A Representation for Spatial Reasoning in Robotic Planning

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Main Objective

- **Main Objective:** enhancing autonomy of robots through AI based planning
- **Challenge:**
  - A plan is often Qualitative – abstraction of the worlds modeled by human
  - Robots' world is Metric
- **How to bridge this gap?**
  - One way is: to employ knowledge representation with explicit metric semantic

Challenges

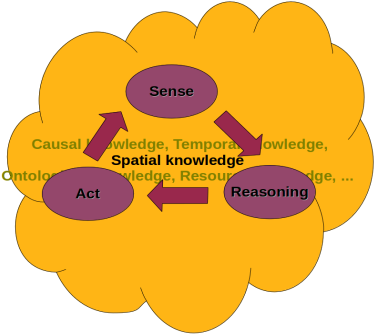
- Imagine we want to model **qualitative spatial relations** such as:

> "the fork should be on the left of the dish"
> "the dish should be between fork and knife"

- **Question-1** : How do we endow a robot with the ability to **translate qualitative knowledge to actionable metric knowledge?**
- **Question-2** : How to explicitly include metric knowledge into qualitative while maintaining convenient modeling?

Main Question

How to include Spatial representation/reasoning in Sense-Plan-Act loop



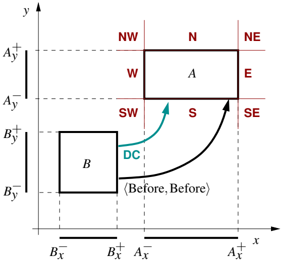
Spatial Reasoning in three Important Phases
Sense-Plan-Act Loop

- **Grounding:** matching perceived context with qualitative knowledge about the environment
- **Planning:** instantiating qualitative plans into the metric space of the real world
- **Plan execution:** detecting and reacting to contingencies

We introduce a qualitative constraint-based calculus augmented with metric relations for use in all three phases

Rectangle Algebra

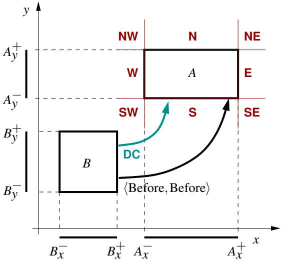
- **Variables:** axis-parallel bounding boxes
- **Constraints:** 2D Allen's Interval relations
  - e.g., B ⟨Before, Before⟩ A



- Subsumes cardinal and topological relations
  - e.g., B ***southwest*** A
  - e.g., A ***disconnected (DC)*** B

Augmented Rectangle Algebra (ARA)

- **Variables:** axis-parallel bounding boxes
- **Constraints:** 2D Allen Interval relations with **metric bounds**
  - e.g., B $\langle \text{Before}[5, \infty), \text{Before} \rangle$ A



- Subsumes cardinal and topological relations
- Specifying explicit metric knowledge within qualitative knowledge

Augmented Rectangle Algebra (ARA)

$\rightsquigarrow$ metric semantics of qualitative relations

$$A\langle \mathsf{b}^{-1}[0,\infty), \mathsf{b}^{-1}[0,+\infty)\rangle B$$
$$\Leftrightarrow$$
$$(A_x^- > B_x^+) \text{ and } (A_y^- > B_y^+)$$

$\rightsquigarrow$ metric specified bounds

$$A\langle \mathsf{b}^{-1}[5,13], \mathsf{b}^{-1}[0,+\infty)\rangle B$$
$$\Leftrightarrow$$
$$(A_x^- > B_x^+ + 5) \text{ and}$$
$$(A_x^- < B_x^+ + 13) \text{ and } (A_y^- > B_y^+)$$

Simple distance constraints can be used
to maintain the **metric semantic of the relation**

ARA$^+$

Binary ARA is not enough $\rightsquigarrow$ ARA plus unary constraints

- ***Size***: bounds distances points of the rectangle along x and y
  - $[l_x, u_x][l_y, u_y]$
- ***At***: bounds absolute placement of bounding boxes along x and y
  - $[l_x^1, u_x^1][l_y^1, u_y^1][l_x^2, u_x^2][l_y^2, u_y^2]$

Expressiveness of ARA$^+$

$\rightsquigarrow$ desired spatial layout of objects

"fork should be left of the dish"

$\Leftrightarrow$

Fork $\langle \mathrm{b}, \mathrm{d}^{-1} \rangle$ Dish

"fork at least 5cm from edge of table"

$\Leftrightarrow$

Fork $\langle \mathrm{d}[5, +\infty)[5, +\infty), \mathrm{d}[5, +\infty)[5, +\infty) \rangle$ Table

$\rightsquigarrow$ observed spatial layout of objects

"table is 70x70 cm"

$\Leftrightarrow$

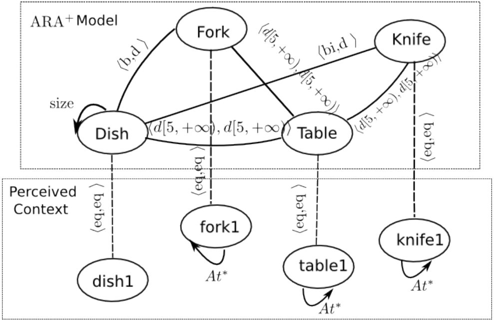
Table $\langle \mathit{Size}[70, 70][70, 70] \rangle$

Position of the fork

$\Leftrightarrow$

fork1 $\langle \mathit{At}[3, 5][10, 20][13, 17][22, 29] \rangle$

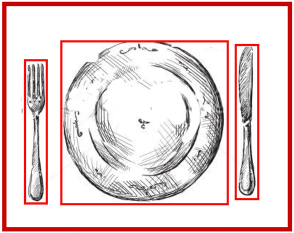
ARA^{+} for Grounding



Is perceived context consistent wrt knowledge?

$\Leftrightarrow$

Is the ARA^{+} network consistent?



Consistency Checking

ARA^+ network translated to two Simple Temporal Networks (STP [Dechter et al., 1991], one for each axis)

Theorem

ARA^+ network is consistent

$\Leftrightarrow$

STP_x and STP_y are path-consistent

Proof based on [Condotta, 2000; van Beek, 1990]

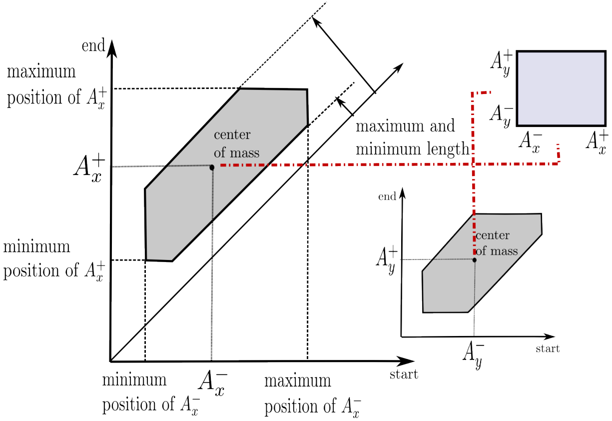
ARA$^+$ for Planning

Instantiating plans into metric space of the real world

- Placement of objects consistent with spatial knowledge = solution of the spatial CSP
- **Q:** There are many solutions (object placements), which one is better?
- **A:** The one that is most robust to inaccuracy of manipulation

Using SOPO representation [Rit, 1986] to obtain "most centered" solution

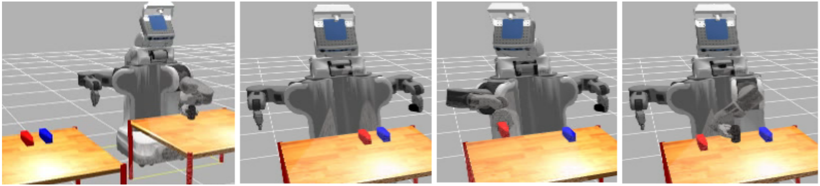
ARA$^+$ for Planning



Two 2D representation of an interval

ARA^+ for Plan Execution

Detecting and reacting to contingencies



ARA$^+$ for Plan Execution

- **Q:** How to fix an inconsistent placement of objects?
- **A:** Each **culprit set** $\{At_1, \ldots, At_n\}$ recommends a set of n objects to re-place
- Employing two heuristics to select a culprit set

Heuristic 1:

> small sets $\Rightarrow$ less pick and place actions

Heuristic 2: (inspired by [Hunsberger, 2002])

> high spatial flexibility $\Rightarrow$ more room to mis-place objects

Ongoing and Future Work

- Explore more expressive, tractable fragments of ARA^{+}
- Integrating spatial reasoning with temporal, resource and causal reasoning
  - use meta-constraint reasoning techniques
- Investigating Augmented Block Algebra

Questions?