Reasoning about Large Taxonomies of Actions in the Situation Calculus

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Motivation

The situation calculus [Reiter, 2001]

- Initially proposed by J. McCarthy, enriched by R. Reiter et al at Univ. of Toronto
- A high-level first-order logic language
- Representing and reasoning about actions in a natural and compact way

Problem: Handling effects of action functions individually and impractical to handle large scales of action functions

Our Idea

- Using common-sense knowledge: Considering one action as a specialization of another
- E.g., traveling and shipping can be considered as specializations of moving

Summary of Contributions

1. Representing large taxonomies of actions in a hierarchical way
2. Representing effects of actions much more compactly based on action hierarchies
3. Reasoning problems can be solved exponentially faster (sometimes)
4. Bringing possible knowledge engineering advantages

Background: The Situation Calculus

Sorts of the language

- *Action functions:* $fry(x,y)$ (frying x using y), $wash(y)$ (washing y)
- *Situations:* S_0 (the initial situation), $do(a,s)$ (the situation after doing a in s)
- *Objects:* persons, locations, food items, ...

Fluents

- System features whose truth values may vary from situation to situation
- Predicates or functions with the last argument of sort situation
  E.g., $FoodReady(x,s)$ – food x is ready in the situation s
  $Dirty(x,s)$ – x is dirty in the situation s

A Basic Action Theory (BAT) $\mathcal{D}$

- Describing actions and their effects in a dynamic system
- A set of first-order axioms, mainly includes:
  $\mathcal{D}_{ap}$ (precondition axioms): For each $A(\vec{x})$, $Poss(A(\vec{x}),s) \equiv \phi_A(\vec{x},s)$
  $\mathcal{D}_{ssa}$ (successor state axioms): For each fluent $F(\vec{y},s)$,
  $$F(\vec{y},do(a,s)) \equiv \bigvee_i \psi_i^+(\vec{y},a,s) \vee F(\vec{y},s) \wedge \neg(\bigvee_j \psi_j^-(\vec{y},a,s))$$
  $\mathcal{D}_{S_0}$ (an initial theory): All facts hold in the initial situation S_0
  $\mathcal{D}_{una}$ (unique name axioms for action names) and Σ (foundational axioms)

An example of kitchen activity domain

- Considering actions involved in a kitchen such as $cook(x)$, $fry(x,y)$, $wash(x)$, ..., etc, and fluents such as $FoodReady(x,s)$, $Dirty(x,s)$, ..., etc. (See actions in the digraph on the right hand-side)
- An example of the precondition axioms:
  $$Poss(wash(x),s) \equiv WashableObject(x) \wedge Dirty(x,s)$$
- An example of the successor state axioms:
  $$\begin{aligned} &Dirty(y,do(a,s)) \equiv \\ &\quad (\exists x)a = steam(x,y) \vee (\exists x)a = boil(x,y) \vee (\exists x)a = pressureCook(x,y) \vee \\ &\quad (\exists x)a = broil(x,y) \vee (\exists x)a = bake(x,y) \vee (\exists x)a = ovenCook(x,y) \vee \\ &\quad (\exists x)a = roast(x,y) \vee (\exists x)a = deepFry(x,y) \vee (\exists x)a = stir(x,y) \vee \\ &\quad (\exists x)a = fry(x,y) \vee (\exists x)a = stew(x,y) \vee (\exists x)a = makeSalad(x,y) \vee \\ &\quad (\exists x)a = prepHotDr(x,y) \vee (\exists x)a = prepColdDr(x,y) \vee \\ &\quad Dirty(y,s) \wedge \neg[a = wash(y) \vee a = handWash(y)]. \end{aligned}$$
- Some examples of the axioms or facts in the initial theory:
  $Food(Egg_0)$, $Vessel(Pot_0)$, ..., $(\forall x)Vessel(x) \supset \neg Dirty(x,S_0)$, $(\forall x)Food(x) \supset \neg FoodReady(x,S_0)$, ..., etc.

Reasoning using regression operator R

- Defined recursively using basic action theories
  E.g., $R[W_1 \vee W_2] = R[W_1] \vee R[W_2]$, $R[(\exists x)W] = (\exists x)R[W]$, ...,
  $R[F(\vec{y},do(a,s))] = R[\phi_F(\vec{y},a,s)]$ where $F(\vec{y},do(a,s)) \equiv \phi_F(\vec{y},a,s)$ using $\mathcal{D}_{ssa}$
- Reiter's regression theorem: $\mathcal{D} \models W$ iff $\mathcal{D}_{una} \cup \mathcal{D}_{S_0} \models R[W]$

Action Hierarchies

An action diagram $\mathcal{H}$

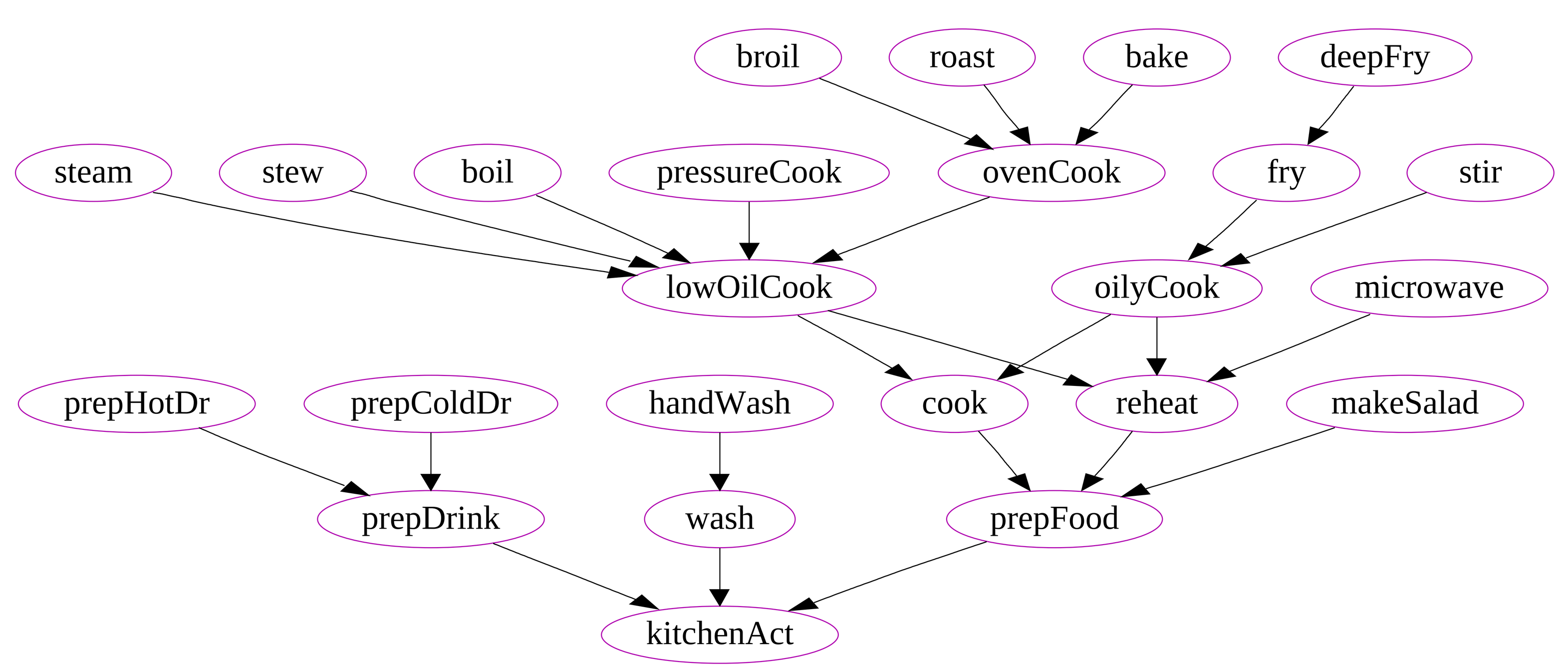
- $sp(a_1,a_2)$: Action a_1 is a (direct) specialization of action a_2
- A collection of finitely many axioms: $sp(A_1(\vec{x}), A_2(\vec{y})) \equiv \phi_{A_1,A_2}(\vec{x},\vec{y})$
  E.g., $sp(fry(x,y), oilyCook(x))$, $sp(oilyCook(x), cook(x))$, ..., etc
- Acyclic, antisymmetric, multiple inheritance

An action hierarchy $\mathcal{H}^\star = \mathcal{H}+$**the definition of** isA

- $isA(a_1,a_2)$: Action a_1 is a (distant) specialization of action a_2
- The reflexive-transitive closure of sp defined in second-order logic
- Theorem:
  For any action functions $A_1(\vec{x})$ and $A_2(\vec{y})$, $\mathcal{H}^\star \models isA(A_1(\vec{x}),A_2(\vec{y})) \equiv \psi_{A_1,A_2}(\vec{x},\vec{y})$, where $\psi_{A_1,A_2}(\vec{x},\vec{y})$ is a first-order formula and can be found in finitely many steps.

Event slots

- $EventSlot(a,x,l)$: x is an event slot l in action a
- Identifying the relationship between an action and each of its argument
  E.g., $EventSlot(fry(x,y),x,ActTarget)$, $EventSlot(fry(x,y),y,Utensil)$, etc.



A Modular Basic Action Theory $\mathcal{D}^H$

Format of axioms

- $\mathcal{D}_{ap}$, $\mathcal{D}_{una}$ and Σ are as usual
- $\mathcal{D}^H_{S_0}$: includes action hierarchy axioms $\mathcal{H}^\star$ and axioms for event slots in addition
- $\mathcal{D}^H_{ssa}$: New representation of basic action theories using isA
  E.g., $Dirty(y,do(a,s)) \equiv (\exists x)isA(a,prepFood(x)) \wedge EventSlot(a,y,Utensil) \vee$
  $(\exists x)isA(a,prepDrink(x)) \wedge EventSlot(a,y,Utensil) \vee$
  $Dirty(y,s) \wedge \neg isA(a,wash(y))$

Regression: operator is extended to handle isA and $EventSlot$

Correctness of Modular Basic Action Theories

1. For any modular BAT $\mathcal{D}^H$, there exists an equivalent $\mathcal{D}$ of Reiter's BAT format, where equivalence means that for any first-order regressable sentence W, $\mathcal{D}^H \models W$ iff $\mathcal{D} \models W$.
2. A regression theorem similar to Reiter's regression theorem is proved: $\mathcal{D}^H \models W$ iff $\mathcal{D}^H_{S_0} \cup \mathcal{D}_{una} \models R[W]$.
3. Although the formal definition of isA is second-order, the reasoning in $\mathcal{D}^H$ can be reduced to a first-order logic reasoning only.

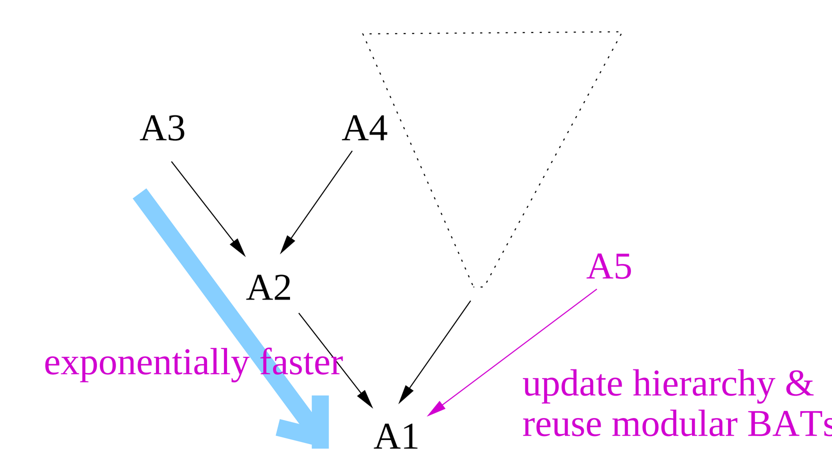
Advantages of The New Approach

Computational advantages

When $\mathcal{H}$ has a tree or forest structure, then the reasoning on isA is exponentially faster than the reasoning on its equivalent clause in Reiter's BAT representation.

Knowledge engineering advantages

- Allowing taxonomic reasoning about event slot hierarchies and action hierarchies
- Possible applications to action/service retrieval
- Easiness for system update and reuse of action hierarchies and modular BATs



Implementation (in progress): E-business domain and kitchen activity domain

References and Most Related Work

[Amir, 2000] (De)Composition of Situation Calculus Theories
[Barker, Porter & Clark, 2001] A Library of Generic Concepts for Composing KBs
[Gil, 2005] Description Logics and Planning
[Gu & Soutchanski, 2007] Modular Basic Action Theories
[Lifschitz & Ren, 2006] A Modular Action Description Language
[Reiter, 2001] Knowledge in Action: Logical Foundations for Describing and Implementing Dynamical Systems.