The Rôle of Causality in Reasoning about Action

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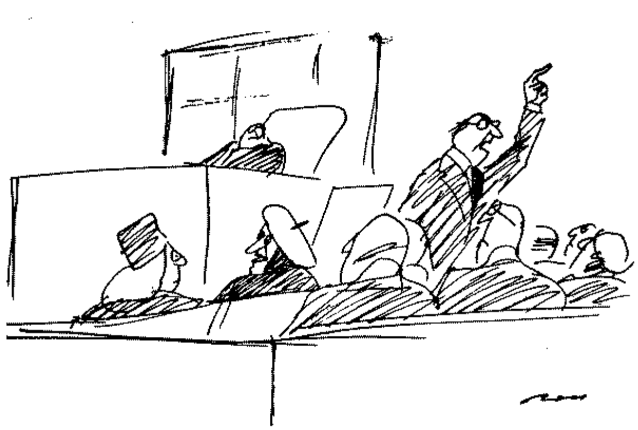


"Logic—the last refuge of a scoundrel."

Causality

Problems arise when using traditional (logical) domain constraints to reason about action

It has been argued that introducing an explicit representation of causality can help overcome these problems

We shall look at some of the more popular proposals in recent literature

References:

Norman McCain and Hudson Turner, A Causal Theory of Ramifications and Qualifications, In *Proceedings of the Fourteenth International Joint Conference on Artificial Intelligence (IJCAI95)*, Montreal, Canada, 1995

Michael Thielscher, Ramification and Causality, *Artificial Intelligence*, 89: 317–364, 1997.

Overview

Traditional domain constraints

Inadequacy of traditional domain constraints

Causal laws (McCain & Turner, 1995)

Causal relationships (Thielscher, 1997)

Conclusions

Terminology

Adopt propositional language

Fluents — propositions that can change value

State — maximal consistent set of literals (positive and negative fluents)

Actions identified with direct effects

Aim: determine ramifications of action

$Res(E,\ S)$: "set of potential next states after performing action with direct effects E in state S"

Traditional Domain Constraints

(Winslett, 1988)

D — set of domain constraints (logical formulae)

$S' \in Res^W_D(E,\ S)$ if and only if

1. S' satisfies $E \cup B$
2. There is no S'' satisfying $E \cup B$ that differs from S' in fewer atoms (in terms of set inclusion)

   Example:

   $S = \{\texttt{alive},\ \texttt{walking}\}$
   $E = \{\neg\texttt{alive}\}$
   $D = \{\texttt{walking} \rightarrow \texttt{alive}\}$
   $Res^W_D(E,\ S) = \{\{\neg\texttt{alive},\ \neg\texttt{walking}\}\}$

Traditional Domain Constraints

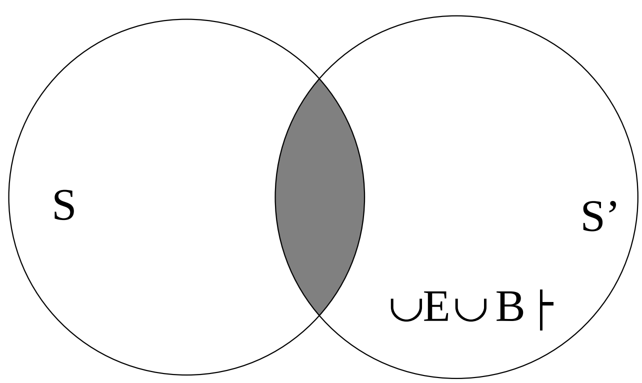
This method can be re-cast in the following form

$S' \in Res_D(E,\ S)$ iff $S' = \{L :\ (S \cap S') \cup E \cup B \vdash L\}$

Idea: minimise change plus satisfy direct effects and domain constraints

Note: fixed-point definition

Traditional Domain Constraints (Winslett, 1988)



Inadequacy of Traditional Domain Constraints

$S = \{\neg\mathtt{alive},\ \neg\mathtt{walking}\}$
$E = \{\mathtt{walking}\}$
$D = \{\mathtt{walking} \rightarrow \mathtt{alive}\}$
$Res_D(E,\ S) = \{\{\mathtt{alive},\ \mathtt{walking}\}\}$

Inadequacy of Traditional Domain Constraints

Example (Lifschitz 1990)

$S = \{\neg\mathtt{up}_1,\ \mathtt{up}_2,\ \neg\mathtt{on}\}$
$E = \{\mathtt{up}_1\}$
$D = \{\mathtt{on} \leftrightarrow (\mathtt{up}_1 \leftrightarrow \mathtt{up}_2)\}$
$Res_D(E,\ S) = \{\{\mathtt{up}_1,\ \mathtt{up}_2,\ \mathtt{on}\},\ \{\mathtt{up}_1,\ \neg\mathtt{up}_2,\ \neg\mathtt{on}\}\}$

Possible solution — use frame fluents

Alternative: use notion of causality

Causal Laws (McCain & Turner 1995)

Causal laws (as domain constraints)

$$\phi \Rightarrow \psi$$

"ϕ *causes* ψ"

Γ — set of formulae

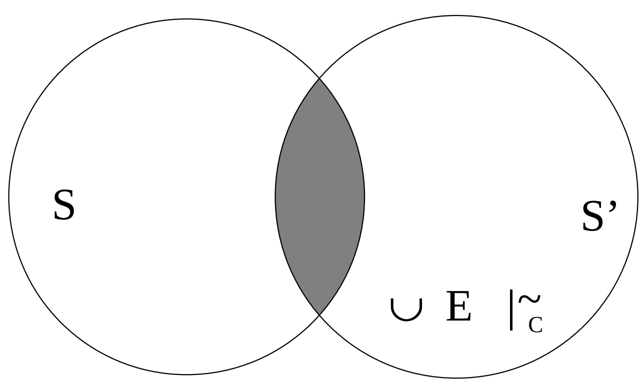
C — set of causal laws

Γ *closed* under C iff whenever $\phi \Rightarrow \psi \in C$ and $\phi \in \Gamma$, then $\psi \in \Gamma$ (denote this by $\Gamma \vdash_C \phi$)

$S' \in Res_C(E,\ S)$ iff

$$S' = \{L :\ (S \cap S') \cup E \vdash_C L\}$$

Causal Laws (McCain & Turner 1995)



Example (McCain & Turner 1995)

$S = \{\texttt{alive}, \texttt{walking}\}$
$E = \{\neg\texttt{alive}\}$
$C = \{\neg\texttt{alive} \Rightarrow \neg\texttt{walking}\}$
$Res_C(E, S) = \{\{\neg\texttt{alive}, \neg\texttt{walking}\}\}$

Example (McCain & Turner 1995)

$S = \{\neg\texttt{alive}, \neg\texttt{walking}\}$
$E = \{\texttt{walking}\}$
$C = \{\neg\texttt{alive} \Rightarrow \neg\texttt{walking}\}$
$Res_C(E, S) = \emptyset$

Action is not applicable (action implies an effect that action does not cause)

A *derived* qualification

Example (McCain & Turner 1995)

$S = \{\neg\mathtt{up}_1,\ \mathtt{up}_2,\ \neg\mathtt{on}\}$
$E = \{\mathtt{up}_1\}$
$C = \{(\mathtt{up}_1 \leftrightarrow \mathtt{up}_2) \Rightarrow \mathtt{on},\ \neg(\mathtt{up}_1 \leftrightarrow \mathtt{up}_2) \Rightarrow \neg\mathtt{on}\}$
$Res_C(E,\ S) = \{\{\mathtt{up}_1,\ \mathtt{up}_2,\ \mathtt{on}\}\}$

Causal Laws

Observation:

C — set of causal laws
$D = \{\phi \rightarrow \psi :\ \phi \Rightarrow \psi \in C\}$

$$Res_C(E,\ S) \subseteq Res_D(E,\ S)$$

Traditional Domain Constraints via Causal Laws

Ramification Constraints

$$\mathtt{True} \Rightarrow \phi$$

Qualification Constraints

$$\neg\phi \Rightarrow \mathtt{False}$$

Causal Relationships (Thielscher 1997)

$\mathcal{F}$ — fluents

$\mathcal{A}$ — action names ($\mathcal{F} \cap \mathcal{A} = \emptyset$)

Action law — $\langle C,\ a,\ E \rangle$
  C — (pre-)condition (set of fluent literals)
  E — effect (set of fluent literals)
  $a \in \mathcal{A}$

Given a state S, an action law $\alpha = \langle C,\ a,\ E \rangle$ is *applicable* at S iff $C \subseteq S$.

Applying α at S *yields* state $(S \setminus C) \cup E$

Causal Relationships

ε `causes` ϱ `if` Φ

  $\varepsilon,\ \varrho$ — fluent literals
  Φ — fluent formula

Causal relationship ε `causes` ϱ `if` Φ is applicable to $(S,\ E)$ iff
  $S \vdash \Phi \wedge \neg\varrho$ and
  $\varepsilon \in E$

Application of ε `causes` ϱ `if` Φ at $(S,\ E)$ yields $(S',\ E')$ where
  $S' = (S \setminus \{\neg\varrho\}) \cup \{\varrho\}$ and
  $E' = (E \setminus \{\neg\varrho\}) \cup \{\varrho\}$

Denoted $(S,\ E) \leadsto_{\mathcal{R}} (S',\ E')$

Causal Relationships

Given: $\mathcal{F}$ — set of fluents

$\mathcal{A}$ — set of action names

$\mathcal{L}$ — set of action laws

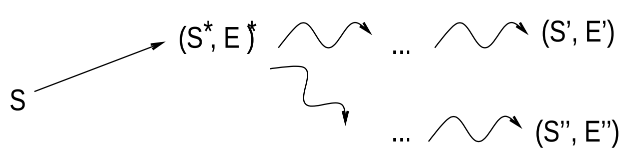
$\mathcal{D}$ — set of domain constraints

$\mathcal{R}$ — set of causal relationships

A state S' is a *successor state* of applying action $a \in \mathcal{A}$ at state S (satisfying $\mathcal{D}$) iff there is an applicable action law $\langle C,\ a,\ E\rangle \in \updownarrow$ such that

1. $((S \setminus C) \cup E,\ E) \overset{*}{\leadsto}_{\mathcal{R}} (S',\ E')$ for some E', and
2. S' satisfies $\mathcal{D}$

Causal Relationships



Example (Thielscher, 1997)

$S = \{\neg\mathtt{up}_1,\ \mathtt{up}_2,\ \neg\mathtt{on}\}$
$\mathcal{D} = \{(\mathtt{up}_1 \wedge \mathtt{up}_2) \leftrightarrow \mathtt{on}\}$
Action laws:

$\langle\{\neg\mathtt{up}_1\},\ toggle_1,\ \{\mathtt{up}_1\}\rangle$ $\langle\{\mathtt{up}_1\},\ toggle_1,\ \{\neg\mathtt{up}_1\}\rangle$
$\langle\{\neg\mathtt{up}_2\},\ toggle_2,\ \{\mathtt{up}_2\}\rangle$ $\langle\{\mathtt{up}_2\},\ toggle_2,\ \{\neg\mathtt{up}_2\}\rangle$

Causal relationships:

$\mathtt{up}_1$ causes $\mathtt{on}$ if $\mathtt{up}_2$ $\mathtt{up}_2$ causes $\mathtt{on}$ if $\mathtt{up}_1$
$\neg\mathtt{up}_1$ causes $\neg\mathtt{on}$ if $\mathtt{True}$ $\neg\mathtt{up}_2$ causes $\neg\mathtt{on}$ if $\mathtt{True}$

$\{\neg\mathtt{up}_1,\ \mathtt{up}_2,\ \neg\mathtt{on}\} \triangleright (\{\mathtt{up}_1,\ \mathtt{up}_2,\ \neg\mathtt{on}\},\ \{\mathtt{up}_1\}) \leadsto$
$(\{\mathtt{up}_1,\ \mathtt{up}_2,\ \mathtt{on}\},\ \{\mathtt{up}_1,\ \mathtt{on}\})$

Conclusions

Explicit representation of causality may provide a *concise* solution to the frame and ramification problems

Where to from here?
A general semantics capable of encompassing many (all?) of these proposals

One step in this direction is Sandewall's *causal propagation semantics* (1998)