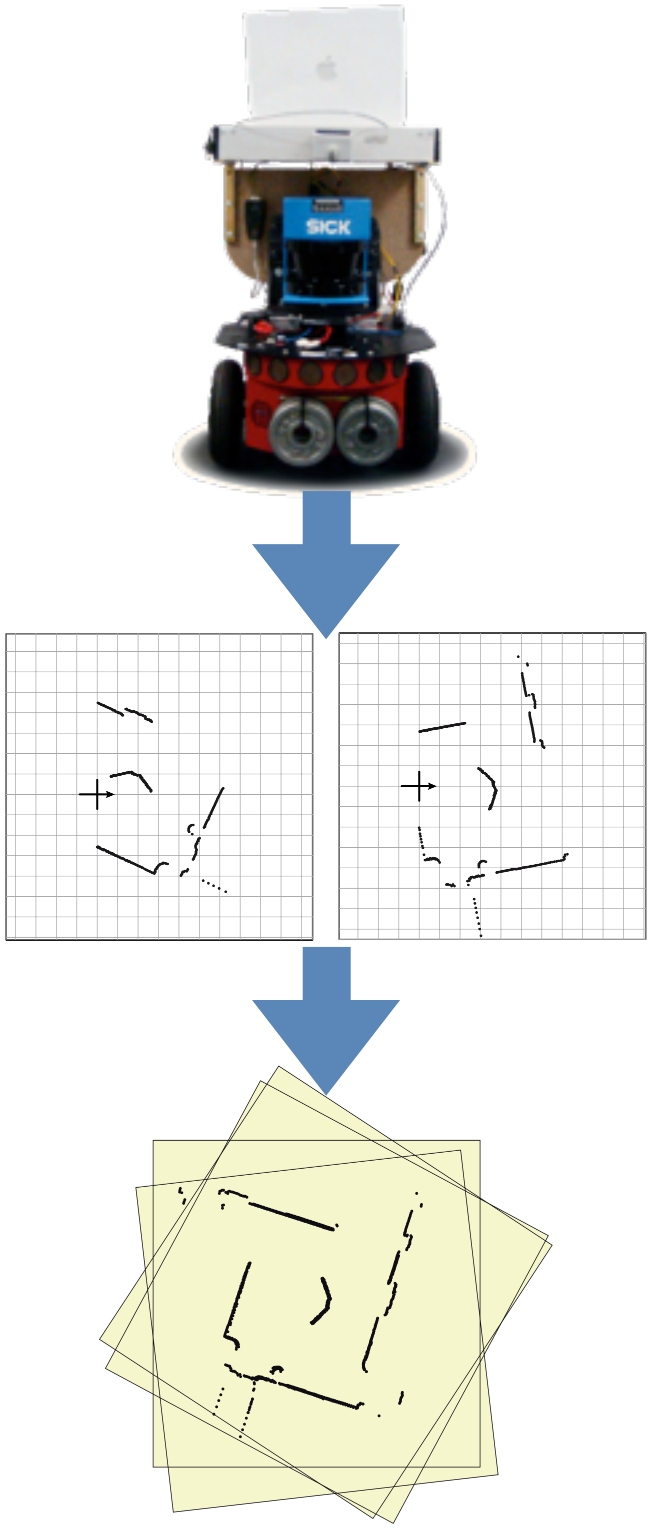
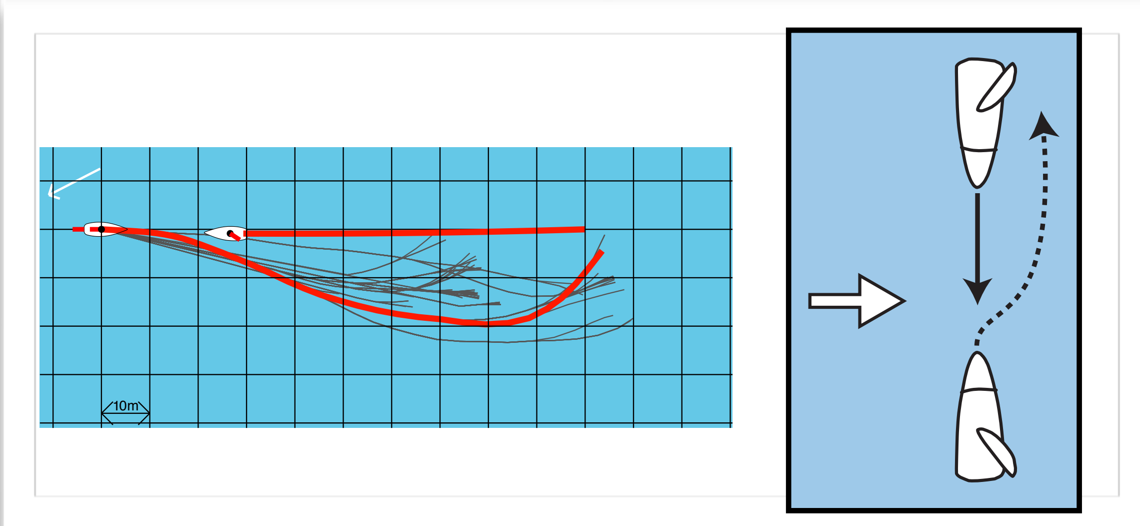
QSR for Robotics



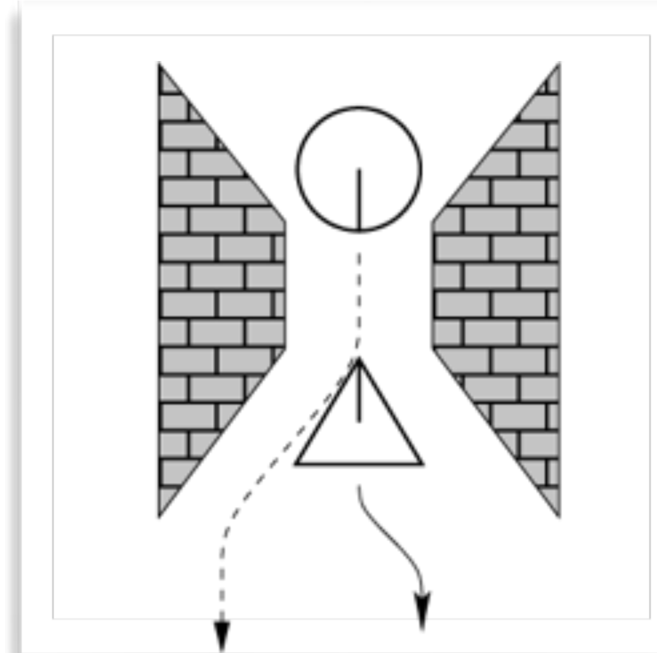
- during PhD got lured back to working on symbolic AI and spatial reasoning
- by now, re-integration of AI and robotics widely recognized as crucial for next leap ahead
  - AI robotics

applications

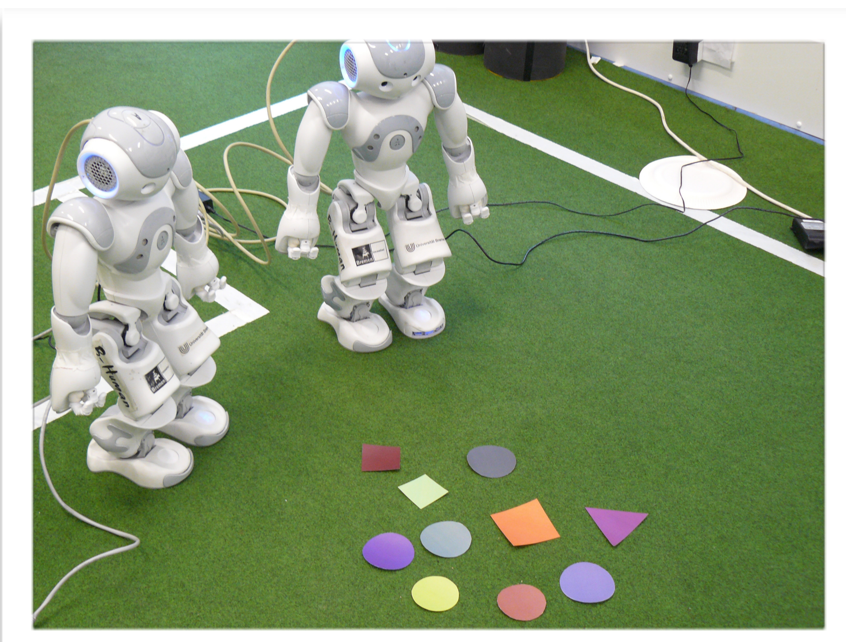


rule-compliant navigation and validation of navigation rules

social robotics



Qualitative Representation and Reasoning



situated object reference

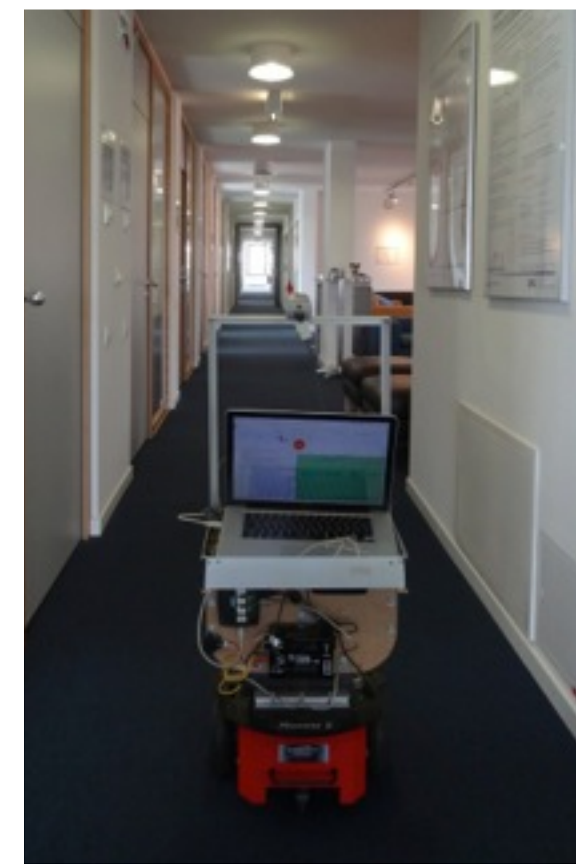
process recognition

Safe Autonomous Navigation

- autonomous cars, autopilots, assistance systems, mobile robots, …
- safety concepts developed by humans – need to be represented

robot arm in factory
(photo: Wikipedia)

vessel on autopilot
(photos: SIMRAD)



mobile robot
(photo: U Bremen)

EuroHawk
(photo: Wikipedia)

autonomous car
(photos: FU Berlin)

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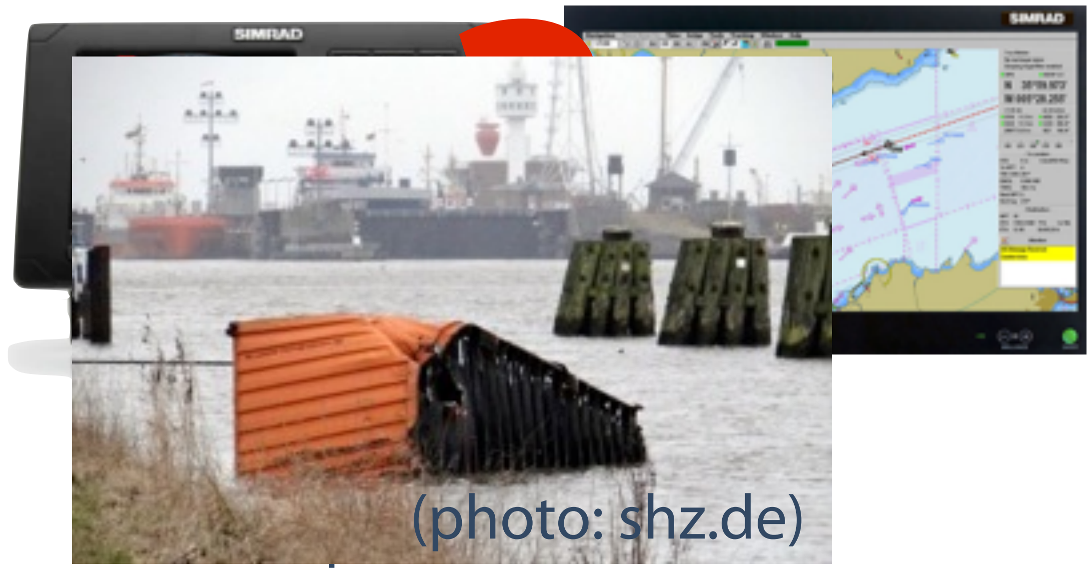


(photo: shz.de)

EuroHawk
(photo: Wikipedia)

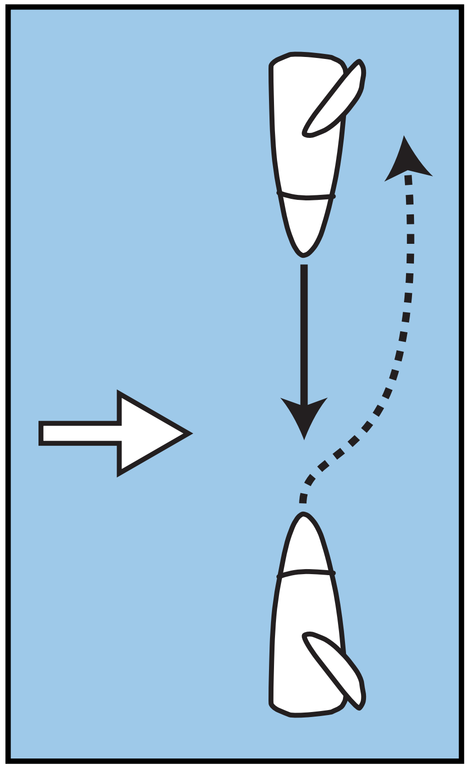
(photo: ABC/youtube)

mobile robot
(photo: U Bremen)

Rule-Compliant Navigation

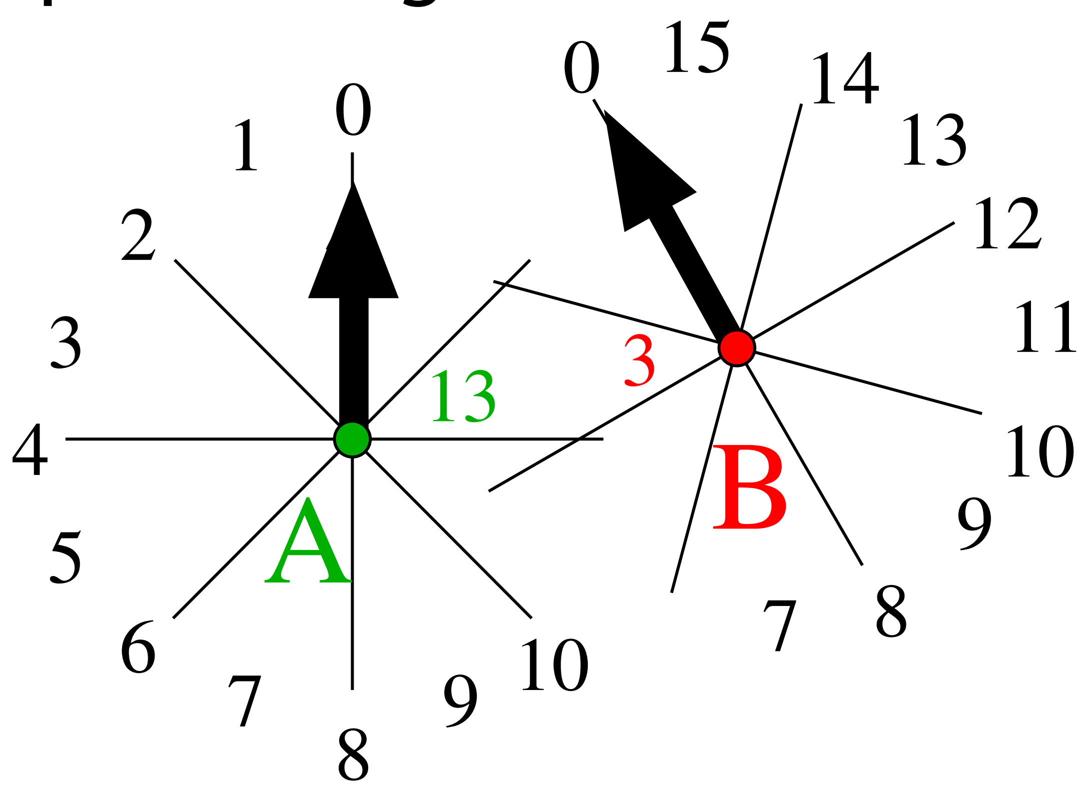
- traveling public spaces requires rule-compliant actions
  - rules need to be formalized
  - idea: use qualitative relations to capture natural language
- challenging and interesting **domain sea navigation**
  - complex configurations, complex rules

Rule 12:
(a) when two sailing vessels are ***approaching one another****, so as to involve risk of collision, one of them shall keep out of the way of the other as follows:*
(i) when each of them has the wind on a different side, the vessel which has the ***wind on the port side*** *shall keep out of the way of the other;*
(ii) …
COLREGS, International Maritime Organization (IMO)

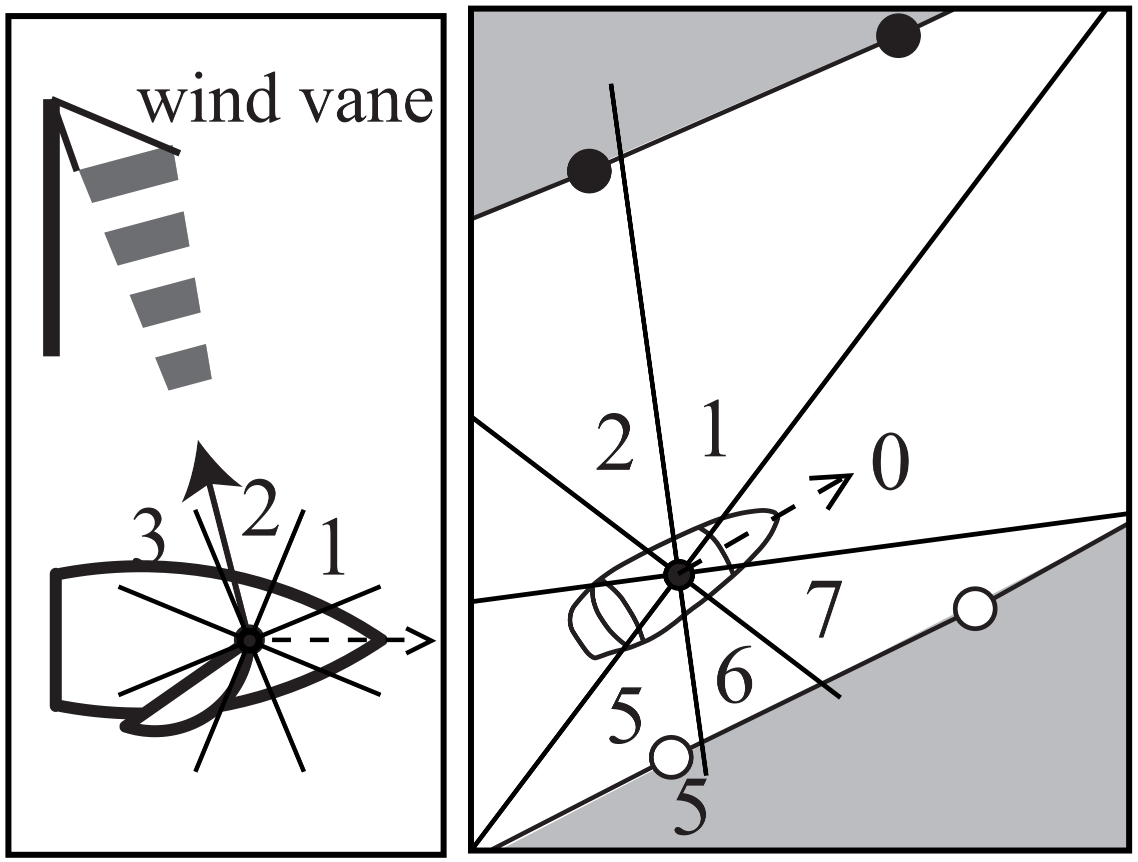


Relative Agent Position

- representing directional information with OPRA relations



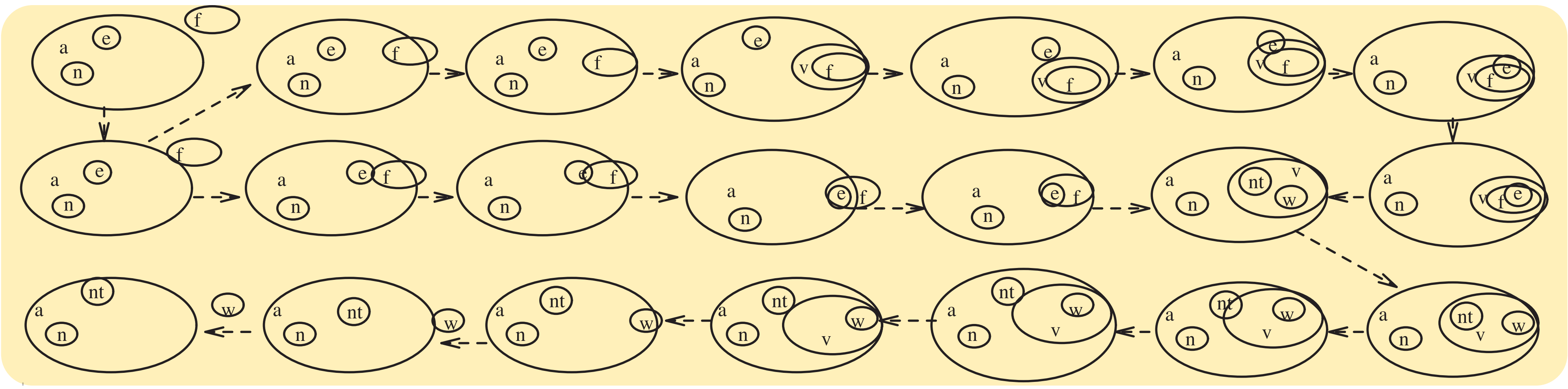
$$A\ {}_4\angle_{13}^{3}\ B$$



- represent knowledge in egocentric frame of reference
- cone- and line-shape sectors at different levels of granularity, according reasoning rules
  - efficient approximative reasoning applicable (Lee et al., 2013)

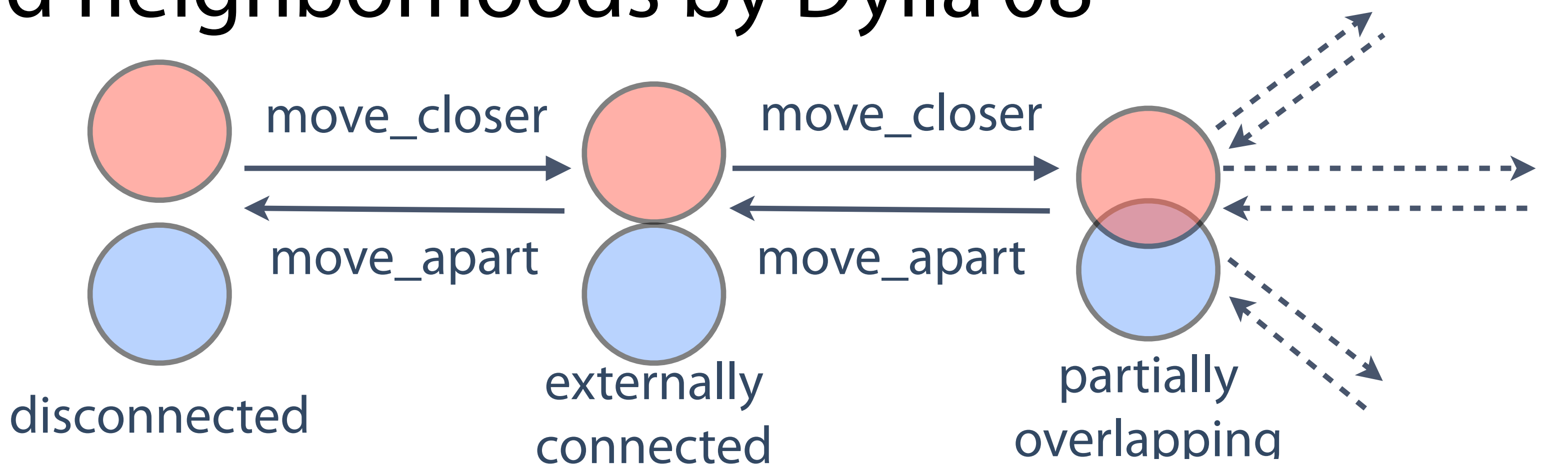
Qualitative Change

- conceptual neighborhoods facilitate temporal interpretation



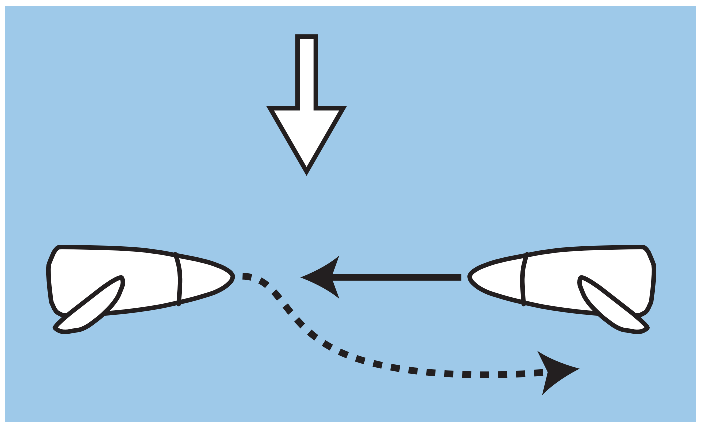
Cui et al., 92

- distinguishing Freksa's neighborhood transitions by actions leading to specific changes enables planning
- cognitive alignment investigated by Knauff et al.; action-augmented neighborhoods by Dylla'08

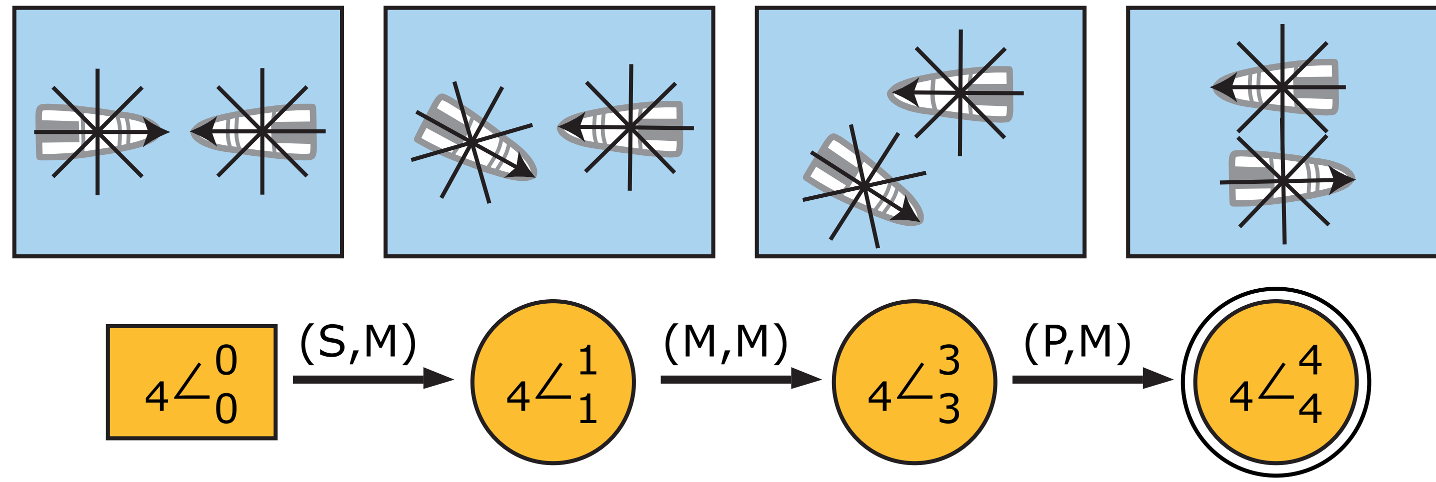


Rule Representation

- represent key configurations of rule-compliant navigation



iconic rule

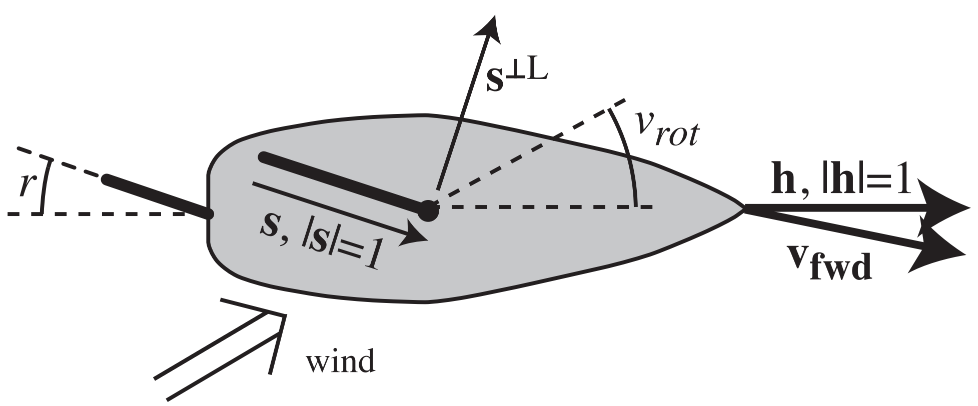


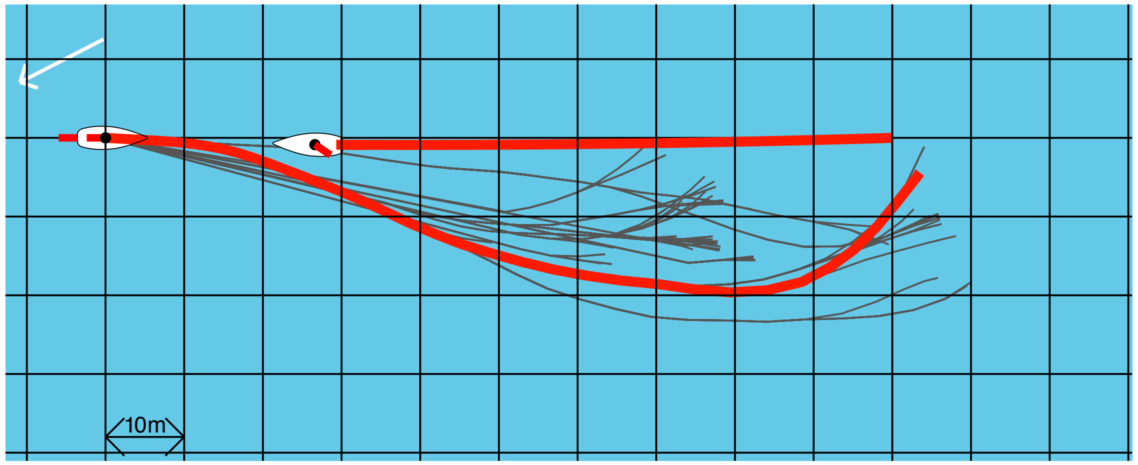
rule representation

  - using textbook on sailing, encode admissible state-transitions
- QSR applicable to identify globally admissible state-transitions
  - multiple agents, but rules teach about two agents only

Planning in Sea Navigation

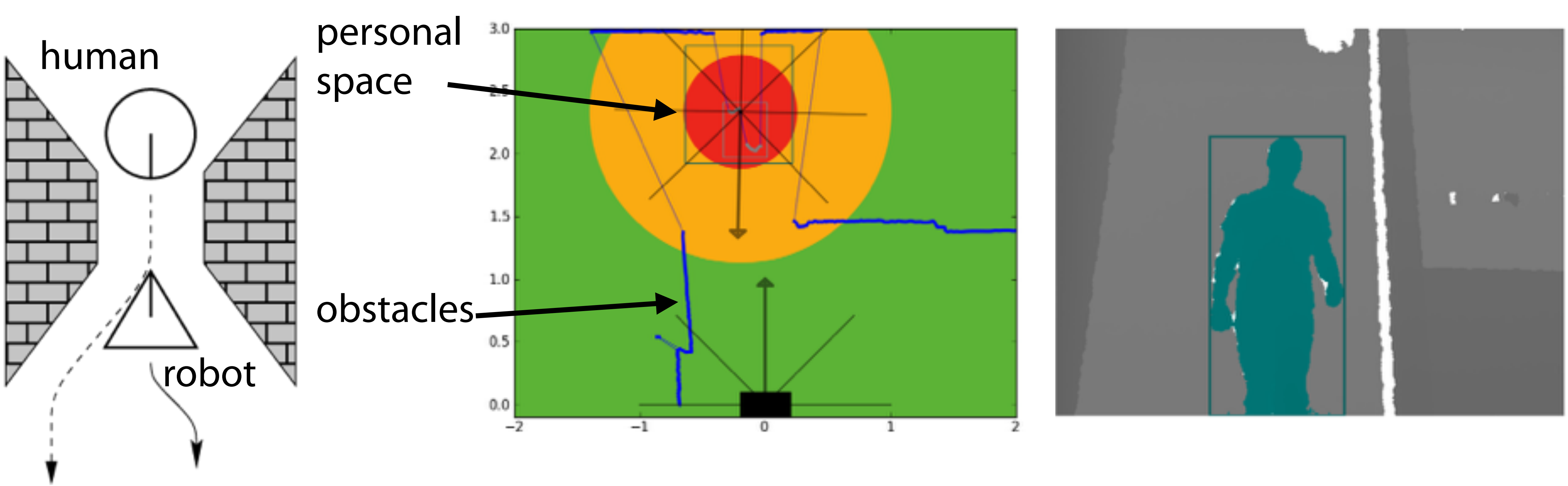
- qualitative-randomized action planning
  - qualitative reasoning about right-of-way rules
  - path-planning using **probabilistic roadmap planning**
    - only keep nodes representing rule-compliant states
- approach avoids symbolic representation of actions
  - unlike Westphal et al's approach, no QSR for planning





Related Applications

- naval traffic monitoring (Colonius '15)
- social robotics: make robot exhibit polite spatial behavior
  - proxemics and selected general rules of politeness
  - Same approach, used with special configuration recognition



iconic rule

fused sensor view

RGBD human detection

Process Recognition

- scenario
  - non-inversive robotic observer in warehouse
  - good identification using tags
- task
  - identify processes from a description
  - query interface for logistics expert
  - build knowledge representation of warehouse and processes occurring
- idea
  - symbolic approach enables versatile query interface

Process Recognition

- **approach**
  - use spatial primitives to model logistic processes within LTL
  - link spatial primitives with robot's perception
  - describe background knowledge as LTL formulae
    (e.g., goods can only be at one location at a time)
  - apply answer set programming (ASP) to detect occurrences
  - ▸ constraint-based reasoning to complement observations
  - ▸ logic reasoning to complement descriptions

example:

QSR: $\mathtt{inside}(\overbrace{\mathtt{G,\ buffer}}^{\text{variables, spatial regions}}) \wedge \mathtt{inside(buffer,\ hall)} \rightarrow \mathtt{inside(G,\ hall)}$

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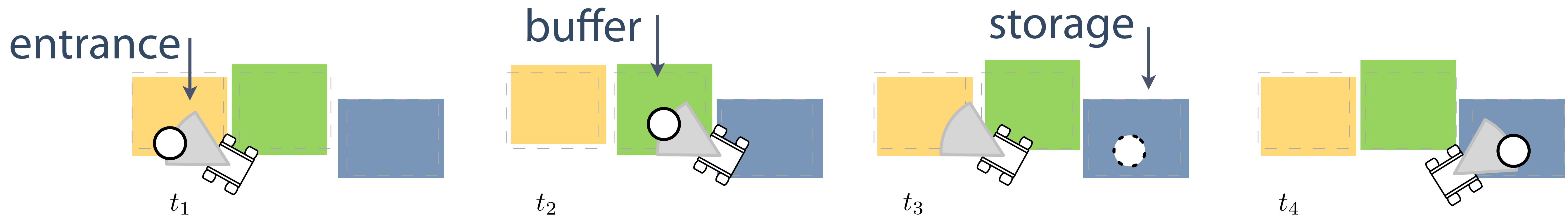
logic: $\underbrace{\mathtt{inside(G,\ buffer)}}_{\text{atom}} \rightarrow \neg\mathtt{inside(G,\ entrance)}$

Example

admission: good enters warehouse, gets handled in buffer, and stored in shelf



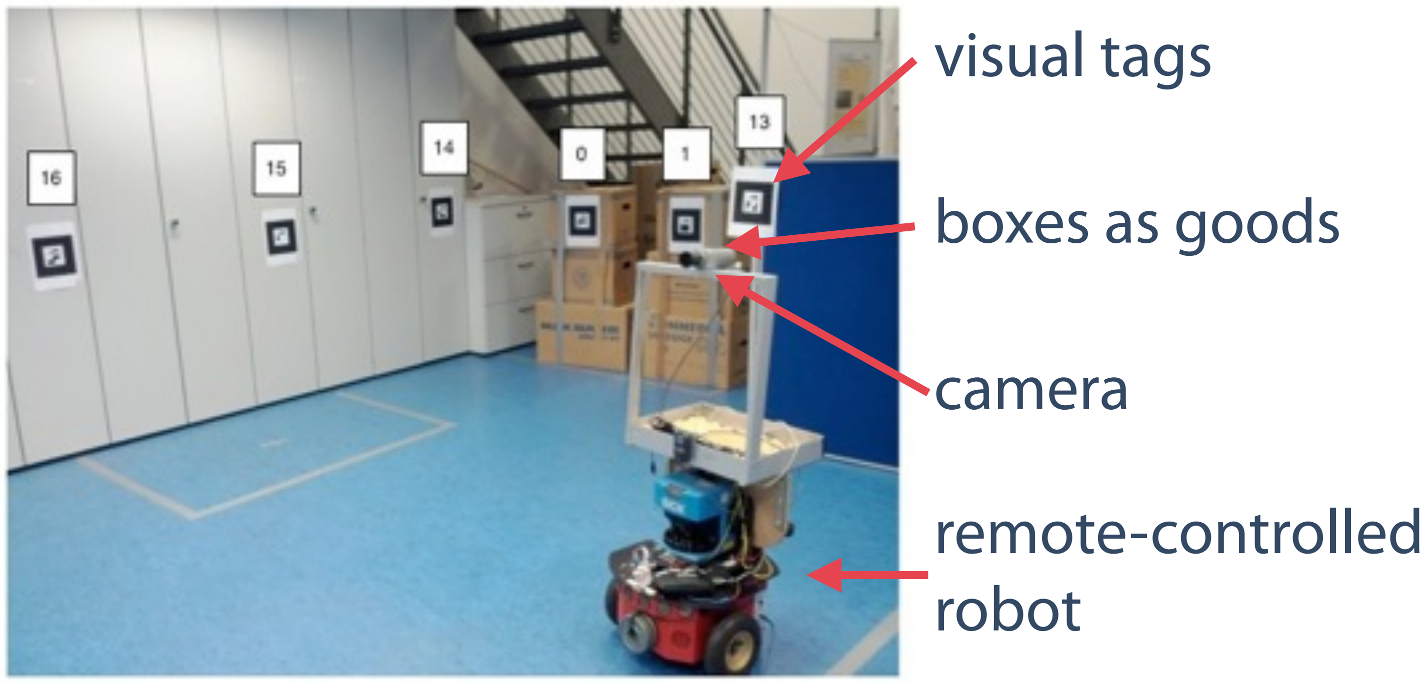
	t_1	t_2	t_3	t_4
observation	$\mathbf{at}(G, L_1)$	$\mathbf{at}(G, L_2)$		$\mathbf{at}(G, L_3)$
background knowledge	$\text{in}(L_1, E)$ $\text{in}(L_2, B) \lor \text{in}(L_2, S)$ $\text{in}(L_3, B) \lor \text{in}(L_3, S)$	$\text{in}(L_1, E)$ $\text{in}(L_2, B) \lor \text{in}(L_2, S)$ $\text{in}(L_3, B) \lor \text{in}(L_3, S)$	$\text{in}(L_1, E)$ $\text{in}(L_2, B) \lor \text{in}(L_2, S)$ $\text{in}(L_3, B) \lor \text{in}(L_3, S)$	$\text{in}(L_1, E)$ $\text{in}(L_2, B) \lor \text{in}(L_2, S)$ $\text{in}(L_3, B) \lor \text{in}(L_3, S)$

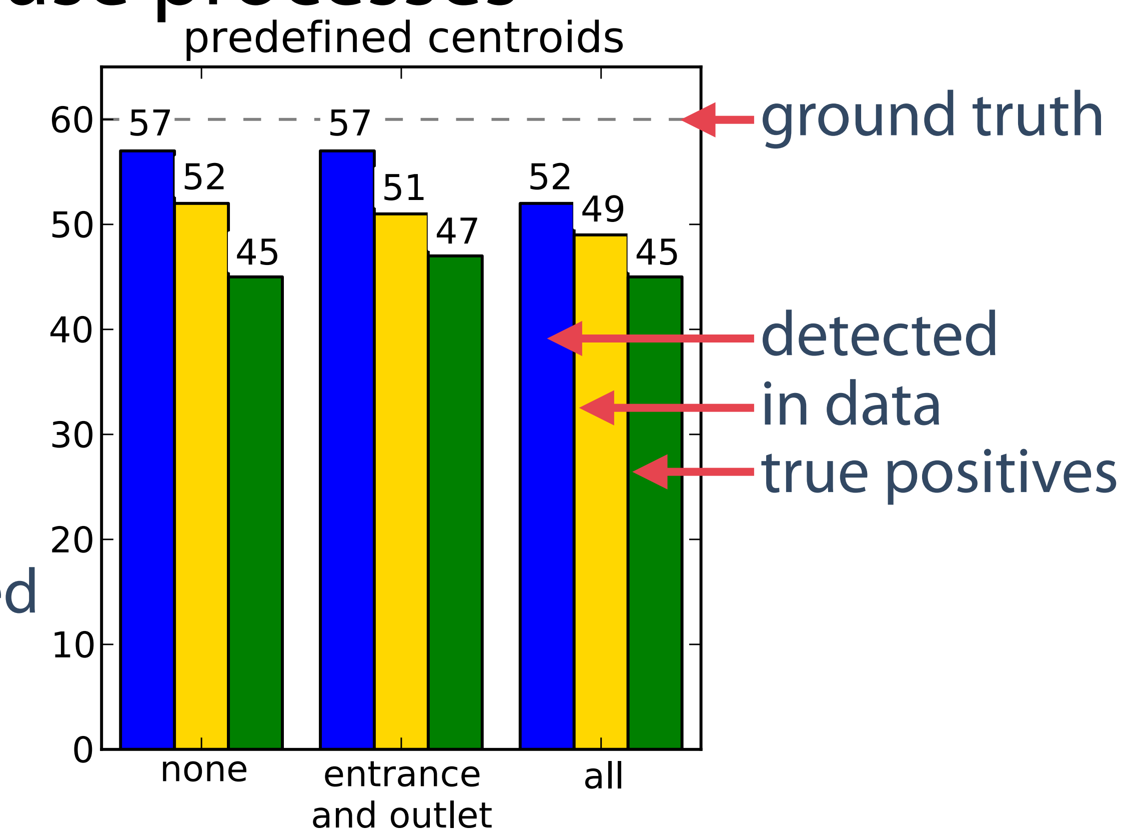
Admission $$\text{at}(G, L_1) \land \text{in}(L_1, E) \land \Diamond\Big(\big(\text{at}(G, L_2) \land \text{in}(L_2, B)\big) \land \Diamond \big(\text{at}(G, L_3) \land \text{in}(L_3, S)\big) \Big)$$

- reasoning provides us with valuable negative knowledge (we cannot **observe** that a good is not in some area)

Results

- experimental evaluation in warehouse mockup
  - visual tags, 5'–30' simulated warehouse processes



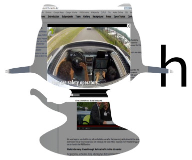


- ASP solver determines models for process occurrences
  - consistent with qualitative spatial background theory
  - missing knowledge (zone whereabouts) gets supplemented

▶ knowledge-level querying **requires** reasoning

Related Application

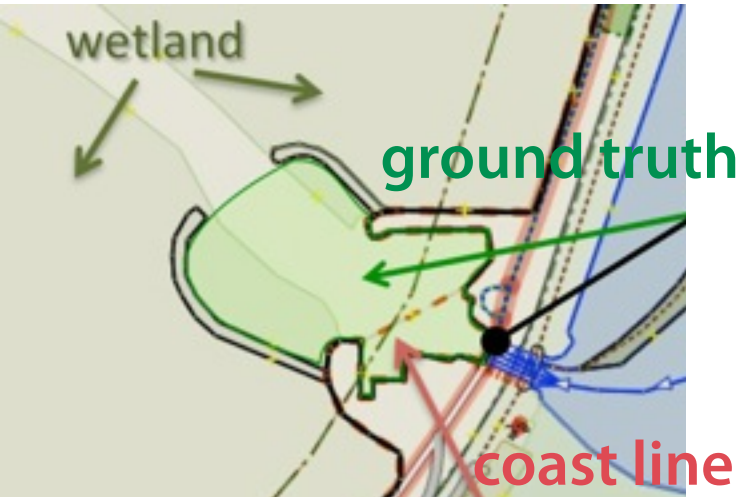
- space usage rules: querying a spatial database whether a specific activity is permitted at a certain location
  - originally motivated by wildfire incident (cp. Samsonov '14)
- dataset collected of signs and areas they refer to



https://github.com/hopfkons/prohibitionSigns

  - about 1/3 of all signs do not refer to OSM entities

▸ reasoning required to implement semantics



Spatio-Temporal Knowledge

- so far action representation remains ad hoc
  - foundations: qualitative calculi, conceptual neighborhoods
  - no formal semantics: no reasoning about rules themselves
- LTL-approach first step towards integrated space-time
  - cannot capture branching time (planning, explanation)
  - cannot capture spatial change

▶ explore temporal logics for integrating spatial and temporal knowledge

Navigation Rules

- in temporal logic, we could specify safe actions using this pattern:

$$\phi_{\text{context}} \wedge \phi_{\text{action}} \rightarrow \circ\,(\phi_{\text{action}'}\, U\, \phi_{\text{safe}})$$

- Kreutzmann defined logic CNL to capture spatial change
  - allows us to state that two time steps must be connected by conceptual neighborhood transitions
- example passive safety of ground transportation vehicles:

$$\Box\phi_{\texttt{rules}} \wedge \phi_{\texttt{drive command}} \wedge \circ\Big(\overbrace{\big(\phi_{\texttt{break command}} \wedge [cn]\,\neg\phi_{\texttt{collision}}\big)}^{\texttt{breaking path is clear}}\, U\, \phi_{\texttt{stopped}}\Big)$$

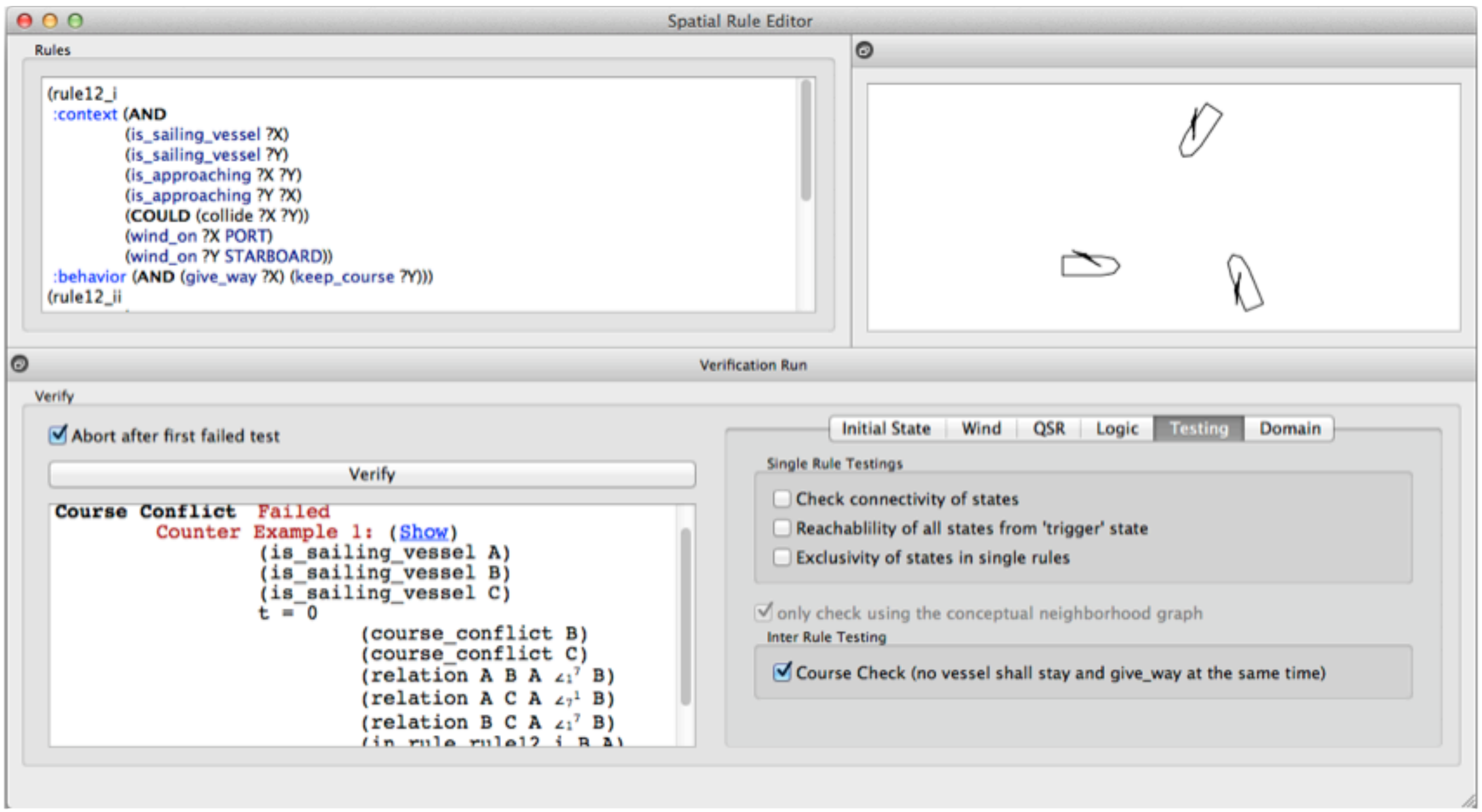
left yields to right,…

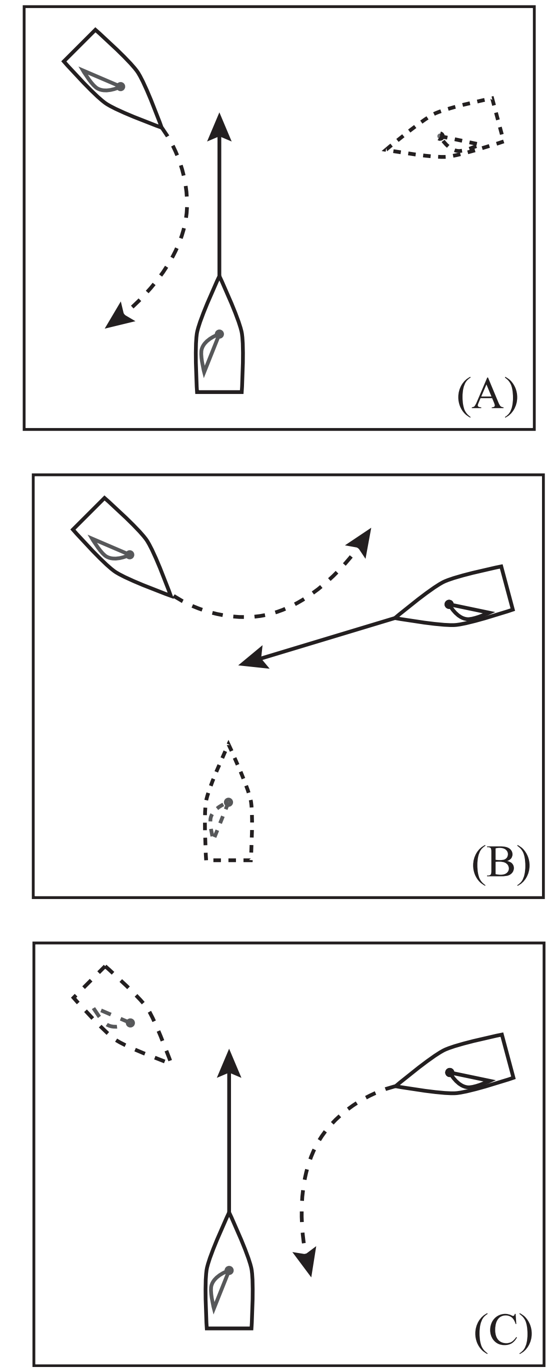
state continuation

stop…full speed

Rule Consistency

- given navigation rules as formulae, one can…
  - check every state allows for an admissible action
  - check rules for contradictions

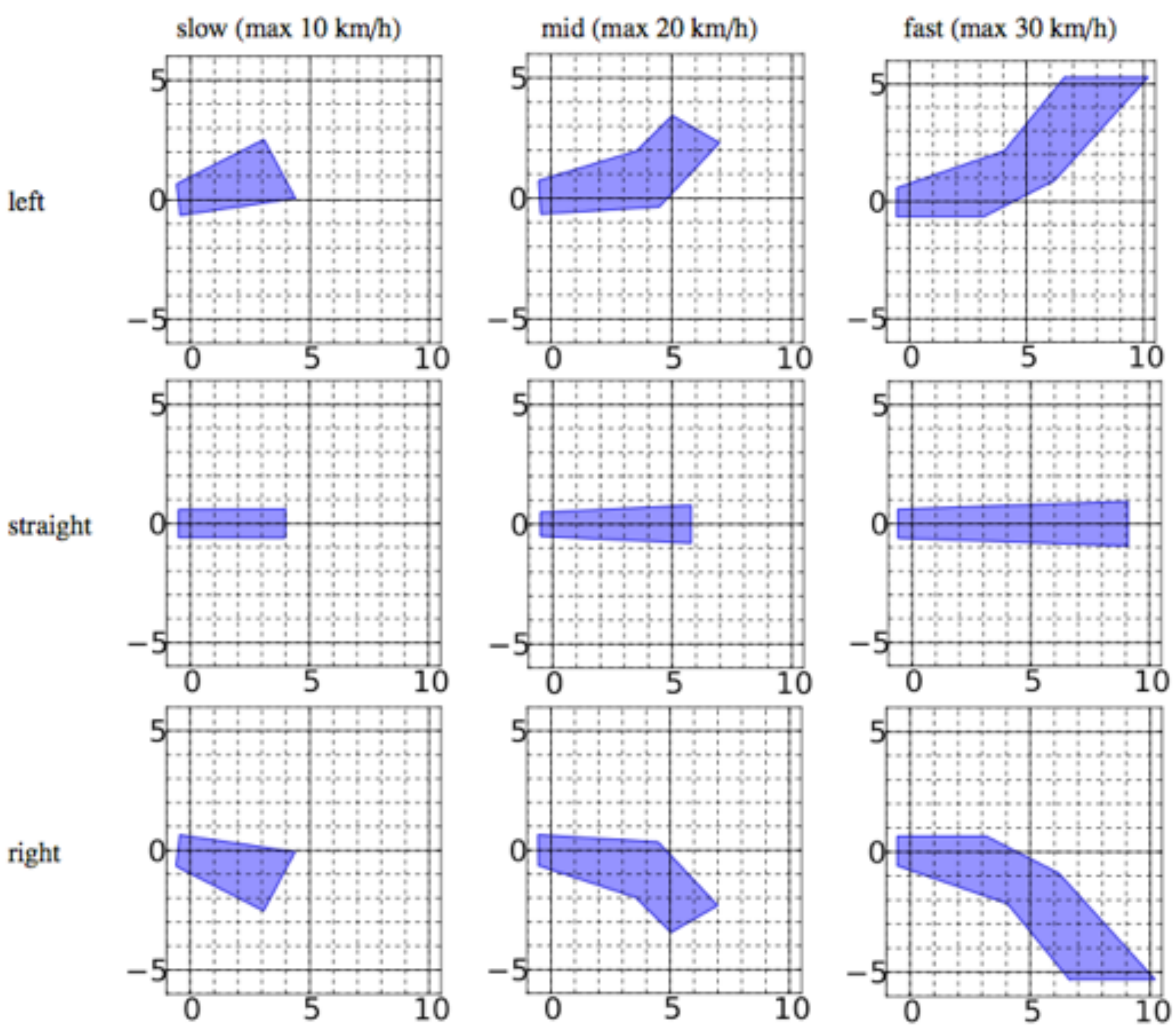


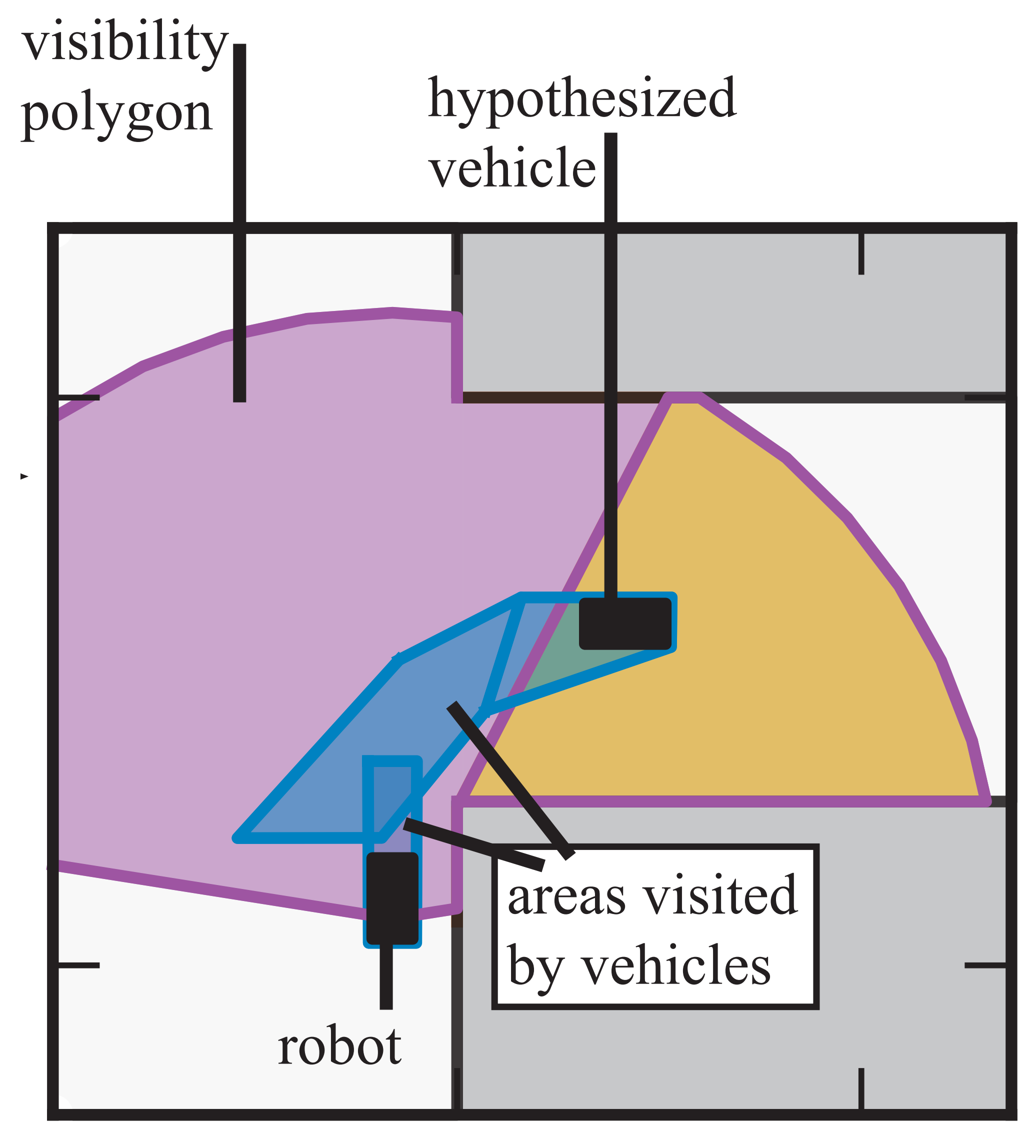


▶ re-discovered that COLREGS are conflicting

Example

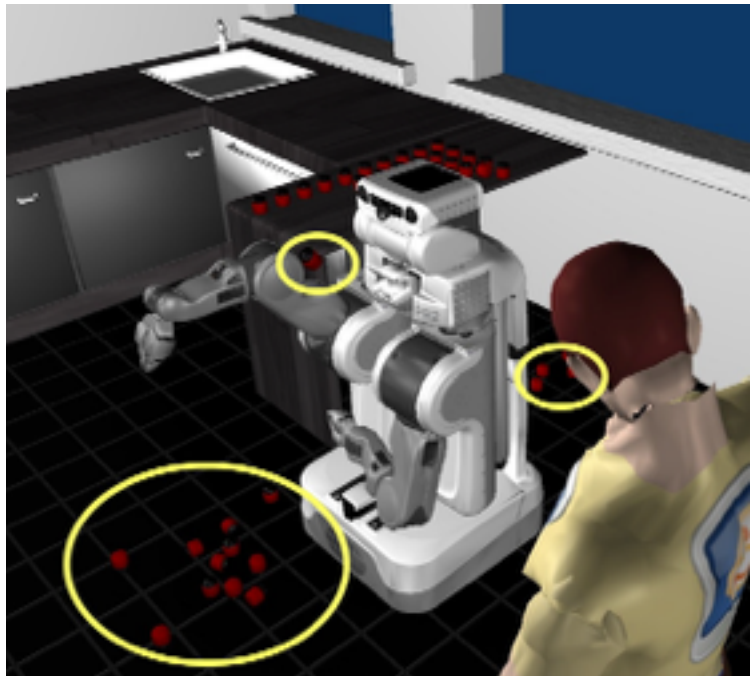
- for the vehicle at hand, appropriate safety regions are modeled
- given knowledge about the environment, safety of actions can be decided

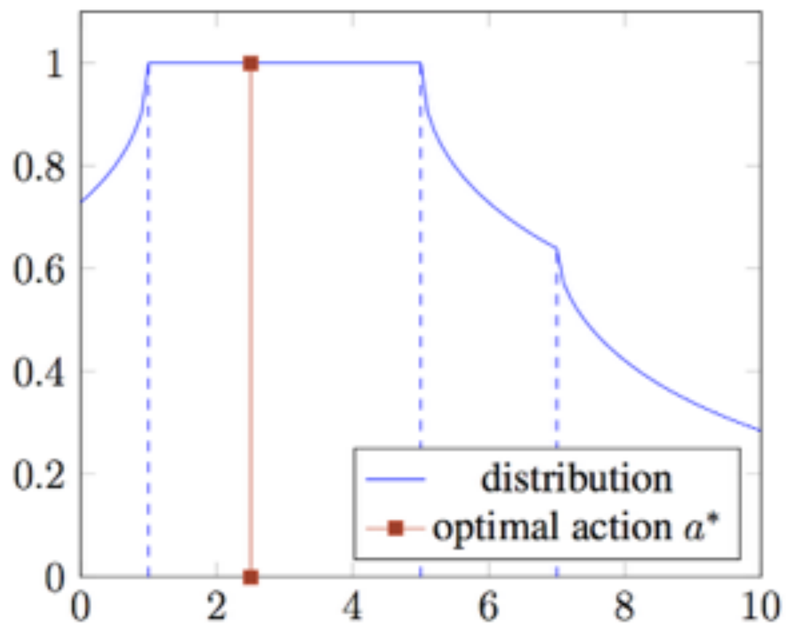


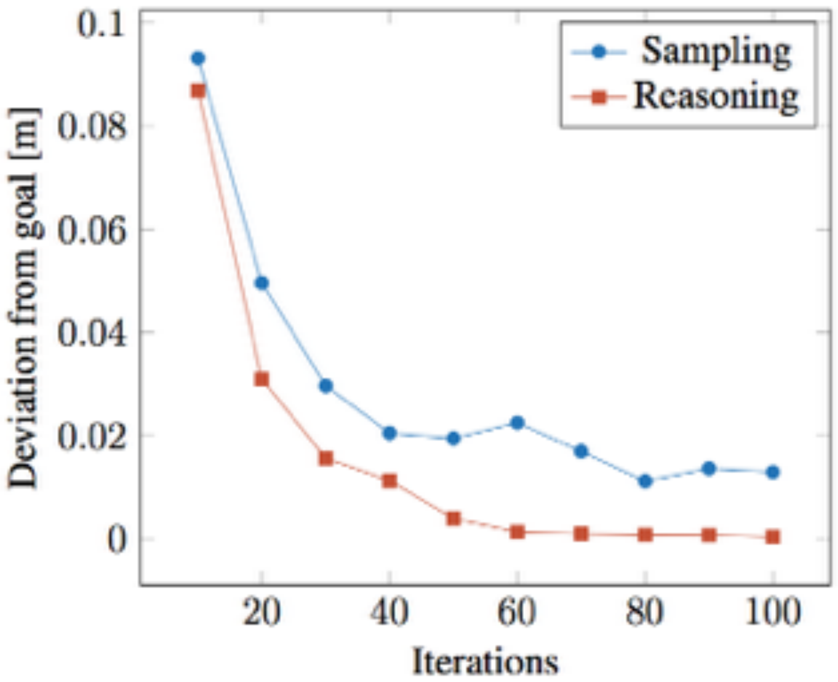


Related Applications

- robot manipulation: learning to toss
  - neither symbolic planning nor learning alone sufficient
  - represent tasks and background knowledge of action effects
  - manipulate random distribution used in randomized planner according to inference



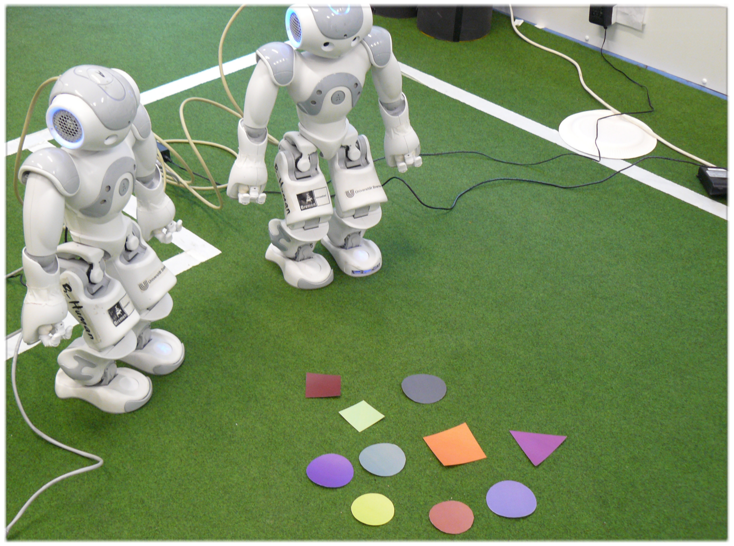


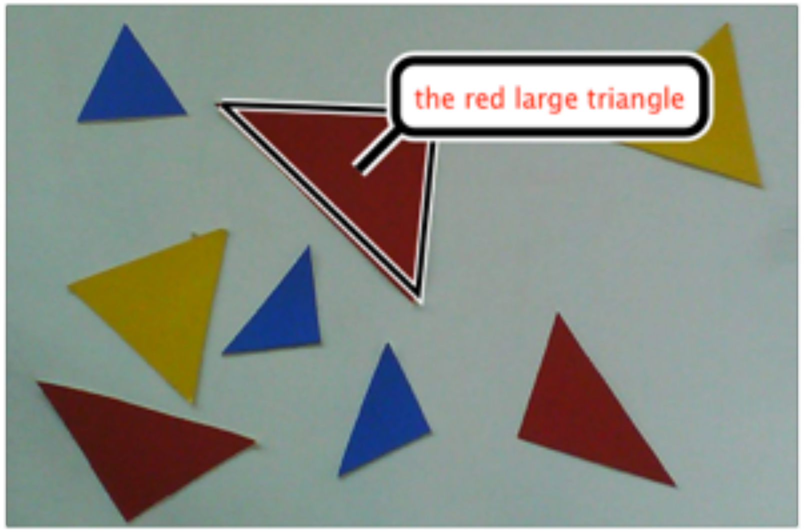


▶ reasoning leads to more efficient and robust learning

QSR for NLP

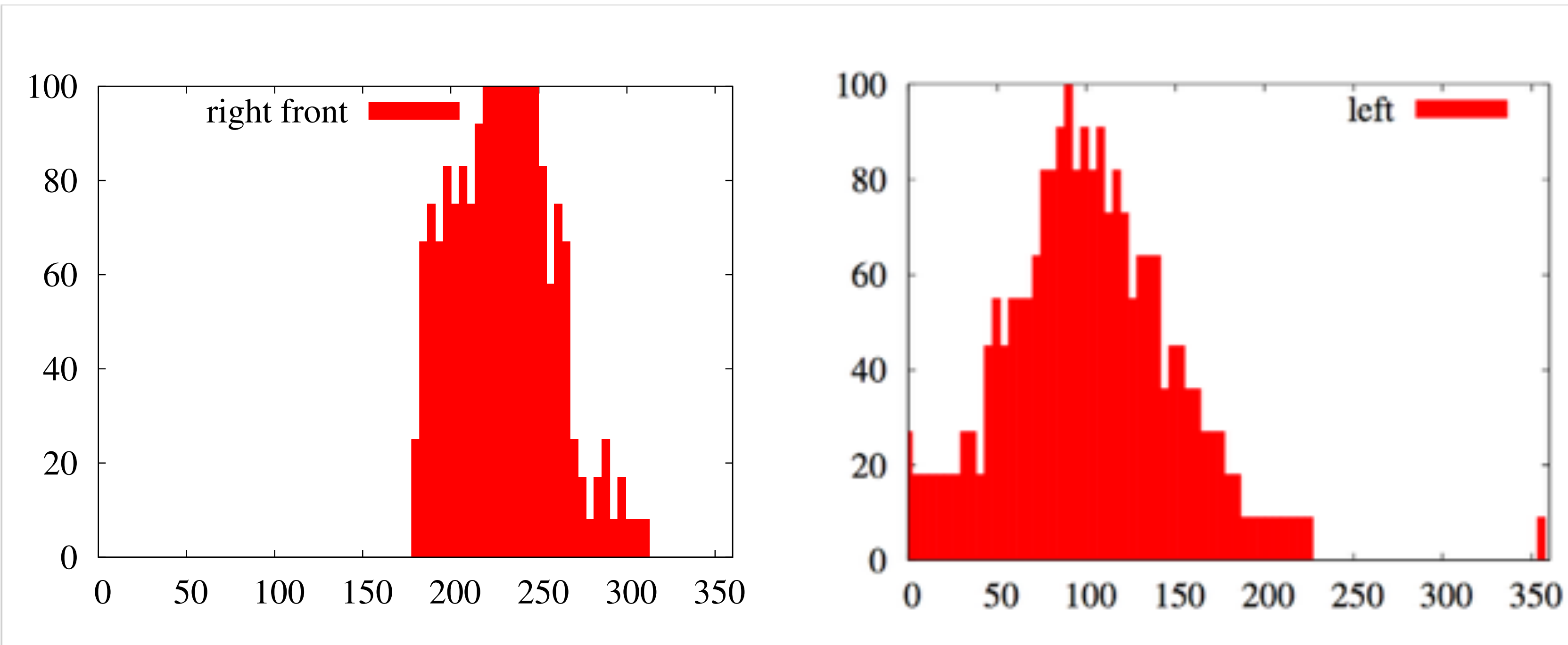
- understanding and generating referring expressions
  - focus on spatial language
  - idea: identify & remove redundancy using spatial reasoning
  - applications considered: route instruction, human-robot collaboration and smart environments





Projective Relations

- several models for projective relations (left of, etc.) proposed
- idea: use machine learning to identify models
  - QSR using probabilistic inference



sample models

grouping experiment

▸ need to handle vague semantics

Application Wrap-Up

- **reasoning for navigation**
  - single calculus
  - qualification, consistency checking
- **process recognition**
  - matching observations against patterns
  - logic inference
- **verifying navigation rules**
  - multiple calculi
  - partially grounded information
  - computing realizations
- **learning manipulation tasks, interpreting and generating referring expressions**
  - vague (probabilistic) relation semantics

QSR for Applications

- representations can often not be restricted to single calculi
  - quantitative knowledge important too
  - ▶ need to learn how to integrate formalisms in a flexible manner
- qualitative reasoning useful in all applications sketched today
  - often needs to be linked with additional techniques
  - ▶ understand the connection of qualitative and other forms of reasoning ('reasoning' in a broad sense)

- Are we ready for applications?
  - Yes, but individual adaptions still required – we are, our tools not yet

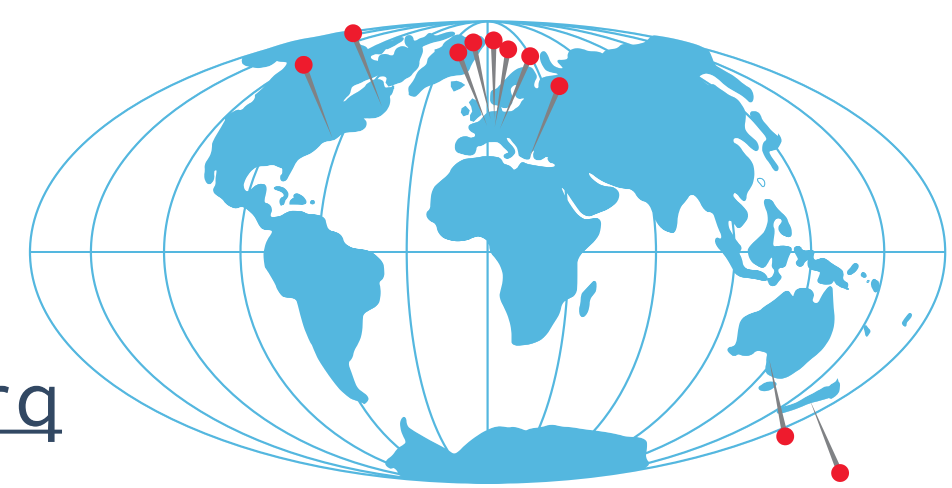
SparQ Toolbox

- applications have been realized using SparQ
- in 2006, no implementation of qualitative reasoning methods
- implementing QSTR methods requires substantial effort
  - inhibits applications using QSTR

SparQ Toolbox

- applications have been realized using SparQ
- in 2006, no implementation of qualitative reasoning methods
- implementing QSTR methods requires substantial effort
  - inhibits applications using QSTR
- SparQ started as an internal project in 2006
- as of today, ~20,000 lines of code, ~28,000 lines of calculus definitions, users in different research communities

http://github.com/dwolter/sparq



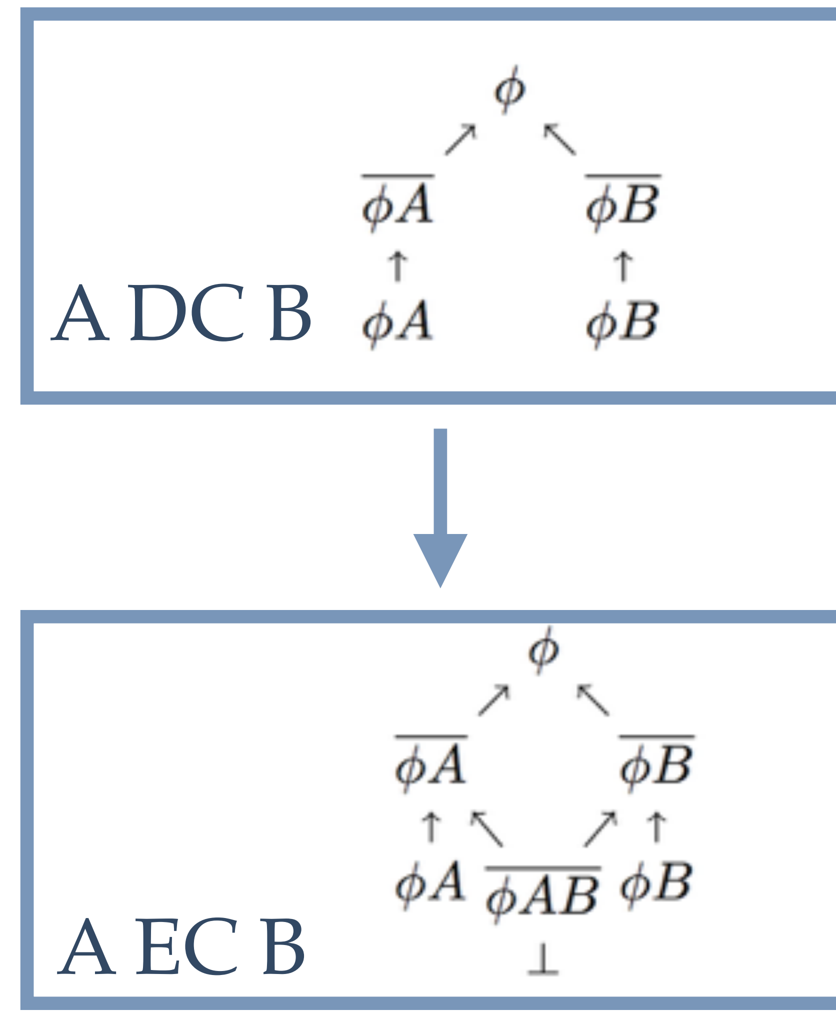
- co-evolution: basic research, tools, applications, benchmarks

Mixed Qualitative-Quantitative Logic

QSTR calculi expressible using disjunctive LPs:

calculus	domain	aspect	encoding
Allen's interval algebra	time intervals	ordering, overlap	✔
INDU	time intervals	ordering, overlap, duraction	✔
cardinal direction calculi	2D points/ polygons	direction, topology	✔
StarVars	2d oriented points	relative direction	✔
OPRA	2d oriented points	relative direction	discretized orientation
RCC	region	topology	N-vertex poly-gons/polyhedra

analogical representations:



Summing up…

- **qualitative spatial representation and reasoning**
  - multi-disciplinary, motivated by human cognition and efficient computability
  - links symbolic reasoning with representation of real-world contexts
  - can be workhorse for many applications
- **Intelligent service robots**
  - broad application area related to many AI problem areas
  - re-integration of AI techniques suggest leap ahead

…and looking ahead

- breakthrough of QSR questioned at times is likely
- some important problems remain

1. gain deep understanding of computational effects of specific relation/domain combinations
   - crisp vs. vague semantics
   - classification of algorithmic categories
   - reasoning based on semantics of relations only
   - overcome (single-)calculus limitations
2. understand links between QSR and other state-of-the-art AI techniques
3. provide application-ready tools

Thank you!

Thank you!

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