Sensor Fusion in the Situation Calculus

Christoph Schwering

RWTH Aachen University

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Scenario: Table Top Perception

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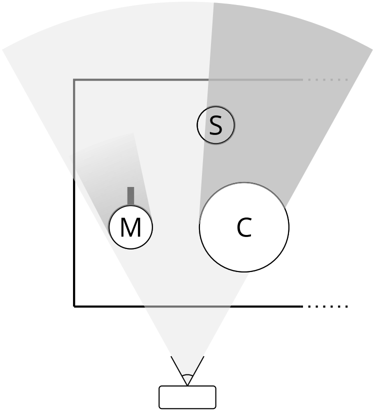

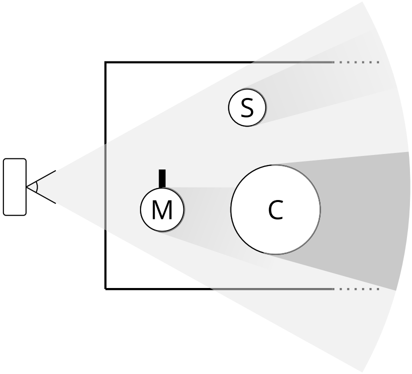

KR approach for . . .

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   - Incorrect sensings
   - Unknown number of objects

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    then I believe it is a Mug

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   After looking at the table for long enough,

   I believe everything I haven't *seen* on the table *is* not the table

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   When I return to the table after an hour,

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Situation calculus + Possible worlds as epistemic states

The Logic $\mathcal{ESF}$

Long story short: $\mathcal{ESF}$ is a modal first-order logic for actions and knowledge

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Long story long:

- Language
  - Terms: M, C, S, Mug, $Coffee$, $Sugar$, $\ldots$
  - Atoms: $On(M)$, $Is(M, Mug)$, $\ldots$
  - Logical connectives: $Is(M, Mug) \vee Is(M, Cup)$, $\ldots$
- Semantics
  - World: truth values of atoms $\longrightarrow$ truth of sentences

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    $[\text{pickup}(o)]\quad \neg On(o)$
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    $[\mathrm{sense}]\ \mathbf{S}^{1}_{\mathrm{sense}} On(o)$
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The Logic $\mathcal{ESF}$

Actions have different kinds of effects:

- physical: change truth value
- sensing: the compatible epistemic state is memorized
- epistemic: rule out or reinstate possible worlds
  - fusion of sensings
  - closed world assumption
  - forgetting

$\mathcal{ESF}$ addresses . . .

1. Sensing
2. Fusion of sensings
3. Closed world assumption
4. Forgetting

Problem 1: Sensing

- Sensor reports wrong values and unknown count of objects
- Real world constrain possible results:

$$\begin{aligned}\Box SR(\text{sense}, x) \supset\ & \exists o . x = obj(o) \lor \\ & \exists o, t . o = type(o, t)\end{aligned}$$

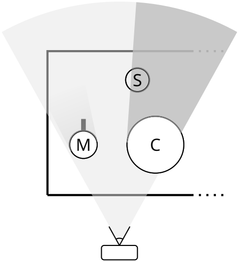
- Possible world must agree:

$$\begin{aligned}\Box SR(\text{sense}, x) \equiv\ & \exists o . x = obj(o) \land On(o) \lor \\ & \exists o, t . o = type(o, t) \land Is(o, t)\end{aligned}$$

- Epistemic state of sensing = possible worlds w' compatible with real world w

$$\{w' \mid w'[SR(\text{sense}, x), z] = w[SR(\text{sense}, x), z] \text{ for all } x\}$$

Problem 1: Sensing



- One epistemic state per sensing
- $\mathbf{S}^n_a \alpha$ iff α holds in all w' from nth last sensing a
  iff α compatible with nth last sensing a
- What was sensed (with projection):

$$[\text{sense}]\ \mathbf{S}^1_{\text{sense}}(On(C) \wedge On(M))$$

$$[\text{sense}][\text{pickup}(M)]\ \mathbf{S}^1_{\text{sense}}(On(C) \wedge \neg On(M))$$

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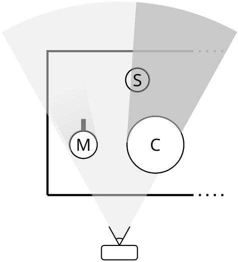
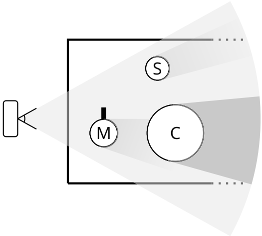


$$[\text{sense}]\ \mathbf{S}^1_{\text{sense}}(On(C) \wedge On(M))$$
$$[\text{sense}][\text{pickup}(M)]\ \mathbf{S}^1_{\text{sense}}(On(C) \wedge \neg On(M))$$
$$[\text{sense}][\text{move}][\text{sense}]\ (\neg \mathbf{S}^2_{\text{sense}} On(S) \wedge \mathbf{S}^1_{\text{sense}} On(S))$$



Problem 2: Fusion

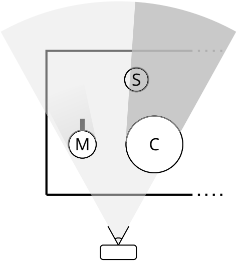
- Fusion formulas:

$$\mathbf{S}^1_{\text{sense}} On(o) \vee \mathbf{S}^2_{\text{sense}} On(o) \supset On(o)$$
$$\mathbf{S}^1_{\text{sense}} Is(o,t) \wedge (t = Cup \supset \neg \mathbf{S}^2_{\text{sense}} Is(o, Mug)) \supset Is(o,t)$$

- Epistemic effect of fuse action:

$$[\text{sense}][\text{fuse}]\ \mathbf{K} Is(M, Cup)$$

$$[\text{sense}][\text{fuse}]\ \mathbf{K}(o \in \{M, C\} \supset On(o))$$



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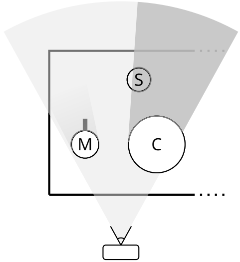

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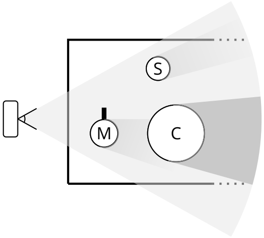
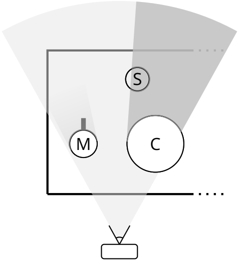
$$[\text{sense}][\text{fuse}]\ \mathbf{K} Is(M, Cup)$$
$$[\text{sense}][\text{move}][\text{sense}][\text{fuse}]\ \mathbf{K} Is(M, \color{red}{Mug})$$
$$[\text{sense}][\text{fuse}]\ \mathbf{K}(o \in \{M, C\} \supset On(o))$$
$$[\text{sense}][\text{move}][\text{sense}][\text{fuse}]\ \mathbf{K}(o \in \{M, C, \color{red}{S}\} \supset On(o))$$



Problem 3: Closed World Assumption



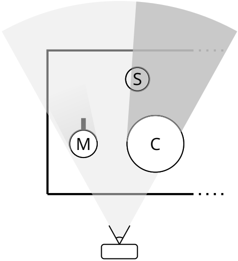
- Local CWA on $On(x)$:

$$CW(\text{close}, x) \equiv On(x)$$

- Epistemic effect of close action:

$$[\text{sense}][\text{fuse}]\ \mathbf{K}(o \in \{M, C\} \supset On(o))$$
$$[\text{sense}][\text{fuse}][\text{close}]\ \mathbf{K}(o \in \{M, C\} \equiv On(o))$$

Problem 4: Forgetting



- forget(a) undoes epistemic effect of a

  reinstates possible worlds

- Epistemic effect of close action:

$$[\text{sense}][\text{fuse}][\text{close}]\,\mathbf{K}(o \in \{M, C\} \equiv On(o))$$
$$[\text{sense}][\text{fuse}][\text{close}][\text{forget}(\text{close})]\,\mathbf{K}(o \in \{M, C\} \supset On(o))$$

Conclusion

- Incorrect sensing results
- Memorize sensing results, no immediate effect on knowledge
- Fusion actions turn memorized sensings into knowledge
- Closed world assumption
- Fusion and CWA can be undone through forgetting

Future Work

- Uncertainties in sensing

  M is a Mug with confidence 0.7

  M is a Cup with confidence 0.3

- Decidable reasoning
- Belief revision

  "it's a cup unless we see a handle, then it's a mug"

Slide Cemetery

$\mathcal{ESF}$ is a modal first order logic for actions and knowledge:

- Situation aka sequence of actions
- When is an object on the table?

$$\Box[a]On(x) \equiv a = \text{putdown}(x) \vee (On(x) \wedge a \neq \text{pickup}(x))$$

- After $\text{pickup}(x)$, do we know that x would be on the table after putting it down?

$$[\text{pickup}(x)]\mathbf{K}[\text{putdown}(x)]On(x)$$

- According to the second to last sense action, M is a mug or a cup:

$$\mathbf{S}^2_{\text{sense}}(Is(M, Mug) \vee Is(M, Cup))$$

- A world $w : atoms \times action\ sequences \rightarrow \{0, 1\}$
- Set of possible worlds aka epistemic state
- The set of possible worlds
- α is known in a set of worlds e iff $w' \models \alpha$ for all $w' \in e$
- Example (informal notation):

$$
\begin{aligned}
e = \{w' \mid w' \models\ & On(M) \wedge Is(M, Mug) \wedge \neg On(S) && \text{or} \\
& On(M) \wedge Is(M, Cup) \wedge \neg On(S) && \text{or} \\
& On(M) \wedge Is(M, Mug) \wedge \quad On(S)\}
\end{aligned}
$$

  - knows that $On(M)$
  - knows that $Is(M, Mug) \vee Is(M, Cup)$
  - doesn't know if $On(S)$ or $\neg On(S)$

- Not much is specified about the real sensing results x in real world w:

$$\begin{aligned}\Box SR(\text{sense}, x) \supset\ & \exists o.x = obj(o) \vee \\ & \exists o, t.o = type(o, t)\end{aligned}$$

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- A possible world w' should agree with all sensing results x:

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- The epistemic state of action sense in situtation z:

$$\{w' \mid w'[SR(\text{sense}, x), z] = w[SR(\text{sense}, x), z] \text{ for all } x\}$$

w' is compatible w iff x is a sensing result in w' iff it's one in w

- $\mathbf{S}_a^n \alpha$ holds iff $w' \models \alpha$ for all w' compatible with the sensing result of the nth last a
-

$$\mathbf{S}^1_{\text{sense}} On(x) \lor \mathbf{S}^2_{\text{sense}} On(x) \supset On(x)$$

- Suppose the first sensing yields:

$$SR(\text{sense}, x) \equiv x \in \{obj(C), type(C, Coffee), \\ obj(M), type(M, Cup)\}$$

- Recall the SR axiom, which formalizes which w' agree with sensings results:

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- Sensing history contains worlds compatible with

$$On(C) \wedge Is(C, Coffee) \wedge On(M) \wedge Is(M, Cup)$$
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$$On(C) \wedge Is(C, Coffee) \wedge On(M) \wedge Is(M, Cup)$$
$$On(C) \wedge Is(C, Coffee) \wedge On(M) \wedge Is(M, Mug) \wedge On(S) \wedge Is(S, Sugar)$$

- Thus we have:

$$\mathbf{S}^1_{\text{sense}} Is(M, Cup) \wedge \mathbf{S}^2_{\text{sense}} Is(M, Mug)$$
$$\neg \mathbf{S}^1_{\text{sense}} \neg On(S) \wedge \mathbf{S}^2_{\text{sense}} On(S)$$

- have a few worlds
- CWA erases all $\neg On(S)$ worlds

- just mention that we reinstate worlds

Initially, the robot is at the long side.

1. It erroneously thinks M is a Cup.

$$[\text{sense}][\text{fuse}]\mathbf{K}Is(M, Cup)$$

Entailments of the example's theory.

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2. It realizes that M is a Mug; $\text{forget}(\text{fuse})$ avoids inconsistency.

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5. ... which it does believe after a CWA on On.
   $$[\text{sense}][\text{fuse}][\text{close}]\mathbf{K}(x = M \lor x = C \equiv On(x))$$

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   $$[\text{sense}][\text{fuse}][\text{close}]\mathbf{K}(x = M \lor x = C \equiv On(x))$$
6. It sees all three objects when it inspects the table from both sides.
   $$[\text{sense}][\text{move}][\text{sense}][\text{fuse}]\mathbf{K}(x = M \lor x = C \lor x = S \supset On(x))$$

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