COGNITIVE ROBOTICS

Introduction

We want to build autonomous agents, e.g. robots, that operate in a changing, incompletely known, unpredictable environments.

We want them to be smart, have autonomous reasoning and planning capabilities.

We also want to have precise specifications of their behavior and to be able to verify that they satisfy some desired properties.

Cognitive Robotics

Theory and **implementation** of agents that **act in an informed way** in changing, incompletely known, partially observable, unpredictable environments.

Basic tools:

- Model of the world state and of how it changes when actions are performed (*representation*).
- Capabilities of making informed selection of the actions to performed (*reasoning*).

Cognitive Robotics (cont.)

Research focus:

- Action theories.
- The frame, ramification and qualification problems.
- Complex actions and procedures.
- Concurrent processes.
- Sensing.
- Exogenous and natural events.
- Deciding when to act.
- Deciding what to do.
- Deciding what to look for.
- Ability of an agent to perform an action.
- Real time (resource bounded) behavior.
- Probabilistic action occurrences and action effects.
- Agent beliefs, desires, intentions and how they condition action.
- Belief revision in the presence of conflicting observations.
- Open world vs closed world representations.
- Execution monitoring and failure recovery.

Contrast with most current robotics research:

- Sensory processing.
- Path planning.
- Manipulator design and control.
- Purely reactive agents, cockroach AI.

The Cognitive Robotics Manifesto

(Proposed at AAAI 1998 Fall Symp. on Cognitive Robotics)

- Interesting agent behaviors require reasoning.
- *Knowledge Representation Hypothesis*: Reasoning over explicitly represented facts leads to decisions about how to act.
- And therefore, mathematical logic (but not excluding probability and decision theory).
- Intellectual foundations within Knowledge Representation.
- But, maybe KR had become too concerned with "pure reason".
- Cogrob is the natural reaction to purely deliberative KR in favor of principled theories of how deliberation relates to:
  - Real time computation and reactivity.
  - Sensing.
  - Deciding when and how to act.
  - Execution monitoring.
  - On-line vs off-line computations.
  - Belief revision.
  - Etc.
- In short, cogrob is concerned with developing a unified theoretical and implementation framework for reasoning, action and perception.
- Robots implemented on these principles provide a criterion for success.

HIGH-LEVEL ROBOT PROGRAMS BASED ON THE SITUATION CALCULUS

http://www.cs.toronto.edu/~cogrobo/

Basic idea

- **Action theory:** high-level (logical) representation of the world used by the robot.
- **Atomic actions:** associated to actual robot's commands. Commands activate complex low-level behaviors (e.g. $followCorridor$, $moveObjOnObj$).
- **High-level robot program:** robot program formulated in terms of high-level representation of the world.

The Toronto approach

- Logical foundation: a variant of McCarthy's (1960) situation calculus.
- Distinguish two categories of actions:
  - *Primitive actions:* Simple, indecomposable, implementable.
    Pick up a block, walk one step, open a door, perceive whether door is open.
  - *Complex actions:* Composed from simple actions using familiar programming language constructs.

    If *car-in-driveway* **then** *drive* **else** *walk*.

    while $\neg Obstacle$ {
    $walkOneStep$;
    $senseForObstacle$
    }
- Develop axiomatizations for these in the sitcalc.
- Develop and implement situation calculus-based programming languages for defining complex actions.
- Extend the "classical" sitcalc to include:
  - Time, processes, concurrency.
  - Probability and decision theory.
  - Knowledge (to account for the effects of perceptual actions).
- Implement on an autonomous robot.

The Situation Calculus (McCarthy, 1963)

- A first order language for representing dynamically changing worlds; all changes are the result of named *actions*.
- A *situation:* a first order term denoting a possible world history (a sequence of actions).
- These sequences are represented using a binary function symbol do: $do(\alpha, s)$ denotes the history resulting from adding the new action α to the history s.
- Actions are first order terms:

  $put(x, y) =$ put object x on object y.

  $do(put(A, B), s) =$ that situation resulting from placing A on B when the current situation is s.

  $do(putdown(A), do(walk(L), do(pickup(A), S_0)))$

  denotes the sequence of actions

  $[pickup(A), walk(L), putdown(A)]$.
- $Fluent =$ relation or function whose values may vary from situation to situation.
  - Denoted by predicate/function symbol taking a situation term as one of its arguments.

    $closeTo(x, y, s)$: x is close to y in situation s.

    $pos(x, s)$: x's position in situation s.

Basic action theories

Basic action theory [Reiter91,Reiter99]:

- Axioms describing initial situation S_0. *The description can be incomplete.*
- Action precondition axioms (one per action). *These solve the qualification problem.*

$$Poss(moveToTable(b), s) \;\equiv\; Clear(b) \wedge \neg OnTable(b, s)$$

- Successor state axioms (one per fluent). *These solve the frame problem.*

$$\begin{aligned} &OnTable(b, do(a, s)) \;\equiv \\ &\qquad a = moveToTable(b, s) \;\vee\; OnTable(b, s) \wedge \neg \exists b'.a = move(b, b') \end{aligned}$$

- Unique name assumption for actions.
- Some foundational domain independent axioms.

A family of programming languages

- Golog, Congolog (reactivity, exogenous events), Temporal Golog.
- Suitable for controlling discrete event systems like elevators and robots performing high level actions. Simulation. Implementing planning systems.
- Purely logical situation calculus semantics.
- Logic based languages. Interpreters require reasoning.
- Implemented (in Prolog).
- Generalize conventional imperative languages:
  - "Normal" imperative languages provide for procedure definitions that "bottom out" in simple operations on *machine* states, e.g. *assignment* statements.
  - With the Golog family, the programmer specifies world states (via fluents), the primitive actions of that world, and how those actions change states (via successor state axioms).

    Machine state $\rightarrow$ world state.
    Primitive operations on machine states $\rightarrow$ the state change actions you want (so long as you axiomatize their effects).
    $\Longrightarrow$
    Executable specifications of complex behaviours at the right level of abstraction.
- Programs in the Golog family adopted in experiments actual autonomous robots at Toronto University, York University, Bonn University, Roma "La Sapienza"

Golog

Golog [Levesque et al.97]: logic-based programming language. Primitive actions formalized in action theory. *GOLOG = alGOL in lOGic*

It includes following constructs:

- nil — empty program
- a — primitive action
- $\phi?$ — test condition
- $(\delta_1; \delta_2)$ — sequence
- $(\delta_1 \mid \delta_2)$ — nondeterministic choice of action
- $\pi v.\delta$ — nondeterministic choice of value
- δ^* — nondeterministic iteration
- $\mathbf{if}\, \phi \,\mathbf{then}\, \delta_1 \,\mathbf{else}\, \delta_2$ — if-then-else
- $\mathbf{while}\, \phi \,\mathbf{do}\, \delta$ — while-loop
- $\mathbf{proc}\ P(\vec{v})\ \ \delta_P$ — procedure definition

In ϕ above the situations argument is suppressed.

Example: Golog program for dismounting all blocks towers

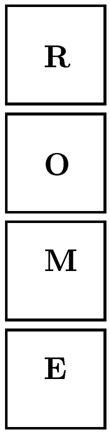
$$
\begin{array}{l}
\mathbf{while}\ \exists b, b'.On(b, b')\ \mathbf{do} \\
\{\quad \pi b.[Clear(b) \wedge \exists b'.On(b, b')]?; \\
\qquad moveToTable(b) \\
\}
\end{array}
$$

Golog (cont.)

Robot executing Golog program does **informed choices** at choice points to guarantee successful termination.

Example: Golog program for building blocks tower spelling "PARIS" or "ROME".

$$makeParis \mid makeRome$$



proc $makeRome$
$\{\quad \pi\, b_0.[E(b_0) \wedge OnTable(b_0) \wedge Clear(b_0)]?\,;$
$\quad\quad \pi\, b_1.M(b_1)?\,; move(b_1, b_0)\,;$
$\quad\quad\quad \pi\, b_2.O(b_2)?\,; move(b_2, b_1)\,;$
$\quad\quad\quad\quad \pi\, b_3.R(b_3)?\,; move(b_3, b_2)$
$\}$

proc $makeParis$
$\{\quad \pi\, b_0.[S(b_0) \wedge OnTable(b_0) \wedge Clear(b_0)]?\,;$
$\quad\quad \pi\, b_1.I(b_1)?\,; move(b_1, b_0)\,;$
$\quad\quad\quad \pi\, b_2.R(b_2)?\,; move(b_2, b_1)\,;$
$\quad\quad\quad\quad \pi\, b_3.A(b_3)?\,; move(b_3, b_2)\,;$
$\quad\quad\quad\quad\quad \pi\, b_4.P(b_4)?\,; move(b_4, b_3)$
$\}$

If only blocks for R, O, M, E, A, I, S available, robot does not consider building tower PARIS, it builds tower ROME.

Golog's computation semantics

Semantics of Golog programs (in absence of external disturbance) is captured by relation

$$Do(\delta, s, s')$$

which selects all situations s' resulting from a **successfully terminating execution** of program δ starting from s.

In [Levesque et al.97] it is shown that for any program δ relation $Do(\delta, s, s')$ can be inductively defined in terms of a pure situation calculus formula not mentioning δ.

$$\begin{array}{rcl}
Do(nil, s, s') & \doteq & s' = s \\
Do(a, s, s') & \doteq & Poss(a[s], s) \wedge s' = do(a[s], s) \\
Do(\phi, s, s') & \doteq & \phi[s] \wedge s' = s \\
Do(\delta_1; \delta_2, s, s') & \doteq & \exists s''. Do(\delta_1, s, s'') \wedge Do(\delta_2, s'', s') \\
Do(\pi v.\delta, s, s') & \doteq & \exists v. Do(\delta, s, s') \\
\ldots & &
\end{array}$$

Offline Golog interpreter

From $Do(\delta, s, s')$, one can immediately lift an **offline** Golog interpreter.

- Interpreter computes an s' such that $Do(\delta, s, s')$ holds.
- From $s' = do(a_n, do(\ldots, do(a_1, s)\ldots))$, sequence of actions $a_1; \ldots; a_n$ to be executed in real world is extracted.

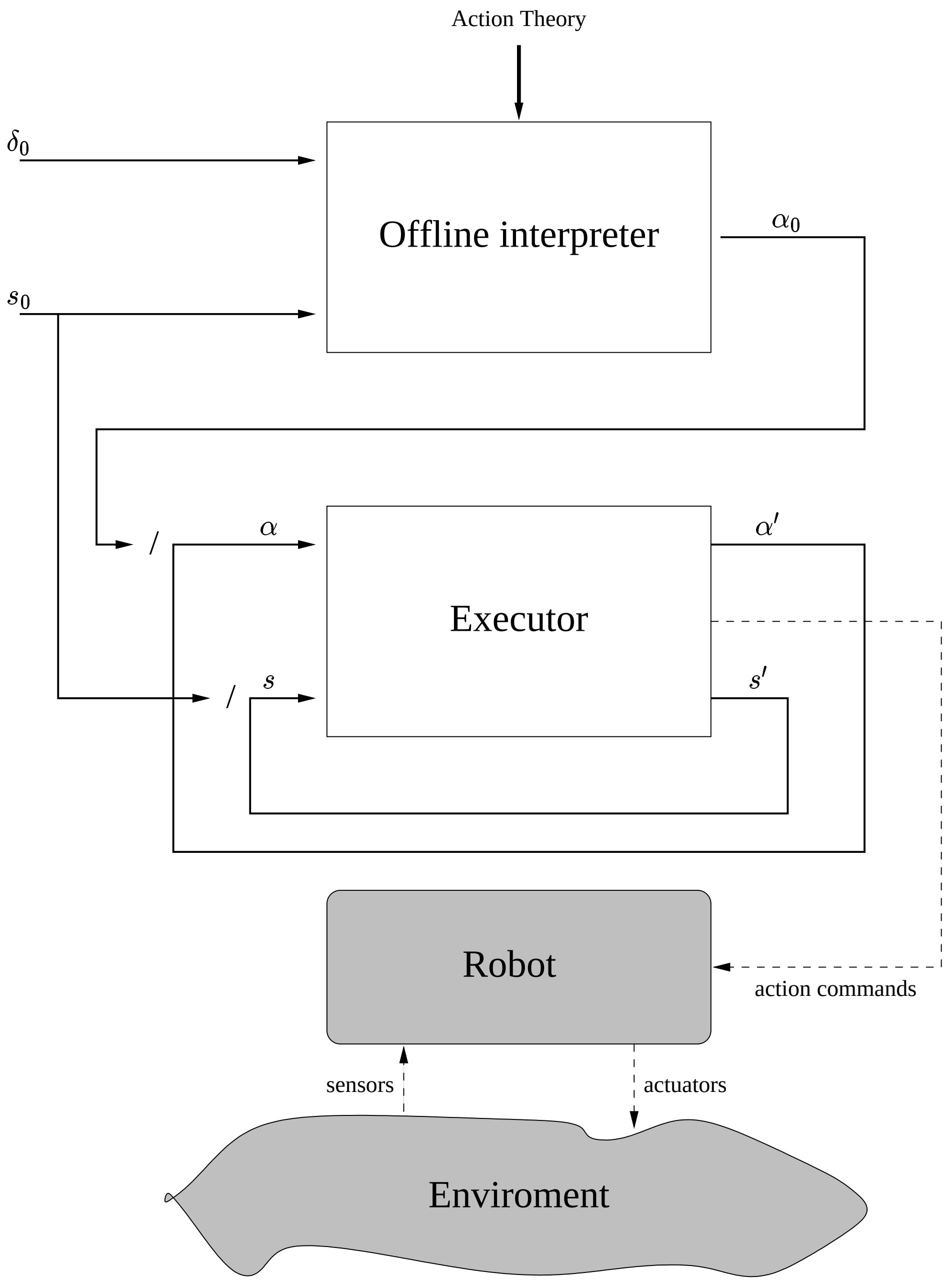
Offline Golog interpreter: implementation

```
do(E1 : E2,S,S1) :- do(E1,S,S2), do(E2,S2,S1).
do(?(P),S,S) :- holds(P,S).
do(E1 # E2,S,S1) :- do(E1,S,S1) ; do(E2,S,S1).
do(if(P,E1,E2),S,S1) :- do(?(P) : E1 # ?(-P) : E2,S,S1).
do(star(E),S,S1) :- S1 = S ; do(E : star(E),S,S1).
do(while(P,E),S,S1):- do(star(?(P) : E) : ?(-P),S,S1).
do(pi(V,E),S,S1) :- sub(V,_,E,E1), do(E1,S,S1).
do(E,S,S1) :- proc(E,E1), do(E1,S,S1).
do(E,S,do(E,S)) :- primitive_action(E), poss(E,S).
```

where

- `sub(Name,New,Term1,Term2)` implements substitution,
- `holds(Formula,Sit)` states that Formula holds in Sit.

Offline-interpreter-based architecture



From open loop to closed loop

Problem: when program **executed** in actual environment, discrepancy between real world and its representation may show up.

$\Longrightarrow$ Without **feedback** from environment:

$$Program + enviroment \longmapsto failure$$

How take into account feedback from environment?

Possible solutions:

- **Sensing controlled by program**

  $$Complex\ program + enviroment \longmapsto success$$

  but requires inserting appropriate sensing actions every time possibility of discrepancy is foreseen.

- **Execution monitoring**

  $$Program||Monitor + enviroment \longmapsto success$$

  Execution monitor senses environment asynchronously wrt program.

  – Program can remain simple, exploiting execution monitor for correct execution under exceptional circumstances.
  – Execution monitors can be designed once and for all, for supervising large classes of programs.

Execution monitoring approach

(Proposed in [DeGiacomo-Reiter-Sutchanski-KR98])

Execution monitoring approach is based on two ideas:

1. **Online interpreter** [DeGiacomo&Levesque-CogRob98]: put ability of making reasoned choices (typical of offline interpreter) into executor. In this way program can react to external stimuli.

2. **Execution monitor**: monitor execution of program in environment, passing appropriate stimuli from environment to program, and possibly dealing with exceptional unexpected circumstances.

Golog's transition semantics

An alternative way to formulate semantics of Golog programs is in terms of **single steps** (either actions or tests). Captured by two relations [DeGiacomo-Levesque-Lesperance-IJCAI97]:

- $Trans(\delta, s, \delta', s')$ – program δ executed in situation s may perform an action resulting in situation s' with program δ' remaining to be executed.
- $Final(\delta, s)$ – program δ may be considered successfully terminated in situation s.

$Do(\delta, s, s')$ can be re-expressed using reflexive-transitive closure of $Trans$ – "single step the program until you can successfully terminate".

Characterizing $Trans$ & $Final$ in situation calculus requires introducing new sort for *programs.*

$$
\begin{aligned}
&Trans(nil, s, \delta', s') \equiv False \\
&Trans(a, s, \delta', s') \equiv Poss(a[s], s) \wedge \delta' = nil \wedge s' = do(a[s], s) \\
&Trans(\phi?, s, \delta', s') \equiv \phi[s] \wedge \delta' = nil \wedge s' = s \\
&Trans(\delta_1; \delta_2, s, \delta', s') \equiv \exists\gamma.\, Trans(\delta_1, s, \gamma, s') \wedge \delta' = \gamma; \delta_2 \;\vee \\
&\qquad\qquad\qquad\qquad\qquad Final(\delta_1, s) \wedge Trans(\delta_2, s, \delta', s') \\
&Trans(\pi v.\delta, s, \delta', s') \equiv \exists x.\, Trans(\delta^v_x, s, \delta', s') \\
&\ldots \\
&Final(nil, s) \equiv True \\
&Final(a, s) \equiv False \\
&Final(\phi?, s) \equiv False \\
&Final(\delta_1; \delta_2, s) \equiv Final(\delta_1, s) \wedge Final(\delta_2, s) \\
&\ldots \\
&Final(\delta^*, s) \equiv True \\
&\ldots
\end{aligned}
$$

Offline (Con)Golog interpreter: implementation

```
/* trans(Prog,Sit,Prog_r,Sit_r) */

trans(act(A),S,nil,do(AS,S)) :- sub(now,S,A,AS), poss(AS,S).
trans(test(C),S,nil,S) :- holds(C,S).
trans(seq(P1,P2),S,P2r,Sr) :- final(P1,S),trans(P2,S,P2r,Sr).
trans(seq(P1,P2),S,seq(P1r,P2),Sr) :- trans(P1,S,P1r,Sr).
trans(choice(P1,P2),S,Pr,Sr) :- trans(P1,S,Pr,Sr) ; trans(P2,S,Pr,Sr).
trans(pick(V,P),S,Pr,Sr) :- sub(V,_,P,PP), trans(PP,S,Pr,Sr).
trans(iter(P),S,seq(PP,iter(P)),Sr) :- trans(P,S,PP,Sr).
trans(if(C,P1,P2),S,Pr,Sr) :- holds(C,S),trans(P1,S,Pr,Sr) ;
                              holds(neg(C),S),trans(P2,S,Pr,Sr).
trans(while(C,P),S,seq(PP,while(C,P)),Sr) :- holds(C,S),trans(P,S,PP,Sr).
trans(conc(P1,P2),S,conc(P1r,P2),Sr) :- trans(P1,S,P1r,Sr).
trans(conc(P1,P2),S,conc(P1,P2r),Sr) :- trans(P2,S,P2r,Sr).
trans(prconc(P1,P2),S,prconc(P1r,P2),Sr) :- trans(P1,S,P1r,Sr).
trans(prconc(P1,P2),S,prconc(P1,P2r),Sr) :-
                            not trans(P1,S,_,_),trans(P2,S,P2r,Sr).
trans(iterconc(P),S,conc(PP,iterconc(P)),Sr) :- trans(P,S,PP,Sr).
trans(pcall(P_Args),S,Pr,Sr) :- sub(now,S,P_Args,P_ArgsS),
                                proc(P_ArgsS,P), trans(P,S,Pr,Sr).

/* final(Prog,Sit) */

final(nil,S).
final(seq(P1,P2),S) :- final(P1,S),final(P2,S).
final(choice(P1,P2),S) :- final(P1,S) ; final(P2,S).
final(pick(V,P),S) :- sub(V,_,P,PP), final(PP,S).
final(iter(P),S).
final(if(C,P1,P2),S) :- holds(C,S),final(P1,S) ;
                        holds(neg(C),S),final(P2,S).
final(while(C,P),S) :- holds(neg(C),S) ; final(P,S).
final(conc(P1,P2),S) :- final(P1,S),final(P2,S).
final(prconc(P1,P2),S) :- final(P1,S),final(P2,S).
final(iterconc(P),S).
final(pcall(P_Args)) :- sub(now,S,P_Args,P_ArgsS),
                        proc(P_ArgsS,P),final(P,S).

/* do(Prog,Sit,Sit_r) */

do(P,S,Sr) :- trans*(P,S,Pr,Sr),final(Pr,Sr).

trans*(P,S,P,S).
trans*(P,S,Pr,Sr) :- trans(P,S,PP,SS), trans*(PP,SS,Pr,Sr).

/* sub(Name,New,Term1,Term2) and  holds(Formula,Sit) -- as before */
```

Online Golog interpreter

From *Trans* & *Final*, one can lift an **online** Golog interpreter:

- At each step interpreter computes a (δ', s') such that $Trans(\delta, s, \delta', s')$ holds.
- From $s' = do(a, s)$ action a to be executed in real world is extracted.
- Interpreter stops when $Final(\delta, s)$ holds.

Note:

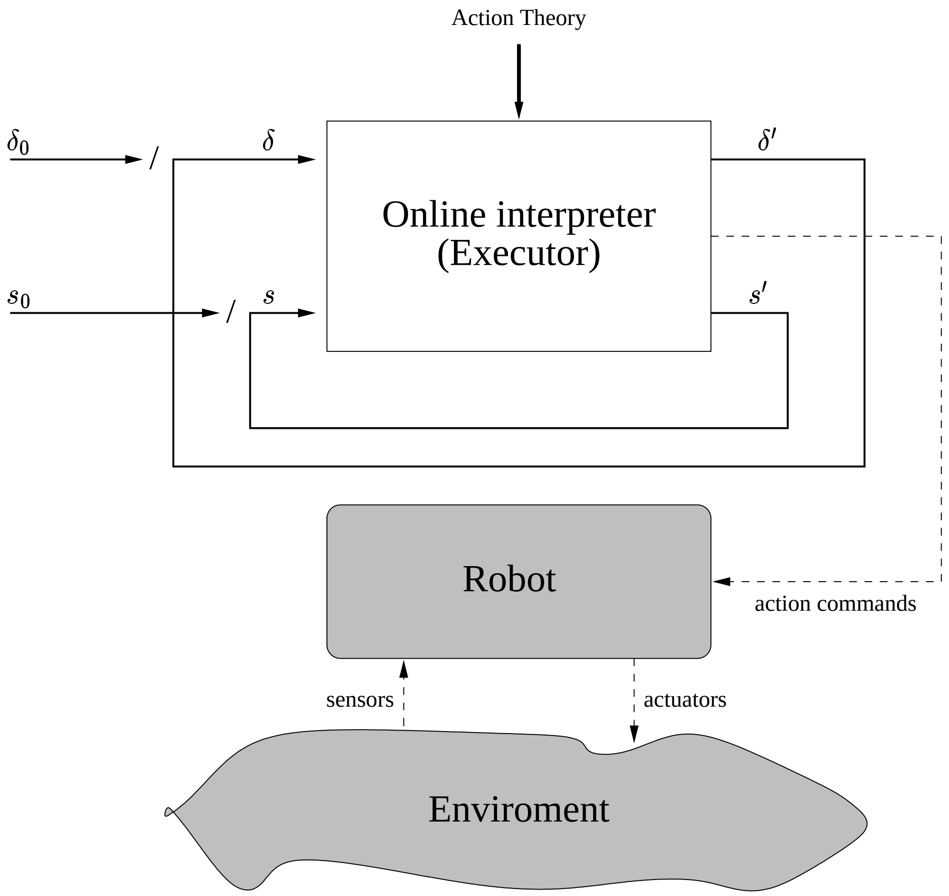
- Interpreter **cannot backtrack**, because it does actions in real world.
- Interpreter **can reason** to choose transitions to execute.

  For example:

  – **Brave online interpreter:** randomly choose any transition.

  – $\boxed{\textbf{Cautious online interpreter}}$**:** choose transition only if from resulting configuration (δ', s') program can successfully terminate, i.e. $\exists s_f.Do(\delta', s', s_f)$.

Online-interpreter-based architecture



Online Golog interpreter with execution monitor

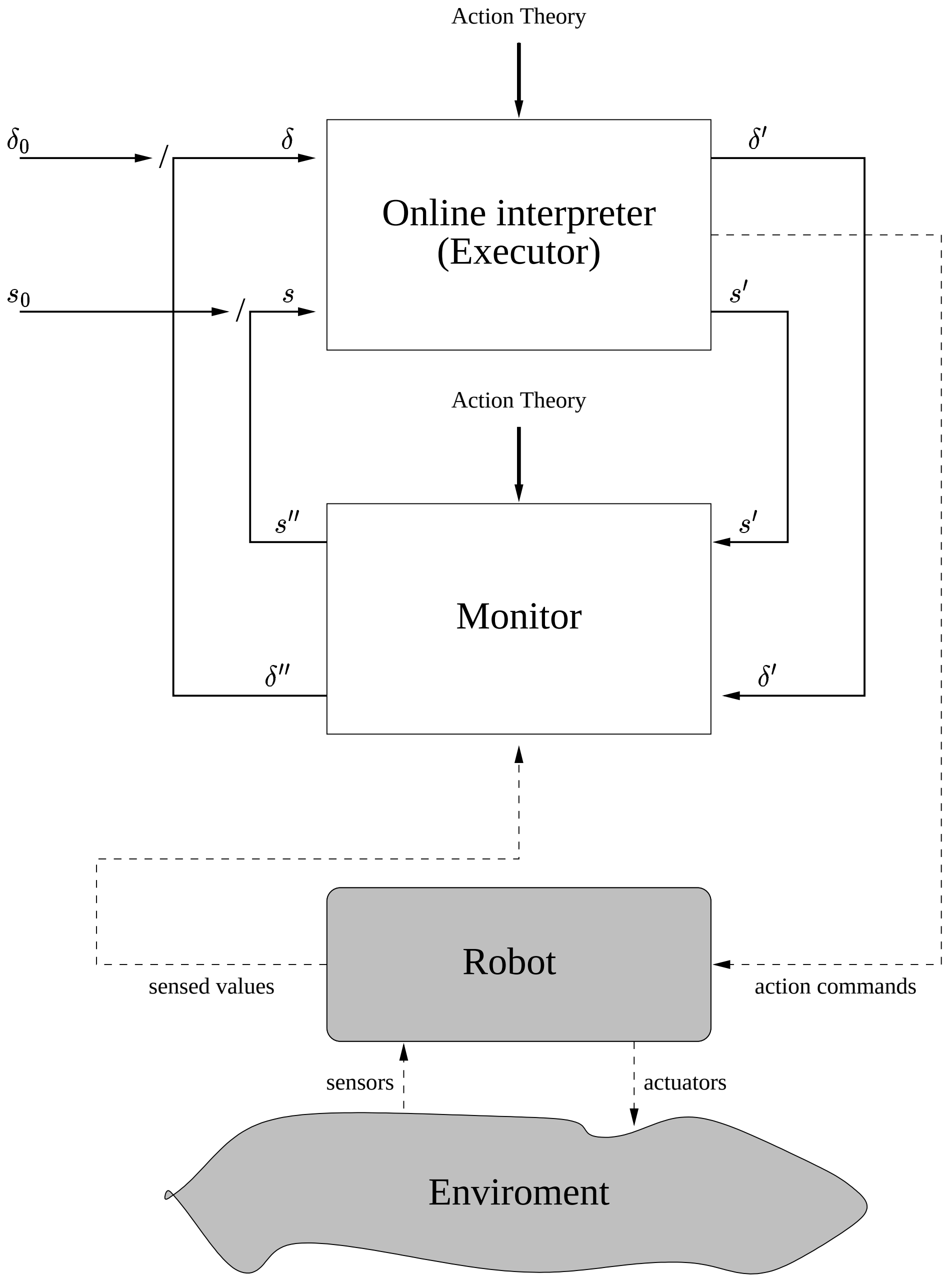
One gets closed loop architecture by cascading **online interpreter** and **execution monitor**.

Execution monitor responsible for:

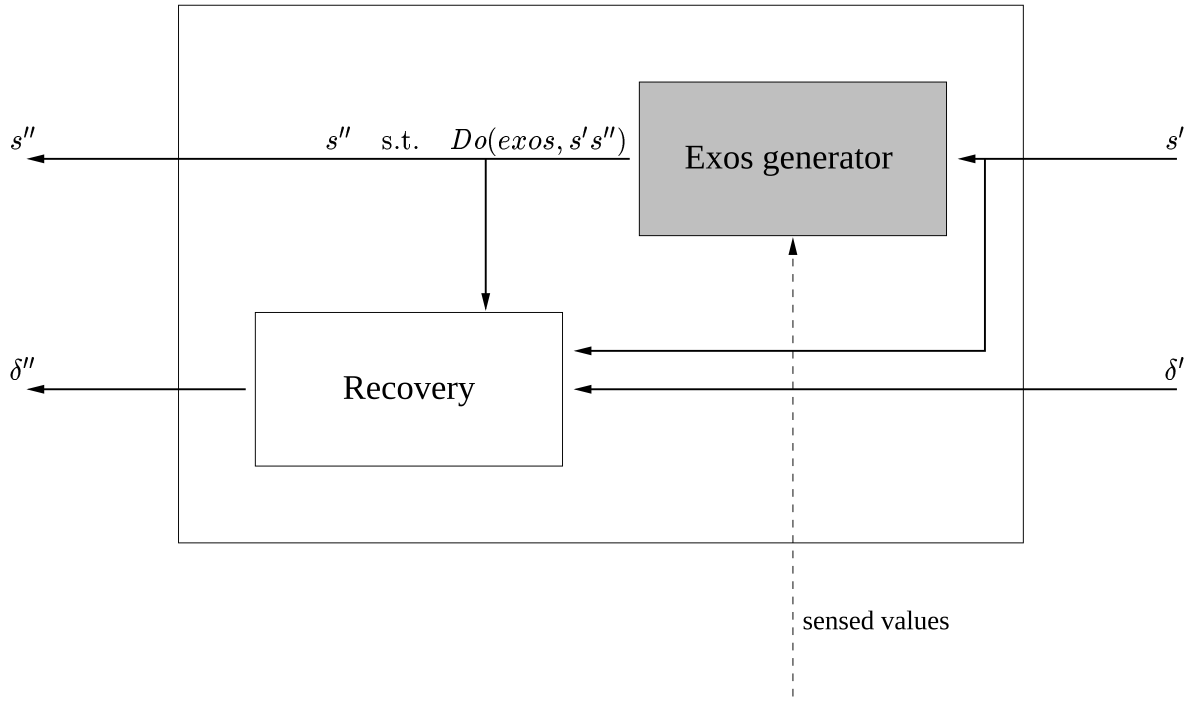
- Updating current situation using view of real world coming out of robot's sensors, i.e. *interfacing low-level sensing processes with high-level representation.*

- Possibly recovering form perceived discrepancies.

Execution monitoring architecture



Execution monitor



Execution monitor:

1. using robot's sensors, checks for **discrepancies** between state of the world as described by current situation and actual one

2. when discrepancy detected, generates one or more **exogenous events** to align current situation with actual state of the world

3. possibly modifies current program to **recover** from discrepancy.

Execution monitor formalization

Formal view of execution monitor:

$$\begin{array}{ll}
Monitor(\delta', s', \delta'', s'') \equiv & \\
\quad \exists exos.Do(exos, s', s'') \wedge & \text{align current situation} \\
\quad Recovery(\delta', s', s'', \delta'') & \text{recover from discrepancy}
\end{array}$$

- $exos$: program (sequence) formed by exogenous events.
  - Process generating program $exos$ is considered **extra-logical**.
  - However **exogenous events** forming $exos$ are **formalized** in theory of actions:
    - *Preconditions* reflect context in which given discrepancy can be detected.
    - *Effects* are used to align current situation to actual state of the world.

- $Recovery$ checks for **relevance** of discrepancy wrt configuration (δ', s'). If discrepancy relevant, a **recovery procedure** is called.

$$\begin{array}{l}
Recovery(\delta', s', s'', \delta'') \doteq \\
\quad \neg Relevant(\delta', s', s'') \wedge \delta'' = \delta' \quad \vee \\
\quad Relevant(\delta', s', s'') \wedge Recover(\delta', s', s'', \delta'')
\end{array}$$

Execution monitor (cont.)

Varying *Relevant* and *Recover* one gets a wide variety of monitors, differing in

- range of applicability
- automated reasoning requirements

Key point: find good trade-off between generality and implementability.

A specific execution monitor

Assumption: programmer provides program δ_0. No analysis of program is done.

Relevant: discrepancies that change state (i.e. values of fluents) of current situation:

$$Relevant(\delta', s', s'') \equiv \neg SameState(s', s'')$$

Recover: determine sequential plan p (a straight-line program) that leads from s'' to a situation s_r equivalent to s' (i.e. $SameState(s', s_r)$), and returns $\delta'' = p\,;\delta'$.

$$\begin{array}{l} Recover(\delta', s', s'', \delta'') \ \equiv \\ \quad \exists p.\ straightLineProg(p) \ \wedge\ \exists s_r.Do(p, s'', s_r) \ \wedge\ SameState(s', s_r) \ \wedge \\ \qquad \delta'' = p\,;\delta' \end{array}$$

Another specific execution monitor

(Implemented)

Assumption: programmer provides program δ_p and postcondition $goal$ (a first order sentence describing the "goal" of δ_p). Program to execute:

$$\delta_0 \;=\; \delta_p ; goal?$$

Relevant: discrepancies that prevent successful termination of current program δ':

$$Relevant(\delta', s', s'') \equiv \neg \exists s_f . Do(\delta', s'', s_f)$$

Recover: determine shortest straight-line program that prefixed to δ' yield to successful termination:

$$\begin{array}{l} Recover(\delta', s', s'', \delta'') \;\equiv \\ \quad \exists p.\; straightLineProg(p) \;\wedge\; \exists s_f . Do(p\,;\delta', s'', s_f) \;\wedge\; \delta'' = p\,;\delta' \quad \wedge \\ \quad [\forall q, s_f .\; straightLineProg(q) \;\wedge\; Do(q\,;\delta', s'', s_f) \;\;\supset\;\; length(p) \leq length(q)] \end{array}$$

Implementation

From logical formalization a Prolog implementation can be easily extracted *(accepting Prolog closed world assumption – see [Reiter98])*:

```
onlineEM(Prog,S) :-

  final(Prog,S) ;

  trans(Prog,S,Prog1,S1), do(Prog1,S1,Sf), !,
  outputAction(S,S1),
  monitor(Prog1,S1,Prog2,S2),
  onlineEM(Prog2,S2).



monitor(Prog1,S1,Prog2,S2) :-
  generateExos(S1,S2),
  recovery(Prog1,S1,S2,Prog2), !.
```

where, for example:

- `outputAction` outputs current action command (deterministic).
- `generateExos` inputs $exos$ and produces aligned situation accordingly (deterministic).
- `recovery` implements recovery strategy in previous slide.

Example: blocks world

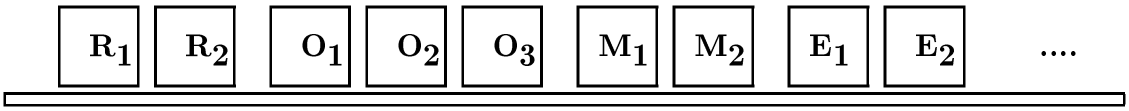
(Implemented)

- Action theory for blocks world.
- Program to execute: $\delta_0 \;=\; \delta_p; goal?$
  - Program $\delta_p \;=\; makeParis \mid makeRome.$
  - Postcondition $goal(s) \;=\; spellsParis(s) \vee spellsRome(s)$

$$\begin{aligned} spellsRome(s) \;\doteq\; \exists b_0, b_1, b_2, b_3.\; & E(b_0) \wedge OnTable(b_0, s) \wedge \\ & M(b_1) \wedge On(b_1, b_0, s) \wedge \\ & O(b_2) \wedge On(b_2, b_1, s) \wedge \\ & R(b_3) \wedge On(b_3, b_2, s) \wedge Clear(b_3, s) \end{aligned}$$

$$spellsParis(s) \;\doteq\; \ldots$$

- Initial situation:



Other blocks are present, e.g. a block with letter "N", one with letter "F", but no block with letter "P".

Example: 1st execution step

Because no "P" block, procedure $makeParis$ cannot be successfully completed. Cautious online interpreter selects procedure $makeRome$.

First execution step:

$$\pi\, b_0.[E(b_0) \wedge OnTable(b_0) \wedge Clear(b_0)]?\,;$$

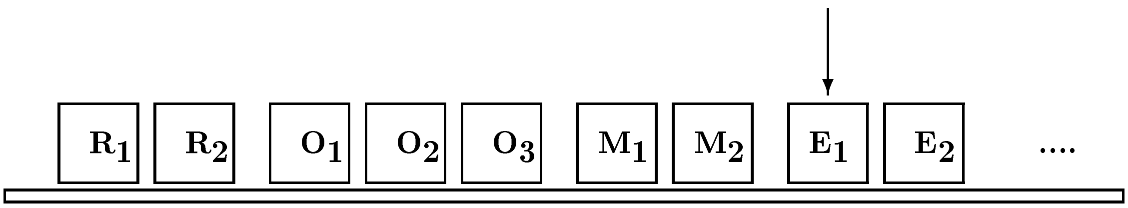
determines block E_1 as base of tower ROME.

Current program δ':

nil ;
$\pi\, b_1.M(b_1)?\,; move(b_1, E_1)\,;$
$\quad\pi\, b_2.O(b_2)?\,; move(b_2, b_1)\,;$
$\quad\quad\pi\, b_3.R(b_3)?\,; move(b_3, b_2)$;
$goal?$

where nil results after first step.

Current situation $s'(= s)$:



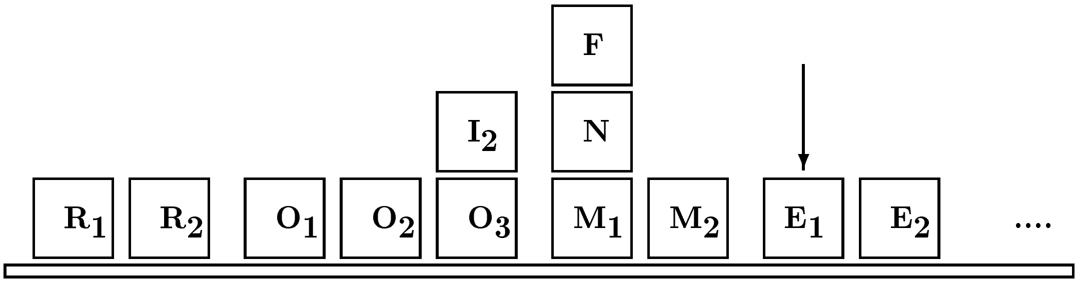
Example: 1st discrepancy

A discrepancy is detected. Sequence of exogenous events:

$$move(N, M_1); move(F, N); move(I_2, O_3)$$

$\Longrightarrow$ aligned situation s'':

$$do(move(I_2, O_3), do(move(F, N), do(move(N, M_1), S_0)))$$



Since program δ'

nil ;
$\pi\, b_1.M(b_1)?\,; move(b_1, E_1)\,;$
$\quad \pi\, b_2.O(b_2)?\,; move(b_2, b_1)\,;$
$\quad\quad \pi\, b_3.R(b_3)?\,; move(b_3, b_2)\,;$
$goal?$

can still be successfully completed (pick M_2, move it on top of E_1, etc.) $\Longrightarrow$ no recovery is necessary.

Example: 2nd execution step & 2nd discrepancy

A further step is performed.

Current program δ' is now:

$$
\begin{array}{l}
nil\,; \\
\quad move(M_2, E_1)\,; \\
\quad\quad \pi\, b_2.O(b_2)?\,; move(b_2, M_2)\,; \\
\quad\quad\quad \pi\, b_3.R(b_3)?\,; move(b_3, b_2)\ ; \\
goal?
\end{array}
$$

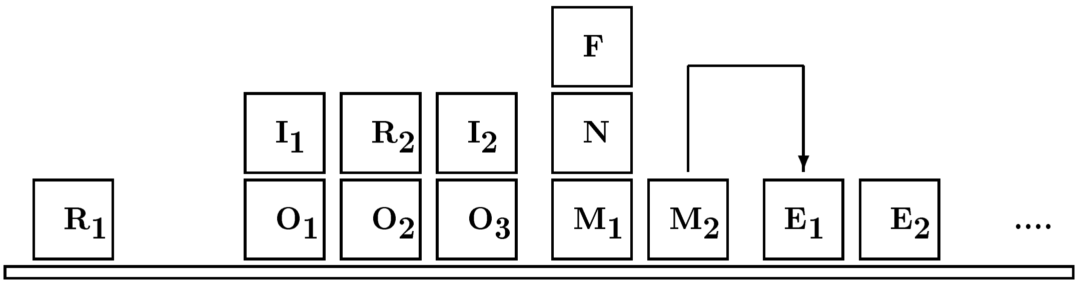
Current situation s': $do(move(I_2, O_3), do(move(F, N), do(move(N, M_1), S_0)))$

Another discrepancy is detected. Sequence of exogenous events:

$$move(I_1, O_1); move(R_2, O_2)$$

$\Longrightarrow$ aligned situation s'':

$$
\begin{gathered}
do(move(R_2, O_2), do(move(I_1, O_1), \\
do(move(I_2, O_3), do(move(F, N), do(move(N, M_1), S_0)))))
\end{gathered}
$$

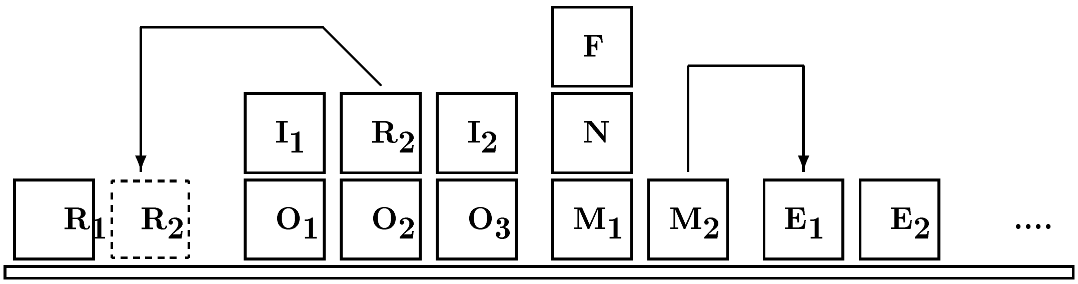


Example: recovery

Current program δ' cannot be completed $\Longrightarrow$ discrepancy is **relevant** $\Longrightarrow$ recovery procedure is called.

Recovery procedure (a **planner**) finds a minimal sequence of actions that prefixed to program δ' results in successful termination. In this case simply:

$$moveToTable(R_2)$$



So current program is now δ'':

$moveToTable(R_2)\,;$
$\quad nil\,;$
$\quad\quad move(M_2, E_1)\,;$
$\quad\quad\quad \pi\, b_2.O(b_2)?\,; move(b_2, M_2)\,;$
$\quad\quad\quad\quad \pi\, b_3.R(b_3)?\,; move(b_3, b_2)\,;$
$goal?$

$\vdots$

Etc.