Architectures for Robot Control

15-494 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.

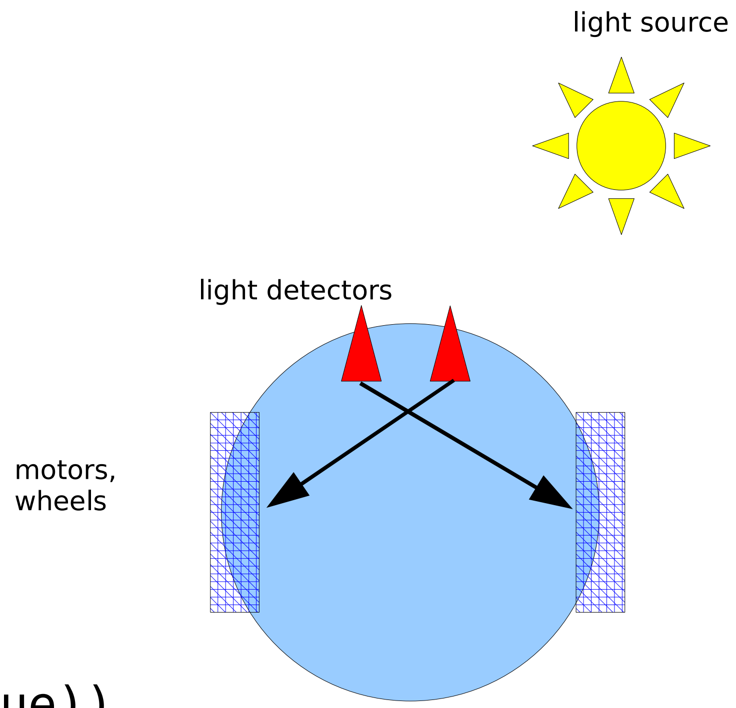
- Low-level control:
  - Example: where to place a leg as robot takes its next step
  - Generally, continuous-valued problems
  - Short time scale (under a second); high frequency loop
- Intermediate level control:
  - Navigating to a destination, or picking up an object.
  - Continuous or discrete valued 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

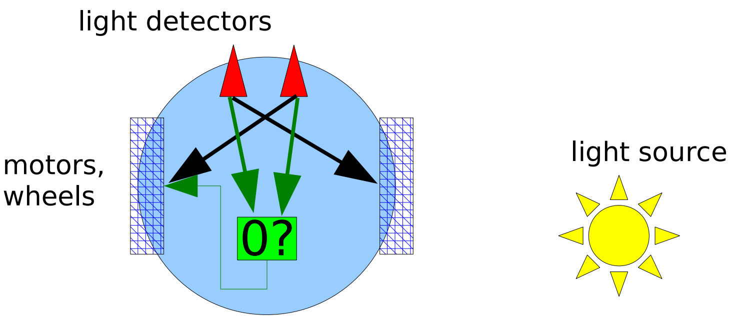
- Sensors directly determine actions.
- In its most extreme form, stateless control.
- “Let the world be its own model.”
- Example: light-chasing robot:




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

Overriding a Behavior

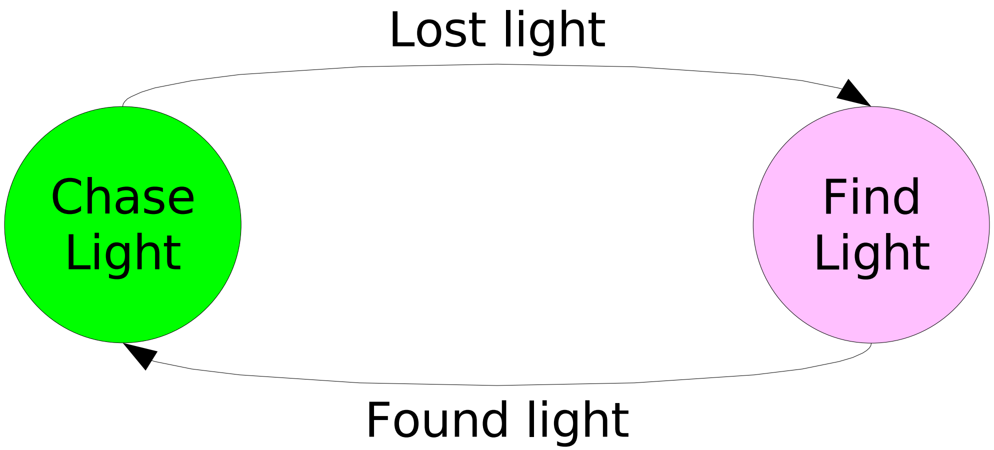
- If robot loses sight of the light, turn clockwise until the light comes back into view.




```
(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)))
```

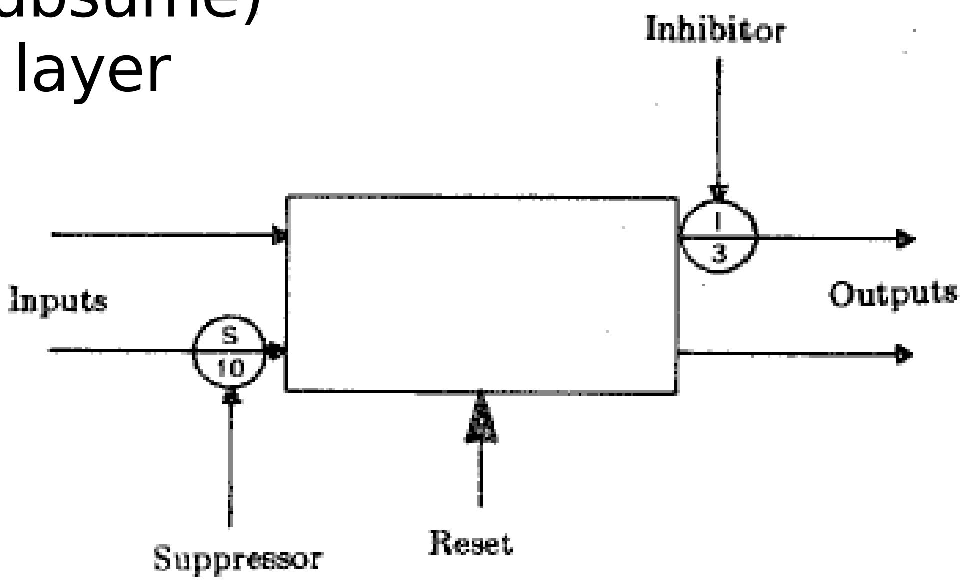
Light Chasing in a State Machine Formalism

- 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).

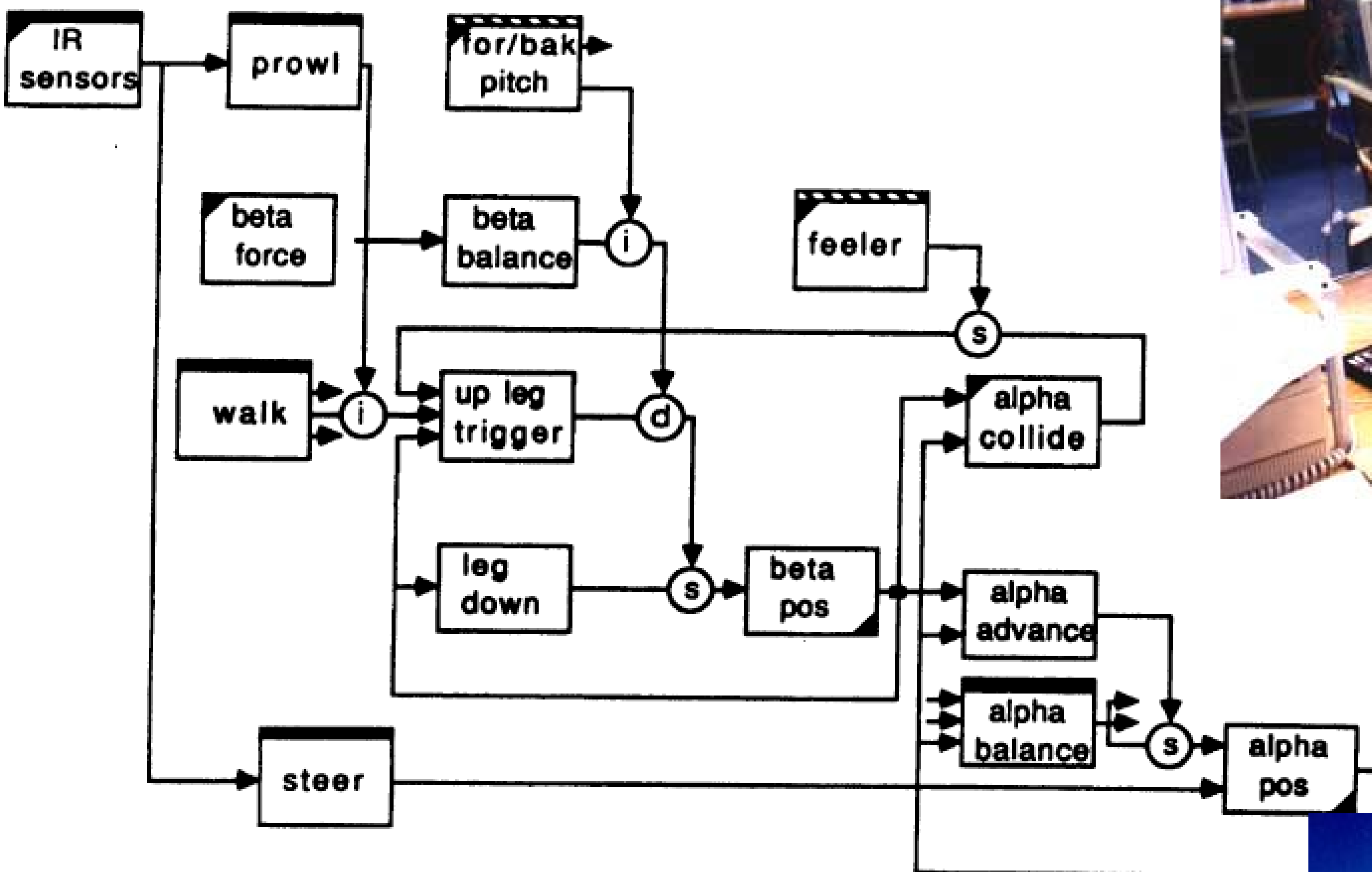


Rod Brooks' Subsumption Idea

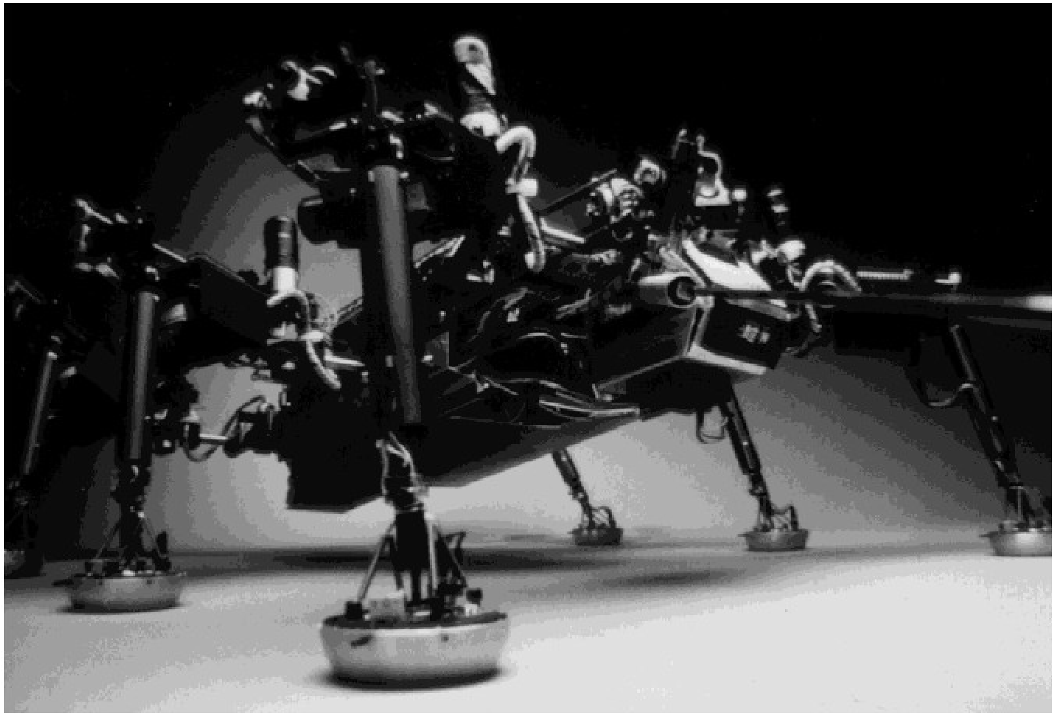
- In 1986 Rod Brooks proposed the "subsumption" architecture, a kind of reactive controller.
- Robot control program is a collection of little autonomous modules (state machines).
- Hierarchy of layers of control.
- Some modules override (subsume) inputs or outputs of lower layer modules.

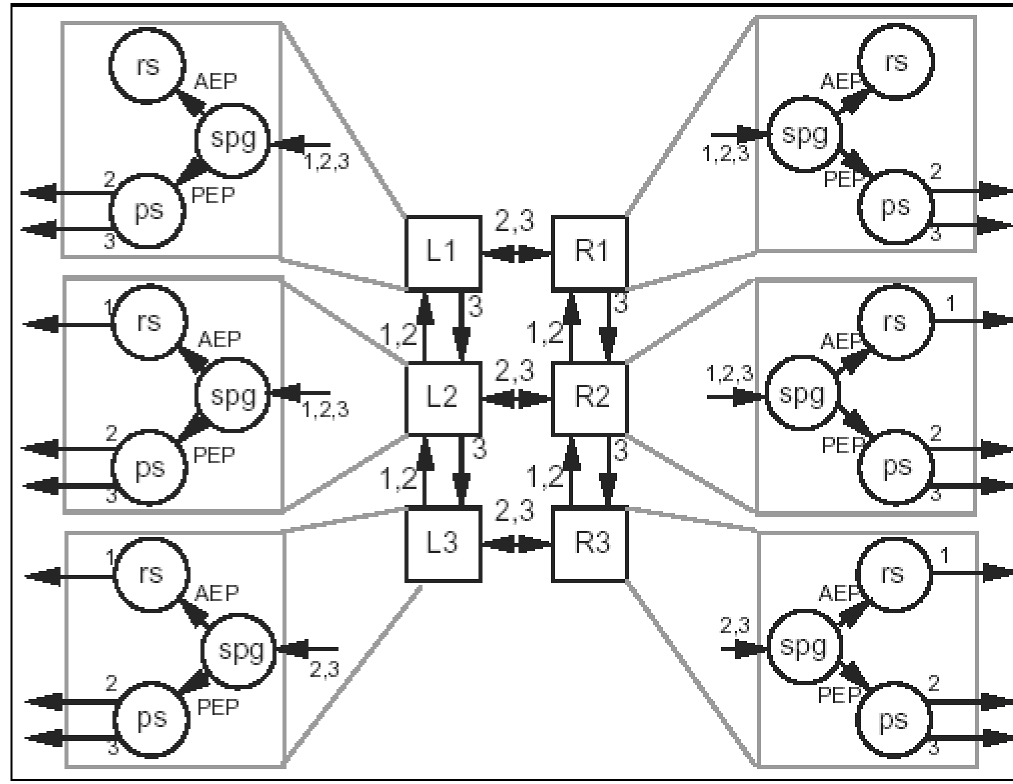


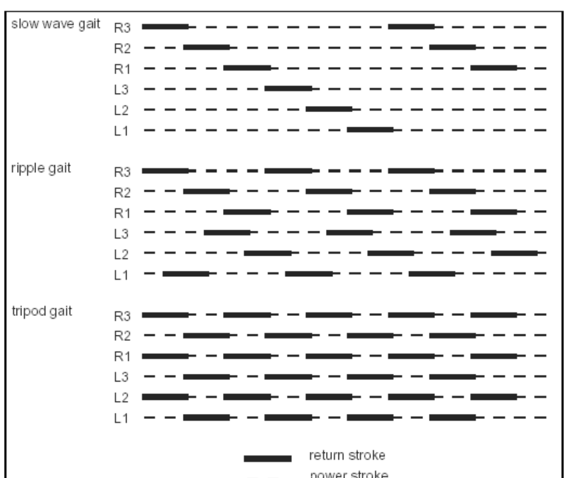
Genghis: Six-Legged Walker



Hannibal (Breazeal)







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

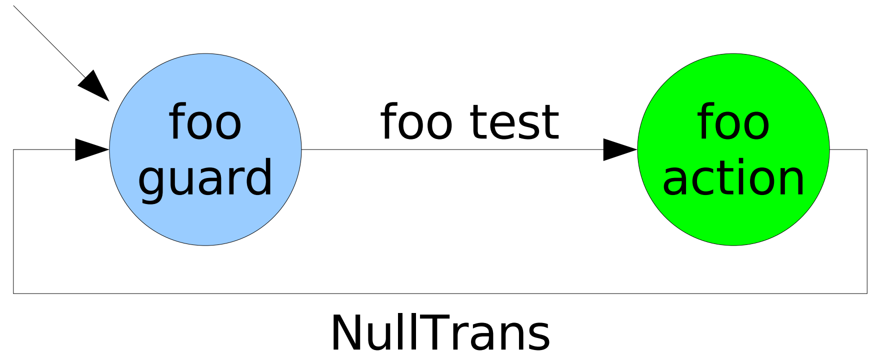
Coping With a Noisy World

- 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.

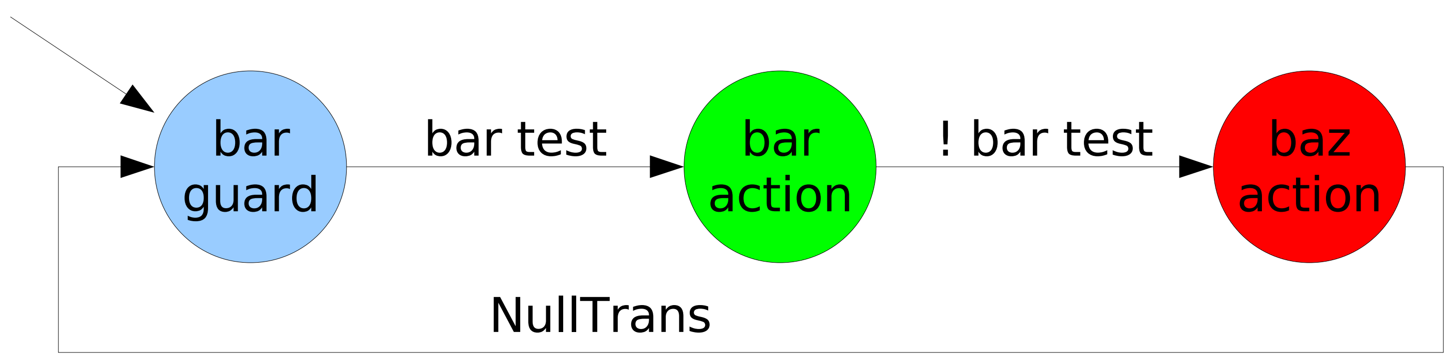
```
// Main behavior
whenever (ball.visible ~ 100ms) {
  headPan  = headPan + ball.a * camera.xfov * ball.x &
  headTilt = headTilt+ ball.a * camera.yfov * ball.y;
};

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

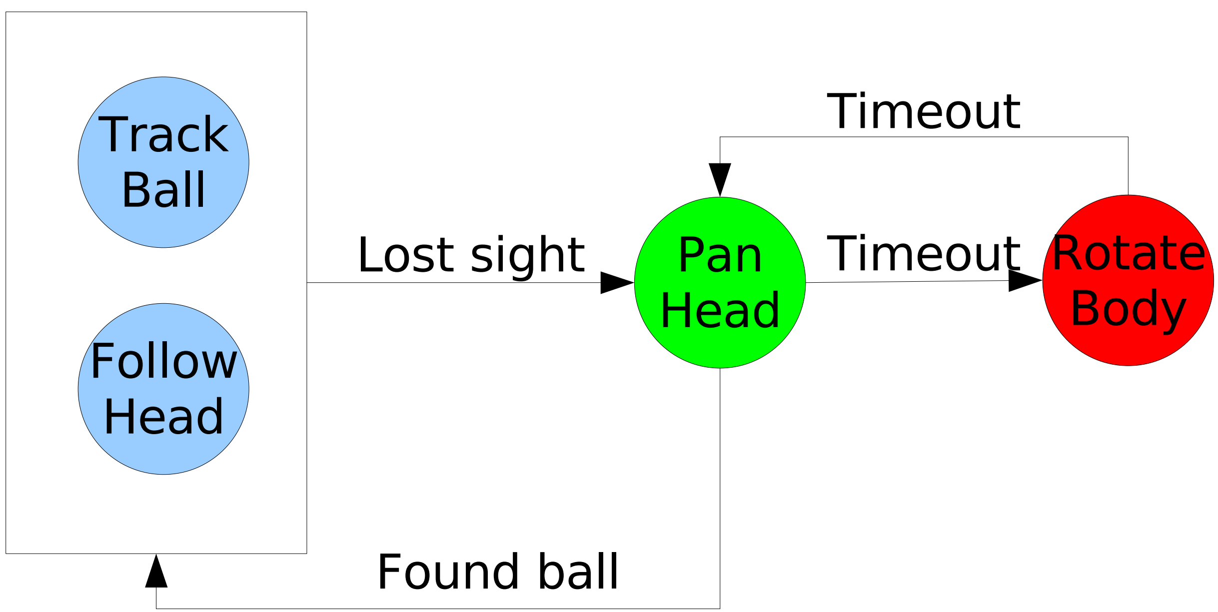
- Cooperation between two simple processes:
  - Point the camera at the ball
  - Walk in the direction the camera is pointing

- 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))
```

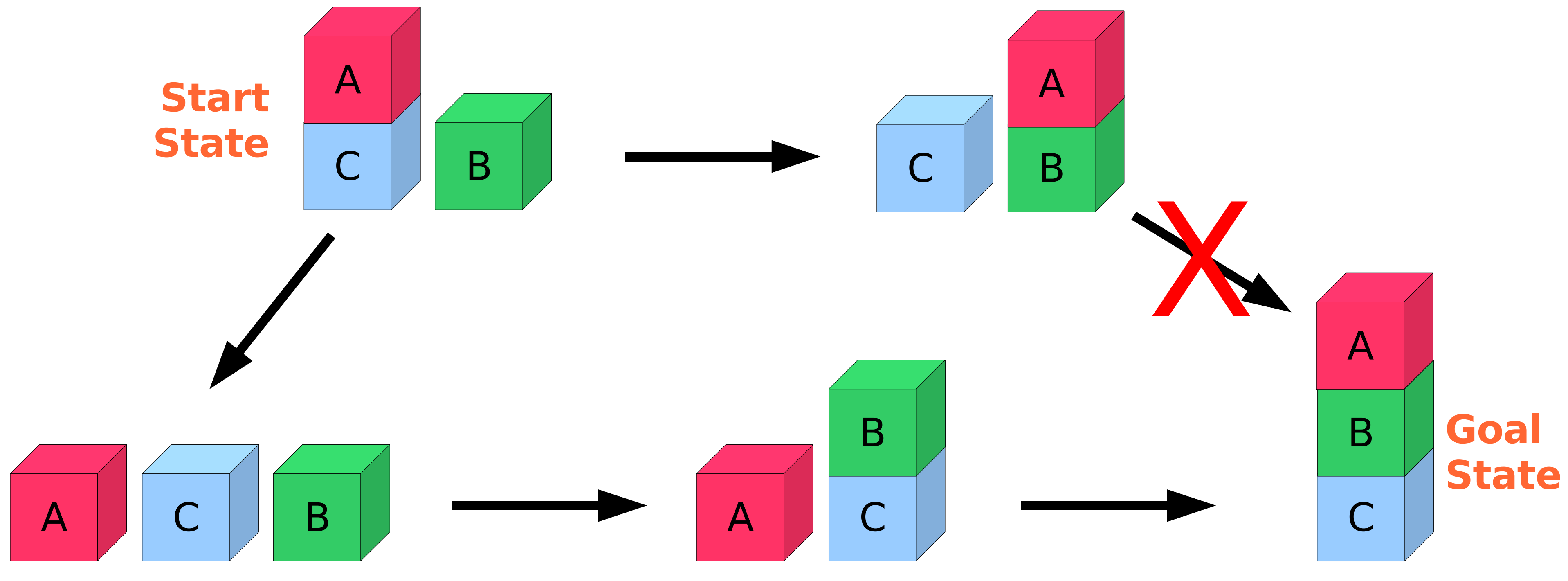
- Deadlock prevention: ESL includes “resource locking” primitives for mutual exclusion and deadlock prevention.

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

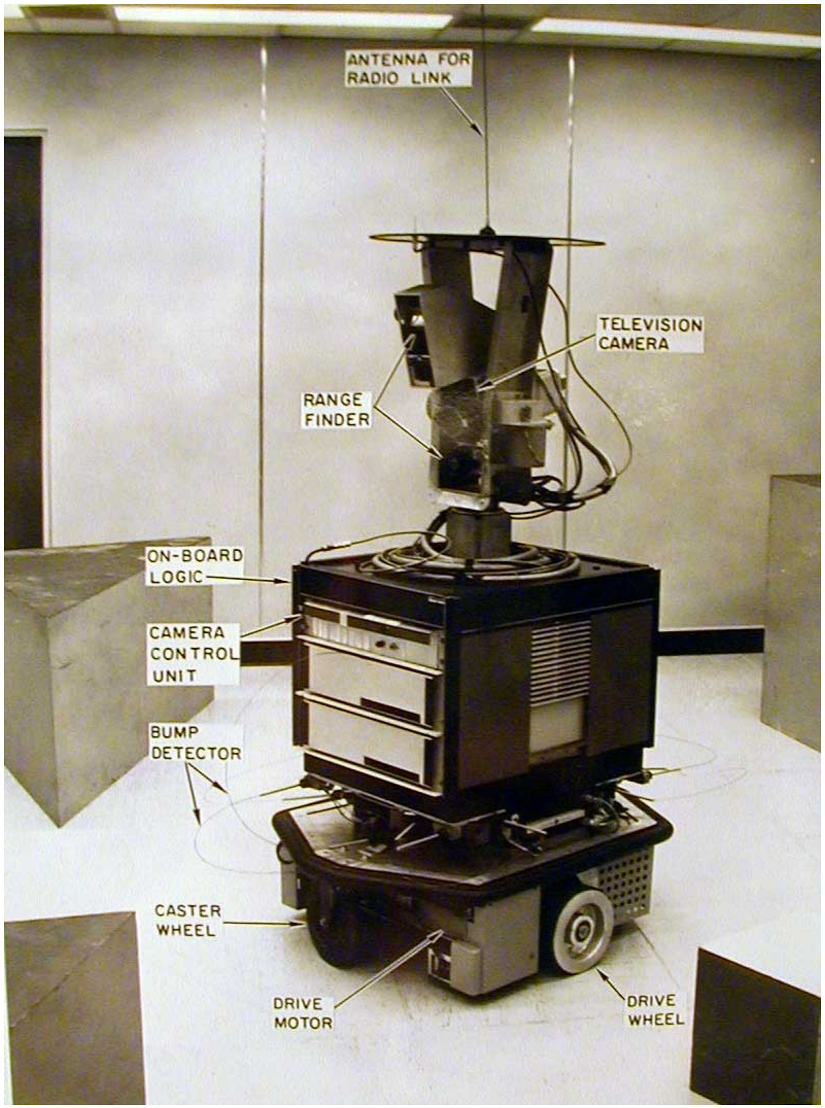
High Level Control: Planning

“Deliberative” architectures may run slowly, infrequently.

- Path planning for navigation.
- Planning as problem solving: achieve A-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) (∃rx)[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 potentially 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.
- Grubb and Proctor (2006): Tekkotsu interface for ACT-R

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?

- State machine formalism can be used for reactive control or 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.
- We could move the really slow, higher level deliberative code out of Main to another process.

Tekkotsu Subsystems

- The Lookout controls the head:
  - visual search
  - target tracking
  - obstacle detection

- 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);

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

- Can also subscribe to state updates using

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

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

Part II

State Machine Signalling
In Tekkotsu

Three Mechanisms for Communication Among States

1) Sketch and shape spaces are shared across all states, so sketches/shapes created by one state can be accessed by another using GET_SKETCH and GET_SHAPE.

2) SignalTrans allows one state to send a message to another as part of a transition, e.g., to send an int:

```
state1 =S<int>=> state2
```

3) Variables defined in a parent state can be accessed by children using the parentAs<T>() construct.

1) Accessing Sketches, Shapes

```
#shortnodeclass state1 : VisualRoutinesStateNode : DoStart
  NEW_SKETCH(camFrame, uchar, sketchFromSeg());
  NEW_SKETCH(pinkx, bool, visops::colormask(camFrame,”pink”));
  NEW_SKETCH(pblobs, uint, visops::labelcc(pinkx));
```

Variable pblobs goes out of scope upon exiting state1::DoStart, but the sketch it points to persists in camSkS.

```
#shortnodeclass state2 : VisualRoutinesStateNode : DoStart
  GET_SKETCH(pblobs, uint, camSkS);
  cout << “I found “ << pblobs->max() << “ blobs” << endl;
```

GET_SKETCH retrieves the sketch from camSKS and binds a new local variable with that name so we can access it.

Using sketch->retain()

- NEW_SKETCH the makes sketch visible in the sketchGUI, which protects from garbage collection.
- If you use NEW_SKETCH_N instead, must call retain() to preserve the sketch when variable goes out of scope.

```
#shortnodeclass state1 : VisualRoutinesStateNode: DoStart
 NEW_SKETCH_N(secret, uchar, ~sketchFromRawY());
 secret->retain();
```

- To drop a retained sketch:

```
secret->retain(false);
```

MapBuilder and retain()

- The MapBuilder automatically clears camSkS and camShS at the start of each request.
- If you need to keep a sketch around across MapBuilder calls, use retain().
- To clear sketches manually, including retained sketches, call camSkS.clear() directly.

2) State Signaling

Two principal uses:

- Transmit an arbitrary value, e.g., a float or struct
- Implement an n-way branch. In this case the signal is an enumerated type.

Both are implemented by posting a DataEvent and using a SignalTrans to test for the event.

Transmit an Arbitrary Signal

```
#nodeclass TransmitDemo : StateNode

  #shortnodeclass Pitcher : StateNode : DoStart
    float x = ...;   // some arbitrary computation
    postStateSignal<float>(x);

  #shortnodeclass Catcher : StateNode : DoStartEvent
    float val = extractSignal<float>(event);
    cout << "Message received: " << val << endl;

  #nodemethod setup
    #statemachine
      startnode: Pitcher =S<float>=> Catcher
    #endstatemachine
  #endnodemethod

#endnodeclass
```

When using DoStartEvent instead of DoStart, the variable event is automatically defined for you and bound to the event that caused the transition into this state. The extractSignal call will fail if this is not a DataEvent<float>.

N-Way Branch

```
#nodeclass ChooseDemo : StateNode
  enum choice {goLeft, goRight, goStraight};

  #shortnodeclass Chooser : StateNode : DoStart
    float x = rand()/(1.0f + RAND_MAX);
    if ( x < 0.1 ) postStateSignal<choice>(goLeft);
    else if ( x < 0.2 ) postStateSignal<choice>(goRight);
    else postStateSignal<choice>(goStraight);

  #nodemethod setup
    #statemachine
      startnode: Chooser
      startnode =S<choice>(goLeft)=> WalkNode($,0,0,1,0)
      startnode =S<choice>(goRight)=> WalkNode($,0,0,-1,0)
      startnode =S<choice>(goStraight)=> WalkNode($,100,0,0,0)
    #endstatemachine

#endnodeclass
```

3) Parent-Defined Variables

```
#nodeclass SharedVarDemo : StateNode : counter()
  int counter;

  #shortnodeclass BumpIt : StateNode
    int &counter = parentAs<SharedVarDemo>()->counter;
    ++counter;

  #shortnodeclass Report : StateNode
    int &counter = parentAs<SharedVarDemo>()->counter;
    cout << “Counter = “ << counter << endl;

  #shortnodemethod DoStart
    counter = 0;  // can't rely on constructor if called twice

  #nodemethod setup
    #statemachine
      startnode: BumpIt =N=> BumpIt =N=> BumpIt =N=> Report
    #endstatemachine

#endnodeclass
```

More State Signaling

- postStateCompletion()
  - Use the =C=> transition
  - Indicates normal completion of the state's action.
- postStateFailure(), postStateSuccess()
  - Use =F=> for abnormal completion, e.g., search failed.
  - Use =S=> for a third outcome if =C=> already used
- postParentCompletion(), postParentFailure()
  - Can be used to trigger a transition out of the parent node.
  - This is how nested state machines can “return” to the parent state machine.

When You Must Use =C=>

```
straight: HeadPointerNode[getMC()->setJoints(0,0,0)]
   =RND=> {left, right}

left: HeadPointerNode[getMC()->setJoints(0,0.5,0)]
   =T(5000)=> straight

right: HeadPointerNode[getMC()->setJoints(0,-0.5,0)]
   =T(5000)=> straight
```

What's the problem? The =RND=> transition won't wait for the head motion to complete. Same for =N=> transition. Can only use =C=> here.