Calculi for Reasoning About Action and Knowledge

Dimitris Plexousakis, Theodore Patkos
{dp, patkos}@ics.forth.gr

Department of Computer Science, University of Crete, Greece

Institute of Computer Science –
Foundation for Research and Technology - Hellas (FO.R.T.H.)

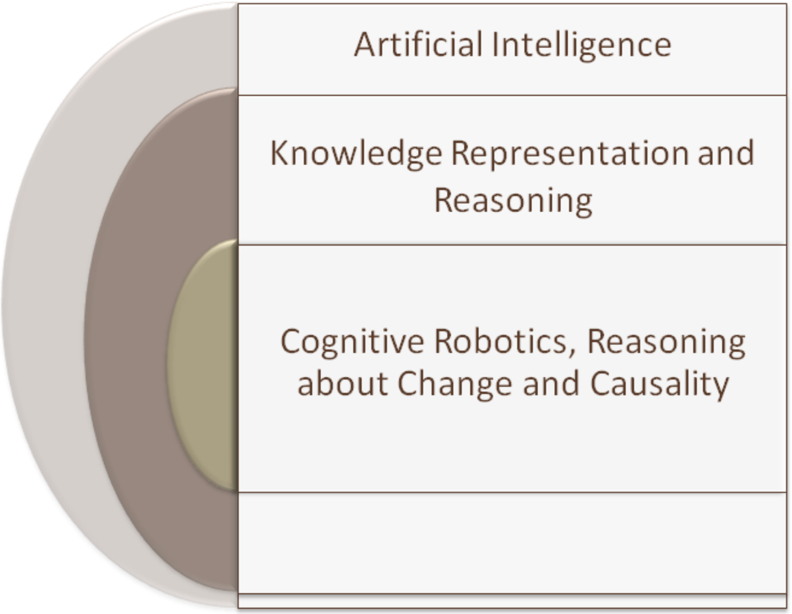
9th Panhellenic Logic Symposium, July 15-18, 2013

Outline

- Reasoning about action and change
- Fundamental issues
- Active Research Domains
- Application Domains
- Epilogue

Action Theories – Introduction

- Action theories are logical languages devised to express the *dynamics* of the world
- They aim at "*formally characterizing the relationship between the knowledge, the perception and the action of autonomous agents*" (Levesque, Reiter [17])
- Action theories model (explicitly or implicitly) the general notions of *time*, *change* and *causality*.
- During the 1990's the attention in action theories revolved around *cognitive robotics*.



Action Theories – Introduction

- Action Theories are formal tools that aim to automate the process of *commonsense reasoning* in dynamically-changing worlds, in order to
  - predict the outcome of a given action sequence
  - explain observations
  - find a situation in which certain goal conditions are met.

- Action theories have much in common with general purpose logics
  - In the general case they are based on *predicate calculus*.

- State transition and plan generation is done by *logical deduction*, rather than by state-space or plan-space search.

Action Theories – Commonsense phenomena

- Related issues
  - Representation
  - Effects of Events and Causal relations
  - Indirect Effects of Events (*Ramification* problem)
  - Context-dependent Effects
  - Non-deterministic Effects
  - Concurrent Events
  - Preconditions
  - Inertia (*Frame* problem)
  - Actions with duration
  - Physical and Triggered events
  - Delayed Effects and Continuous Change
  - Default Reasoning (*Qualification* problem)
  - …

Outline

- Reasoning about action and change
- *Fundamental issues*
    - Prominent Calculi
- Active Research Domains
- Application Domains
- Epilogue

Fundamental Issues – The Frame Problem

- Example (definitions of sorts are missing):

  $Happens(?e, ?t) \wedge Initiates(?e, ?f, ?t) \Rightarrow HoldsAt(?f, ?t+1)$ (4.0)

  $Initiates(TurnOn(?x), On(?x), ?t)$ (4.1)

  $\neg HoldsAt(On(Light1), 0)$ (4.2)

  $\neg HoldsAt(On(Light2), 0)$ (4.3)

  $Happens(TurnOn(Light2), 0)$ (4.4)

- Ok about *Light2*, but what can we say about *Light1*??

Fundamental Issues – The Frame Problem

- The *frame problem* refers to the task of
  - expressing the effects of a world changing action
  - without having to explicitly specify all the aspects that are not affected by this action.

- Different solutions have been proposed

- A popular one is the axiomatization of the commonsense *Law of Inertia*:
  - "*things tend to persist unless affected by some event*".

Fundamental Issues – Ramification Problem

- An action can cause a series of direct effects, but can also have dramatic *side-effects*.
- The problem of representing and reasoning about the indirect effects of events is known as the *ramification problem*.
- A multitude of solutions have been proposed, but still this is an open and very challenging issue.

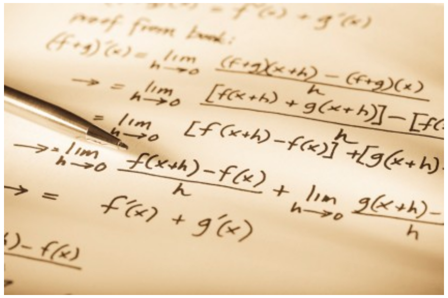
Fundamental Issues – Qualification Problem

- Whenever we intend to execute some plan we know that many *things may go wrong*, i.e.,
  - in order to drive to the university the car must have gas,
  - its engine must not be broken,
  - its tailpipe must not be blocked by a potato or other object,
  - the roads must not be blocked
  - … … … …
- If we *lack evidence to the contrary*, commonsense instructs to proceed assuming that none of the potential problematic cases holds.

- It is impossible to list all contingencies! This is the so-called *qualification problem*:
  - *“an agent needs not consider unexpected qualifications for an action, unless there is evidence to justify their existence*”.

Fundamental Issues – Challenging research topics

- Incorporating a *uniform solution* for all three problems is a challenging task
- For instance, while many existing approaches to the frame problem are monotonic, the qualification problem inherently requires a non-monotonic solution
- Additionally, ramifications in real world are *too complex* (delayed effects, unknown parameters) and require a combination of different reasoning types, e.g., temporal reasoning.



Outline

- Reasoning about action and change
- *Fundamental issues*
  - *Prominent Calculi*
- Active Research Domains
- Application Domains
- Epilogue

Prominent Calculi – Languages and implementations

- Situation Calculus [1,2,3]
  - First-order language with some second-order features
  - Defines disjoint *sorts* for actions, fluents, situations (history of actions)
  - *Idea*: Reachable states are definable in terms of the actions required to reach them
  - *Branching* time structure (all actions are hypothetical)
  - Solutions to most problems in the area (not unified solutions)
  - High-level Robot Programming Languages: Golog, IndiGolog etc
- Event Calculus
- Action Languages $\mathcal{A}$, $\mathcal{C}$, $\mathcal{C}+$, $\mathcal{K}$ [6,7]

Prominent Calculi – Languages and implementations

- Situation Calculus [1,2,3]
- Event Calculus [4,5]
  - First-order *non-monotonic* language, augmented with an explicit representation of *time*
  - *Idea*: Representation of causal and narrative information
  - *Linear* time structure, discrete or continuous time (actual actions)
  - Supports the modeling of a wide variety of phenomena for commonsense reasoning
  - SAT- and ASP-based solvers
- Action Languages $\mathcal{A}$, $\mathcal{C}$, $\mathcal{C}+$, $\mathcal{K}$ [6,7]

Prominent Calculi – Languages and implementations

- Situation Calculus [1,2,3]
- Event Calculus [4,5]
- Action Languages $\mathcal{A}$, $\mathcal{C}$, $\mathcal{C}+$, $\mathcal{K}$ [6,7]
  - Define independent *semantics* to distinguish between a claim that a formula is true and the stronger claim that there is a cause for it to be true
  - Concise syntax, parts of natural language
  - Developed originally as a means to *translate* the different action languages in a common formalism for correctness assessment; but significantly extended since.
  - Close relation with *Answer Set Programming*: Efficient ASP solvers, Causal Calculator (CCALC) etc

Outline

- Reasoning about action and change
- Fundamental issues
- *Active Research Domains*
  - *Epistemic Reasoning*
  - Reasoning with multiple agents
- Application Domains
- Epilogue

The AI Landscape – Dynamic Worlds

- Commonsense Reasoning in the presence of incomplete knowledge

Epistemic Action Theories

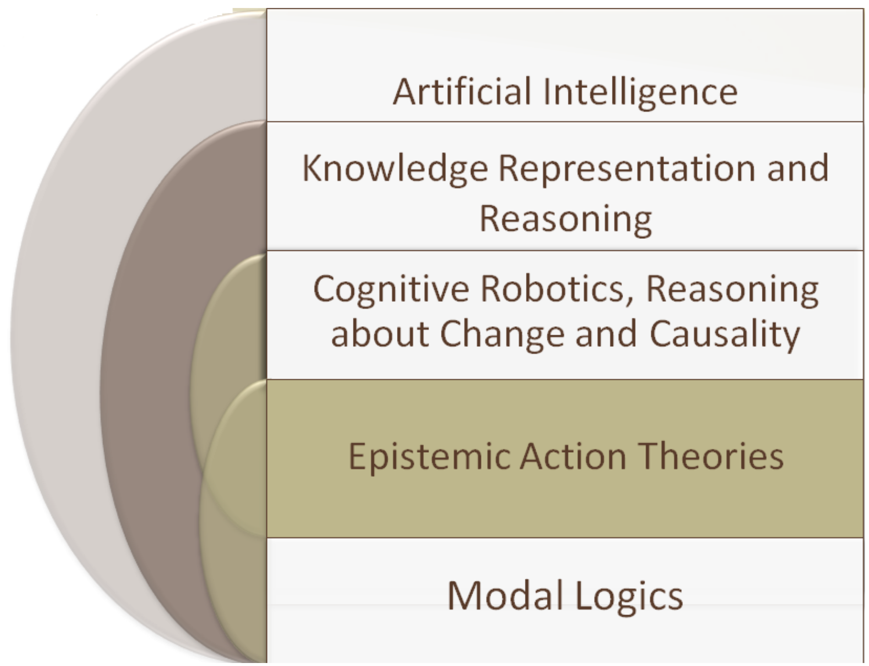
- Epistemic (modal) logic: *An agent is said to* ***know a fact*** *if this is true in all possible worlds.*

$$t=0$$

$$s_1^0 : \langle \neg f, f' \rangle$$

$$s_2^0 : \langle \neg f, \neg f' \rangle$$

$$Knows(\neg f), \neg Kw(f')$$

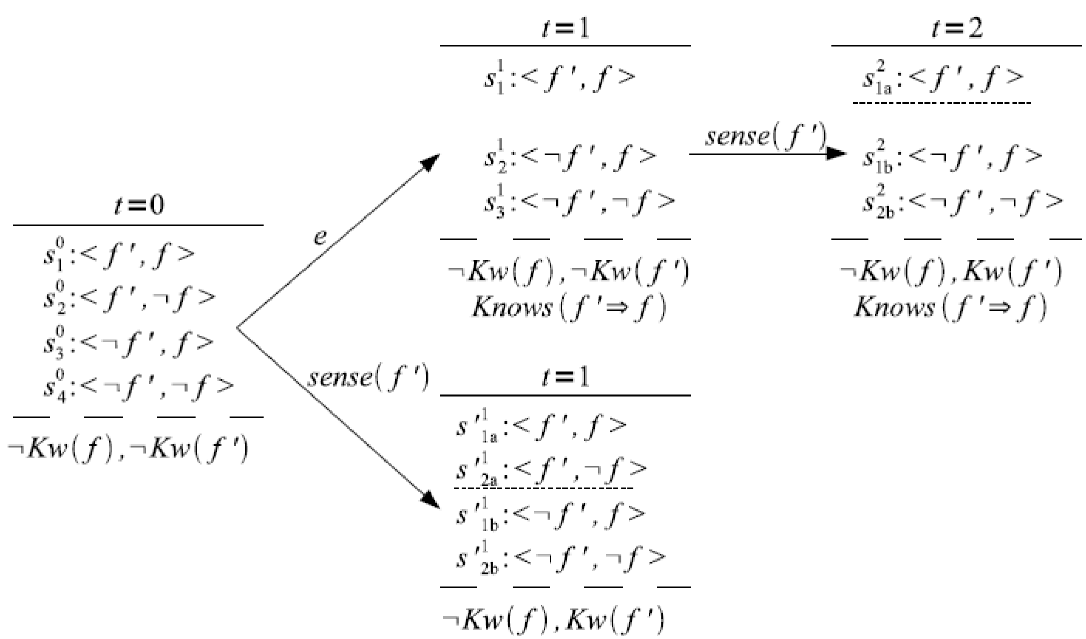


Epistemic Action Theories – Relevant Issues

- How to reason about actions in partially observable worlds
  - What do we know about the (direct/indirect) effects of an action, when some preconditions are unknown?
  - When to perform *sensing* and how knowledge should be updated
    - affects our previous knowledge about preconditions
    - affects our assumptions about exogenous actions
  - Build *epistemically feasible plans* (the goal is always *known* to be achievable)
  - What do we know about the effects of *natural/triggered events* when it is not certain whether the state of the world justifies their occurrence?
  - Etc…

Epistemic Action Theories – Possible worlds semantics

- Epistemic action theories [8] are *very expressive* and have been extended in a multitude of way:
  - concurrent actions,
  - belief,
  - future/past knowledge,
  - potentially triggered events,
  - etc…



- But they are *computationally intensive*.

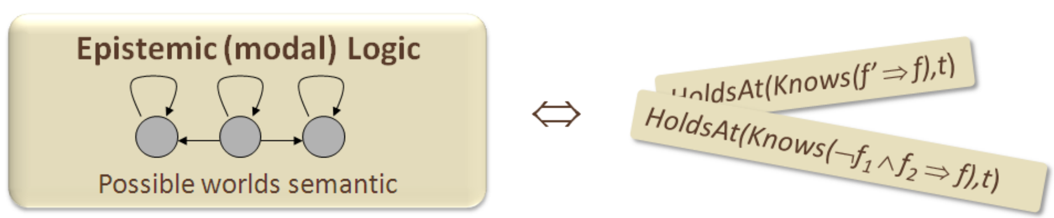
Epistemic Action Theories – Alternative Approaches

- Defining knowledge using the accessibility relation introduces serious *complexity issues*
- … and there is always the logical omniscience problem.

- Alternate approaches, aiming at tractability, either
  - *restrict expressiveness* (do not support knowledge about disjunctions, restrict the domain) or
  - *sacrifice completeness* with respect to possible worlds semantics.

Epistemic Action Theories – Alternative Approaches & DECKT

- At FORTH we have been working on the Discrete time Event Calculus Knowledge Theory (DECKT) [9]
- DECKT uses a *deduction-oriented* rather than a possible-worlds based model of knowledge.
- It adopts a meta-approach to transform a non-epistemic domain description into an epistemic axiomatization

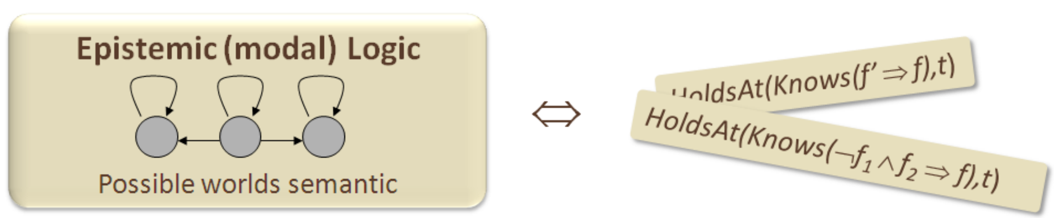


Epistemic Action Theories – Alternative Approaches & DECKT

- At the core is an established *translation* of the standard possible worlds approach of epistemic reasoning into a form of epistemic implication rules

- When appropriately restricted, it is shown to be sound and complete with respect to possible worlds-based theories

- And more appropriate for *practical implementations* in terms of computational complexity and efficiency in implementing the cognitive skills for agents.



Outline

- Reasoning about action and change
- Fundamental issues
- *Active Research Domains*
    - Epistemic Reasoning
    - *Reasoning with multiple agents*
- Application Domains
- Epilogue

Multi-Agent Reasoning – Active Research Domains

- *"After agent A distracts agent B and takes her key, B will not know that A has the key, and will believe that A does not have it; A knows that B does not know that A has the key"*. [10]

- Observability of actions
  - Some actions are *broadcast*; others may be *private*; their effects may be *partially observable* etc

- Nested epistemic notions
  - Reasoning about the epistemic implications of actions on *the mental state of other agents* is instrumental for decision making

Multi-Agent Reasoning – Active Research Domains

- Group-level epistemic modalities
  - Group knowledge, common knowledge, common goals

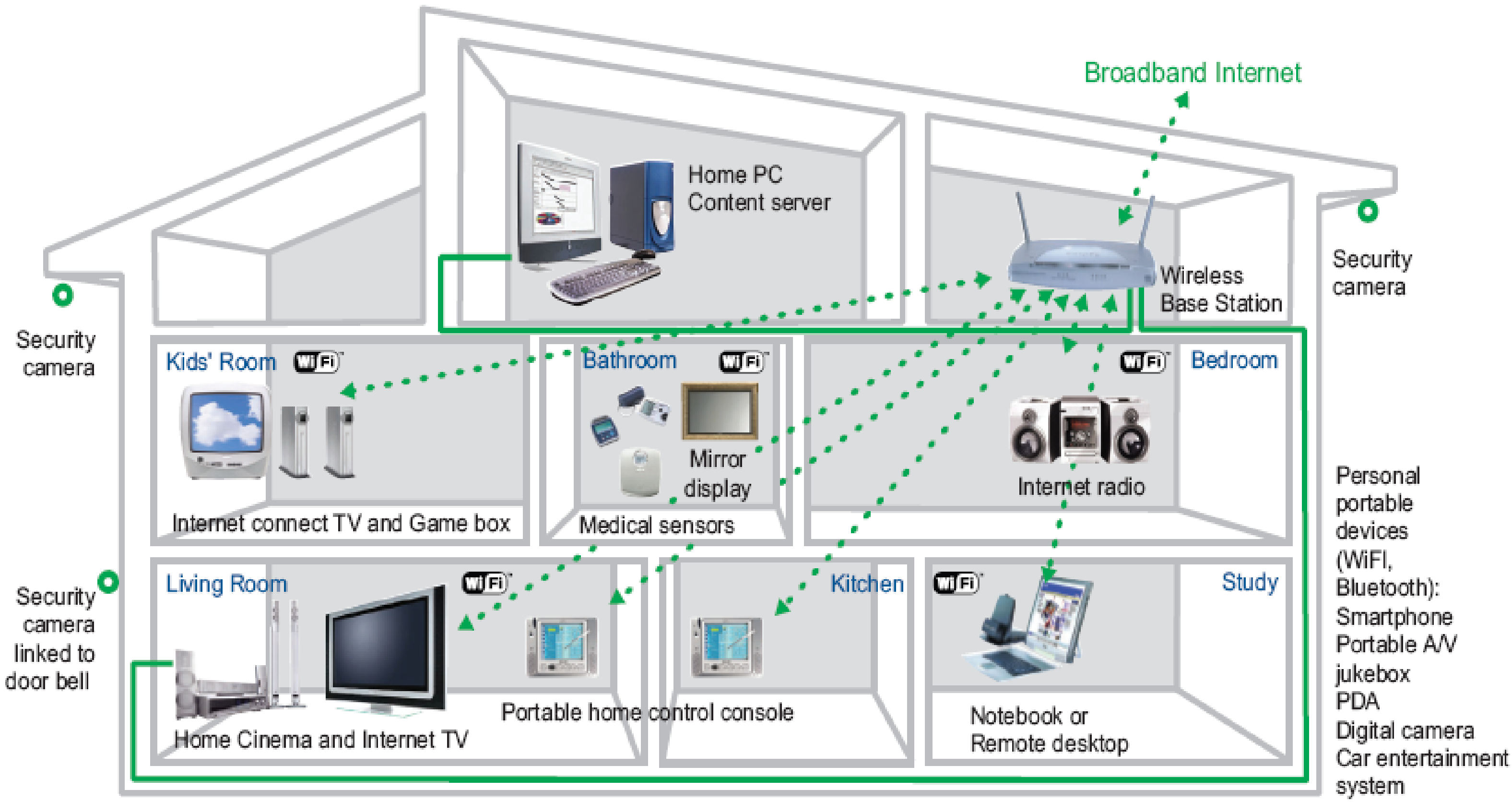
- Prospective/Retrospective/Counterfactual Reasoning
  - deliberating about the ramifications of a potential action *in the future* or about how current observations can be explained *in the past*
  - resembles the type of commonsense reasoning humans extensively perform to decide their actions.

Outline

- Reasoning about action and change
- Fundamental issues
- Active Research Domains
- *Application Domains*
    - *Ambient Intelligence*
    - Cognitive Robotics
    - Others
- Epilogue

Ambient Intelligence

- Sensor-rich collaborative environments
- Temporal constraints are ubiquitous

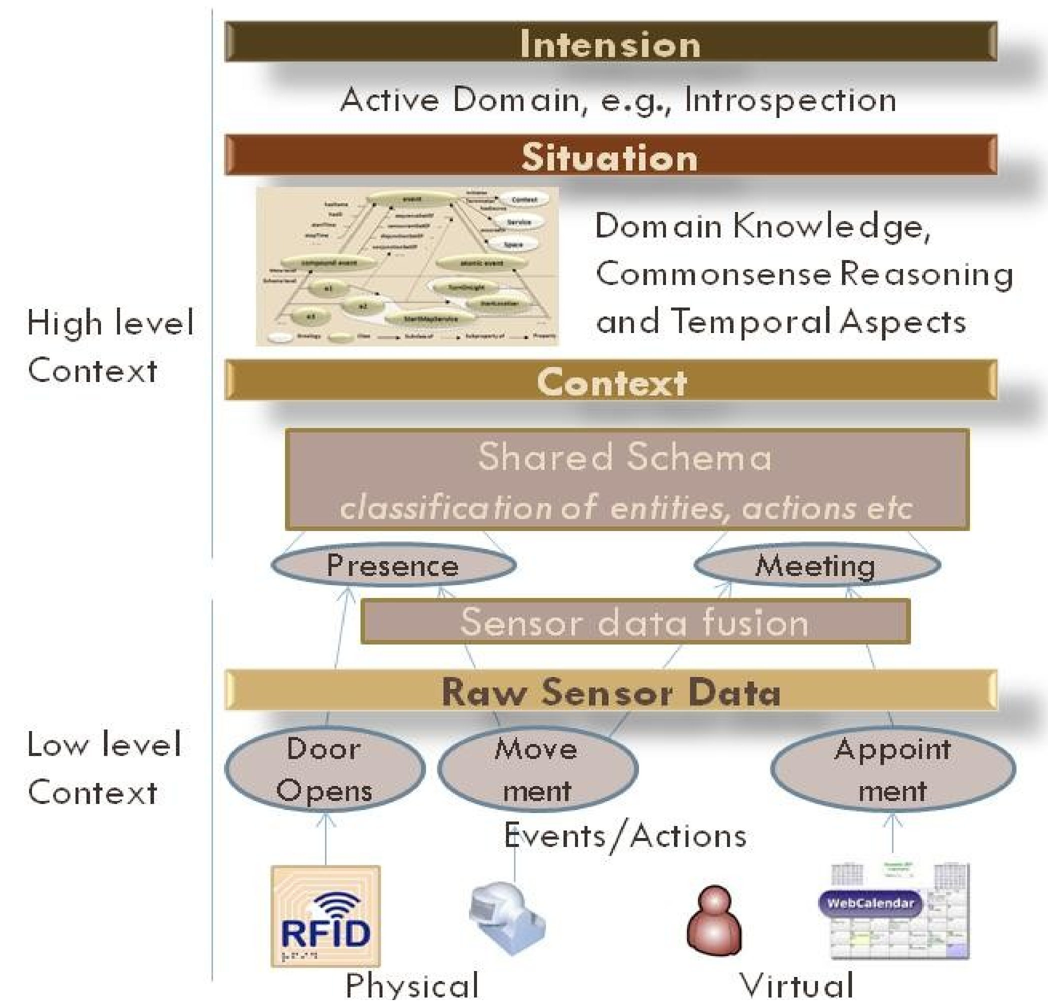


Ambient Intelligence – and AI

- AmI follows on from work in *Artificial Intelligence*.

- AI has a decisive role to play:
  - representation of contextual knowledge,
  - context inference,
  - collaboration of devices to achieve common objectives,
  - planning in dynamic domains,
  - commonsense reasoning

Ambient Intelligence – Information flow within AmI



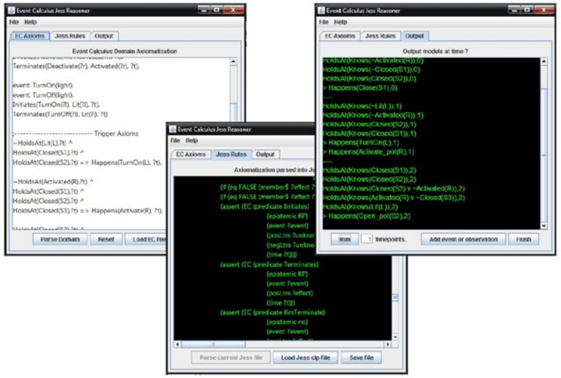
- Moving from low-level data to *high-level knowledge* expressive languages and powerful reasoning are needed [11].
- Capturing the causal and temporal relations of events, especially under partial observability, is essensial for *activity/situation/intension recognition*.
- Action theories are applied in the top layers

Ambient Intelligence – Related Research at FORTH

- At FORTH we implemented a *Semantic Web-based framework* for AmI domains that enables the gathering and dissemination of contextual knowledge..

- ..as well as the design of a *reasoner* [12] for causal, epistemic and temporal reasoning.

- The reasoner translates Event Calculus axiomatizations into production rules for execution of runtime reasoning tasks.



Ambient Intelligence – Event Calculus Rule-based Reasoner

Theoretical foundations

Event Calculus

- Reasoning about action and time
- Solution to problems (frame, ramification, qualification)
- Commonsense phenomena

DECKT

- Epistemic reasoning
- Hidden causal dependencies, rather than possible worlds structures
- Sensing, potential actions etc

Implementation

Rule-based forward-chaining production system

- NaF, semi-destructive update
- Salience values, subsumption…

Contribution

- Online/offline reasoning
- Multiple model generation
- GUI/Java interface

Application Domain

- Ambient Intelligence, AAL
- Benchmark problems (e.g., Shanahan's circuit)

Outline

- Reasoning about action and change
- Fundamental issues
- Active Research Domains
- *Application Domains*
  - Ambient Intelligence
  - *Cognitive Robotics*
  - Others
- Epilogue

Cognitive Robotics Today

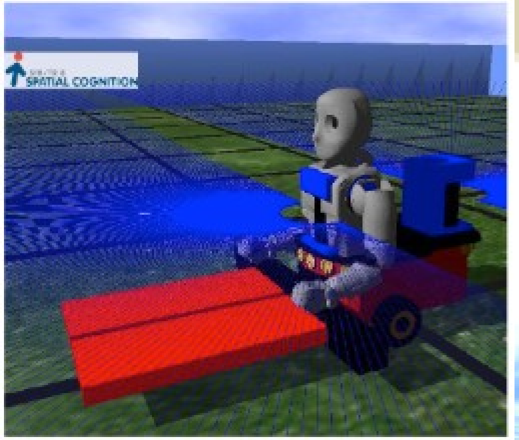
- Attention is focusing on bringing closer *traditional* with *cognitive robotics*.
- *Bilateral interaction* between causal reasoning and motion planning
- Embedding of *commonsense knowledge*

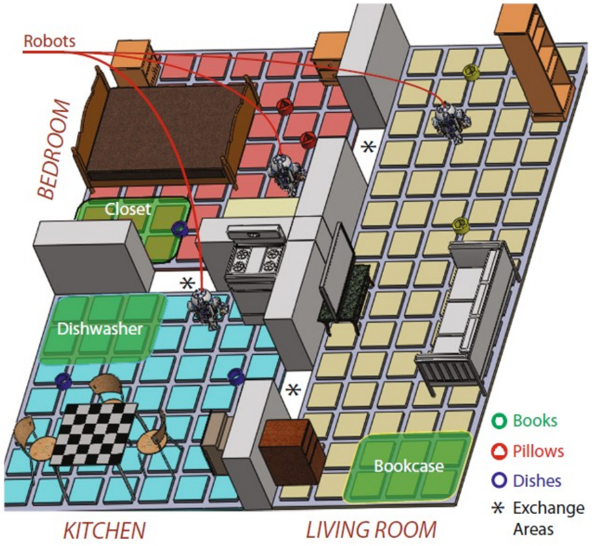
Cognitive Robotics Today

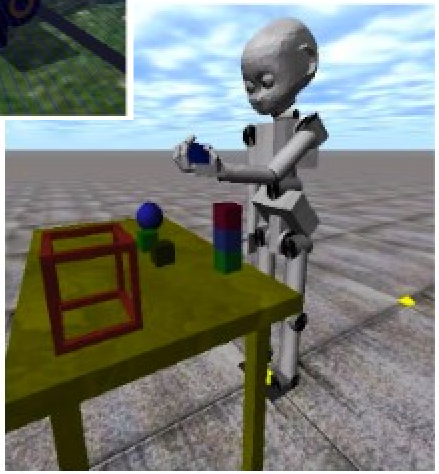
- Housekeeping robots, simulation platforms and others

- Action theories are now translated and implemented in the new logic-based problem solving paradigm of *Answer Set Programming* (ASP) [18]

- ASP solvers outperform SAT- or Prolog-based reasoners

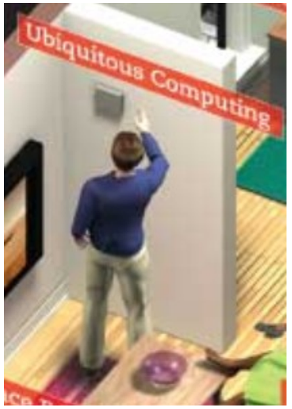






Other Application Domains

- Complex Event Detection
  - Emergency rescue operations of the Fire Department of Dortmund [13]
  - City Transportation Management [14]
  - Recognition of human activities from video streams [15]
- Web Service Composition
- Commitment Tracking
- and others…



Outline

- Reasoning about action and change
- Fundamental issues
- Active Research Domains
- Application Domains
- *Epilogue*

Epilogue

- Action Theories constitute an active research domain with
  - open theoretical research questions and
  - clear applied orientation
  - (sometimes even a bit beyond:

    Leora Morgenstern, "*A Formal Theory of Time Travel*" [16])

- Research in Action Theories both feeds and takes advantage of the progress in logic formalisms
  - Non-monotonic logics: default logic, circumscription, answer set programming

The end

Thank you!

Indicative References

- [1] J. McCarthy. **Situations, actions and causal laws**. In Stanford University. Reprinted in Semantic Information Processing (M. Minsky ed.), MIT Press, Cambridge, Mass., 1968.

  [2] H. Levesque, F. Pirri, and R. Reiter. **Foundations for the situation calculus**. In Linkoping Electronic Articles in Computer and Information Science, volume 3, 1998.

  [3] R. Reiter. **Knowledge in Action: Logical Foundations for Specifying and Implementing Dynamical Systems**. MIT Press, 2001.

  [4] R Kowalski and M Sergot. **A Logic-based Calculus of Events**. New Generation Computing, 4(1):67-95, 1986.

  [5] Rob Miller and Murray Shanahan. **Some alternative formulations of the event calculus**. In Computational Logic: Logic Programming and Beyond, Essays in Honour of Robert A. Kowalski, Part II, pages 452-490, London, UK, 2002. Springer-Verlag.

  [6] V. Lifschitz M. Gelfond. **Iterated belief change in the situation calculus**. Journal of Logic Programming, 17:301-321, 1993.

  [7] Esra Erdem and Volkan Patoglu. **Correct reasoning**. chapter Applications of action languages in cognitive robotics, pages 229-246. 2012.

Indicative References

- [8] R. C. Moore. **A formal theory of knowledge and action**. In Formal Theories of the Commonsense World, pages 319-358. J. Hobbs, R. Moore (Eds.), 1985.

  [9] Theodore Patkos and Dimitris Plexousakis. **Reasoning with Knowledge, Action and Time in Dynamic and Uncertain Domains**. In Proceedings of the 21st international joint conference on Artificial intelligence, IJCAI'09, pages 885-890, 2009.

  [10] Tran Cao Son Enrico Pontelli Chitta Baral, Gregory Gelfond. **An action language for reasoning about beliefs in multi-agent domains**. In 14th International Workshop on Non-Monotonic Reasoning, 2012.

  [11] Daniele Riboni, Linda Pareschi, Laura Radaelli, and Claudio Bettini**. Is ontology-based activity recognition really effective?** In 9th Annual IEEE International Conference on Pervasive Computing and Communications, PerCom 2011, Workshop Proceedings, pages 427–431, 2011.

  [12] Theodore Patkos, Abdelghani Chibani, Dimitris Plexousakis, and Yacine Amirat. **A production rule-based framework for causal and epistemic reasoning**. In Rules on the Web: Research and Applications, volume 7438 of Lecture Notes in Computer Science, pages 120–135. 2012.

Indicative References

- [13] Alexander Artikis, Robin Marterer, Jens Pottebaum, and Georgios Paliouras. **Event processing for intelligent resource management**. In ECAI, pages 943–948, 2012.

  [14] Alexander Artikis, Marek Sergot, and Georgios Paliouras. **Run-time composite event recognition**. In Proceedings of the 6th ACM International Conference on Distributed Event-Based Systems, DEBS ’12, pages 69–80, 2012.

  [15] Alexander Artikis, Marek Sergot, and Georgios Paliouras. **A logic programming approach to activity recognition**. In Proceedings of the 2nd ACM international workshop on Events in multimedia, EiMM ’10, pages 3–8, 2010.

  [16] Leora Morgenstern. **A formal theory of time travel**. In 11th International Symposium on Logical Formalizations of Commonsense Reasoning (Commonsense'13), 2013.

  [17] Hector Levesque and Ray Reiter. **High-level Robotic Control: Beyond Planning**. A Position Paper. In AIII 1998 Spring Symposium: Integrating Robotics Research: Taking the Next Big Leap, 1998.

  [18] Thomas Eiter, Giovambattista Ianni, and Thomas Krennwallner. **Answer Set Programming: A Primer**, in **Reasoning Web**, pages 40–110. 2009.