KU LEUVEN

DTAI

From Atoms to Possible Worlds

Probabilistic Inference in the Discrete-Continuous Domain

Pedro Zuidberg Dos Martires

Probabilistic Artificial Intelligence

Artificial Intelligence?

Artificial Intelligence?

agent machine program

that queries the world

Probabilistic Artificial Intelligence

Artificial Intelligence?

agent machine program

that queries the world

How is the world queried?

Through **measurement devices**

➔ inevitability of **noise and uncertainty**

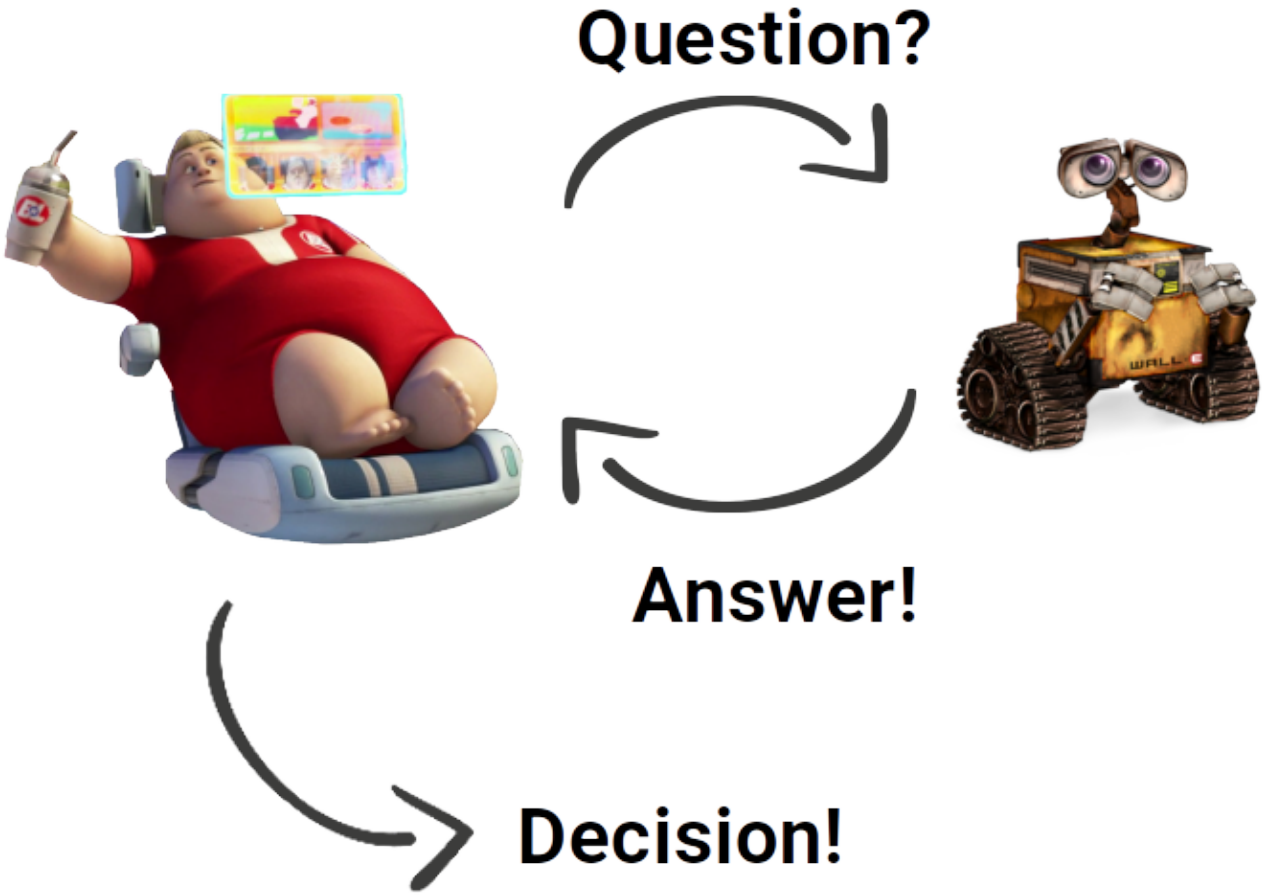
Artificial Intelligence?

agent machine program

that queries the world
and
makes decisions

Humans and AI

Humans and AI



Humans and AI

Humans and AI

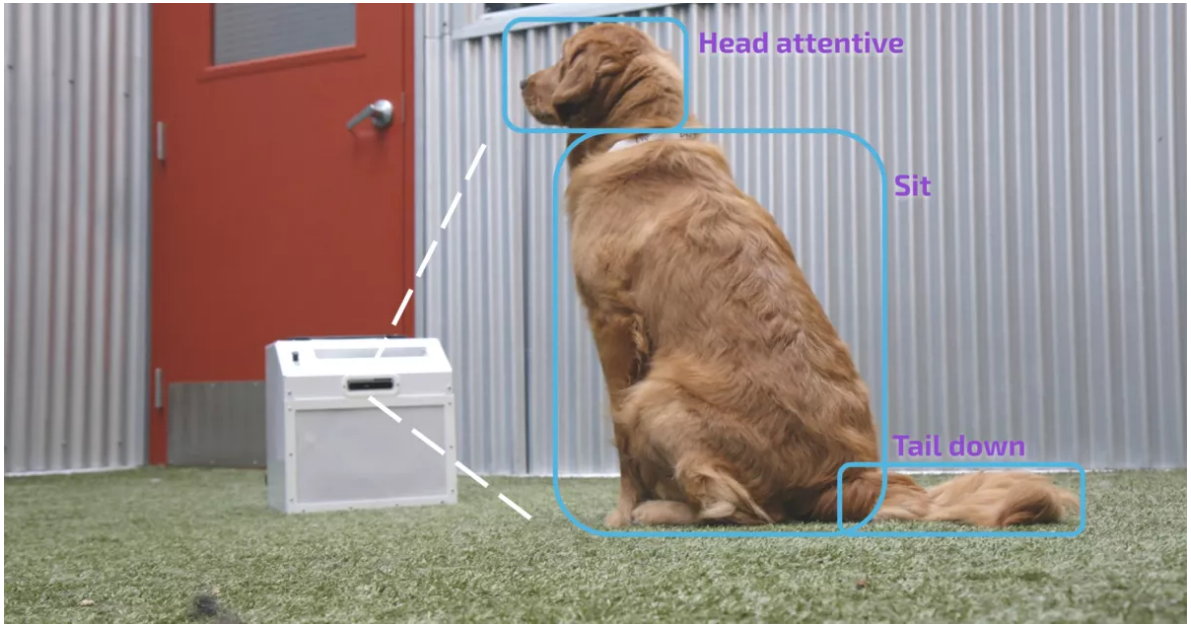
Which decisions do we want an AI to make for us?

This is a social question not a technical one!

Human Intelligence vs. Artificial Intelligence

What is the difference?

Human Intelligence vs. Artificial Intelligence



“But the AI does not know what it means.”

Human Intelligence vs. Artificial Intelligence

- Nigel Richards
- French Scrabble champion

Clearly intelligent.

Human Intelligence vs. Artificial Intelligence

- Nigel Richards
- French Scrabble champion

Clearly intelligent.

- Is from New Zealand
- Does not speak French

Does not know what the words mean.

Human Intelligence vs. Artificial Intelligence

Bottom line: human intelligence is a tricky concept.

Let alone artificial intelligence: when is a machine intelligent?

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Probabilistic AI at Three Levels of Abstraction

1. **Microscopic Level:** Weighted Model Integration
2. **Macroscopic Level:** Probabilistic Logic Programming
3. **Cognitive Level:** Probabilistic Perceptual Anchoring

Probabilistic AI at Three Levels of Abstraction

1. **Microscopic Level:** Weighted Model Integration
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focus on discrete-continuous domains

Microscopic Level

Weighted Model Integration

$$\phi \leftrightarrow a \wedge (0 < x) \wedge (x < 3) \wedge (0 < y) \wedge (y < 2) \wedge (x < y) \bigvee$$
$$\neg a \wedge (0 < x) \wedge (x < 3) \wedge (0 < y) \wedge (y < 2) \wedge (x < y + 1)$$

$w(a) = 0.2$, $w(\neg a) = 0.8$, $w(x) = 2x$, $w(y) = y^2$

- Weighted SMT formulas constitute an **assembly language** for probabilistic modeling.
- SMT atoms are the **indivisible building blocks**.

Microscopic Level

Weighted Model Integration

$$\phi \leftrightarrow a \wedge (0 < x) \wedge (x < 3) \wedge (0 < y) \wedge (y < 2) \wedge (x < y) \bigvee$$
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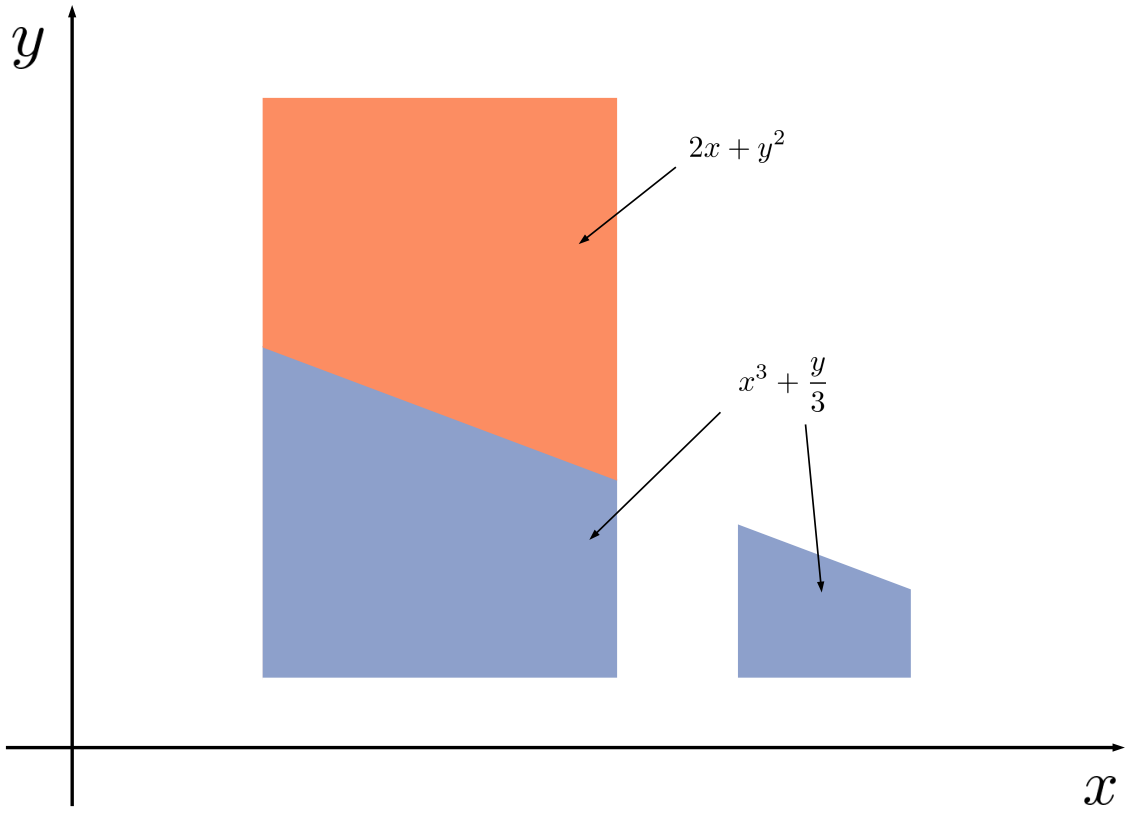
- Weighted SMT formulas constitute an **assembly language** for probabilistic modeling.
- SMT atoms are the **indivisible building blocks**.

How do we perform inference?

$$w(\phi) = ?$$

Microscopic Level

Geometric Interpretation



How big are the colored areas?

Microscopic Level

RQ1

Can we adopt inference algorithms from the purely discrete domain or the purely continuous domain to develop novel weighted model integration solvers?

Microscopic Level

Contribution 1

A set of novel algorithms that perform probabilistic inference for WMI.

	exact	approximate
Symbo	✓	
Sampo		✓
F-XSDD(BR)	✓	
F-XSDD(MCAD)		✓

Microscopic Level

What do all four solvers have in common?

$$
\begin{aligned}
&\text{inference (answering a query)} \\
= \;&\text{knowledge compilation} + && \text{(hard)} \\
&\text{algebraic model count} + && \text{(easy)} \\
&\text{integration} && \text{(hard)}
\end{aligned}
$$

Microscopic Level

A set of novel algorithms that perform probabilistic inference for WMI.

	exact	approximate	integration
Symbo	✓		symbolic
Sampo		✓	MC
F-XSDD(BR)	✓		symbolic
F-XSDD(MCAD)		✓	hybrid

Microscopic Level

How are they different?

Symbo: KC + AMC + symbolic integration

Sampo: KC + AMC +Monte Carlo integration

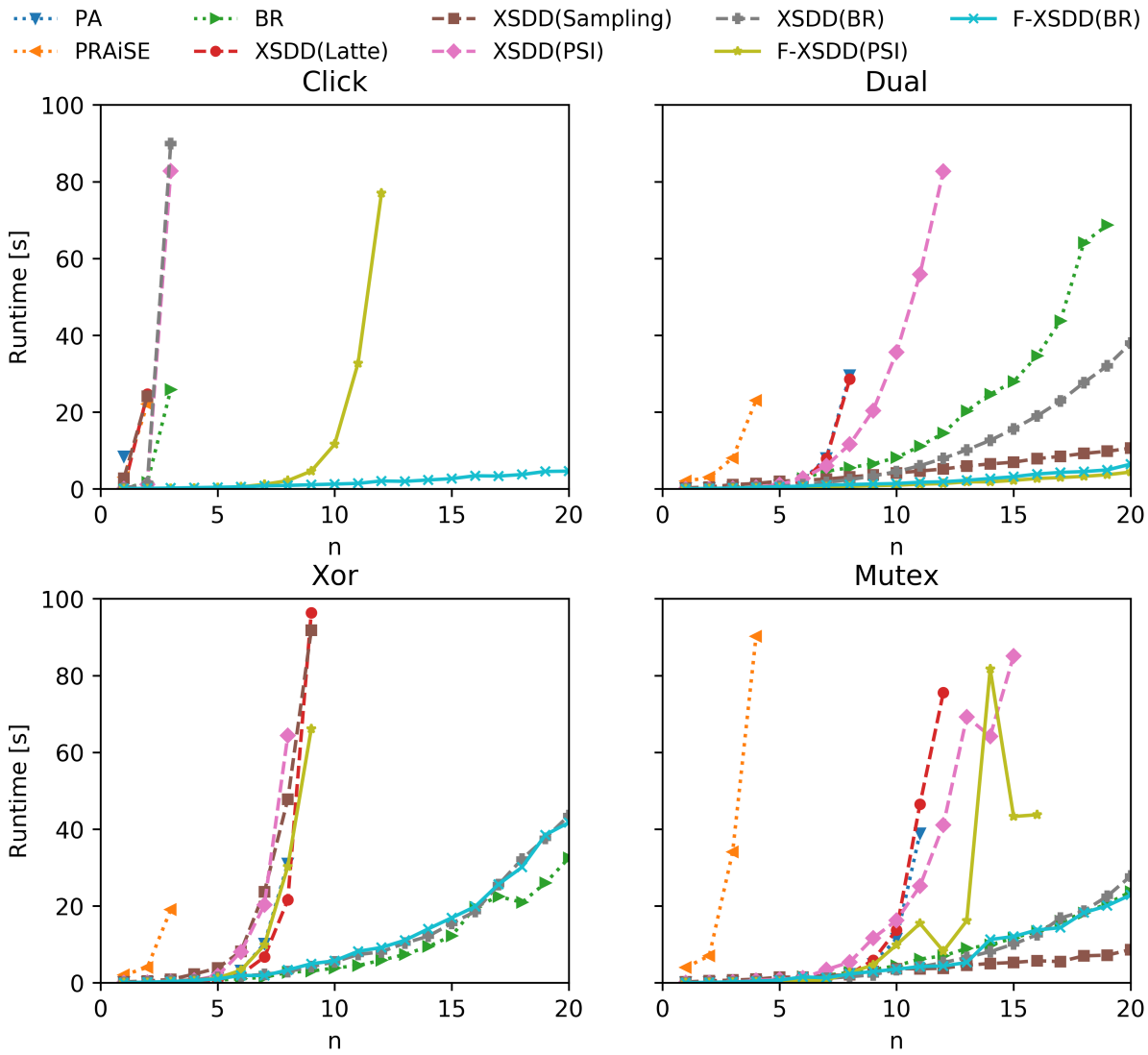
FXSDD(BR): KC + interleaving (AMC and symbolic integration)

FXSDD(MCAD): KC + interleaving (AMC and Monte Carlo integration)

New solvers are obtained by recombining and alternating KC, AMC and integration.

Microscopic Level

Experimental results for F-XSDD(BR)



Microscopic Level

Why different solvers?

Probabilistic AI is a hard problem

➔ There is no one solvers that works ‘best’ for every problem.

Probabilistic AI at Three Levels of Abstraction

1. **Microscopic level:** Weighted Model Integration
2. **Macroscopic level:** Probabilistic Logic Programming
3. **Cognitive Level:** Probabilistic Perceptual Anchoring

Macroscopic Level

Motivation: Expressive Power

"I estimate that rules of chess, in propositional logic [...], would be about 100.000 pages. As opposed to 1 page in first-order logic."

— Stuart Russell

Macroscopic Level

Motivation: Expressive Power

"I estimate that rules of chess, in propositional logic [...], would be about 100.000 pages. As opposed to 1 page in first-order logic."

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➔ modeling problems at a low level can be cumbersome

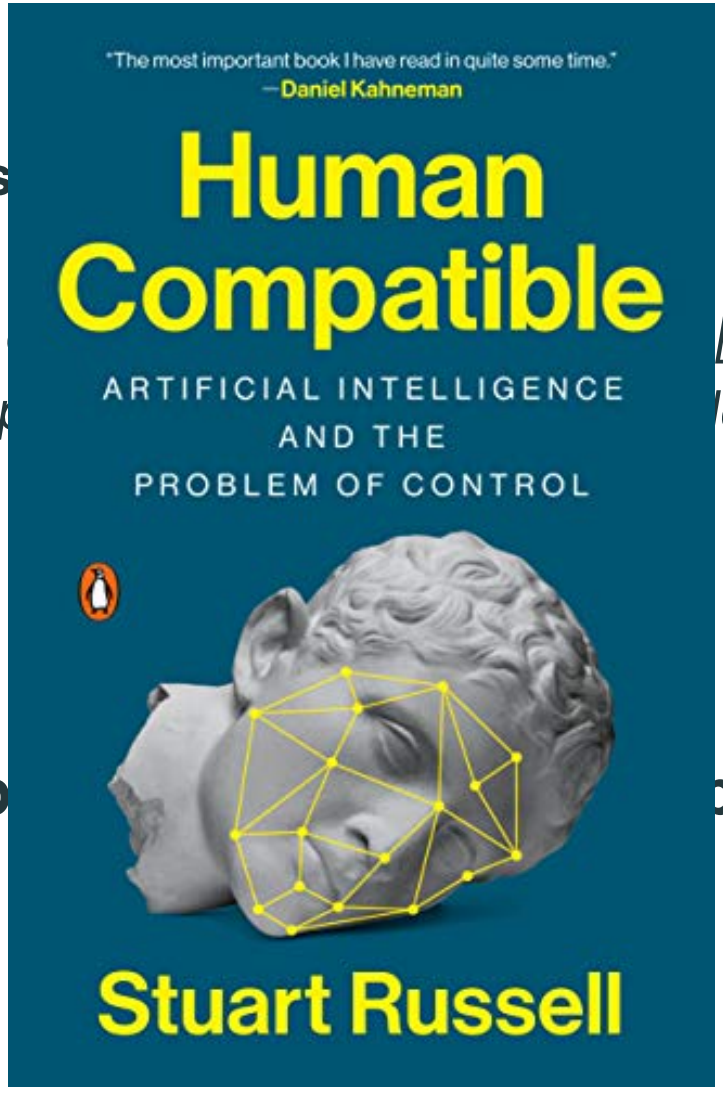
Macroscopic Level

Motivation: Express

"I estimate that rules [...], would be about 100.000 pages. As op logic."

— Stuart Russell

➔ modeling prob be cumbersome



Macroscopic Level

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"I estimate that rules of chess, in propositional logic [...], would be about 100.000 pages. As opposed to 1 page in first-order logic."

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➔ modeling problems at a low level can be cumbersome

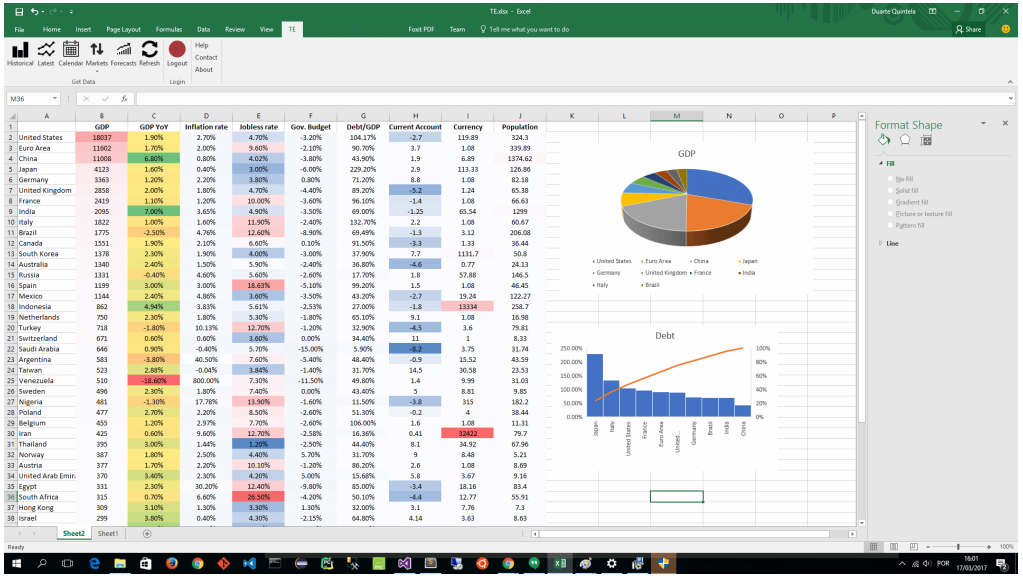
Macroscopic Level

RQ2

Can we develop a high-level probabilistic logic programming language for which inference reduces to weighted model integration?

Macroscopic Level

Probabilistic Programming?



deterministic:

Cell = 420

probabilistic:

Cell = FLIP()

Macroscopic Level

Contribution 2

DC-ProbLog: a probabilistic logic programming language for the discrete-continuous domain.

Macroscopic Level

Contribution 2

DC-ProbLog: a probabilistic logic programming language for the discrete-continuous domain.

1. **type system** for DC-ProbLog → **neat and clean syntax**

Macroscopic Level

Contribution 2

DC-ProbLog: a probabilistic logic programming language for the discrete-continuous domain.

1. **type system** for DC-ProbLog → **neat and clean syntax**
2. purely **declarative semantics** → independent of inference algorithm

Macroscopic Level

Contribution 2

DC-ProbLog: a probabilistic logic programming language for the discrete-continuous domain.

1. **type system** for DC-ProbLog → **neat and clean syntax**
2. purely **declarative semantics** → independent of inference algorithm
3. **reduce inference to weighted model integration** using algebraic model counting

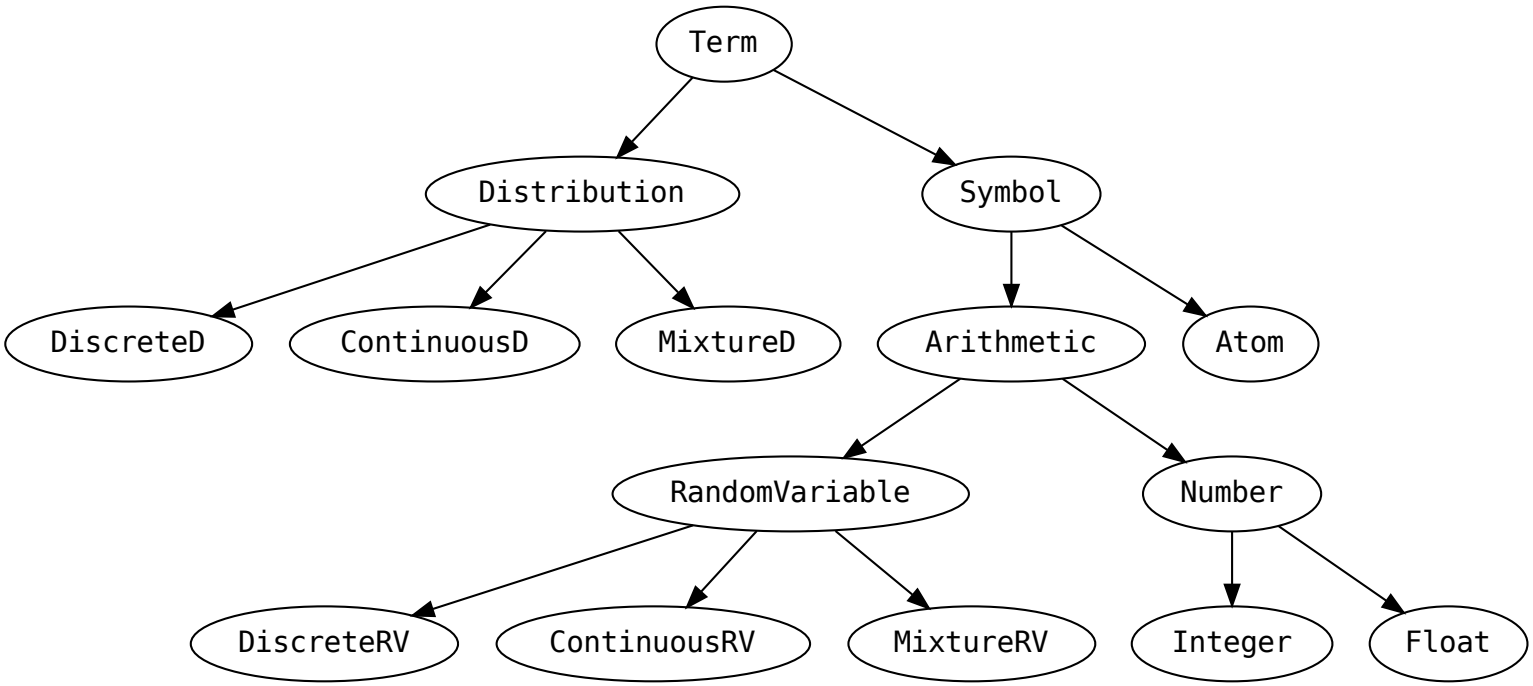
Macroscopic Level

Contribution 2

DC-ProbLog: a probabilistic logic programming language for the discrete-continuous domain.

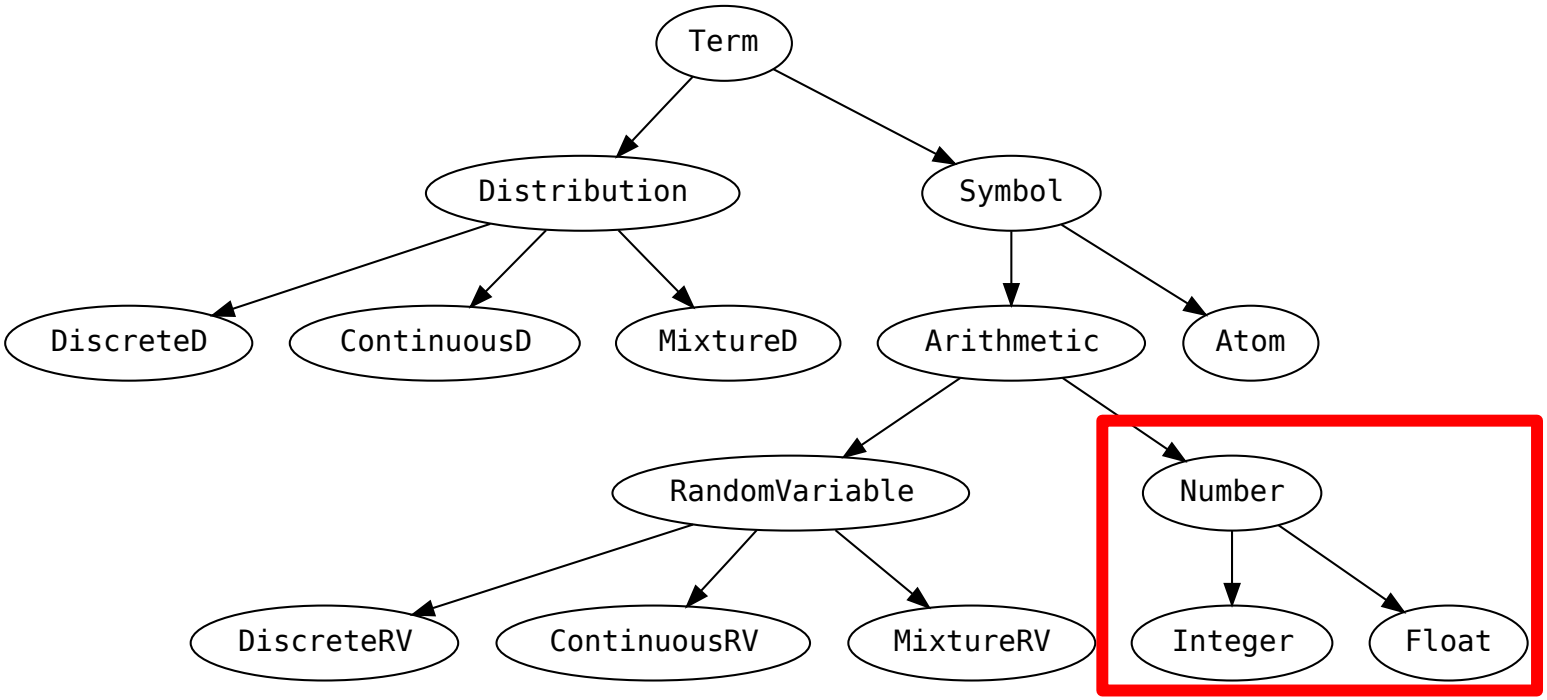
1. **type system** for DC-ProbLog → **neat and clean syntax**
2. purely **declarative semantics** → independent of inference algorithm
3. **reduce inference to weighted model integration** using algebraic model counting
4. **implementation of DC-ProbLog** → reduces naturally to ProbLog in the absence of continuous variables

DC-ProbLog Type System



Macroscopic Level

DC-ProbLog Type System



Macroscopic Level

How to define semantics? (Semantics is a fancy word for ‘meaning’.)

1. Specify core language ➔ DC-ProbLog

A DC-ProbLog program consists of three disjoint sets:

1. A countable set of **rules and facts**: how does the world work?
2. A countable set of ground **probabilistic facts**: what is uncertain?
3. A countable set of ground **distributional facts**: what is uncertain?

Macroscopic Level

How to define semantics? (Semantics is a fancy word for ‘meaning’.)

1. Specify core language ➔ DC-ProbLog
2. Specify language with minimal syntax ➔ DC-PLP

define **program transformation** and **semantics**

Macroscopic Level

How to define semantics? (Semantics is a fancy word for ‘meaning’.)

1. Specify core language ➔ DC-ProbLog
2. Specify language with minimal syntax ➔ DC-PLP
3. Add syntactic sugar ➔ DC-ProbLog with distributional clauses

```
temperature ~ normal(27,5):- hot.
```

Macroscopic Level

How to perform inference?

$$p(\texttt{query(q)}) = p(\phi_q) = \mathrm{WMI}(\phi_q, w_q)$$

Reduction to weighted model integration.

"Compilation" from the macroscopic level to the microscopic level.

Introduced new algorithm for conditioning on zero-probability events.

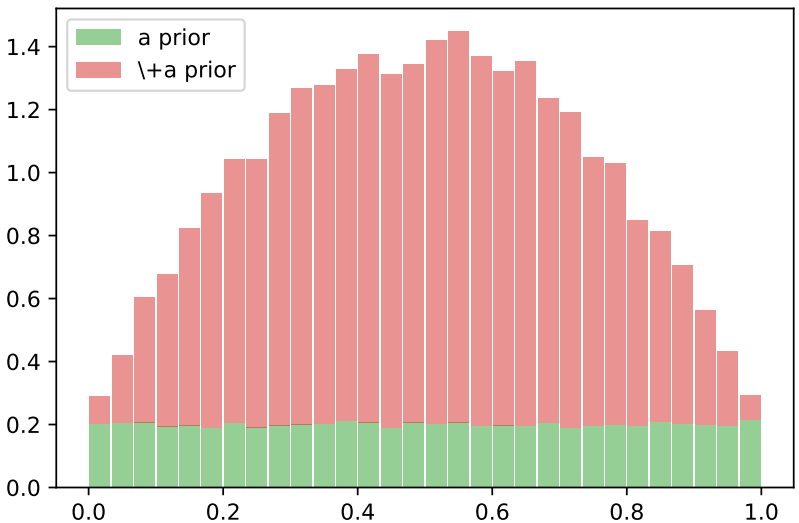
Macroscopic Level

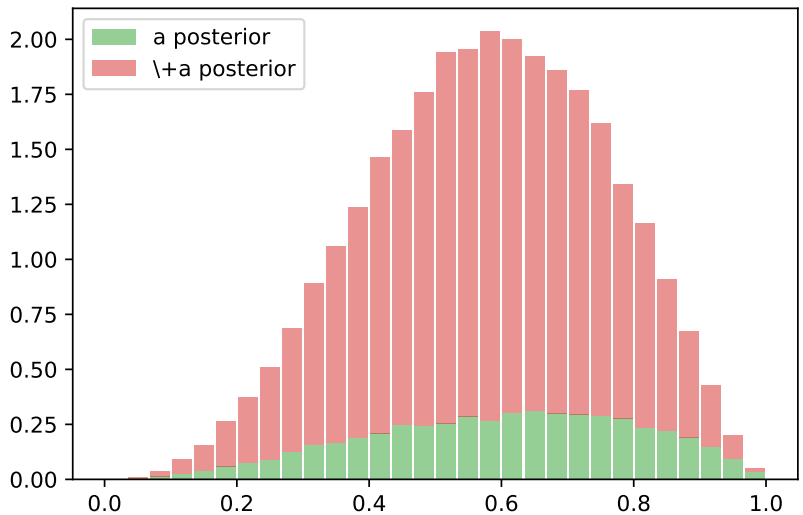
Bayesian Learning

```
0.2::a.
b~beta(1,1):- a.
b~beta(1,2):- \+a.
B::coin_flip(N):- B is b.

evidence(coin_flip(1), true).
evidence(coin_flip(2), false).
evidence(coin_flip(3), true).

query_density(b).
```

Macroscopic Level

Bayesian Learning





Macroscopic Level

Unique Selling Point

Our implementation uses **directed acyclic graphs** to represent probability distributions.

Probabilistic AI at Three Levels of Abstraction

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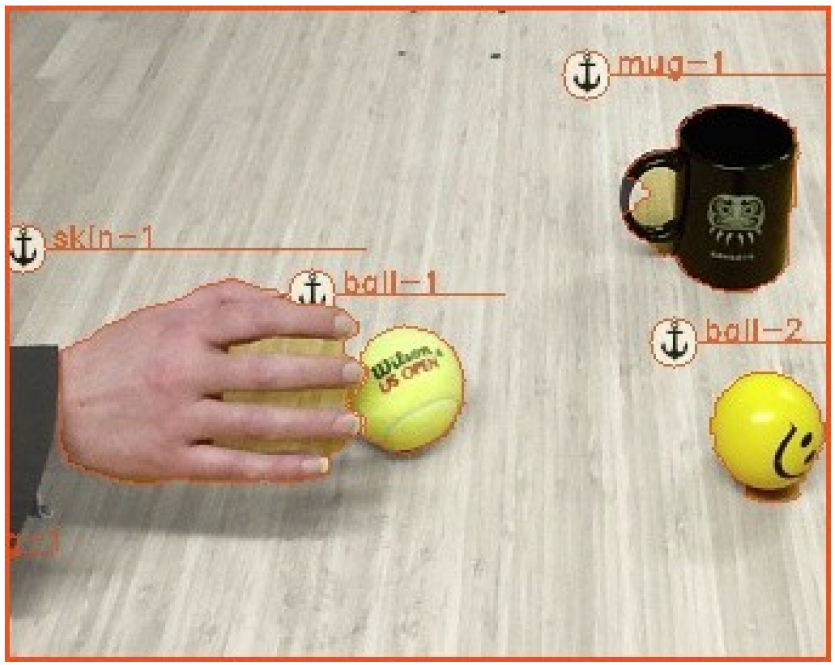
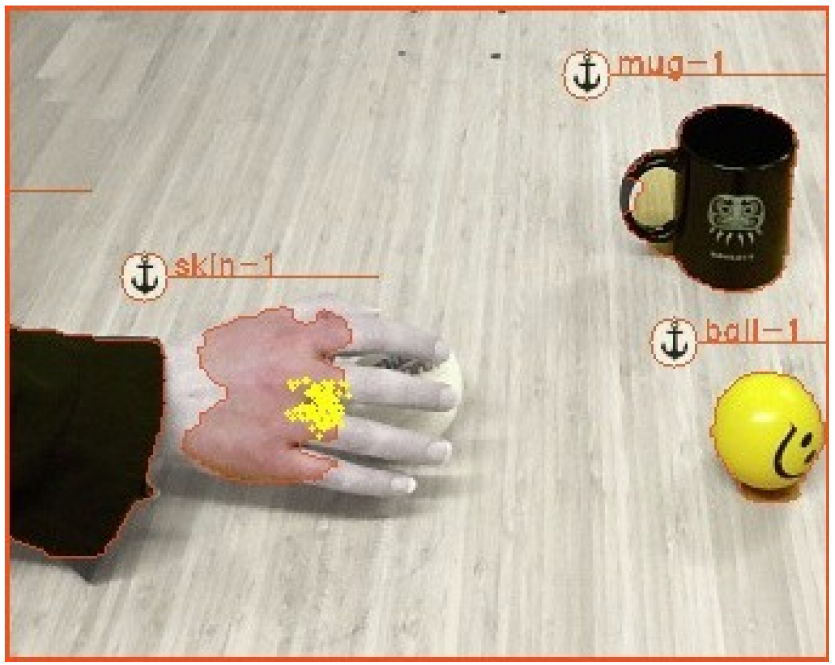
Cognitive Level

Motivation



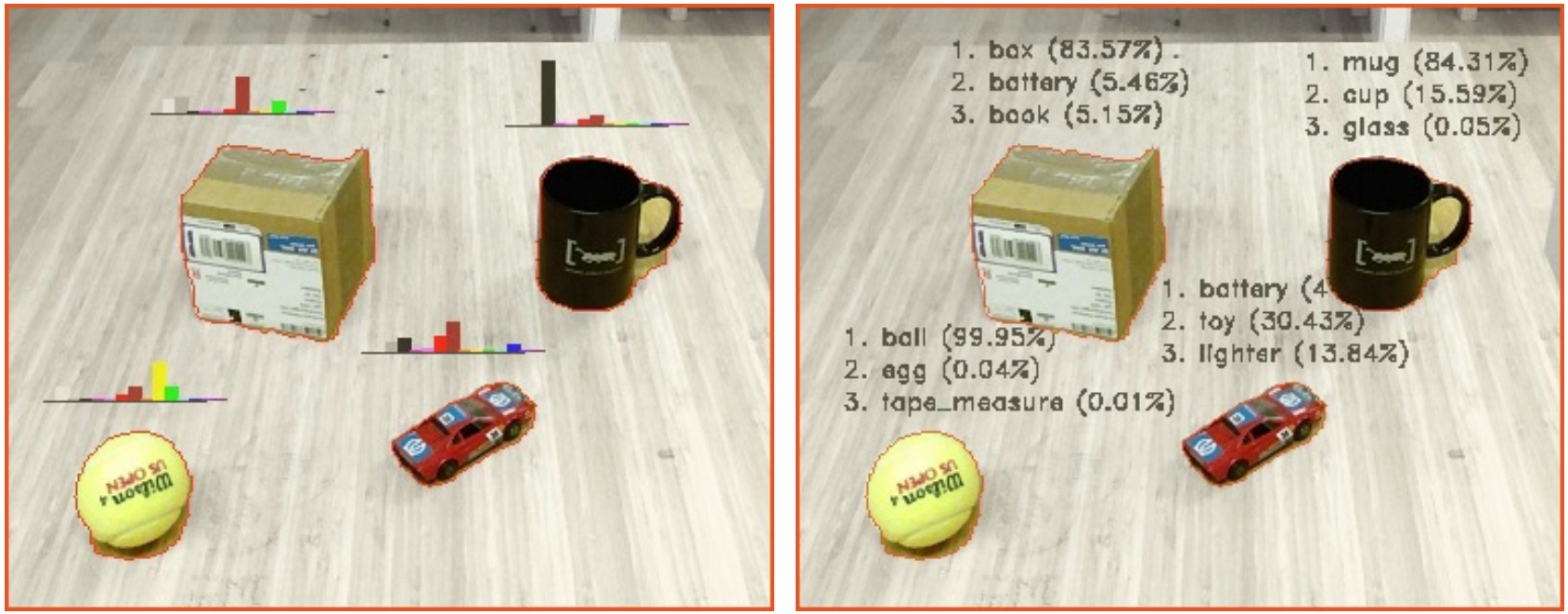


perception + reasoning + **uncertainty**

Cognitive Level

Problem

Creating and maintaining over time the correspondence between symbols and sensor data.



Cognitive Level

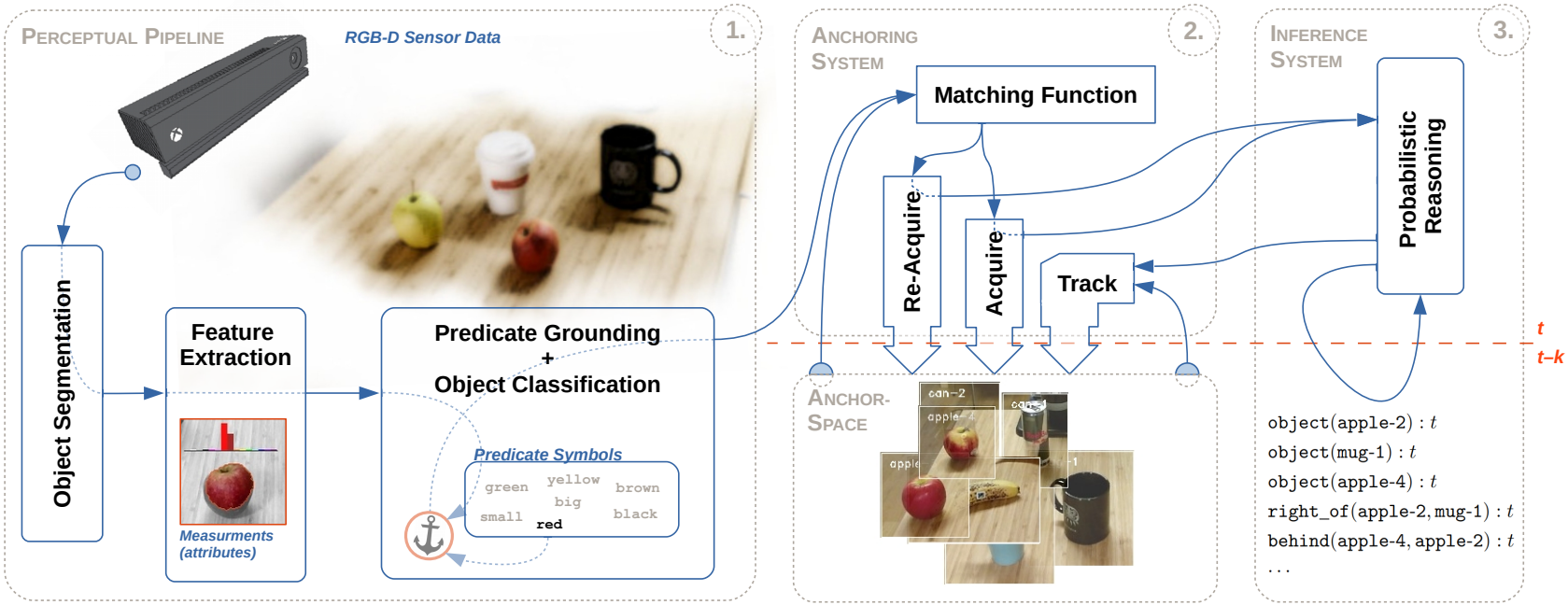
RQ3

Can we equip a cognitive robotics systems with the capability of probabilistic reasoning?

Cognitive Level

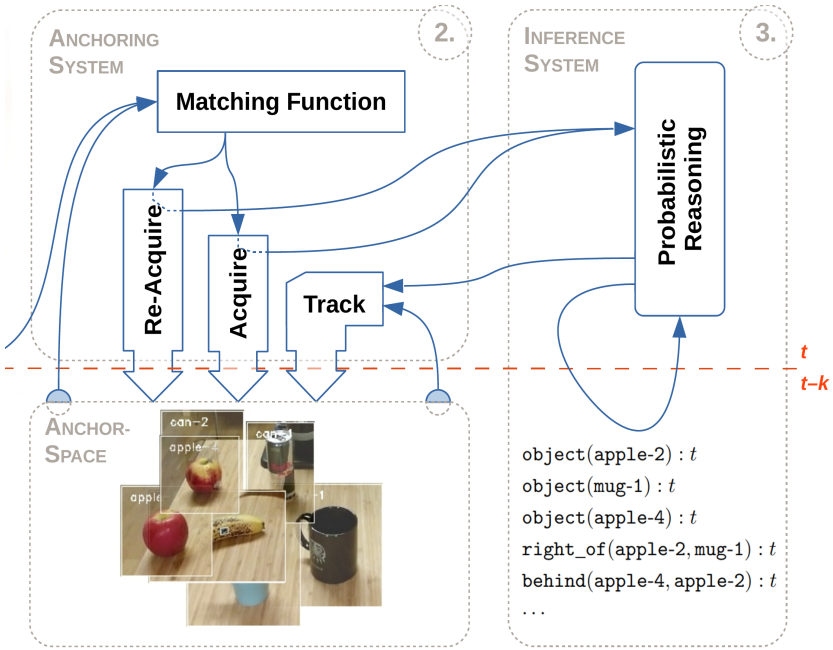
Contribution 3

A cognitive robotics architecture that couples perceptual anchoring and probabilistic logic programming.



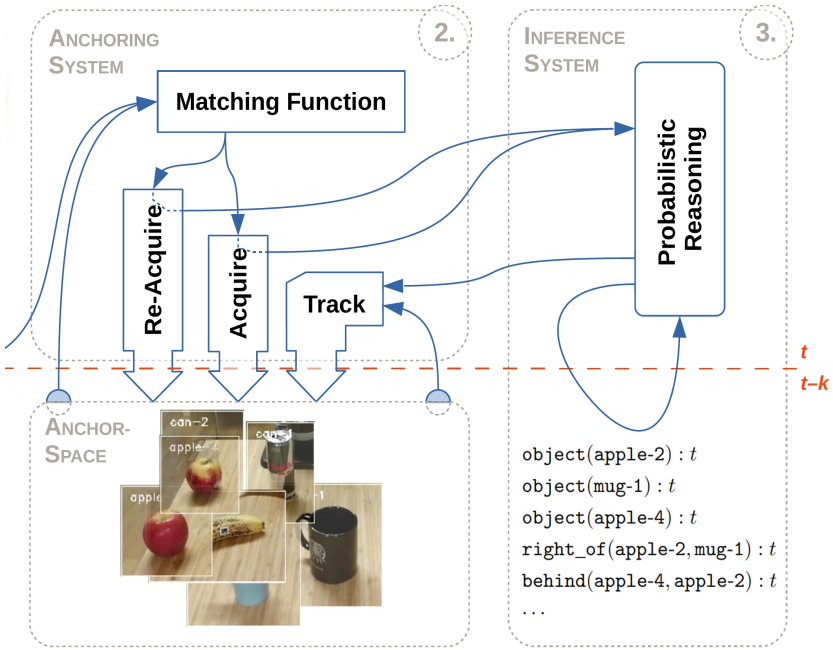
Cognitive Level

Contribution 3



Cognitive Level

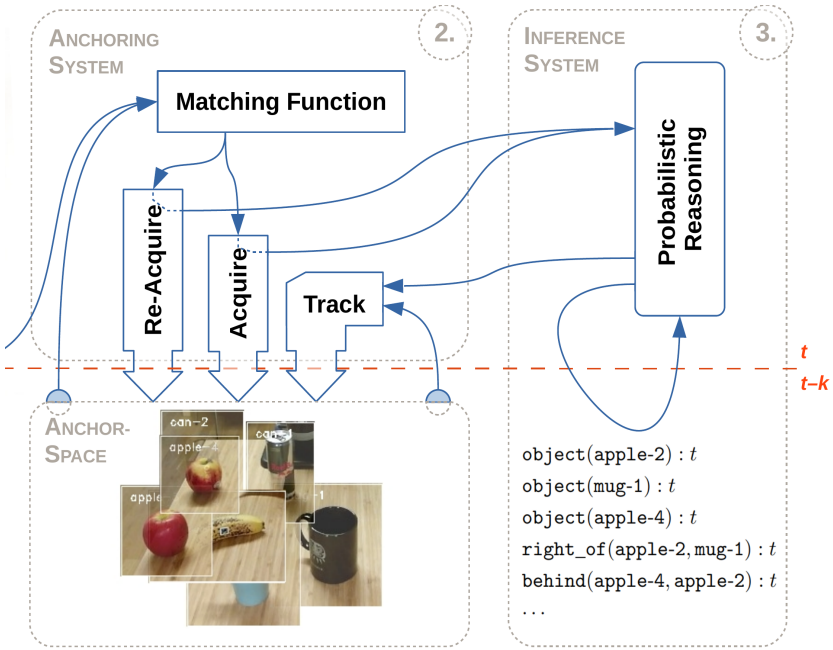
Contribution 3



- New object or not?

Cognitive Level

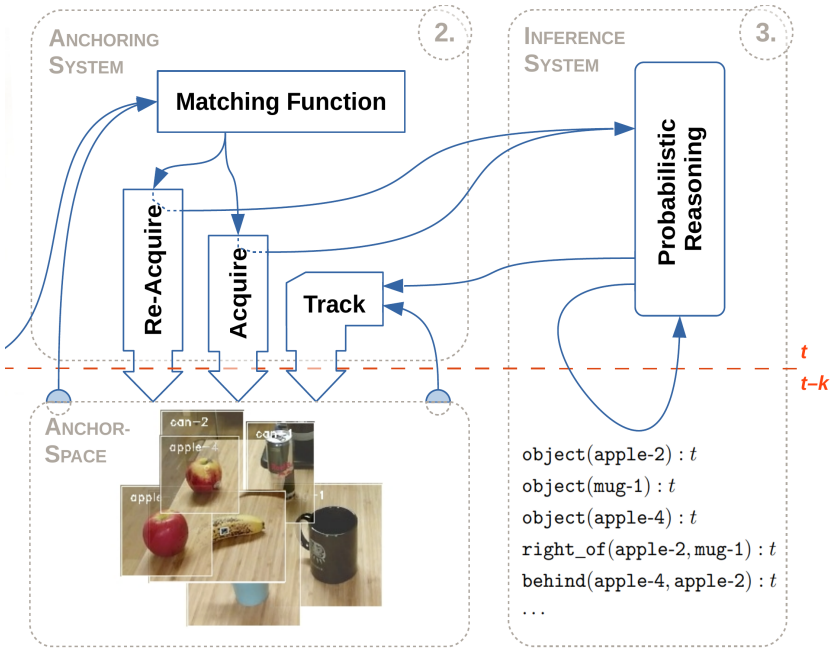
Contribution 3



- New object or not?
- Update probabilistic rules (database).

Cognitive Level

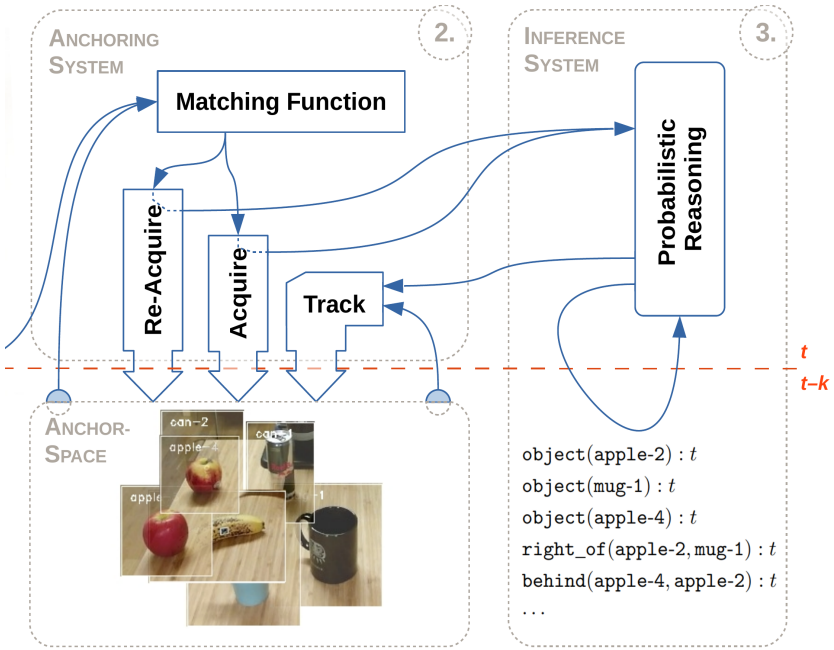
Contribution 3



- New object or not?
- Update probabilistic rules (database).
- Anything that is not observed anymore?

Cognitive Level

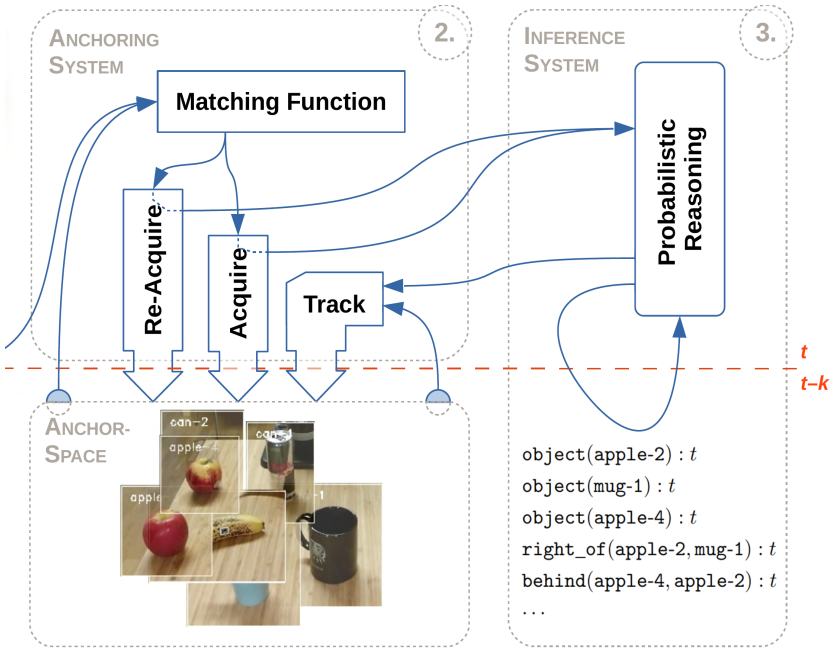
Contribution 3



- New object or not?
- Update probabilistic rules (database).
- Anything that is not observed anymore?
- Perform filtering step.

Cognitive Level

Contribution 3



- New object or not?
- Update probabilistic rules (database).
- Anything that is not observed anymore?
- Perform filtering step.
- Query tracked objects.

Cognitive Level

Demo Time!

Conclusions

My thesis studies probabilistic AI at three levels of abstraction:

1. **Microscopic Level**
   ➔ probabilistic AI at the most elementary level
2. **Macroscopic Level**
   ➔ human-friendly language for probabilistic AI
3. **Cognitive Level**
   ➔ combine cognitive robotics and probabilistic AI

(Whishful) Take-Home Messages

1. **Fully embrace uncertainty to make decisions**
   This also counts for humans. It is inevitable.

2. Probabilistic AI is a hard problem.

3. There is something called **probabilistic programming**.

4. How to use AI has to be a public debate: inform yourself!