Knowledge, Action, and Ability in the Situation Calculus

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Cognitive Robotics

Principled accounts of the relationships among knowledge, perception, and action

Toronto group: co-authors + Ray Reiter + students

Theoretical framework formulated in the language of the situation calculus

- exploiting a recent solution to the frame problem
- with extensions to handle (eventually)
  - complex actions
  - knowledge
  - state constraints
  - ☞ ability
  - indexicals
  - exogenous events, multiple agents
  - noisy sensors / effectors
  - ...

Results in **GOLOG**, a novel programming language for high-level robotic control

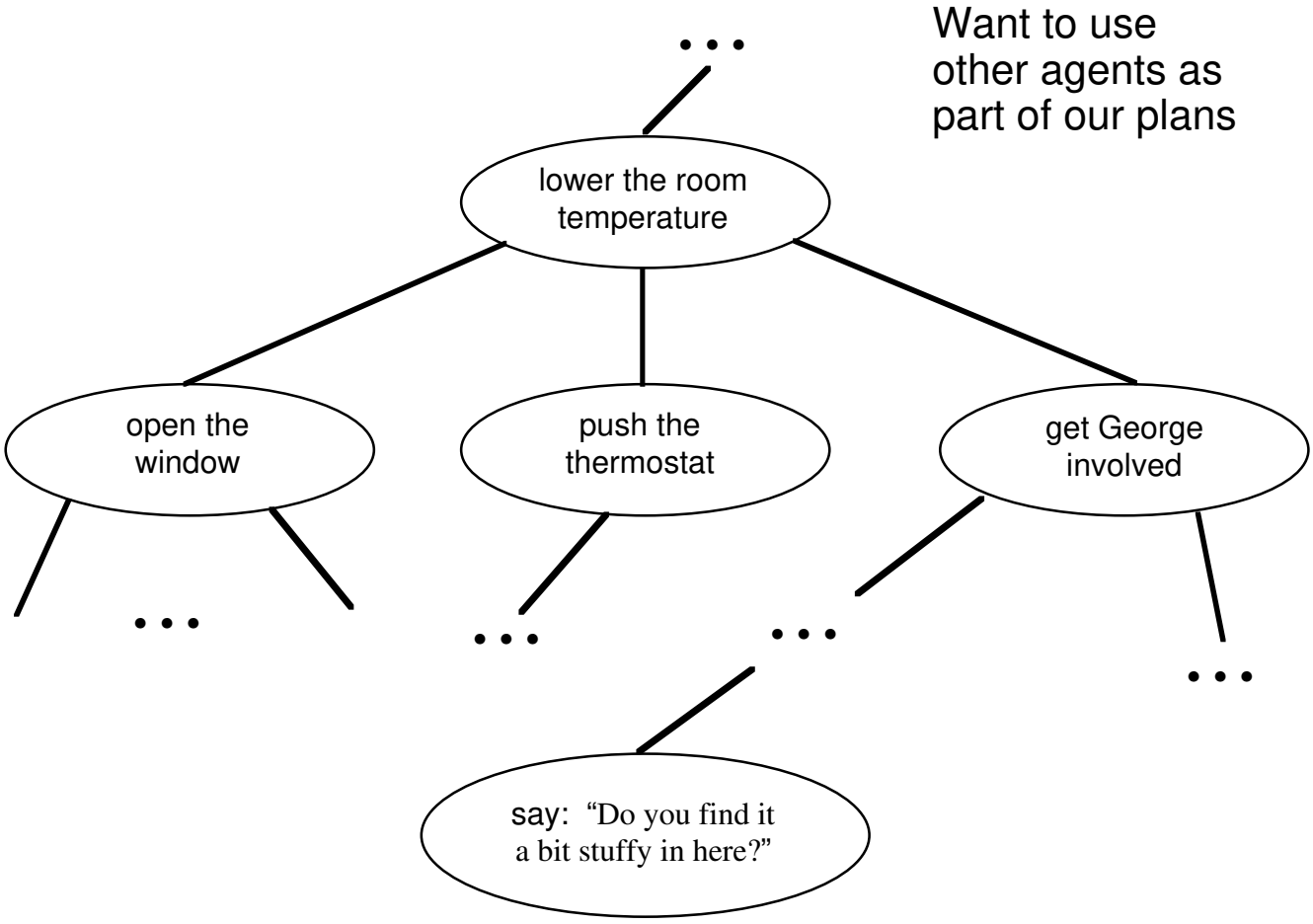
- prototype implementation is running
- currently: link to simulated actions, sensors

  "Truckworld" variant
- anticipated: link to ARK mobile platform

Introduction

Why communicate?

- to indicate our mental state? ✘
- to affect the mental state of others? ✘
- to advance our non-linguistic goals! ✔



But then: What do I need to *know* about the agent, and what do I need to *do* to use the agent in this way?

Delegation

Understand agents as acting *rationally*, given a set of beliefs and goals (which vary over time)

The Principle

> If there is an agent who
>
> 1. knows how to bring about ϕ
> 2. is committed to doing so
>
> then ϕ will obtain

This principle provides a strategy for achieving ϕ, by getting another agent into a certain mental state

and leaving the rest to him/her/it

But what is this mental state?

- committed to the goal of achieving ϕ

  see Cohen and Levesque: intention

☞ • knowing how to achieve ϕ: ability

  would like an account that is sufficient to validate above principle

  but here: single agent case only

Planning?

If it turns out that

knowing how to achieve ϕ

$\equiv$

having a plan P for achieving ϕ

why not simply use a formalization of planning?

The issue is not

planning = *finding* a plan

but

ability = *having* a plan

For example, need to be able to reason from facts like

Bill knows how to open the mystery lock.

without *our* being able to generate a plan to do it.

Need a specification of $Can(\phi)$ that is more than just a procedure for generating plans for ϕ.

planning procedure should be correct
relative to this specification

Overview

1. Motivation
2. This slide
3. Crash course in the situation calculus:
   - the frame problem
   - complex actions
   - knowledge
4. Achieving a goal
   - the classical approach
   - using programs
   - iterative / fixed point versions
5. A path-based definition of CAN
   - some properties
   - relation to programs
6. Rethinking the “what” of planning

Advisory: The following presentation contains explicit formulas and other highly graphic material.

Situation Calculus

McCarthy

A second-order logical language for representing dynamically changing worlds

- The world is thought of as being in some state
- This state changes only as the result of an agent performing some named action

Syntactically: predicate calculus with special sorts for

- actions: a, jump, rotate(90°), putIn(b, box3)
- situations: s, S_0, $do(a, s)$ ← the state resulting from performing action a in state s

  $s_1 \leq s_2$

Fluents: predicates (or functions) whose final argument is a situation

$$\text{Happy}(S_0), \quad \text{NextTo}(x, y, s), \quad \text{location}(x, do(\text{kick}(x), s))$$

Actions may have preconditions: $Poss(a, s)$

$$Poss(\text{pickup}(r,x), s) \equiv \text{NextTo}(r, x, s) \wedge \neg\text{Heavy}(x) \wedge \forall z\, \neg\text{Holding}(r, z, s)$$

World dynamics are specified by <u>effect axioms</u> like

$$Poss(\text{drop}(r,x), s) \wedge \text{Fragile}(x) \supset \text{Broken}(x, do(\text{drop}(r,x), s)) \quad \text{+ve}$$

$$Poss(\text{repair}(r,x), s) \supset \neg\text{Broken}(x, do(\text{repair}(r,x), s)) \quad \text{–ve}$$

The Frame Problem

McCarthy & Hayes

Given a specification of the "causal laws" via effect axioms, derive a succinct specification of what does *not* change as the result of performing an action

Should not have to write down frame axioms like

$$Poss(\text{drop}(r,y), s) \wedge \neg\text{Broken}(x, s) \wedge (x \neq y \vee \neg\text{Fragile}(x)) \supset \neg\text{Broken}(x, do(\text{drop}(r,y), s))$$

Solution: Pednault, Haas, Schubert, Reiter

- Can group all the effect axioms for a fluent F into two:

$$Poss(a, s) \wedge \gamma^{+}(\bar{x}, a, s) \supset F(\bar{x}, do(a,s))$$
$$Poss(a, s) \wedge \gamma^{-}(\bar{x}, a, s) \supset \neg F(\bar{x}, do(a,s))$$

- Assume these axioms characterize all the conditions under which any action a can change F

$$Poss(a, s) \wedge \neg F(\bar{x}, s) \wedge F(\bar{x}, do(a,s)) \supset \gamma^{+}(\bar{x}, a, s)$$
$$Poss(a, s) \wedge F(\bar{x}, s) \wedge \neg F(\bar{x}, do(a,s)) \supset \gamma^{-}(\bar{x}, a, s)$$

- Under suitable conditions, these four together are logically equivalent to a single successor state axiom

$$Poss(a, s) \supset [F(\bar{x}, do(a,s)) \equiv \gamma^{+}(\bar{x}, a, s) \vee F(\bar{x}, s) \wedge \neg\gamma^{-}(\bar{x}, a, s)]$$

For example: $Poss(a, s) \supset [\text{Broken}(x, do(a,s)) \equiv \exists r \{a = \text{drop}(r,x) \wedge \text{Fragile}(x)\} \vee \text{Broken}(x, s) \wedge \neg\exists r\, a = \text{repair}(r,x)$

The Frame Problem (contd.)

For each fluent F, the successor state axiom for F reduces $F(do(a,s))$ to some condition on the state s

$$Poss(a,s) \supset F(do(a,s)) \equiv \Phi(s)$$

this entails appropriate frame axioms

- significantly generalizes STRIPS

  wrt initial state S_0 and effect axioms

The conciseness of the succ. state axiom depends on

- quantification over actions
- assumption that relatively few actions will affect a given fluent
- assumption that <u>all</u> effect axioms have been enumerated and are of the form

$$Poss(-, s) \wedge \ldots \supset \pm F(do(-, s))$$

Limitations:

- only actions with determinate effects

  ✘ $Poss(\text{flip}, s) \supset \text{Heads}(do(\text{flip}, s)) \vee \text{Tails}(do(\text{flip}, s))$

- actions are all independent primitives

  no sequences, iterations, *etc.*

  see below

- no indirect effects

  all effect axioms must be in hand

  (ramification problem)

Complex Actions in the Situation Calculus

Would like a way of expressing and reasoning about actions that are constructed out of primitive actions

- **`If`** Car_In_Driveway **`then`** drive **`else`** walk
- **`While`** Tree_Still_Standing **`do`** chop
- $\Pi\, x$ [Block(x)?; grasp(x)]

Need to extend the notation $do(a, s) = s'$ to handle a complex action / program A:

$Do(A, s, s')$

s' is one possible final situation that could result from doing program A in situation s

However, previous solution to the frame problem depended on all actions being determinate primitives

(and would like to inherit this solution)

Method: treat $Do(...)$ as a macro that expands to a formula in the sit. calculus that only uses $do(...)$

Result: complex actions are completely eliminated by macro expansion

Limitation: cannot quantify over complex actions

- can only use in the context $Do(A, s, s')$, where A is a specific program

The Do Macro

1. $Do(a, s, s') \doteq Poss(a, s) \wedge s' = do(a, s)$

2. $Do([A;B], s, s') \doteq \exists s^* Do(A, s, s^*) \wedge Do(B, s^*, s')$

3. $Do([\textbf{if } \phi \textbf{ then } A \textbf{ else } B], s, s') \doteq$
$(\phi[s] \supset Do(A, s, s')) \wedge (\neg\phi[s] \supset Do(B, s, s'))$

4. $Do([\textbf{while } \phi \textbf{ do } A], s, s') \doteq$
$\forall P (\bullet\bullet\bullet) \supset P(s , s')$ 2nd order!

... others

$\forall s_1 \neg\phi[s_1] \supset P(s_1, s_1)$

$\forall s_1 s_2 s_3 \ \phi[s_1] \wedge Do(A, s_1, s_2) \wedge P(s_2,s_3) \supset P(s_1, s_3)$

Notation

$\phi[s]$ means take all fluents in ϕ and add s as a situation argument, if one is missing

if Happy **then** laugh **else** cry $\Rightarrow$
Happy(s) $\supset Do($laugh, $s, s') \ldots$

Sometimes use '*now*' as a pseudo-situation argument to be replaced

if Happy(*now*) **then** laugh **else** cry

Knowledge in the Situation Calculus

Moore

Following Moore, introduce accessibility relation as a fluent predicate in the language: $K(s', s)$

in situation s, as far as the agent knows, s' could be the current situation

Note order of arguments, to be compatible with

$\text{Broken}(\text{obj1}, s)$, $\text{Happy}(s)$, $\text{NextTo}(x, y, s)$

↑ final argument is always the current situation

Knowledge: truth in all accessible situations

$$Know(\phi, s) \doteq \forall s' \, K(s', s) \supset \phi[s']$$

Like complex actions, knowledge is treated as a macro

Note: $Know(\text{Raining}(\underline{now}), S_0)$ expands to

$\forall s' \; K(s', S_0) \supset \text{Raining}(s')$ ✔

But: $Know(\text{Raining}(S_0), S_0)$ expands to

$\forall s' \; K(s', S_0) \supset \underline{\text{Raining}(S_0)}$?

So non-fluents and fluents that do not use the situation term '$\underline{now}$' always have known values!

Knowledge and Action

The fluent K is affected by ordinary actions and by special "knowledge-producing" perceptual actions

For ordinary actions, we have causal laws like

$$K(s', do(\text{jump}, s)) \equiv \exists s^* \; s' = do(\text{jump}, s^*) \wedge K(s^*, s))$$

the situations that are accessible after doing a jump are the images of those that were accessible before

$\therefore$ after jumping, it is known that a jump has occurred

Each knowledge-producing action is associated with a formula (or term) whose value will become known

For example, we might have the action rainchk which can be used to find out if it is raining:

$$K(s', do(\text{rainchk}, s)) \equiv \exists s^* \; s' = do(\text{rainchk}, s^*) \wedge K(s^*, s) \wedge \text{Raining}(s^*) \equiv \text{Raining}(s)$$

the situations accessible after checking are the images of those from before where Raining had the correct truth value

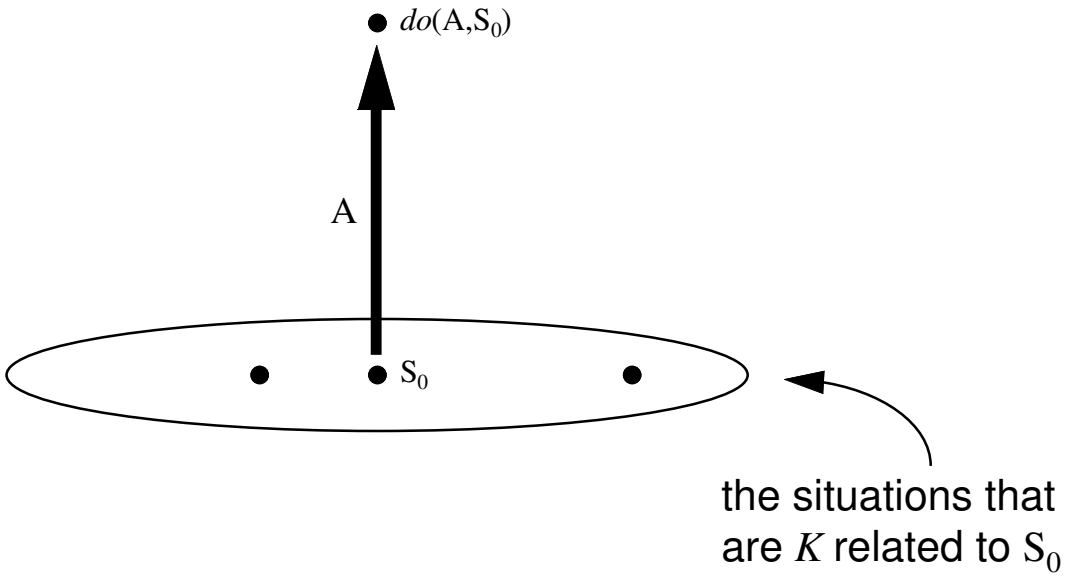
$\therefore$ after checking, it is known *whether or not* it is raining

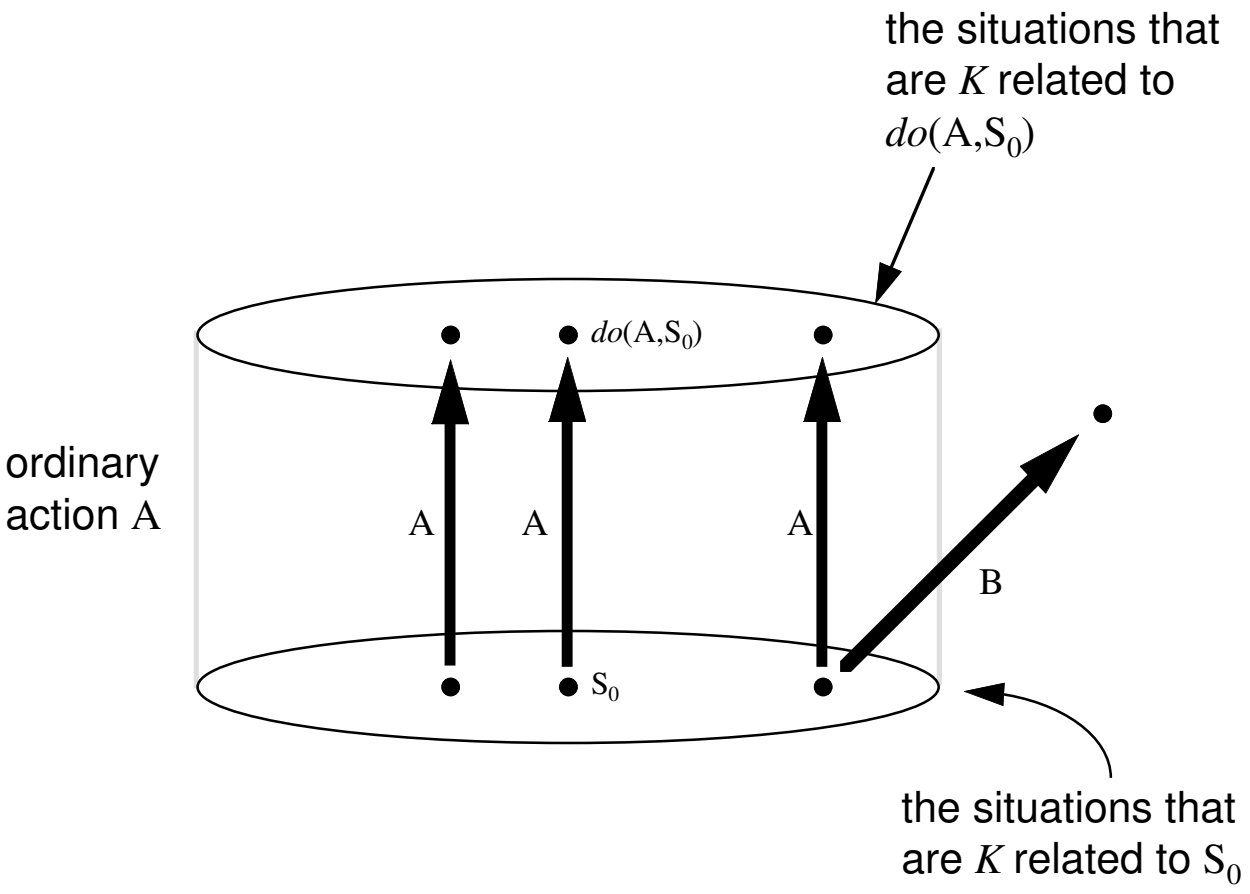
Assume n knowledge-producing actions $kp_1, ..., kp_n$. We get a successor-state axiom like

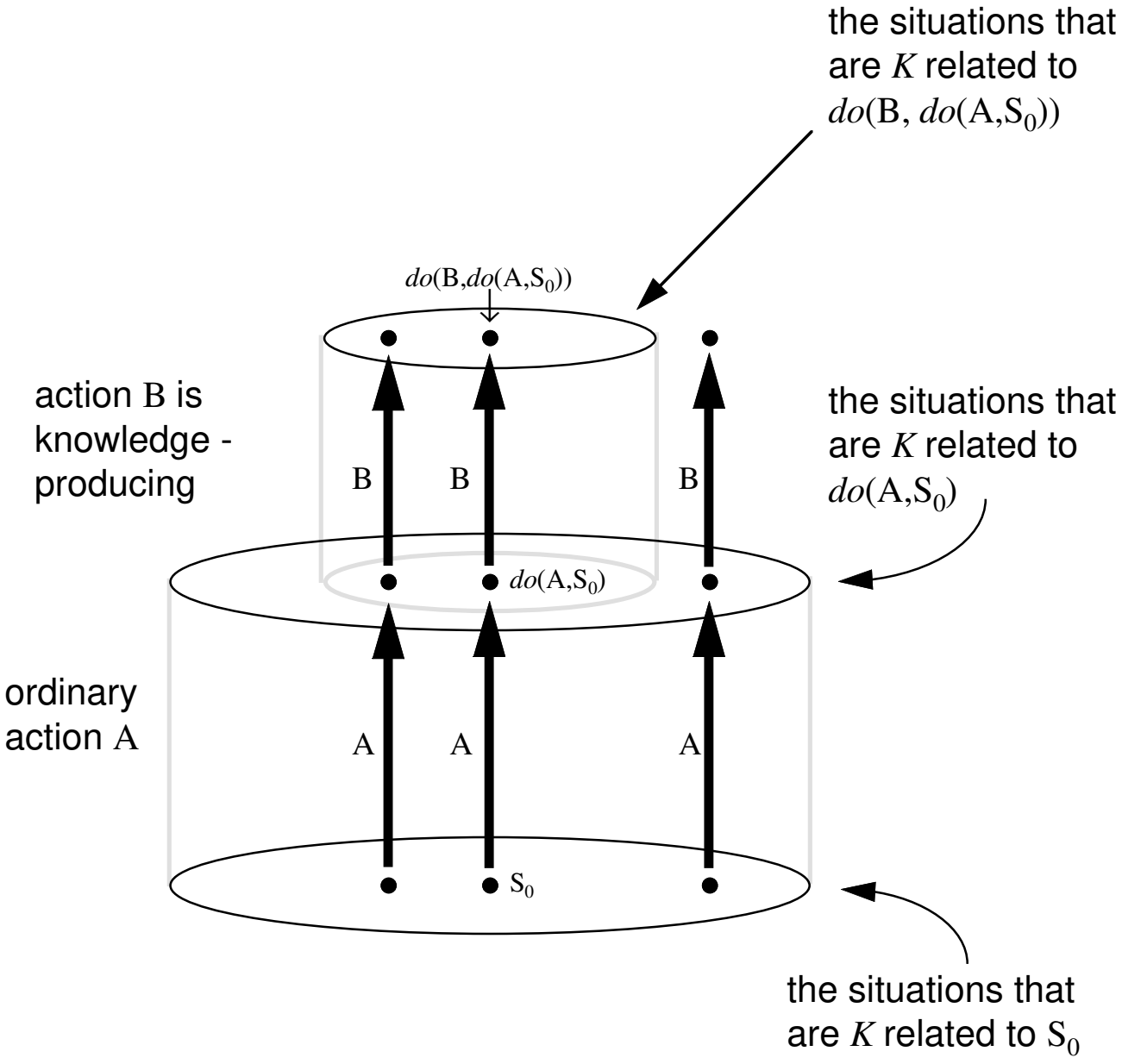
$$Poss(a,s) \supset [\, K(s', do(a,s)) \equiv \exists s^* \; s' = do(a, s^*) \wedge K(s^*, s) \wedge (a = kp_1 \supset \phi_1[s^*] \equiv \phi_1[s]) \wedge \ldots \wedge (a = kp_n \supset \phi_n[s^*] \equiv \phi_n[s])\,]$$

This completely determines K at $do(a,s)$ in terms of K at s

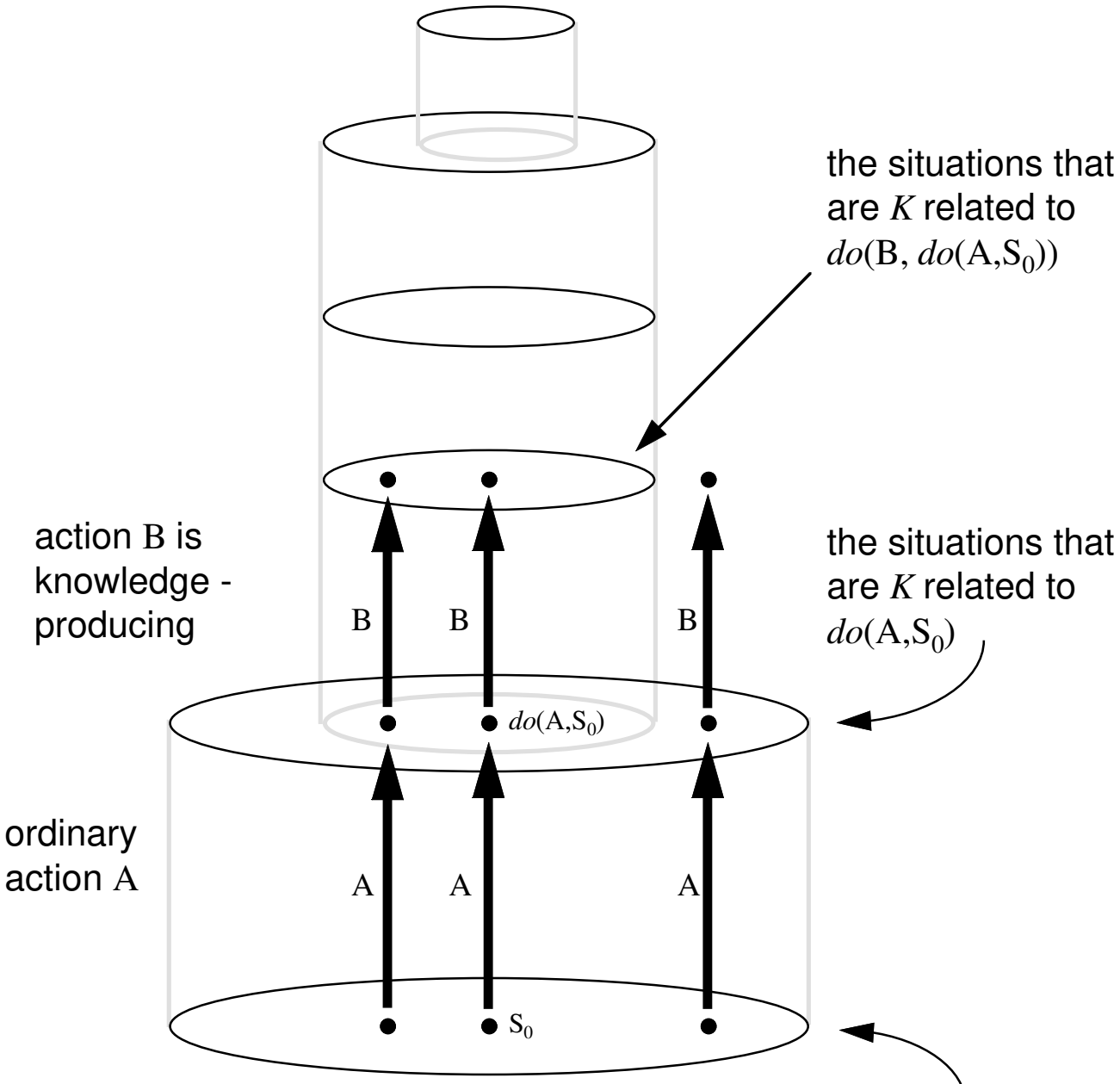
Pictorially ...




the situations that are K related to $do(A,S_0)$
$do(A,S_0)$
ordinary action A
A
A
A
B
S_0
the situations that are K related to S_0


the situations that are K related to $do(B, do(A,S_0))$
$do(B,do(A,S_0))$
action B is knowledge - producing
B
B
B
the situations that are K related to $do(A,S_0)$
$do(A,S_0)$
ordinary action A
A
A
A
S_0
the situations that are K related to S_0

Knowledge, The Picture



The K fluent at $do(a,s)$ is fully determined by a and its value at s

Plans in the Situation Calculus

Green

To achieve goal $\phi[s]$, pose $\Sigma \stackrel{?}{\models} \exists s\ \phi[s]$

then use answer extraction

Get: $s = do(a_n, do(a_{n-1}, \ldots do(a_1, S_0) \ldots))$

i.e. doing $a_1, a_2, \ldots a_n$ is sufficient to achieve ϕ

Two strong assumptions:

1. Background knowledge Σ is such that there will be a fixed sequence of actions from S_0 to a goal state

   No conditionals, loops as in

   ```
   begin
      go_outside;
      look_in_driveway;
      if Car_In_Driveway
         then drive
         else walk
   end
   ```

   Never a need for perceptual actions

2. The agent always knows enough to be able to execute each action in the sequence

   Example: want block moved to John's favourite location on the table (unchanging), given that the block can be moved anywhere.

   ϕ = At(block, favLoc(john, s), s)

   Get: a = move(block, favLoc(john, S_0))

I. Using programs

Characterize agents ability to achieve ϕ in terms of complex actions / programs

addresses problem 1 directly

$$Can(\phi, A, s) \doteq KnowHow(A, s) \wedge \forall s' Do(A, s, s') \supset \phi[s']$$

agent can achieve ϕ by doing program A iff
the agent knows how to do A, and
doing it results in a state where ϕ holds

variants: require agent to know that ϕ holds or
require agent to know 2nd conjunct *etc.*

KnowHow(A, s) is characterized by a set of axioms:

$KnowHow(t, s) \equiv \exists a\, Know(t=a, s)$, t is a prim. action term

addresses problem 2

$$KnowHow([\textbf{if } \phi \textbf{ then } A \textbf{ else } B], s) \equiv Know(\phi, s) \wedge KnowHow(A, s) \vee Know(\neg\phi, s) \wedge KnowHow(B, s)$$

$$KnowHow([A; B], s) \equiv KnowHow(A, s) \wedge Know(\forall s' Do(A, \underline{now}, s') \supset KnowHow(B, s'), s)$$

or some such

$$KnowHow([\textbf{while } \phi \textbf{ do } A], s) \equiv Know(\neg\phi, s) \vee Know(\phi, s) \wedge KnowHow(A; [\textbf{while } \phi \textbf{ do } A], s)$$

Some problems

1. Takes program text too literally

   "dumb" interpreter

   $KnowHow([\textbf{if } \phi \textbf{ then } A \textbf{ else } A], s) \supset$
   $Know(\phi, s) \vee Know(\neg\phi, s)$

2. Too weak on while loops

   $KnowHow([\textbf{while } \text{TRUE } \textbf{do } A], s)$ is not ruled out

   But then, get $Can(\text{Anything}, [\textbf{while } \text{TRUE } \textbf{do } A], s)$
   since $\forall s' \neg Do([\textbf{while } \text{TRUE } \textbf{do } A], s, s')$

   Problem: loops need a <u>least</u> fixed point

3. How to get $Can(\phi, s)$?

   One way: $\exists\, Program{:}x \;\; Can(\phi, x, s)$

   But this requires *quantifying over programs*

   Conflicts with our solution to frame problem

However, this approach gets at the main issue:

the agent must always know
what primitive action to do next

Want: at each step s, $\exists a\, Know($'should do a now', $s)$

The tree example

Assume that a certain tree will fall down after some number of primitive chopping actions

$$\text{Down}(s) \doteq \text{magicNum}(s) = 0$$

$$\text{magicNum}(do(a,s)) = k \equiv$$
$$a = \text{chop} \wedge \text{magicNum}(s) = k+1 \vee$$
$$a \neq \text{chop} \wedge \text{magicNum}(s) = k$$

succ state axiom

and that the agent can always find out by looking whether or not the tree is down.

$$K(s', do(\text{look}, s)) \equiv \exists s^* \; s' = do(\text{look}, s^*) \wedge K(s^*, s) \wedge \text{Down}(s) \equiv \text{Down}(s^*)$$

$$\therefore \quad \forall s \; Know(\text{Down}, do(\text{look}, s)) \vee Know(\neg\text{Down}, do(\text{look}, s))$$

But we do not assume that the agent knows

- how many chop actions are necessary: $magicNum(S_0)$
- which chop will be the final action

Want a definition of *Can* such that $Can(\text{Down}, S_0)$.

Why? Intuitively, by doing program choploop:

```
look;
while ¬Down do
      chop;
      look
end while
```

II. Iterative version

$Can(\phi, s) \doteq \exists k\ Can^k(\phi, s)$ where

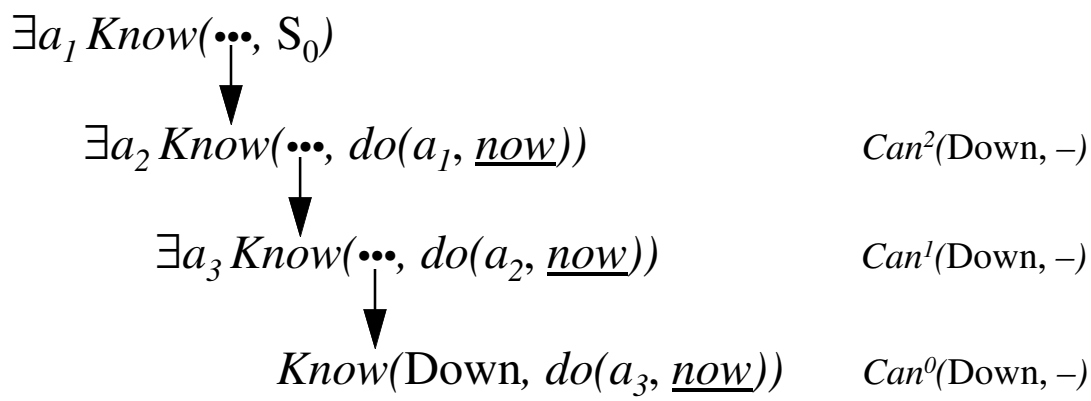
$Can^0(\phi, s) \equiv Know(\phi, s)$

$Can^{k+1}(\phi, s) \equiv \exists a\ Know(Can^k(\phi, do(a, \underline{now})), s)$

Handles many (most? all?) examples that do not use unbounded while loops

However, it fails on the chopping-tree example

for example, $Can^3(\text{Down}, S_0)$ is equivalent to



So Can^k requires knowing initially that k steps are sufficient to achieve the goal

Instead of $\underline{\exists k}$ ... $\exists a\ Know(Can^k(\bullet\bullet\bullet), s)$,

would prefer ... $\exists a\ Know(\underline{\exists k}\ Can^k(\bullet\bullet\bullet), s)$,

which is just ... $\exists a\ Know(Can(\bullet\bullet\bullet), s)$

III. Fixed-point version

Would like a definition of Can that satisfies

1. $Know(\phi, s) \supset Can(\phi, s)$
2. $\exists a\ Know(Can(\phi, do(a,\underline{now})), s) \supset Can(\phi, s)$

Try characterizing Can by axiom:

$$Can(\phi, s) \equiv Know(\phi, s) \vee \exists a\ Know(Can(\phi, do(a,\underline{now})), s)$$

done

know what to do next

Problem: too weak

$Can(\phi, s) \equiv \text{TRUE}$ is consistent with this axiom

Better idea: use *least* fixed point

Idea: $Can_{\perp}(\phi, s)$ holds iff $C(s)$ where C is the *smallest* predicate that satisfies the axiom

Formally: $Can_{\perp}(\phi, s) \doteq \forall C\ (\bullet\bullet\bullet \supset C(s))$

$$\forall s'\ C(s') \equiv [Know(\phi, s') \vee \exists a\ Know(C(do(a,\underline{now})), s')]$$

Problem: too strong!

Fails on tree example: $\neg Can_{\perp}(\text{Down}, S_0)$

Why? consider $D(s)$ defined as $Know(\text{Down}, s)$

Then D is a fixed point, given $\neg Know(D(do(a,\underline{now})), s')$

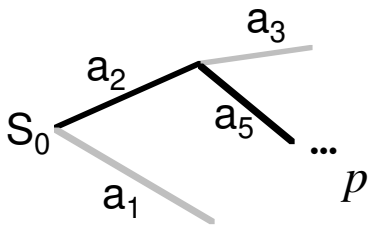
But $Can_{\perp}$ must hold in no more situations than D

Thus: $\neg Can_{\perp}(\text{Down}, S_0)$, unless $Know(\text{Down}, S_0)$

Final version: path-based

Path: provides a mapping from situations to actions

– intuitively: the next action to perform



$next(p, S_0) = a_2$

$next(p, do(a_2, S_0)) = a_5$

...

Characterized by a 2nd-order axiom:

$$\forall f{:}[sit \rightarrow action]\ \exists p{:}Path\quad \forall s\ next(p, s) = f(s)$$

Might also require: $Poss(next(p, s), s)$ the actions on p are physically possible

$OnPath(p, s, s')$ means path p goes from s to s' at least

$$OnPath(p, s, s') \doteq s \leq s' \wedge \forall a \forall s^* (s < do(a, s^*) \leq s') \supset next(p, s^*) = a$$

Useful for

- time, occurrences
- correctness of non-terminating programs

  fairness, etc.

Definition of CAN

$CanFollow(p, s, s') \doteq$

$OnPath(p, s, s') \wedge$

$\forall s^* (s \leq s^* \prec s') \supset \exists a\ Know(a=next(p, \underline{now}), s^*)$

at every step between s and s', the agent knows the value of p at that situation

$\therefore$ the agent knows how to stay on the path

Notation: goals ϕ to be achieved may use <u>two</u> pseudo-situation arguments

- the initial state, written '*<u>start</u>*' (often S_0)
- the desired goal state, written '*<u>end</u>*'

Example: $\forall x\ \mathrm{On}(x,\mathrm{table},\underline{start}) \supset \mathrm{In}(x,\mathrm{box},\underline{end})$

get everything on the table into the box

$$CanGet(\phi, p, s) \doteq \exists s'\ CanFollow(p, s, s') \wedge \phi[s, s']$$

starting at s, the agent can follow p to a state s' where ϕ holds

$$Can(\phi, s) \doteq \exists p\ Know(CanGet(\phi, p, \underline{now}), s)$$

Two variants: $\exists p\ CanGet(\phi, p, s)$ agent unaware

$Know(\exists p\ CanGet(\phi, p, \underline{now}), s)$??

Some general properties*

1. *Can* is implied by the iterative version

   $\exists k\ Can^k(\phi, s) \supset Can(\phi, s)$

   – If know how many steps are required and what to do at each step, then $Can(\phi, s)$.

   – But not conversely, (cf. tree example below)

2. *Can* satisfies the two properties of the fixed-point

   1. $Know(\phi, s) \supset Can(\phi, s)$
   2. $\exists a\ Know(Can(\phi, do(a,\underline{now})), s) \supset Can(\phi, s)$

      – Thus, it is implied by the least-fixed point

      $$Can_{\perp}(\phi, s) \supset Can(\phi, s)$$

      – But again not conversely, (cf. tree example)

*Hedge:

In the following it is assumed that the K relation is transitive and Euclidian. However, it is not required to be reflexive.

Thus, **weak S5** (*aka* **K45**), which avoids the difficulties of **strong S5** regarding introspection, may be used.

Also, for simplicity, ϕ is assumed not to use the *start* parameter

CAN and Programs

Moore's version of CAN depended on programs and an auxilliary definition of *KnowHow(A,s)*

Here: we can do the converse!

$$KnowHow(A, s) \doteq Can(Do(A, \underline{start}, \underline{end}), s)$$

note use of *start*

Some theorems:

Assume that $\forall s\, KnowHow(A, s) \wedge KnowHow(B, s)$

- $KnowIf(\phi, s) \supset KnowHow([\mathbf{if}\ \phi\ \mathbf{then}\ A\ \mathbf{else}\ B], s)$

  like Moore's account

- $KnowHow([\mathbf{if}\ \phi\ \mathbf{then}\ A\ \mathbf{else}\ A], s)$

  smart interpreter, unlike Moore's

- $Know(\exists s'\, Do([\mathbf{while}\ \phi\ \mathbf{do}\ A], \underline{now}, s'), s) \supset KnowHow([\mathbf{while}\ \phi\ \mathbf{do}\ A], s)$

  smart interpreter can just do *A* forever

  (ability to "stop" not required)

But <u>not</u>

- $Know(\exists s'\, Do([\mathbf{while}\ \phi\ \mathbf{do}\ A], \underline{now}, s'), s) \supset KnowHow([\mathbf{while}\ \phi\ \mathbf{do}\ A]; B, s)$

  need to know when done loop to do *B*

The tree example revisited

Theorem: $Can(Know(\text{Down}, \underline{end}), S_0)$ can fell the tree (& stop)

Proof:

Let path p be defined by $next(p, s) = \text{chop}$, if $s = do(\text{look}, -)$
$next(p, s) = \text{look}$, otherwise

Claim: $\forall s \; \exists a \; Know(a = next(p, \underline{now}), s)$

Observe: by succ. state axiom for K, we have that
$s = do(\text{look}, -)$ iff $\forall s' \; K(s', s) \supset s' = do(\text{look}, -)$

So, if $s = do(\text{look}, -)$, then $\forall s' \; K(s', s) \supset next(p, s') = \text{chop}$,
and otherwise, $\forall s' \; K(s', s) \supset next(p, s') = \text{look}$

Let s_1 be any situation such that $K(s_1, S_0)$.

Claim: $CanGet(Know(\text{Down}, \underline{end}), p, s_1)$

We have that $\exists s' \; Do(\text{choploop}, s_1, s')$,
since $\text{magicNum}(s_1)$ chops are always sufficient

So $\exists s' \; OnPath(p, s_1, s') \wedge \text{Down}(s') \wedge s' = do(\text{look}, -)$

and thus: $\exists s' \; CanFollow(p, s_1, s') \wedge Know(\text{Down}, s')$

Since s_1 was chosen arbitraily, we have that
$Know(CanGet(Know(\text{Down}, \underline{end}), p, \underline{now}), S_0)$ ■

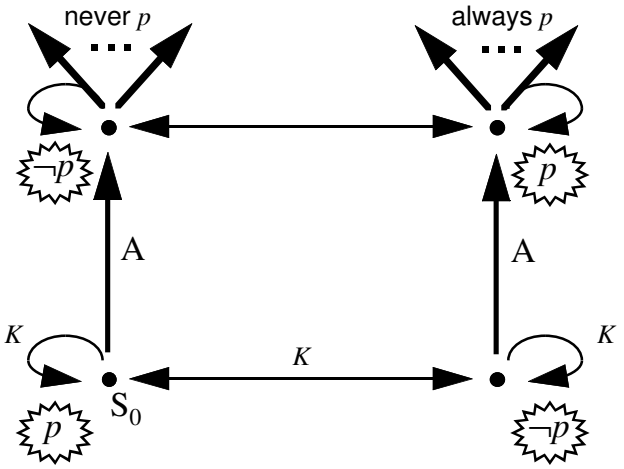
Note: proof requires knowing whether tree is down.
But without this, we still get $Can(\text{Down}(\underline{end}), S_0)$

agent knows that chopping forever will achieve it!

Fixed-points reconsidered

Can does <u>not</u> satisfy the fixed-point equivalence

$$Can(\phi, s) \equiv Know(\phi, s) \vee \exists a\, Know(Can(\phi, do(a, \underline{now})), s)$$



counter-model

$Can(p, S_0)$ but
$\neg Know(p, S_0)$
$\neg Know(Can(p, do(A, \underline{now})), S_0)$

However, it does* when the goal is of the form $Know(\psi)$

Let $Can^+(\phi, s) \doteq Can(Know(\phi, \underline{end}), s)$

Then $Can^+(\phi, s) \equiv Know(\phi, s) \vee \exists a\, Know(Can^+(\phi, do(a, \underline{now})), s)$

This can also be generalized* to any goal ϕ for which there is a sense action A:

$$\forall s\ Know(\phi, do(A, s)) \vee Know(\neg\phi, do(A, s))$$

*Restrictions on K apply

Are programs necessary?

Having a program is <u>sufficient</u> for Can:

$$KnowHow(A, s) \wedge Know(\bullet\bullet\bullet, s) \supset Can(\phi, s)$$

$$\forall s' Do(A, \underline{now}, s') \supset \phi[\underline{now}, s']$$

doing A results in a situation where ϕ holds

Follows from:

$$Can(\psi, s) \wedge Know(\bullet\bullet\bullet, s) \supset Can(\phi, s)$$

$$\forall s' \; \underline{now} \leq s' \wedge \psi[\underline{now}, s'] \supset \phi[\underline{now}, s']$$

ψ implies ϕ in all future states

Does the converse hold?

Is it the case that if $Can(\phi, s)$, there must be some implicit program A that determines the path to follow?

If not, then perhaps the language is too strong.

Planning revisited: $\Sigma \models Can(\phi, s)$

constructive proof for $\Sigma \models \exists p \; Know(\bullet\bullet\bullet, s)$?

from which can we <u>derive</u> a program ??