Architectures for Robot Control

15-494/694 Cognitive Robotics

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Why Is Robot Control Hard?

Coste-Maniere and Simmons (ICRA 2000):

- High-level, complex goals
  - Assemble this water pump
  - Cook my breakfast
- Dynamic (changing) environment
- Robot has dynamic constraints of its own (don't fall over)
- Sensor noise and uncertainty
- Unexpected events (collisions, dropped objects, etc.)

Approaches To Control

1. Hierarchical: classic sense-plan-act
   - "Top-down" approach
   - Start with high level goals, decompose into subtasks
   - Not very flexible
2. Behavioral
   - "Bottom-up" approach
   - Start with lots of independent modules executing concurrently, monitoring sensor values and triggering actions.
   - Hard to organize into complex behaviors; gets messy quickly.
3. Hybrid
   - Deliberative at high level; reactive at low level

Levels of Control Problem

Robots pose *multiple* control problems, at different levels.

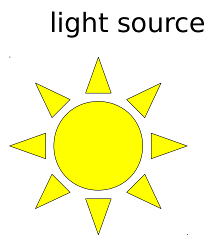
- Low-level control:
  - Example: where to place a leg as robot takes its next step
  - Generally, continuous-valued problems
  - Short time scale (under a second); high frequency loop
- Intermediate level control:
  - Navigating to a destination, or picking up an object.
  - Continuous or discrete valued problems
  - Time scale of a few seconds
- High level control:
  - What is the plan for moving these boxes out of the room?
  - Discrete problems, long time scale (minutes)

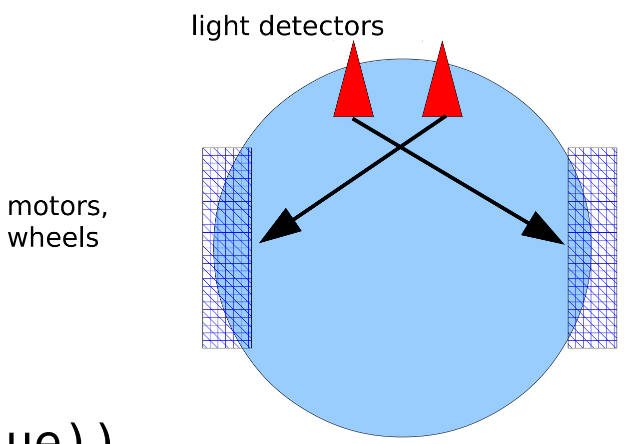
Low-Level Control Issues

- Real-time performance requirement
  - Code to issue motor commands or process sensor readings must run every so many milliseconds.
- Safety: avoid states with disastrous consequences
  - Never turn on the rocket engine if the telescope is uncovered.
  - Never fail to turn off the rocket engine after at most *n* seconds.
  - Therac-25 accident (see IEEE Computer, July 1993)
  - Safety properties sometimes provable using temporal logic.
- Liveness: every request must eventually be satisfied
- Deadlock-free

“Reactive” Architectures

- Sensors directly determine actions.
- In its most extreme form, stateless control.
- “Let the world be its own model.”
- Example: light-chasing robot:

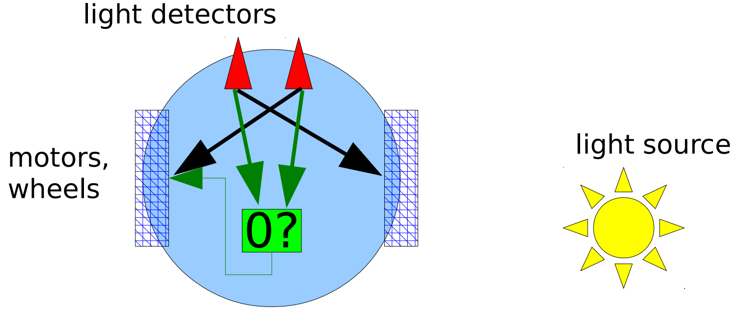





```
(behavior chase-light
  :period (1 ms)
  :actions
    ((set left-motor (right-sensor-value))
     (set right-motor (left-sensor-value))))
```

Overriding a Behavior

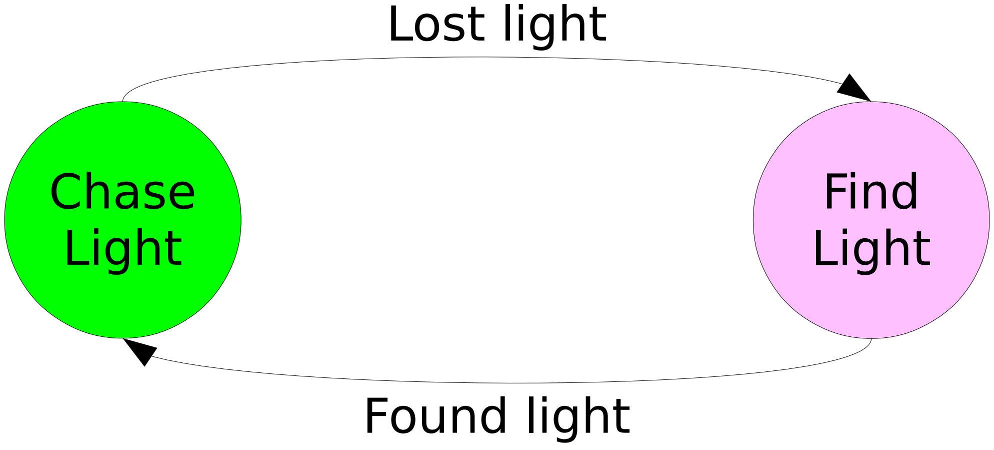
- If robot loses sight of the light, turn clockwise until the light comes back into view.




```
(behavior chase-light
  :period (1 ms)
  :actions
    ((set left-motor (right-sensor-value))
     (set right-motor (left-sensor-value))))


(behavior find-light
  :overrides (chase-light)
  :test (0? (+ (left-sensor-value)
               (right-sensor-value)))
  :actions
    ((set left-motor 0.5)))
```

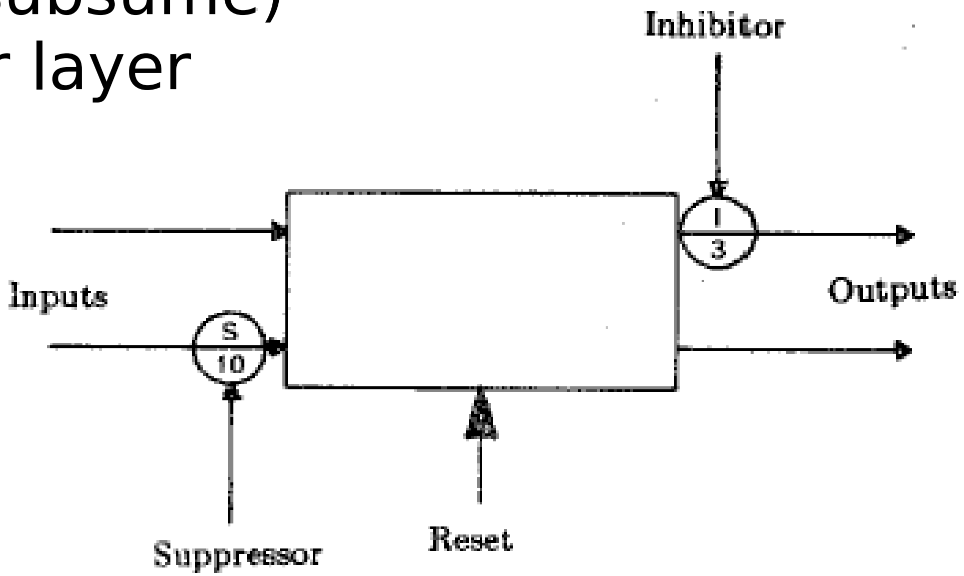
Light Chasing in a State Machine Formalism

- States treated as equal alternatives.
- State is discrete, but control signal is continuous.
- “Find Light” has to know which state to return control to when the light is found.
- Usually not parallel (but can be).

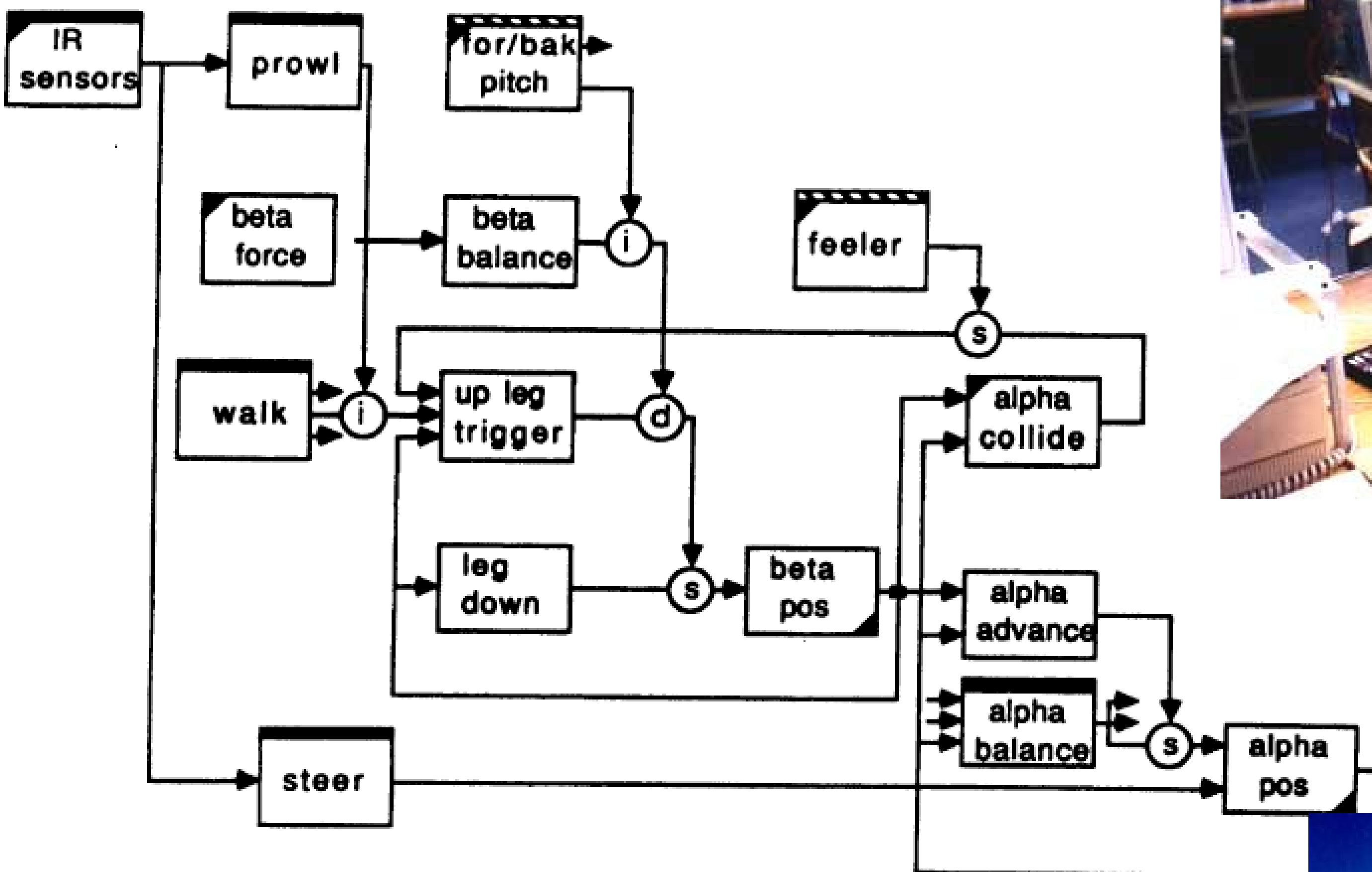


Rod Brooks' Subsumption Idea

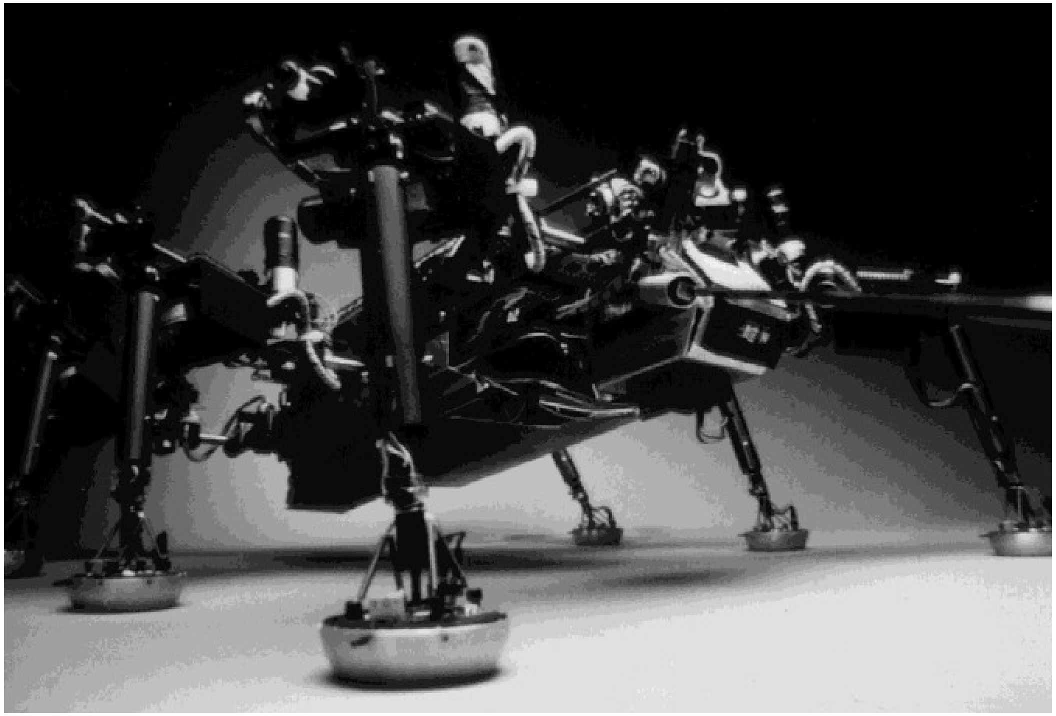
- In 1986 Rod Brooks proposed the "subsumption" architecture, a kind of reactive controller.
- Robot control program is a collection of little autonomous modules (state machines).
- Hierarchy of layers of control.
- Some modules override (subsume) inputs or outputs of lower layer modules.

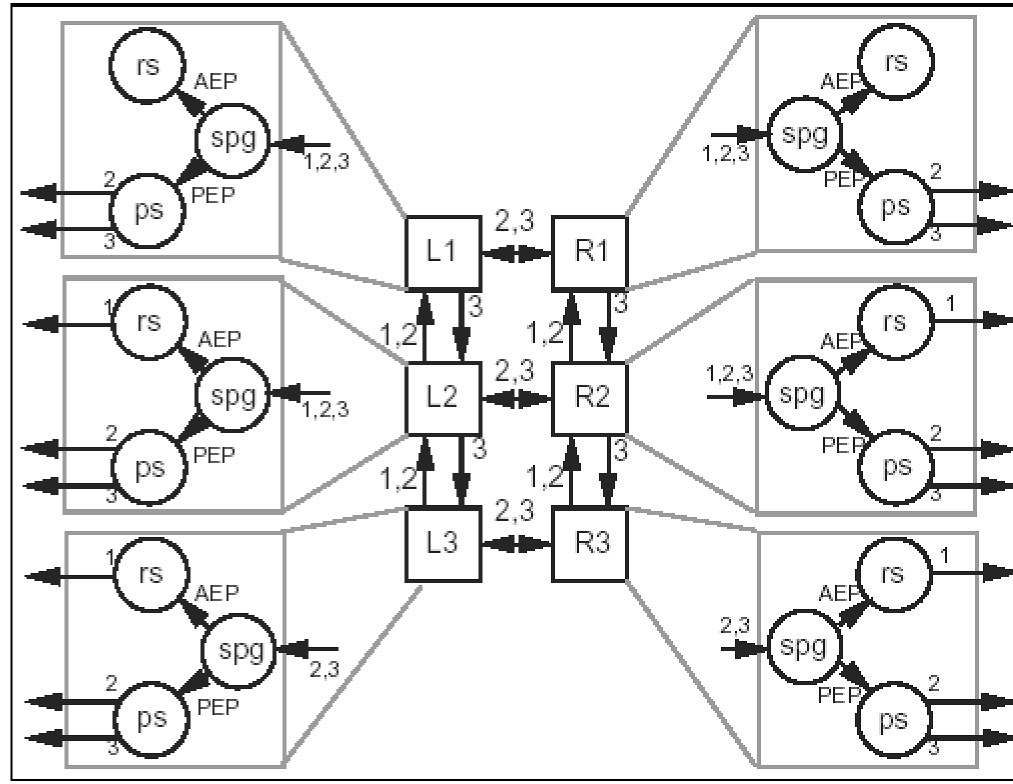


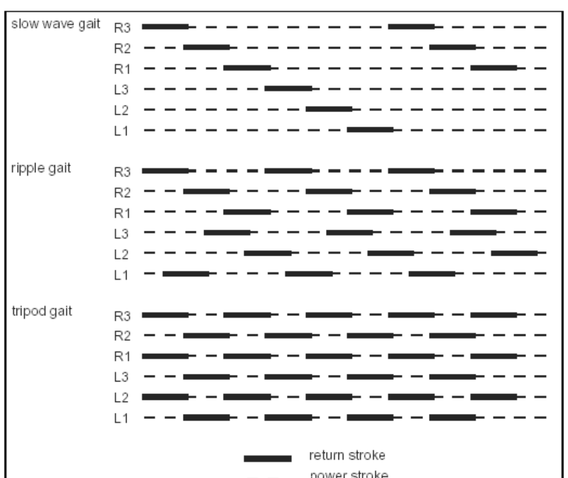
Genghis: Six-Legged Walker



Hannibal (Breazeal)







Three Distinct Insect Gaits:
(1) slow wave, (2) ripple,
(3) tripod

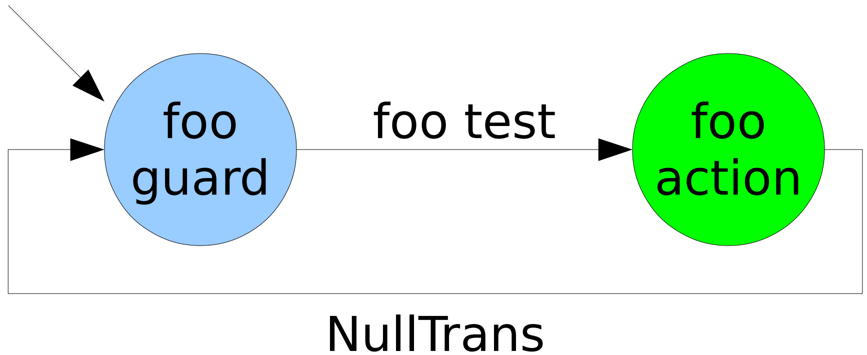
Coping With a Noisy World

- URBI (Baillie, 2005) provides a ~ operator to test if a condition has held true for a certain duration.
- Onleave test is true when condition ceases to hold.
- You can build a state machine from these primitives.

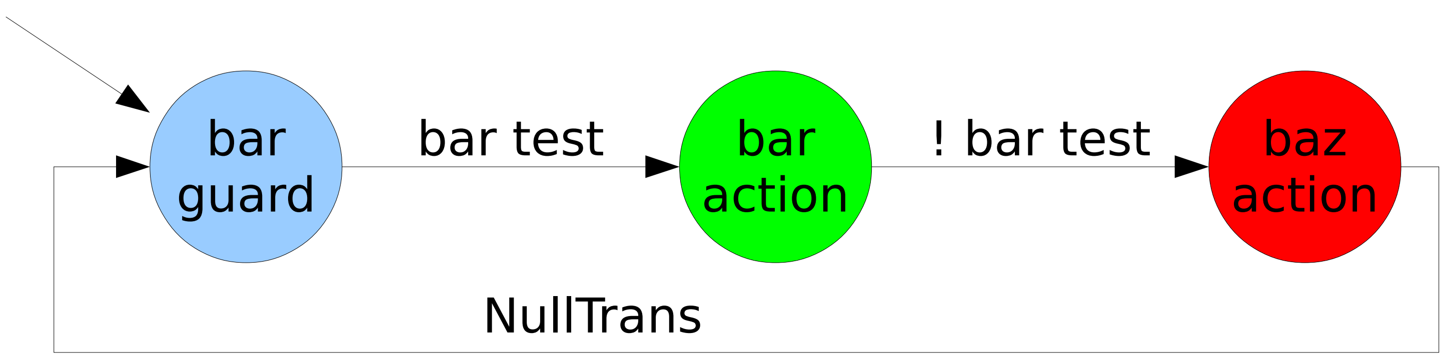
```
// Main behavior
whenever (ball.visible ~ 100ms) {
  headPan  = headPan + ball.a * camera.xfov * ball.x &
  headTilt = headTilt+ ball.a * camera.yfov * ball.y;
};

at (!ball.visible ~ 100ms)
  search:  {
    { headPan'n  = 0.5 smooth:1s &
      headTilt'n = 1 smooth:1s } |
    { headPan'n  = 0.5 sin:period ampli:0.5 &
      headTilt'n = 0.5 cos:period ampli:0.5 }
  };
at (ball.visible) stop search;

// Sound behavior
at (ball.visible ~ 100ms) speaker = found
onleave speaker = lost;
```

Guarded Commands vs. Finite State Machines

whenever (foo_test) foo_action;



at (bar_test) bar_action; onleave baz_action;



Why Is Complex State Bad?

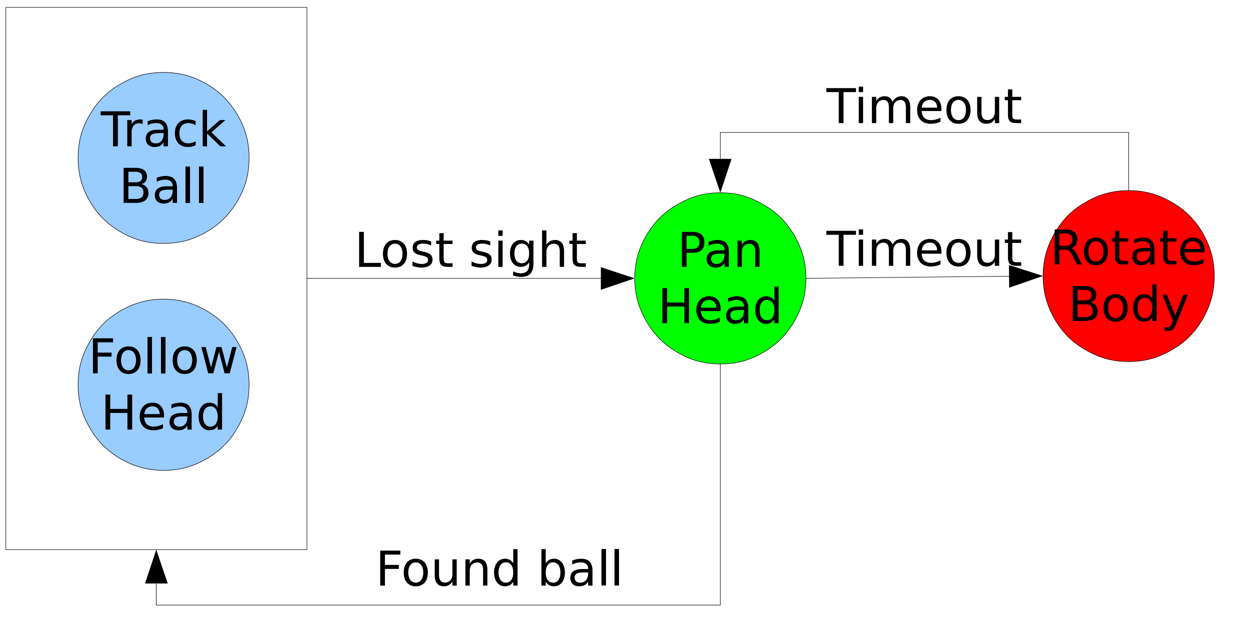
- Can be expensive to compute (vision)
- Error-prone: what if you make a map, and it's wrong?
- Goes stale quickly: the world constantly changes
- But...
  - Non-trivial intelligent behavior can't be achieved without complex world state.
  - You really do need a map of the environment.
  - Can't use a subsumption architecture to play chess.
  - Or even chase a ball well...

Chase Ball 1

- Cooperation between two simple processes:
  - Point the camera at the ball
  - Walk in the direction the camera is pointing
- Each process can execute independently.
- Purely reactive control.

Chase Ball 2

- If we lose sight of the ball, must look for it.
- Now we introduce some internal state:



Chase Ball 3

- More intelligent search: direction of turn should depend on where the ball was last seen.

- Now we need to maintain world state (ball location).

Chase Ball 4

- Must avoid obstacles while chasing the ball.
  - May need to move the head to look for obstacles.
  - Attention divided between ball tracking and obstacle checking.
- May need to detour around obstacles.
  - Subgoal “detouring” temporarily overrides “chasing”.
- Where will the ball be when the detour is completed?
  - Mapping, trajectory extrapolation...

Say “goodbye” to reactive control!

Mid-Level Control: Task Control Languages

- Takes the robot through a sequence of actions to achieve some simple task.
- Must be able to deal with failures, unexpected events.
- There are many architectures for mid-level control. Various design tradeoffs:
  - Specialized language vs. extensions to Lisp or C
  - Client/server vs. publish/subscribe communication model
  - Provide special exception states, or treat all states the same?
  - How to provide for and manage concurrency.
- Lots of languages/tools: RAPs, TCA, PRS, Propice, ESL, MaestRo, TDL, Orccad, ControlShell, 3T, Circa.

Gat's ESL

- ESL: Execution Support Language (Gat, AAAI 1992; AAAI Fall Symposium, 1996) provides special primitives for handling failures and limiting retries.

```
(defun move-object-to-table ()
  (with-recovery-procedures
      ((:dropped-object :retries 2)
       (locate-dropped-object)
       (retry))
    (pick-up-object)
    (move-to-table)
    (put-down-object)))


(defun pick-up-object ()
  (open-gripper)
  (move-gripper-to-object)
  (close-gripper)
  (raise-arm)
  (if (gripper-empty)
    (fail :dropped-object)))
```

ESL (Continued)

- Cleanup procedures are necessary to ensure safe state after failure.

```
(with-cleanup-procedure
    ((shut-down-motors)
     (close-camera-port))
  (do-some-thing-that-might-fail))
```

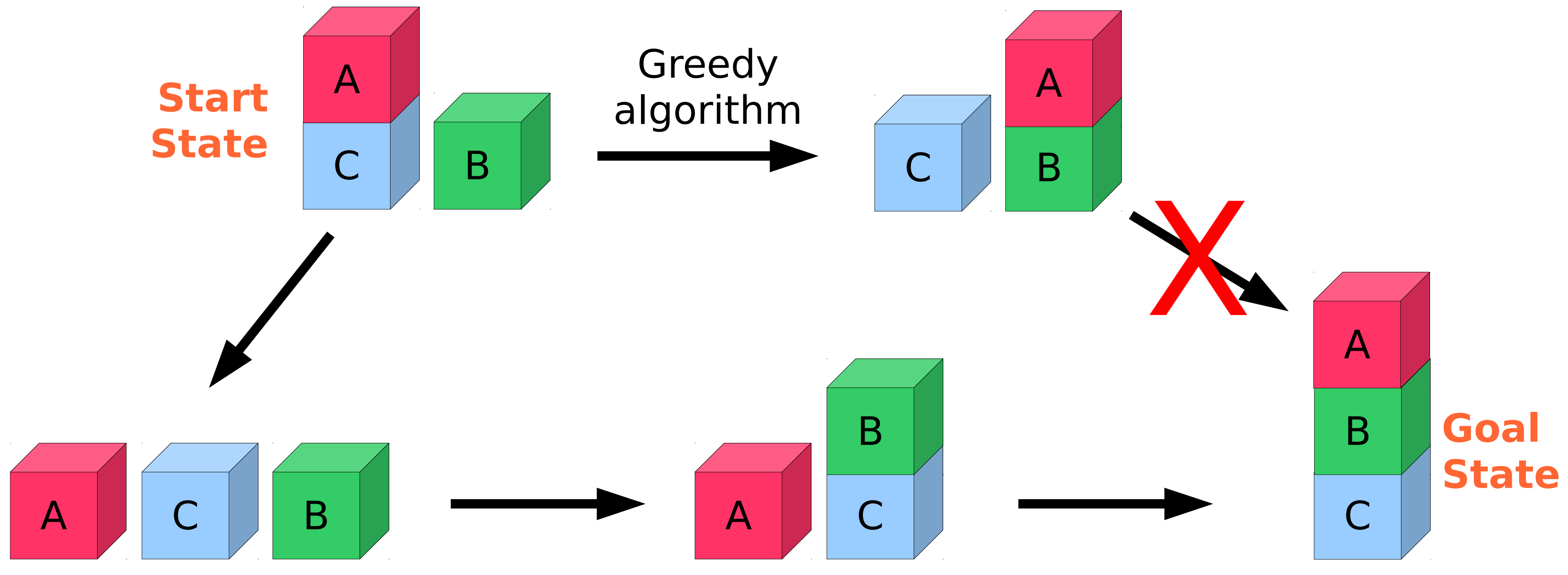
- Deadlock prevention: ESL includes “resource locking” primitives for mutual exclusion and deadlock prevention.

- Synchronization: “checkpoints” allow one process to wait until another has caught up.

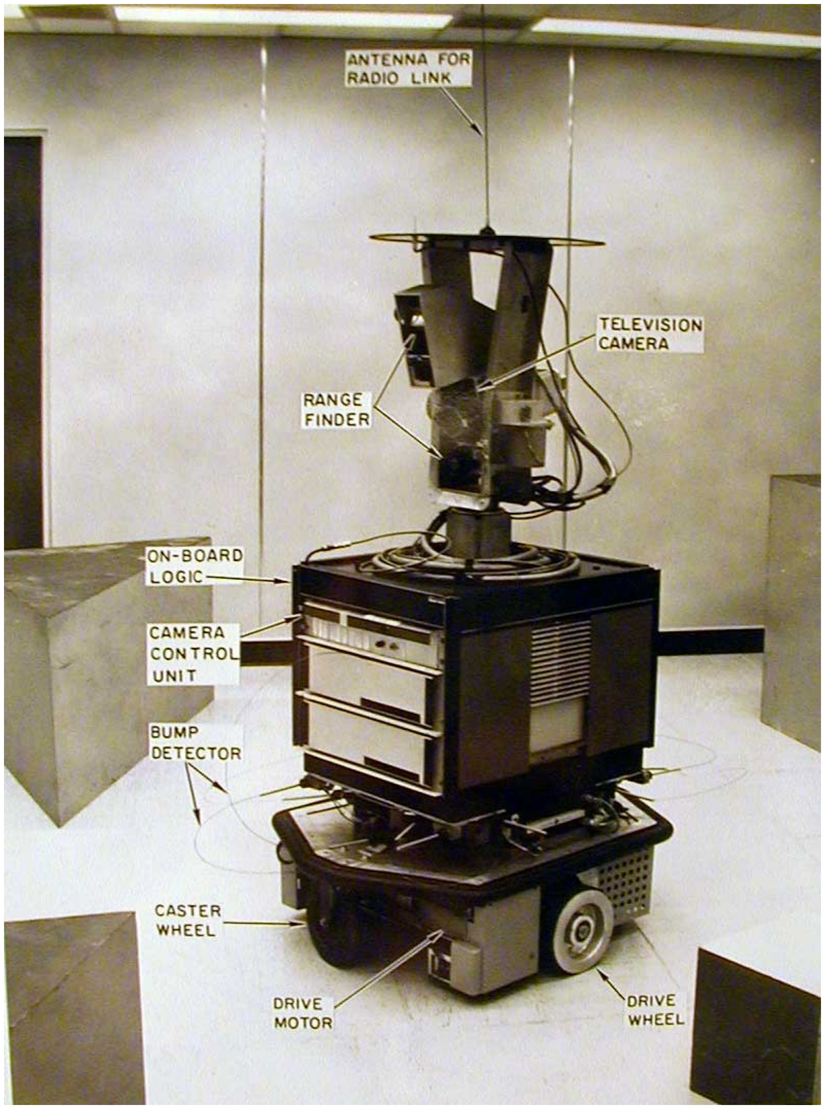
High Level Control: Planning

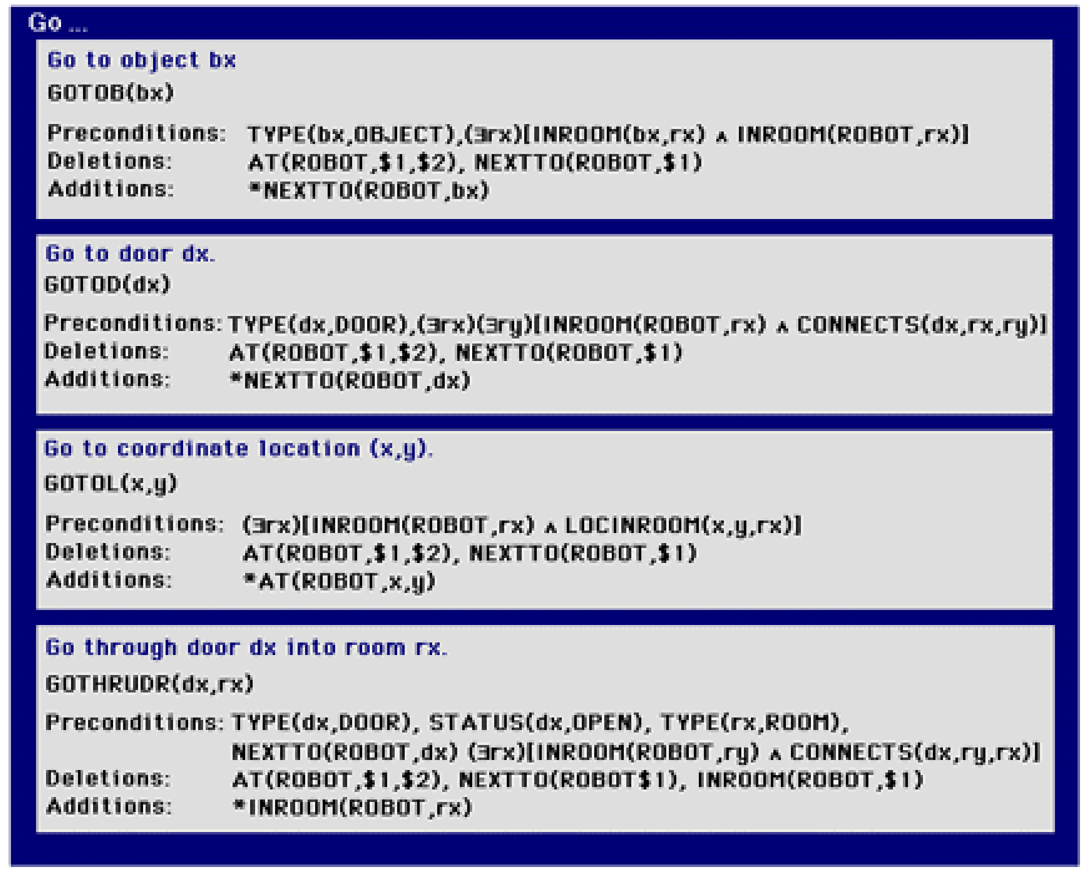
"Deliberative" architectures may run slowly, infrequently.

- Path planning for navigation.
- Planning as problem solving: achieve (on A B) & (on B C) by moving only one block at a time (gripper can't hold two blocks).



Shakey the Robot (1968) And The STRIPS Planner





Go ...

Go to object bx

GOTOB(bx)

Preconditions: TYPE(bx,OBJECT),(∃rx)[INROOM(bx,rx) ∧ INROOM(ROBOT,rx)]
Deletions: AT(ROBOT,$1,$2), NEXTTO(ROBOT,$1)
Additions: *NEXTTO(ROBOT,bx)

Go to door dx.

GOTOD(dx)

Preconditions: TYPE(dx,DOOR),(∃rx)(∃ry)[INROOM(ROBOT,rx) ∧ CONNECTS(dx,rx,ry)]
Deletions: AT(ROBOT,$1,$2), NEXTTO(ROBOT,$1)
Additions: *NEXTTO(ROBOT,dx)

Go to coordinate location (x,y).

GOTOL(x,y)

Preconditions: (∃rx)[INROOM(ROBOT,rx) ∧ LOCINROOM(x,y,rx)]
Deletions: AT(ROBOT,$1,$2), NEXTTO(ROBOT,$1)
Additions: *AT(ROBOT,x,y)

Go through door dx into room rx.

GOTHRUDR(dx,rx)

Preconditions: TYPE(dx,DOOR), STATUS(dx,OPEN), TYPE(rx,ROOM), NEXTTO(ROBOT,dx) (∃ry)[INROOM(ROBOT,ry) ∧ CONNECTS(dx,ry,rx)]
Deletions: AT(ROBOT,$1,$2), NEXTTO(ROBOT$1), INROOM(ROBOT,$1)
Additions: *INROOM(ROBOT,rx)

Really High Level Control

- Can use cognitive modeling architectures such as SOAR (Newell) or ACT-R (Anderson) to control robots.
- RoboSoar (Laird and Rosenbloom, 1990): plan-then-compile architecture.
  - Generate high level plan.
  - Then compile into reactive rules for execution.
- ACT-R has been used in simulated worlds (Unreal Tournament).
- Grubb and Proctor (2006): Tekkotsu interface for ACT-R. Patton & Brudzinski (2009): ACT-R solving Towers of Hanoi with the Tekkotsu planar hand/eye system.

Gat's Three-Level Architecture

- Gat (Artificial Intelligence and Mobile Robots, ch. 8, 1998) proposed a different three-level architecture:
- The Controller:
  - collection of reactive “behaviors”
  - each behavior is fast and has minimal internal state
- The Sequencer
  - decides which primitive behavior to run next
  - doesn't do anything that takes a long time to compute, because the next behavior must be specified soon
- The Deliberator
  - slow but smart
  - can either produce plans for the sequencer, or respond to queries from it

What Does Tekkotsu Provide?

- Low-level control implemented by motion commands, e.g., for walking.
- Mid-level control via state machine formalism can be reactive or use a more hybrid approach.
- Behaviors can execute in parallel; event-based communication follows a publish/subscribe model.
- Main/Motion dichotomy – but Motion is only for ultra-low-level control.
- Specialized path planners for navigation and manipulation, but no general high level control layer.
- Future plans: add a high level task planner to Tekkotsu.

The Tekkotsu "Crew"

- The Lookout controls the head:
  - visual search
  - target tracking
  - obstacle detection
- The MapBuilder does vision
- The Pilot controls the body:
  - walking, rotating in place
  - path planning
  - trajectory following
- The Grasper controls the arm
  - grasping, pushing, toppling, flipping, etc.

Potential for Lookout/Pilot Interactions

- The Lookout may need to turn the body in order to conduct a visual search, when head motion alone isn't enough.
  - Lookout makes a request to the Pilot for a turn.
- The Pilot may need to ask the Lookout to locate some landmarks so it can self-localize.
  - Pilot makes a request to the Lookout for a search.
- Interactions must be managed to prevent deadlock, infinite loops.
- But the user shouldn't have to worry about this.

Robot Cooperation

- An even higher level of control is cooperation among multiple robots working as a team.
- Tekkotsu allows robots to communicate by subscribing to each other's events.

```
doStart:
  int ip = EventRouter::stringToIntIP("172.16.0.4");
  erouter->addRemoteListener(this, ip, EventBase::motmanEGID);

doEvent:
  if ( event.getHostID() == ip )
    cout << "Got remote event " << event.getDescription() << endl;
```

- Can also subscribe to state updates using

  `requestRemoteStateUpdates(`*`ip, state_type, interval)`*

- This is only a low-level form of coordination, but cooperation could be built on top of this.