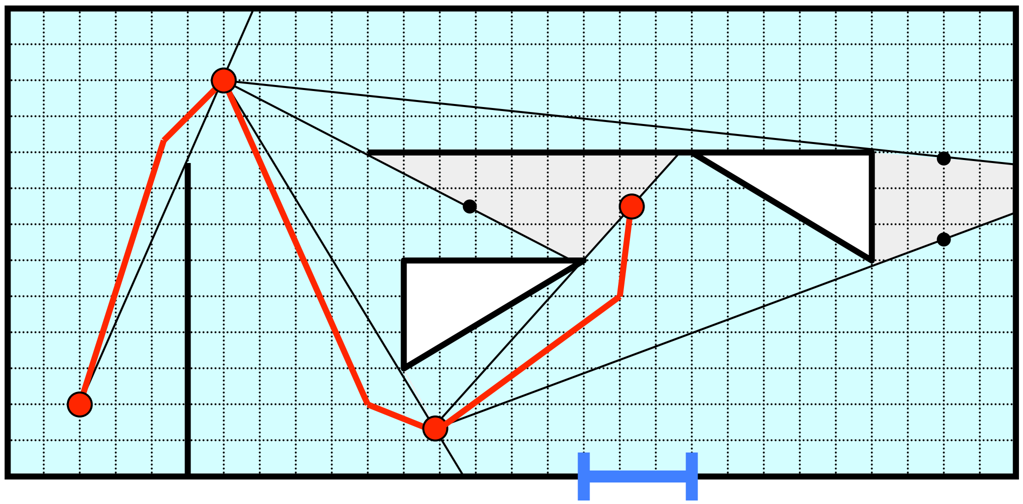
Behavior for Mobile Robots



Bhaskar Mookerji

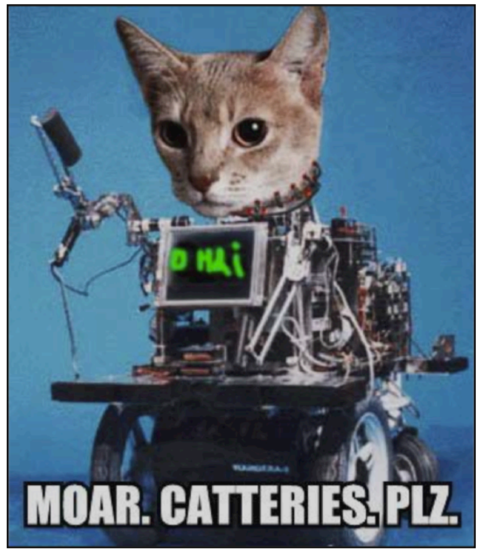
(updated from Chris Batten's IAP 2007 Talk)

Maslab IAP Robotics Course

January 4, 2011

What is so hard about designing a mobile robot controller?

Sensors



Actuators

Sensors are far from perfect

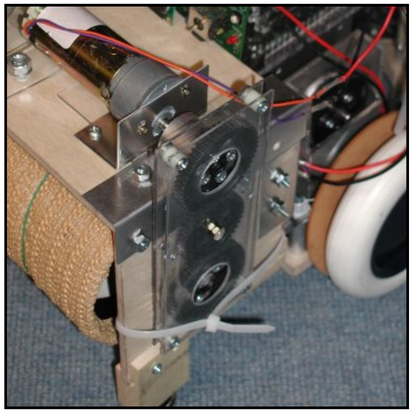
Camera white balance = bad colors
Ultrasound reflections
Infrared sensors can be noisy
… and many more!

Actuators are far from perfect

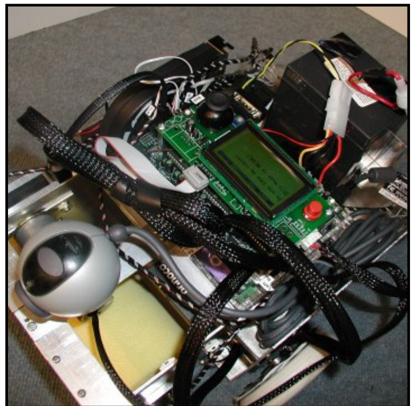
Motor velocity changes over time
Wheels and gears slip
Servos get stuck
… and many more!

Even if the world was perfect, the sheer complexity of a robot can be daunting

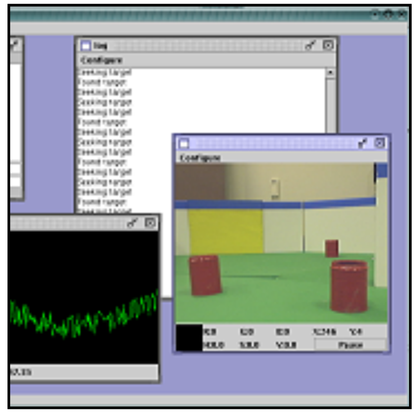
Mechanical

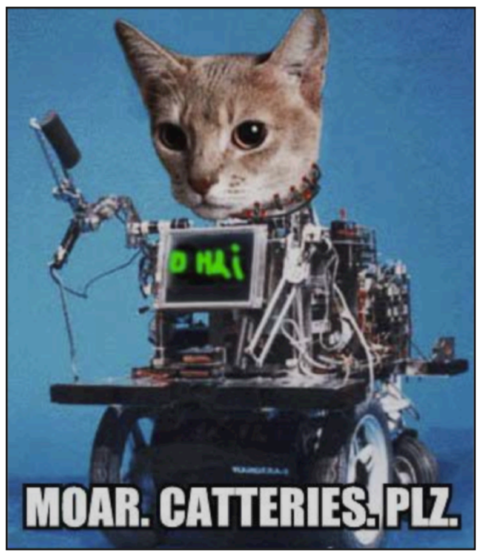


Electrical



Software





Don't just code a control system, design a control system!

Just as you must carefully **design** your robot chassis you must carefully **design** your robot control system

- How will you debug and test your robot?
- What are the performance requirements?
- Can you easily improve aspects of your robot?
- Can you easily integrate new functionality?

An example of how not to design your robot control system

```
void moveForward( int time ) {

  while ( t < time ) {

    // Drive forward a bit
    ----------------------------------------
    ----------------------------------------

  }
}
```

An example of how not to design your robot control system

```
void moveForward( int time ) {

  while ( t < time ) {

    // Drive forward a bit
    ---------------------------------------
    ---------------------------------------

    // Check ir sensor and stop if necessary
    ---------------------------------------
    ---------------------------------------

  }
}
```

An example of how not to design your robot control system

```
void moveForward( int time ) {

  while ( t < time ) {

    // Drive forward a bit
    -------------------------------------
    -------------------------------------

    // Check ir sensor and stop if necessary
    -------------------------------------
    -------------------------------------

    // Rotate if there is an obstacle
    -------------------------------------
    -------------------------------------

  }
}
```

An example of how not to design your robot control system

```
void moveForward( int time ) {

  while ( t < time ) {

    // Drive forward a bit
    -------------------------------------
    -------------------------------------

    // Check ir sensor and stop if necessary
    -------------------------------------
    -------------------------------------

    // Rotate if there is an obstacle
    -------------------------------------
    -------------------------------------

    // Need to find some balls
    -------------------------------------
    -------------------------------------

    // Somehow pick up a ball
    -------------------------------------
    -------------------------------------

    // What if there is more than one ball?
    -------------------------------------
    -------------------------------------

  }
}
```

An example of how not to design your robot control system

```
void moveForward( int time ) {

  while ( t < time ) {

    // Drive forward a bit
    --------------------------------------
    --------------------------------------

    // Check ir sensor and stop if necessary
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    --------------------------------------

    // Rotate if there is an obstacle
    --------------------------------------
    --------------------------------------

    // Need to find some balls
    --------------------------------------
    --------------------------------------

    // Somehow pick up a ball
    --------------------------------------
    --------------------------------------

    // What if there is more than one ball?
    --------------------------------------
    --------------------------------------

   . . .
```

```
    . . .

    // Need to find some goals
    --------------------------------------
    --------------------------------------

    // What if there are no goals visible?
    --------------------------------------
    --------------------------------------

    // Drop off some balls
    --------------------------------------
    --------------------------------------

    // Find more balls I guess
    --------------------------------------
    --------------------------------------

    // Make sure to ignore balls in goal
    --------------------------------------
    --------------------------------------

    // Try to go somewhere new
    --------------------------------------
    --------------------------------------

  }
}
```

An example of how not to design your robot control system

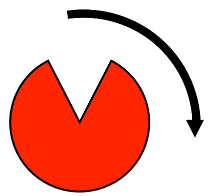
```
void moveForward( int time )
  while ( t < time ) {
```

```
    -------------------------------------
    // Check ir sensor and stop if necessary
    -------------------------------------
    -------------------------------------
    // Rotate if there is an obstacle
    -------------------------------------
    -------------------------------------
    // Need to find some balls
    -------------------------------------
    -------------------------------------
    // Somehow pick up a ball
    -------------------------------------
    -------------------------------------
    // What if there is more than one ball?
    -------------------------------------
    -------------------------------------
    // Need to find some goals
    -------------------------------------
    -------------------------------------
    // What if there are no goals visible?
    -------------------------------------
    -------------------------------------
    // Drop off some balls
    -------------------------------------
    -------------------------------------
    // Find more balls I guess
    -------------------------------------
    -------------------------------------
    // Make sure to ignore balls in goal
    -------------------------------------
    -------------------------------------
```

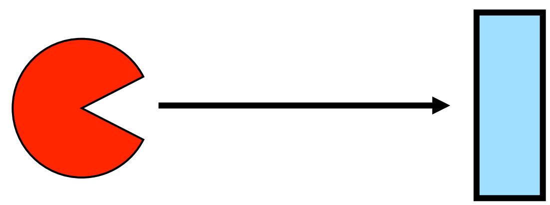
```
    // What if there are no goals visible?
    ----------
    ----------
    // Drop of
    ----------
    ----------
    // Find mor
    ----------
    ----------
    // Make su
    ----------
    ----------
    // Try to g
    ----------
    ----------
    // Find mor
    ----------
    ----------
    // Make su
    ----------
    ----------
    // Try to g
    ----------
    ----------
  }
}
```

Basic primitive of a control system is a behavior

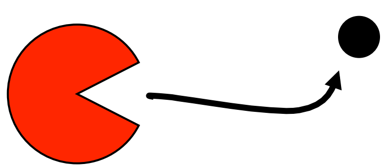
Behaviors should be well-defined, self-contained, and independently testable



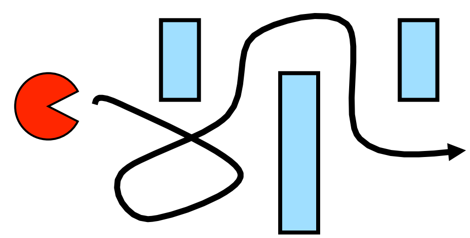
Turn right 90°



Go forward until reach obstacle

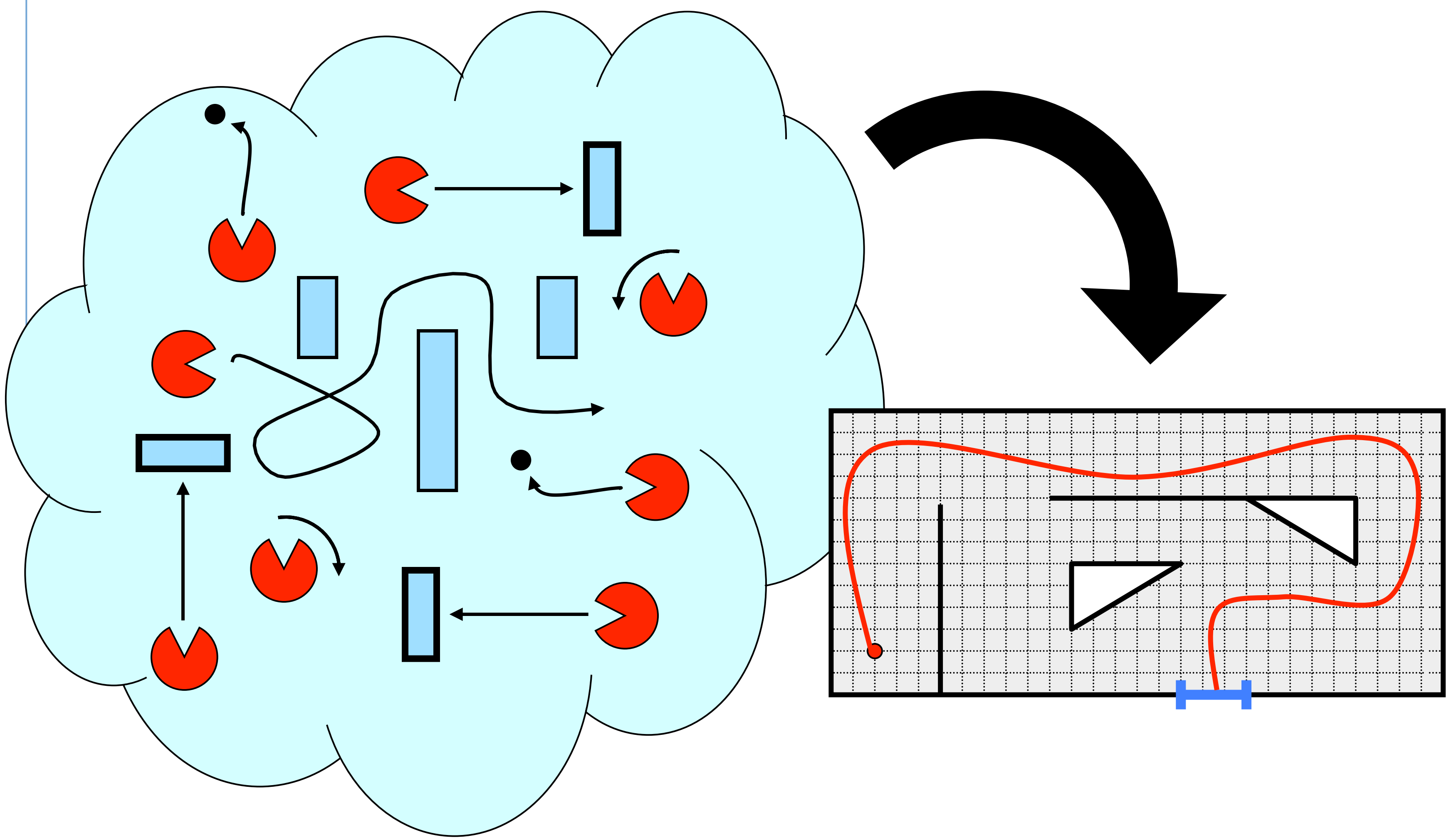


Capture a ball

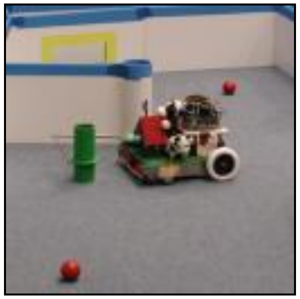


Explore playing field

Key objective is to compose behaviors so as to achieve the desired goal

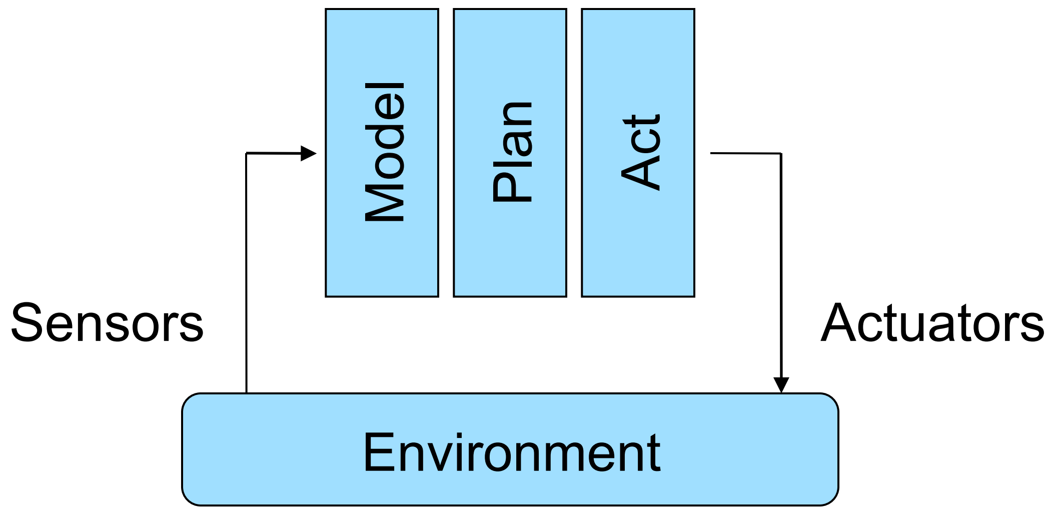


Outline



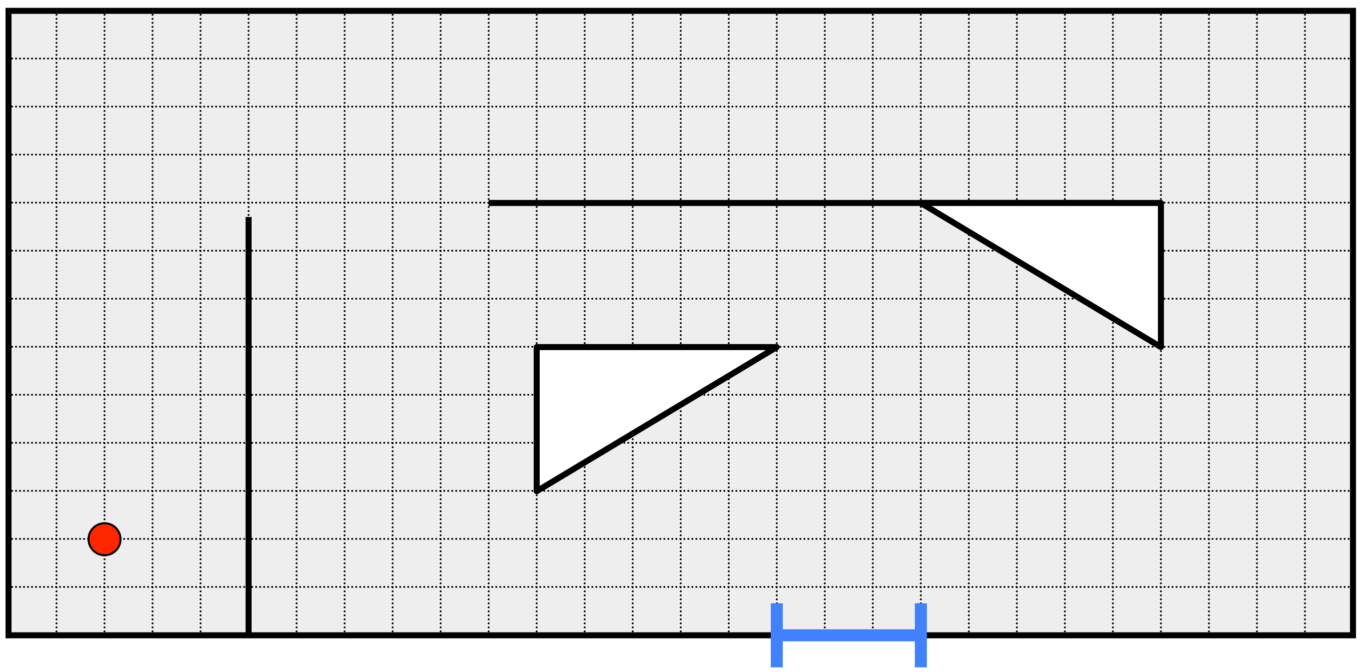
- **High-level control system paradigms**
  - **Model-Plan-Act Approach**
  - **Emergent Approach**
  - **Finite State Machine Approach**
- Low-level control loops (Tomorrow)
  - PID controllers for motor velocity
  - PID controllers for robot drive system
- Examples from past years

Model-Plan-Act Approach



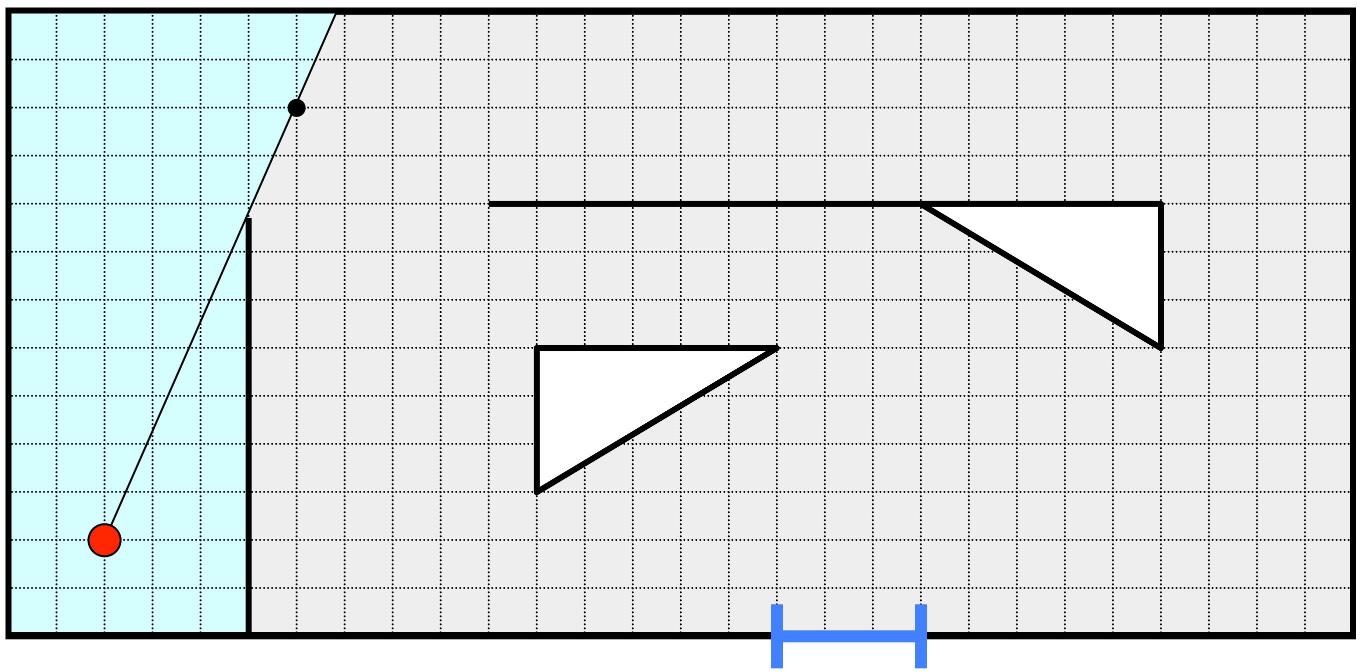
1. Use sensor data to create model of the world
2. Use model to form a sequence of behaviors which will achieve the desired goal
3. Execute the plan (compose behaviors)

Exploring the playing field to create a model of the world



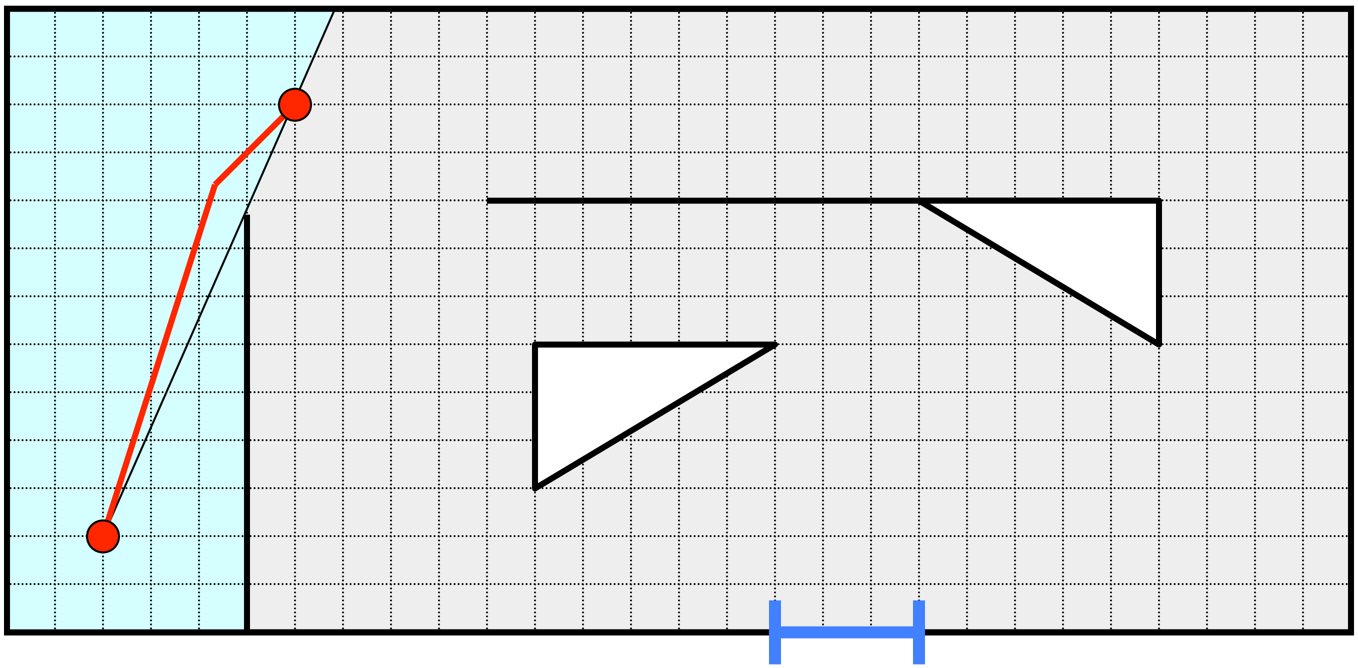
Red dot is the mobile robot
while the blue line is the mousehole

Exploring the playing field to create a model of the world



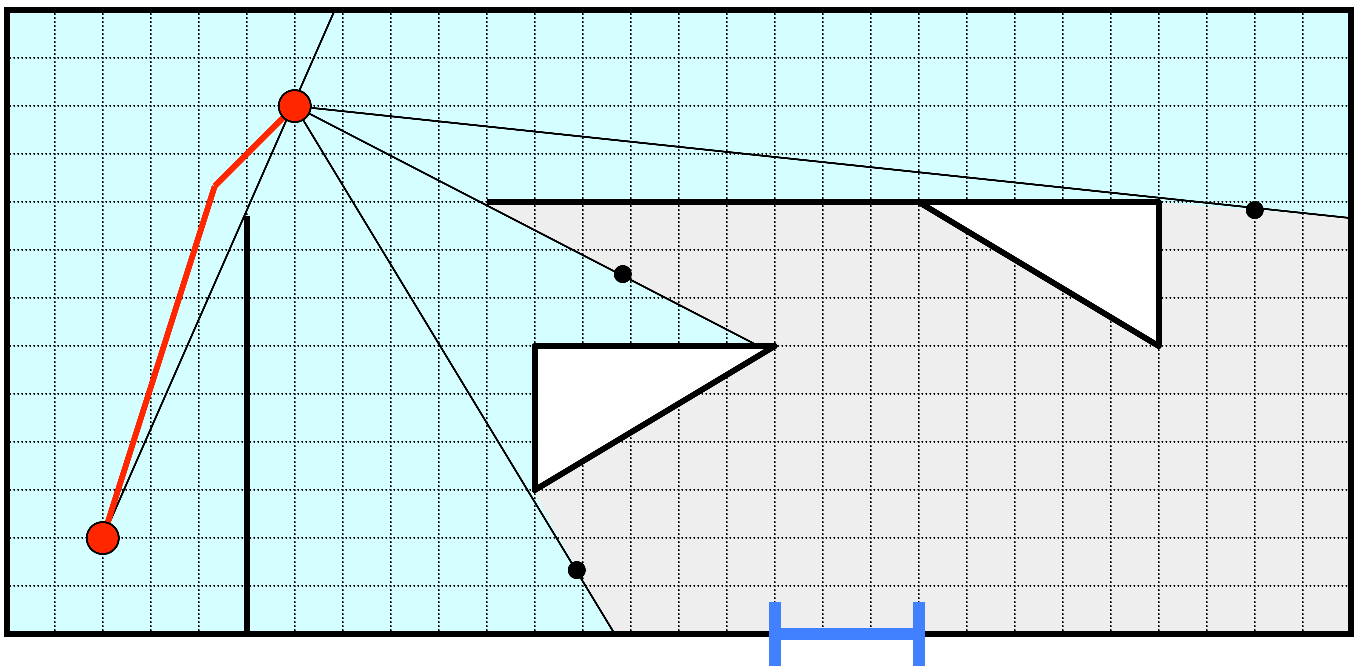
Robot uses sensors to create local map of the world and identify unexplored areas

Exploring the playing field to create a model of the world



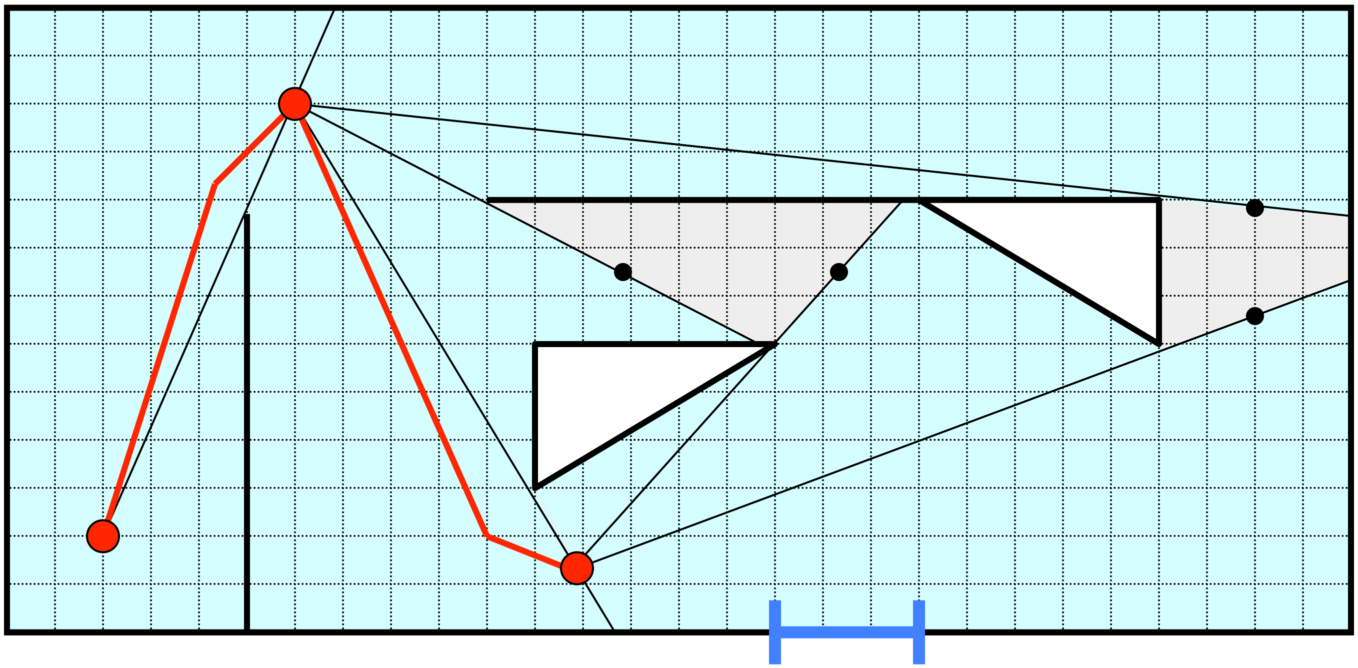
Robot moves to midpoint of unexplored boundary

Exploring the playing field to create a model of the world



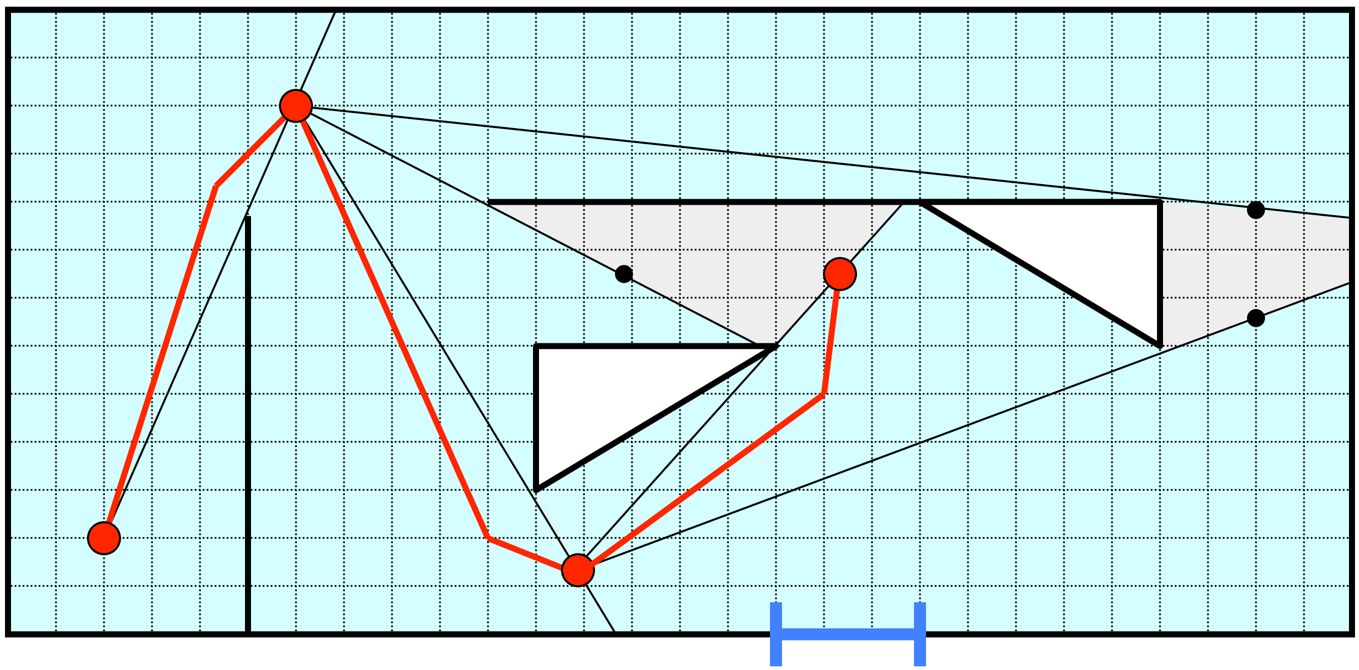
Robot performs a second sensor scan and must align the new data with the global map

Exploring the playing field to create a model of the world



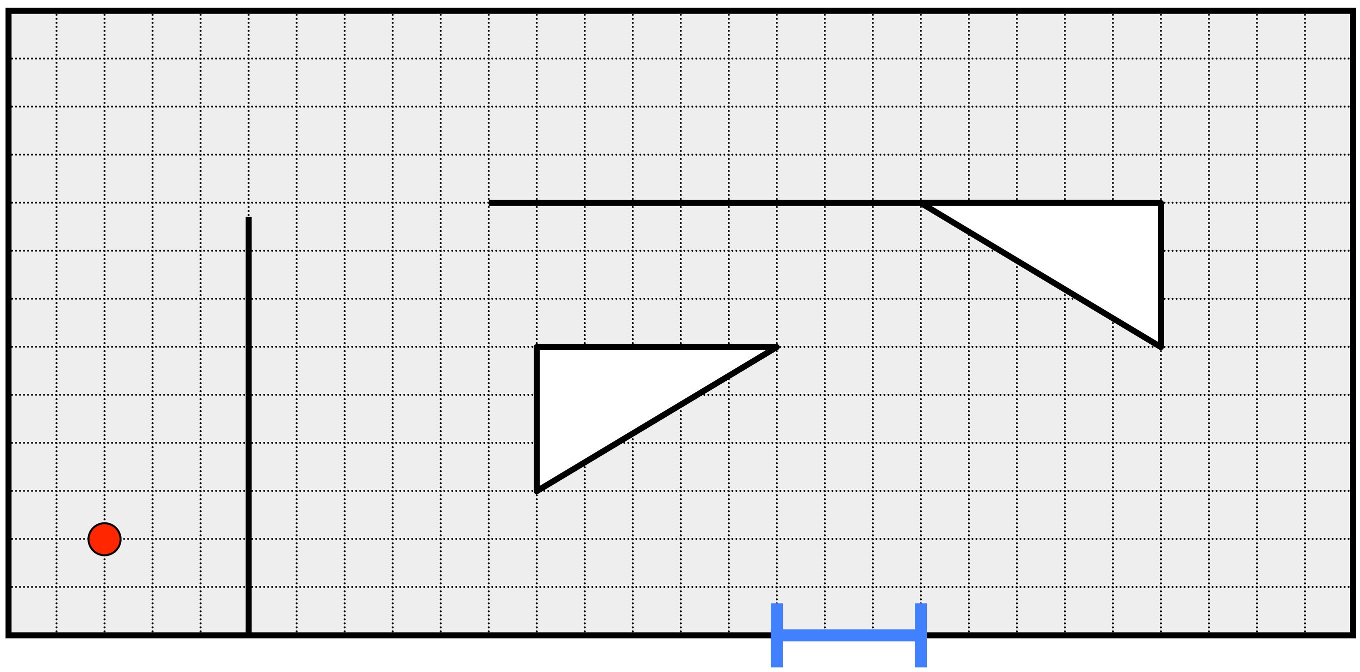
Robot continues to explore
the playing field

Exploring the playing field to create a model of the world



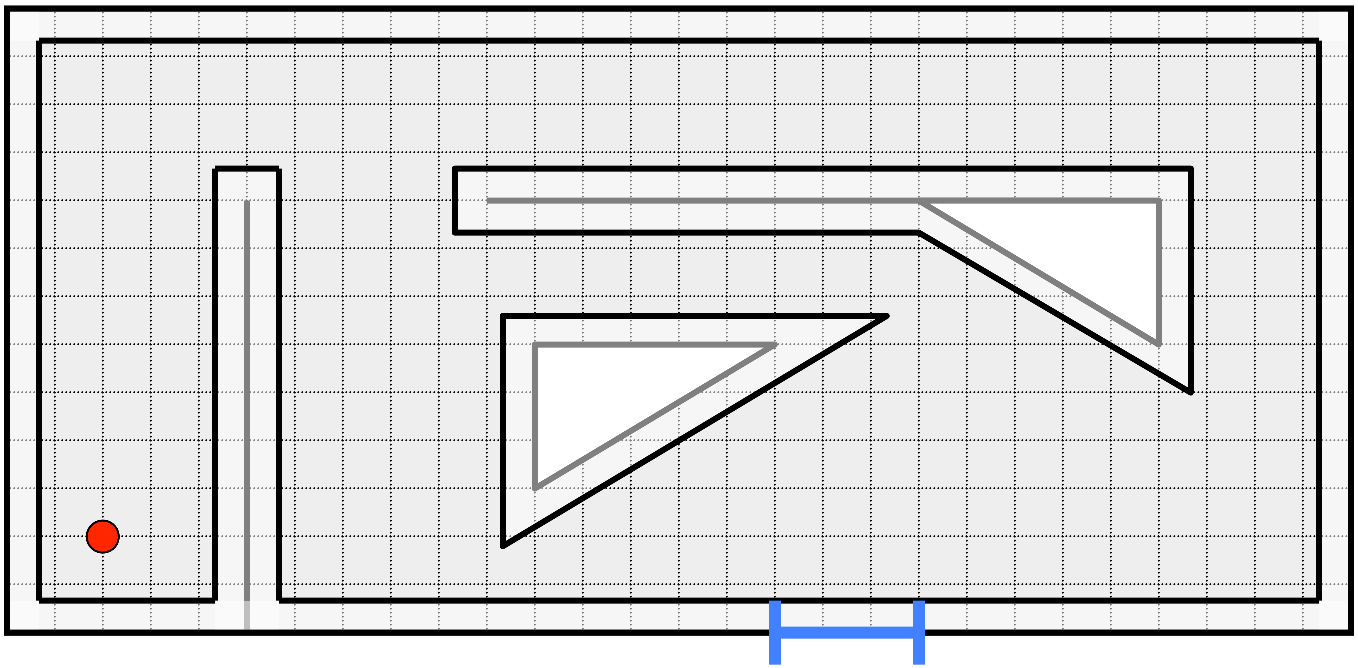
Robot must recognize when it starts to see areas which it has already explored

Finding a path to the mousehole using the convex cell algorithm



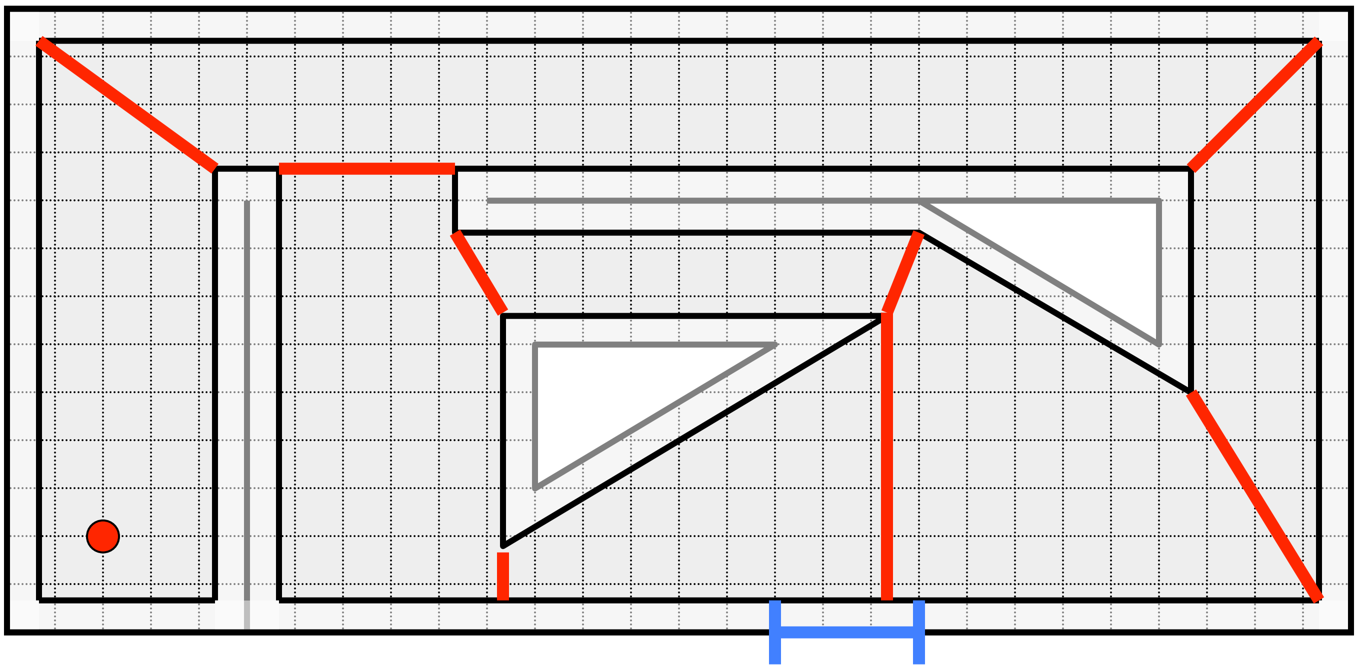
Given the global map,
the goal is to find the mousehole

Finding a path to the mousehole using the convex cell algorithm



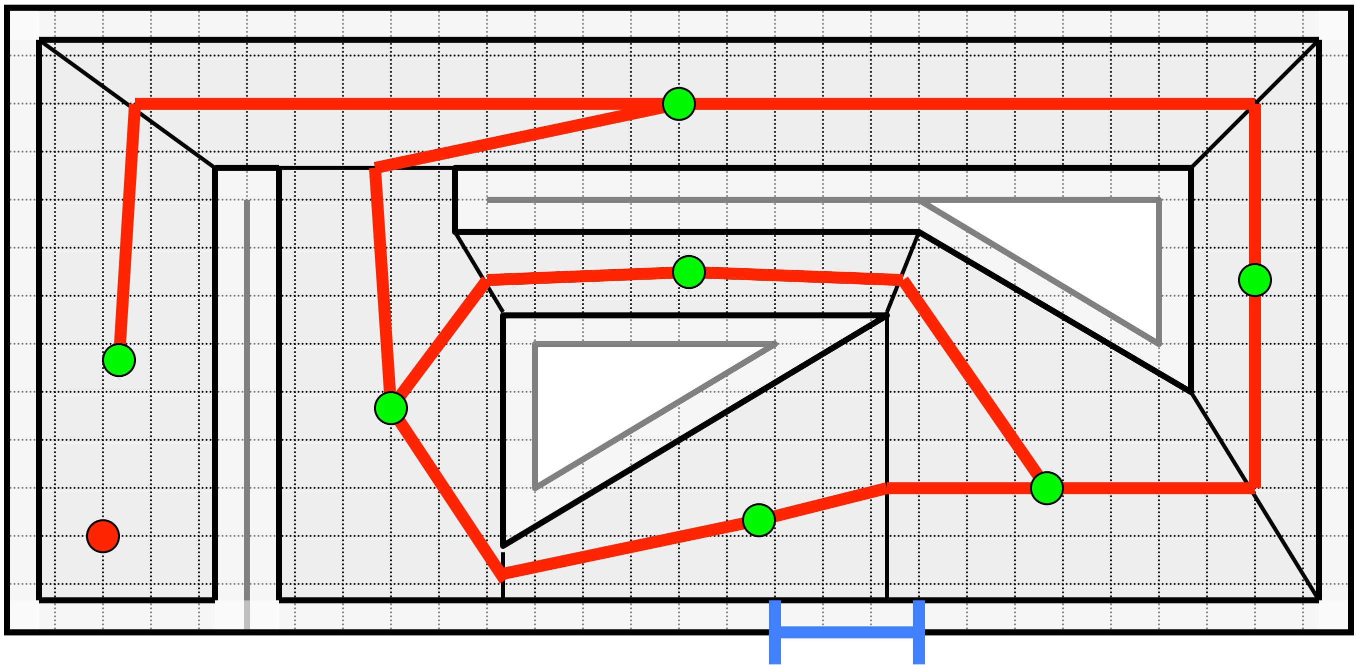
Transform world into configuration space by convolving robot with all obstacles

Finding a path to the mousehole using the convex cell algorithm



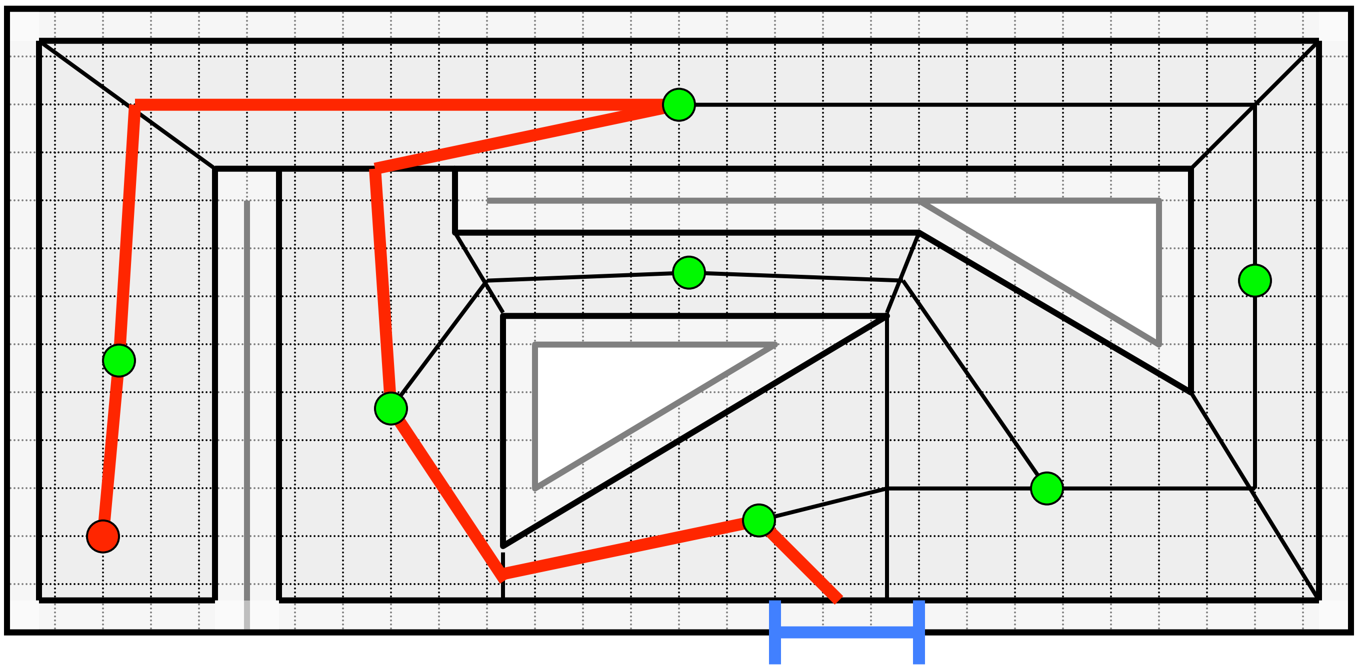
Decompose world into convex cells
Trajectory within any cell is free of obstacles

Finding a path to the mousehole using the convex cell algorithm



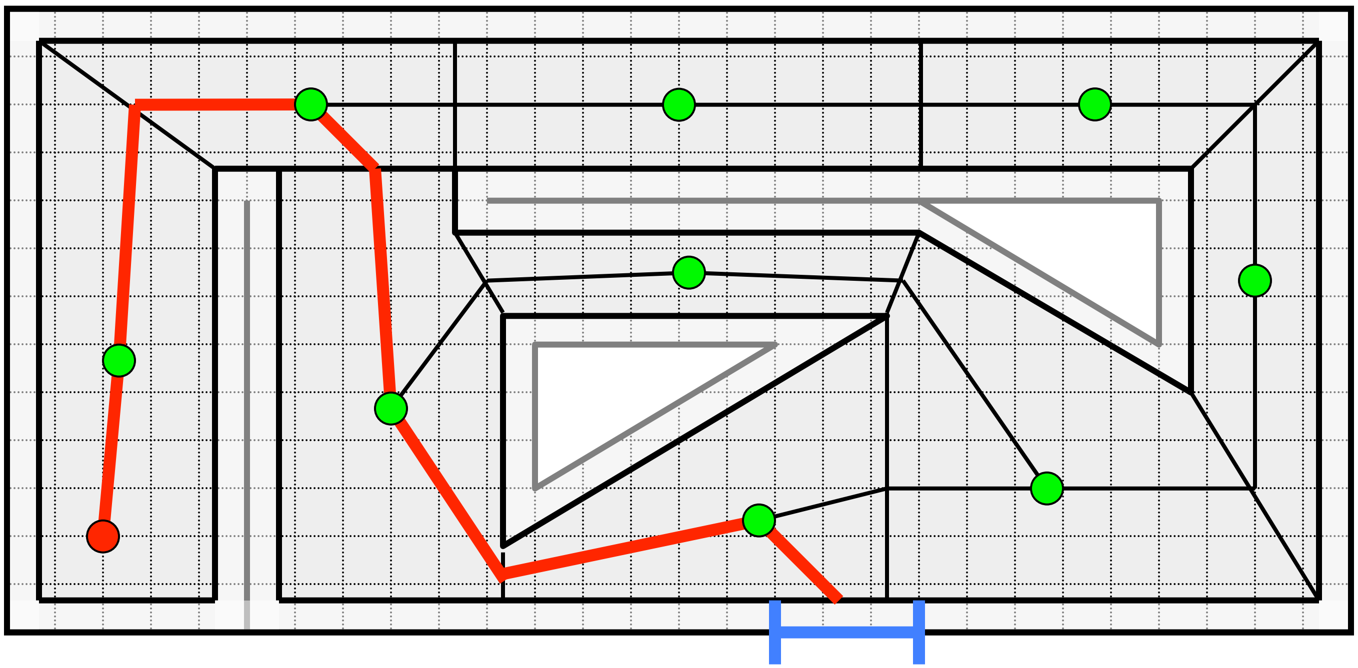
Connect cell edge midpoints and centroids to get graph of all possible paths

Finding a path to the mousehole using the convex cell algorithm



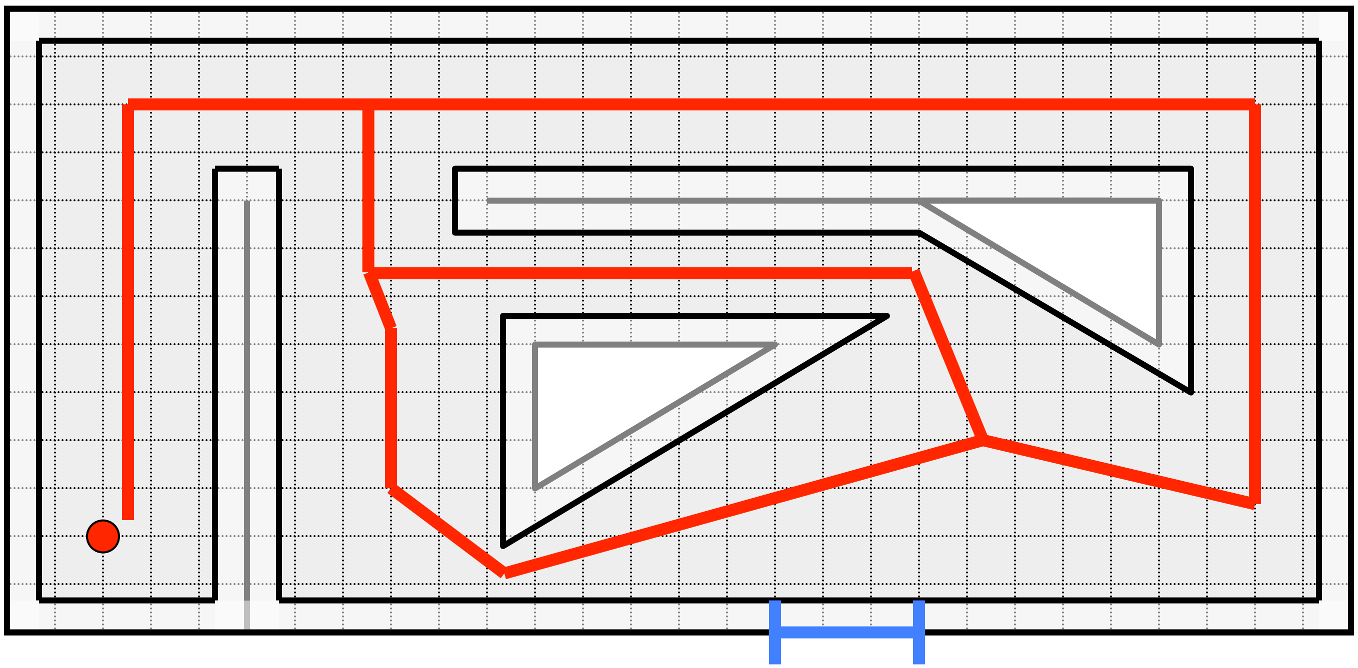
Use an algorithm (such as the A* algorithm) to find shortest path to goal

Finding a path to the mousehole using the convex cell algorithm



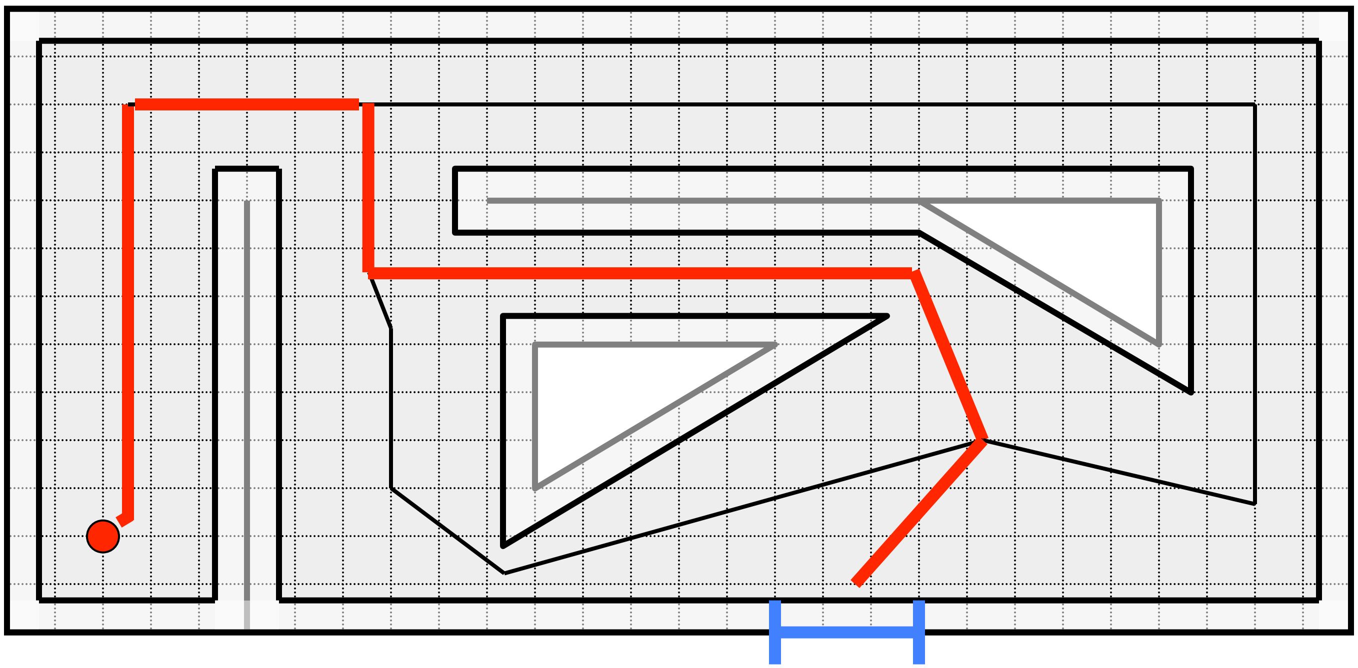
The choice of cell decomposition can greatly influence results

Finding a path to the mousehole using the Voronoi cell algorithm



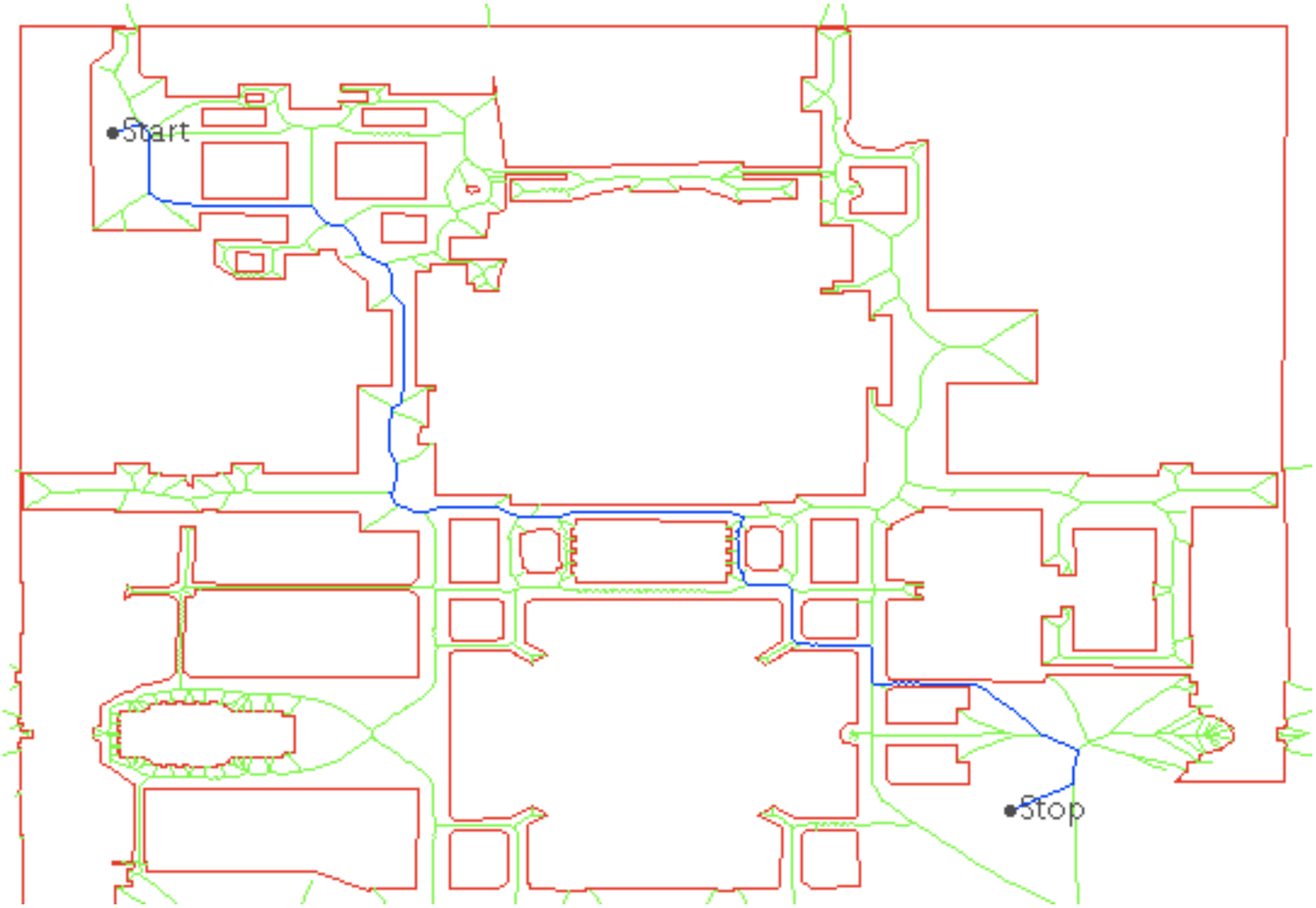
Create a Voronoi partitioning - paths are equidistant from obstacles

Finding a path to the mousehole using the Voronoi cell algorithm



Treat Voronoi paths as "highways"
Maximally avoids obstacles

Example using Voronoi path planning in real world office environment



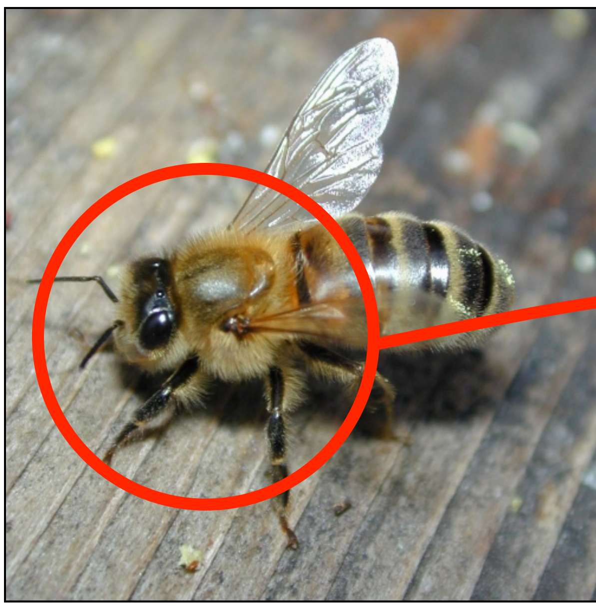
http://www.cs.columbia.edu/~pblaer/projects/path_planner

Advantages and disadvantages of the model-plan-act approach

- Advantages
  - Global knowledge in the model enables optimization
  - Can make provable guarantees about the plan
- Disadvantages
  - Must implement all functional units before any testing
  - Computationally intensive
  - Requires very good sensor data for accurate models
  - Models are inherently an approximation
  - Works poorly in dynamic environments

Emergent Approach

Living creatures like honey bees are able to explore their surroundings and locate a target (honey)



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Is this bee using the model-plan-act approach?

Emergent Approach

Living creatures like honey bees are able to explore their surroundings and locate a target (honey)

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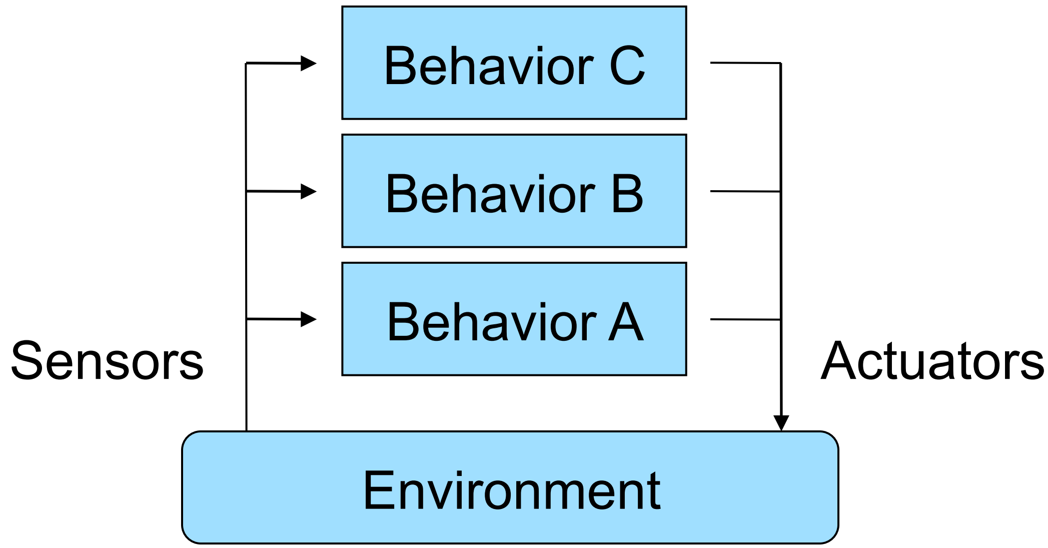
Probably not! Most likely bees layer simple reactive behaviors to create a complex emergent behavior

Emergent Approach

Should we design our robots so they act less like robots and more like honey bees?

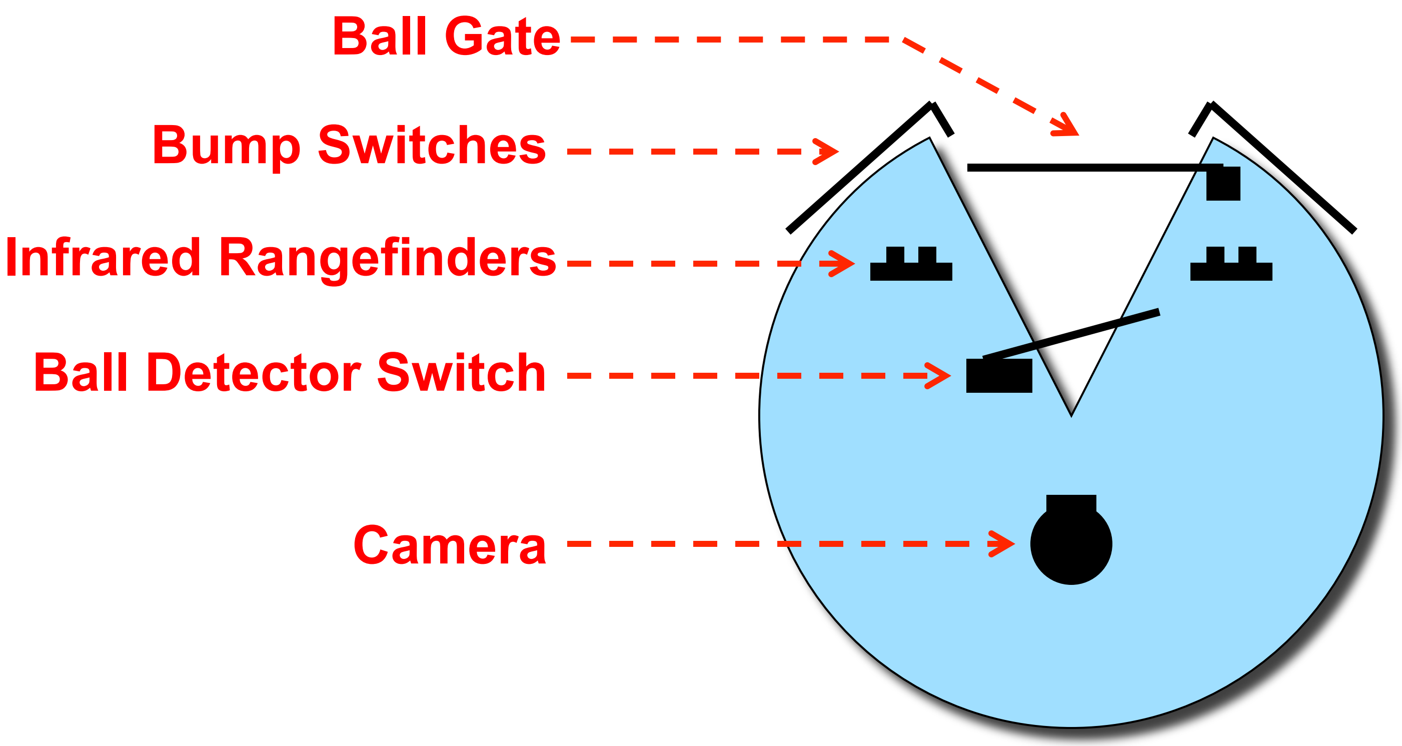
Emergent Approach



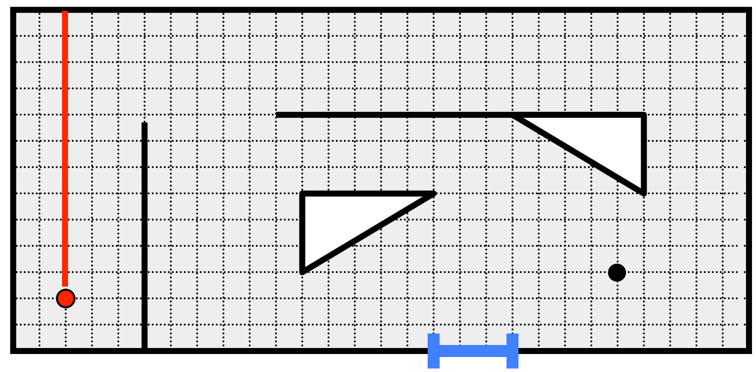
As in biological systems, the emergent approach uses simple behaviors to directly couple sensors and actuators

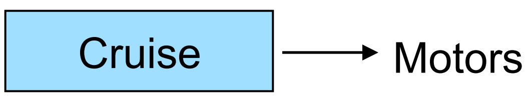
Higher level behaviors are layered on top of lower level behaviors

To illustrate the emergent approach we will consider a simple mobile robot



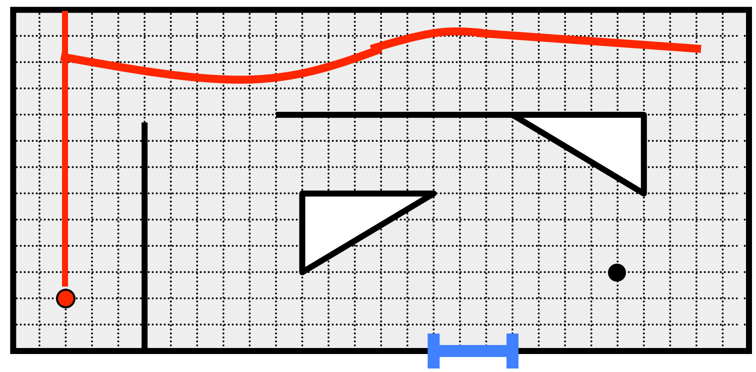
Layering simple behaviors can create much more complex emergent behavior

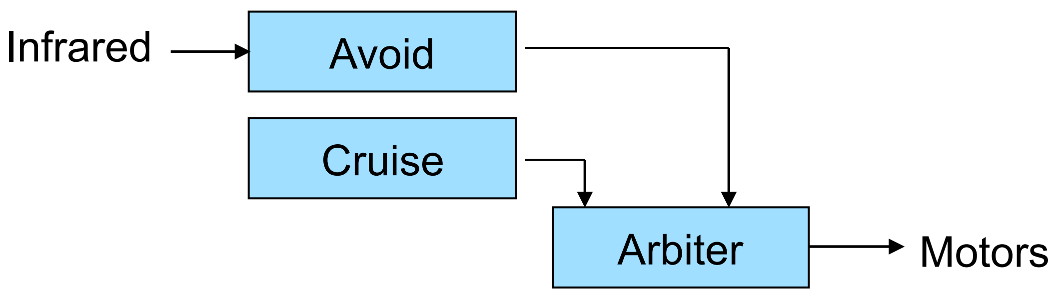




Cruise behavior simply moves robot forward

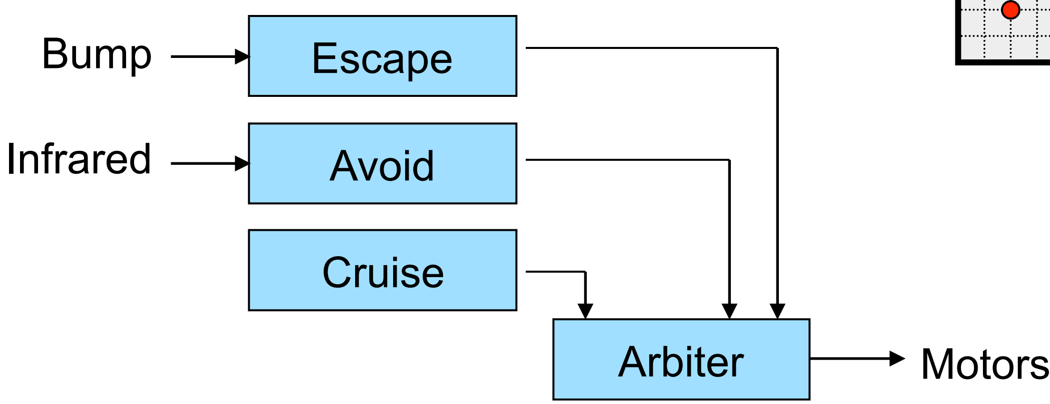
Layering simple behaviors can create much more complex emergent behavior

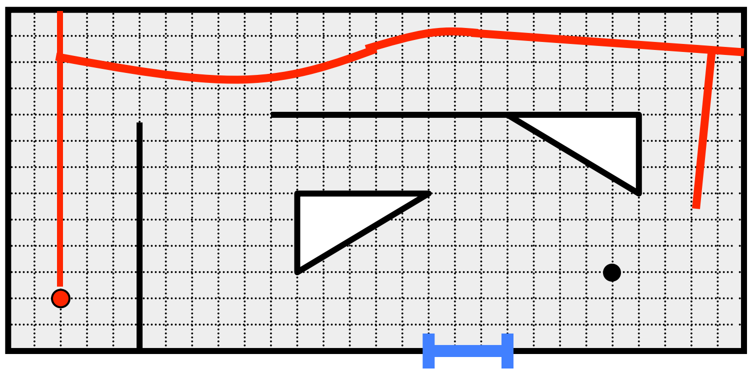




Left motor speed inversely proportional to left IR range
Right motor speed inversely proportional to right IR range
If both IR < threshold stop and turn right 120 degrees

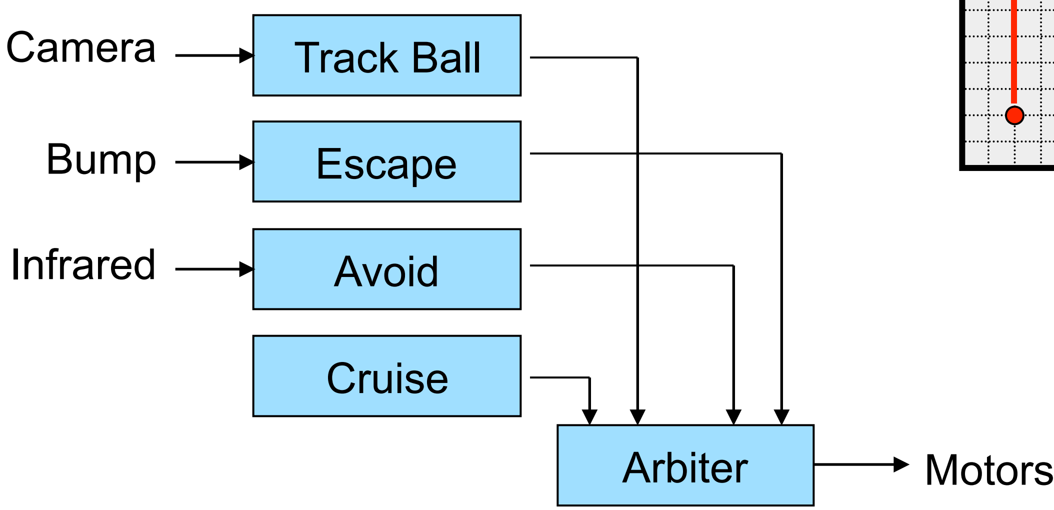
Layering simple behaviors can create much more complex emergent behavior

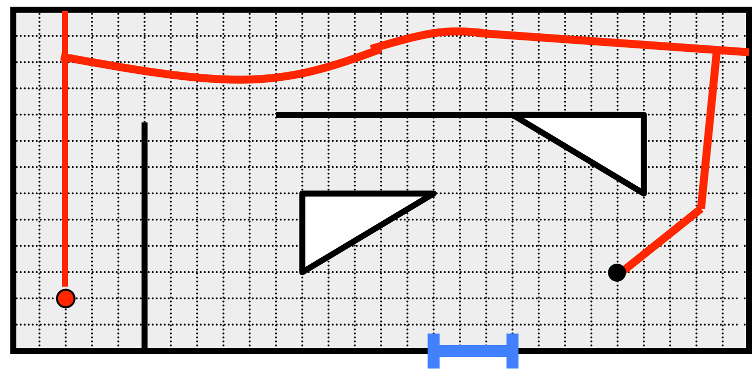




Escape behavior stops motors,
backs up a few inches, and turns right 90 degrees

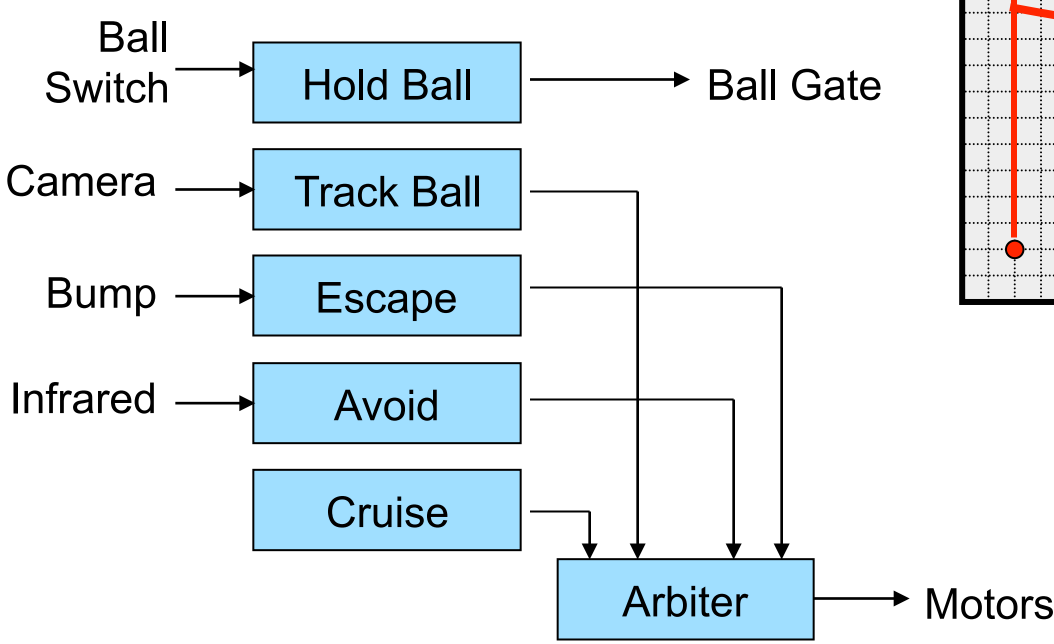
Layering simple behaviors can create much more complex emergent behavior

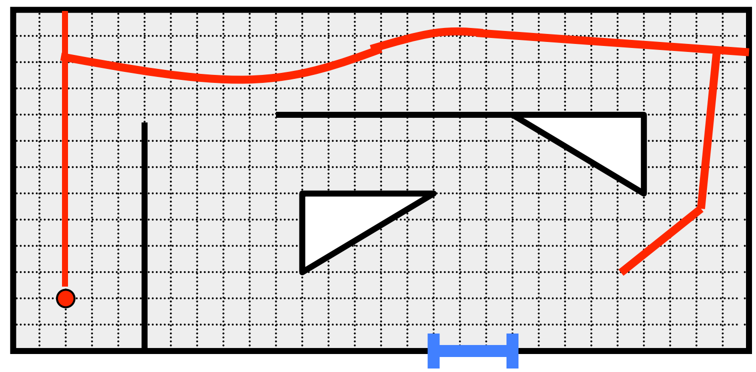




The track ball behavior adjusts the motor differential to steer the robot towards the ball

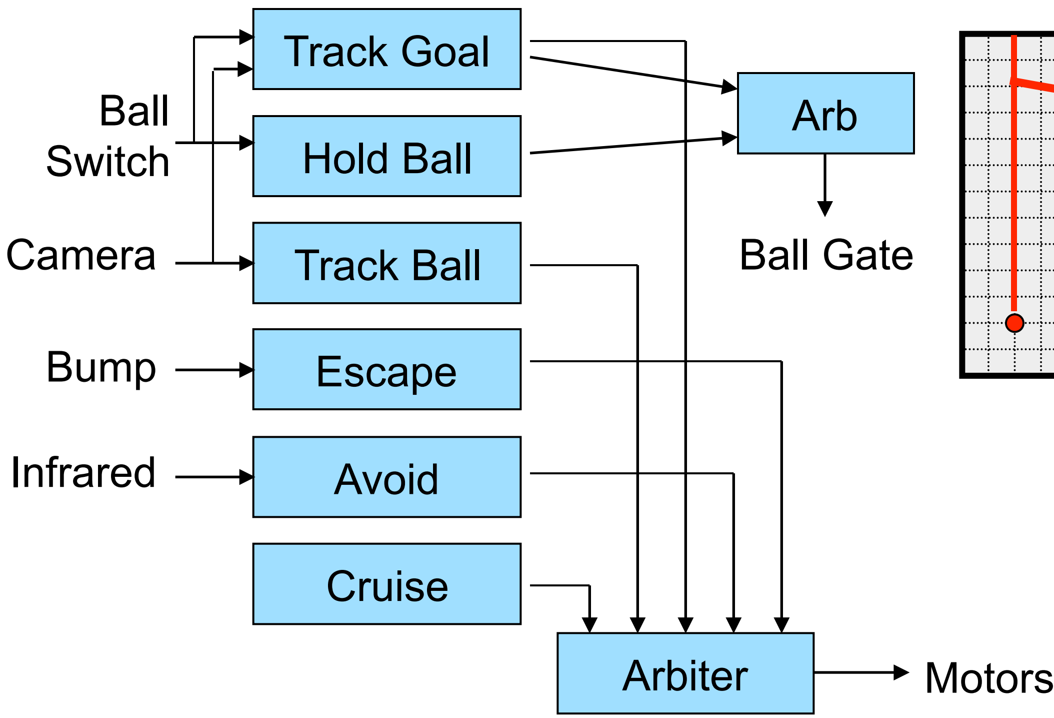
Layering simple behaviors can create much more complex emergent behavior

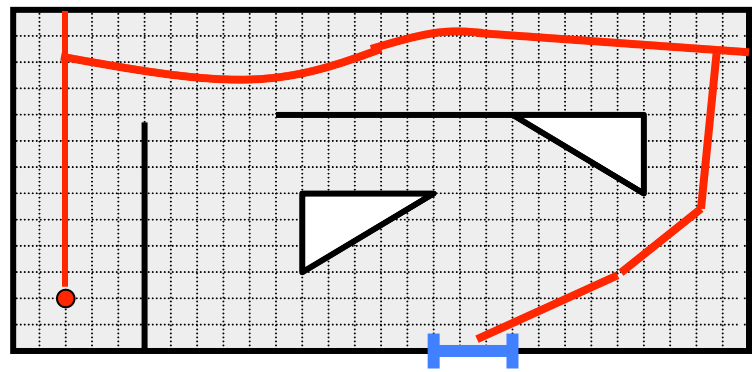




Hold ball behavior simply closes ball gate when ball switch is depressed

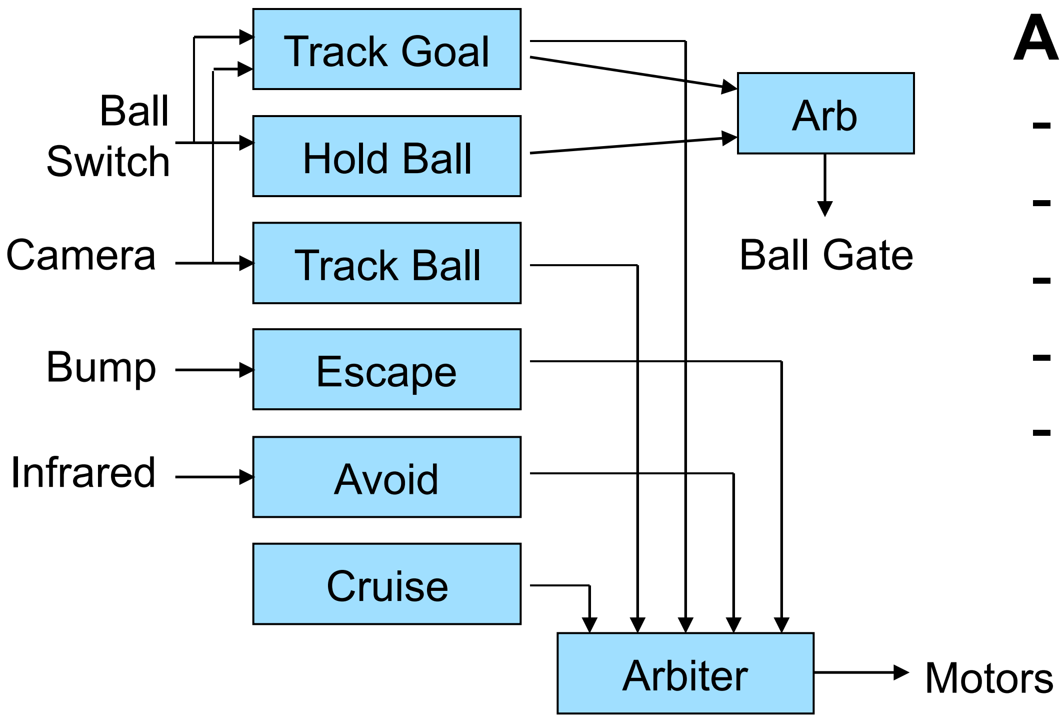
Layering simple behaviors can create much more complex emergent behavior





The track goal behavior opens the ball gate and adjusts the motor differential to steer the robot towards the goal

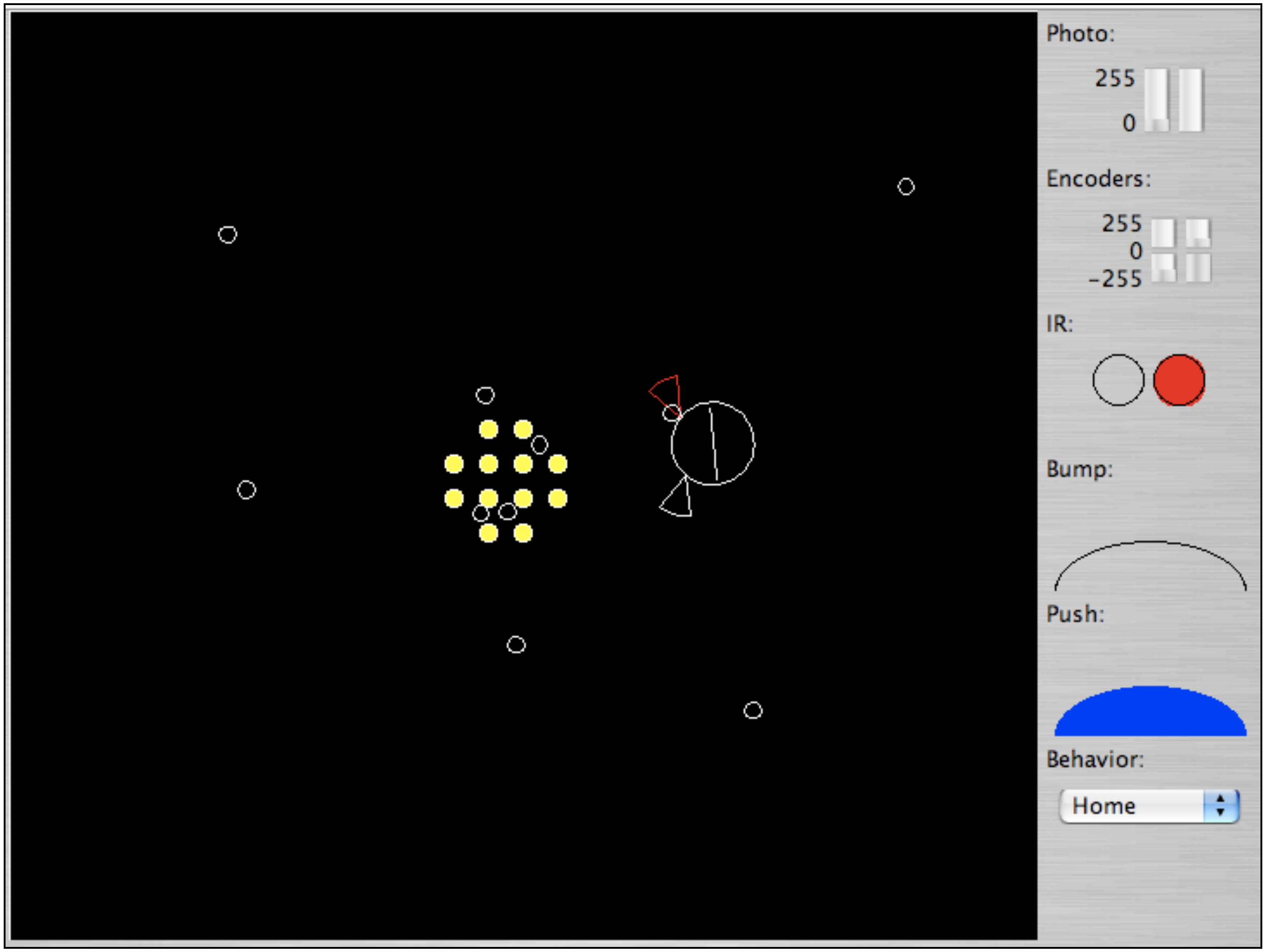
Layering simple behaviors can create much more complex emergent behavior



Arbitration Techniques

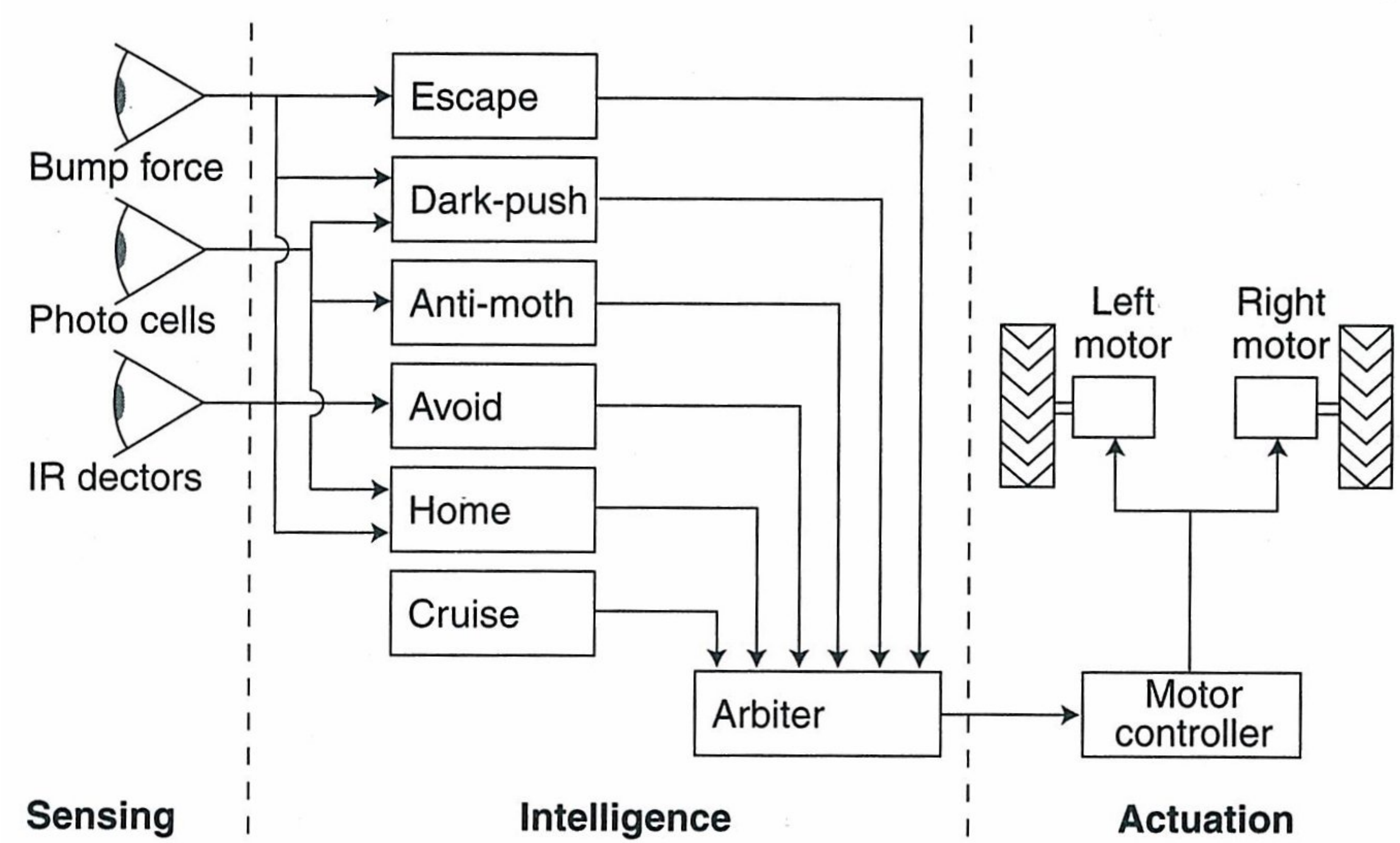
- Fixed priority
- Round-robin
- Random
- Merge messages
- Vote

Bsim robot simulator illustrates emergent approach



http://www.behaviorbasedprogramming.com

Controller architecture for collection simulation

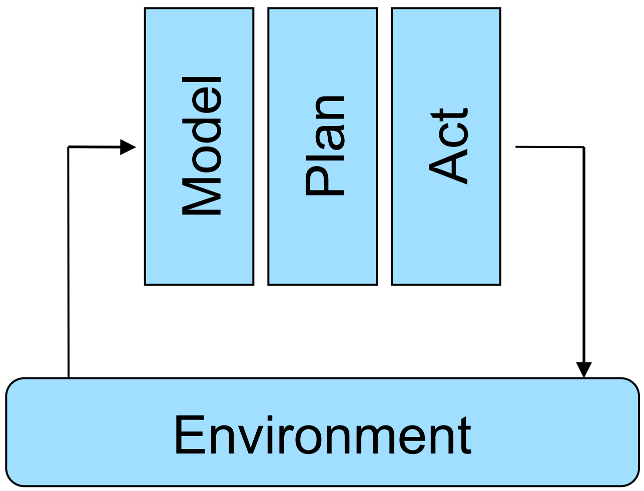


From “Robot Programming: A Practical Guide to Behavior Based Robotics”, Joseph Jones

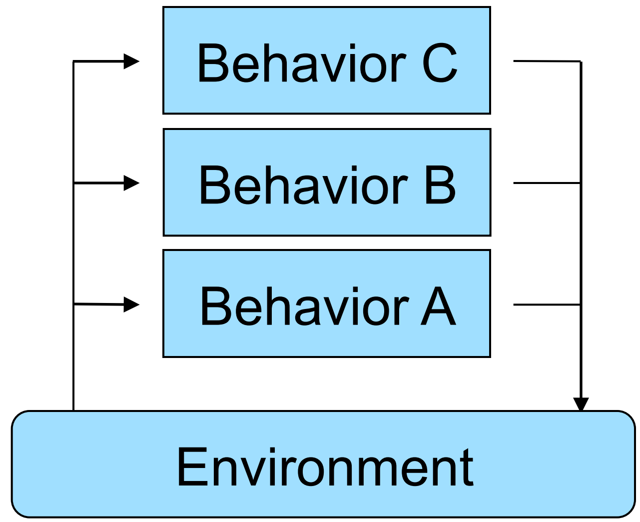
Advantages and disadvantages of the behavioral approach

- Advantages
  - Incremental development is very natural
  - Modularity makes experimentation easier
  - Cleanly handles dynamic environments
- Disadvantages
  - Difficult to judge what robot will actually do
  - No performance or completeness guarantees
  - Debugging can be very difficult

Model-plan-act fuses sensor data, while emergent fuses behaviors



Model-Plan-Act

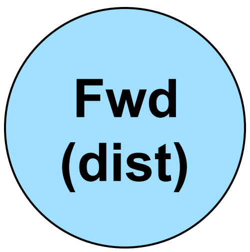


Emergent

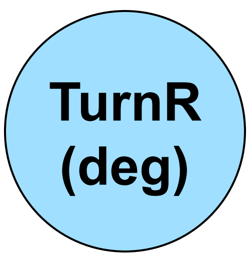
Model-Plan-Act	Emergent
Lots of internal state	Very little internal state
Lots of preliminary planning	No preliminary planning
Fixed plan of behaviors	Layered behaviors

Finite State Machines offer another alternative for combining behaviors

FSMs have some preliminary planning and some state. Some transitions between behaviors are decided statically while others are decided dynamically.

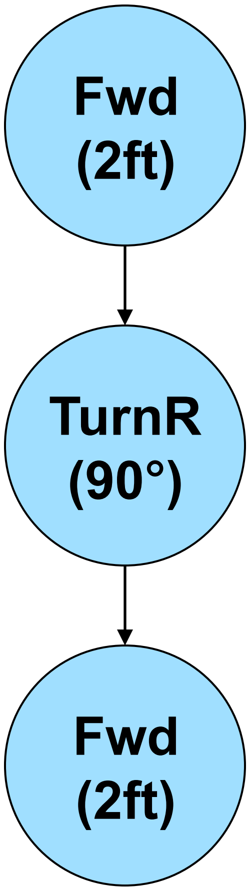


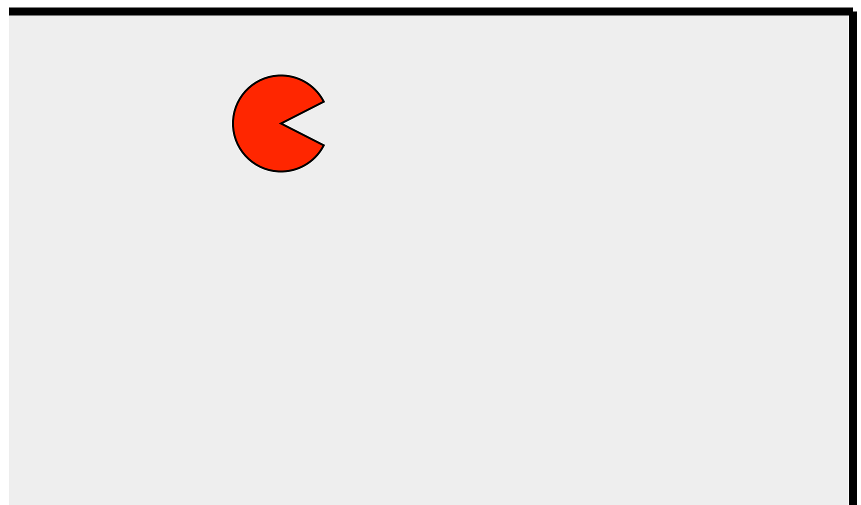
Fwd behavior moves robot straight forward a given distance



TurnR behavior turns robot to the right a given number of degrees

Finite State Machines offer another alternative for combining behaviors





Each state is just a specific behavior instance - link them together to create an open loop control system

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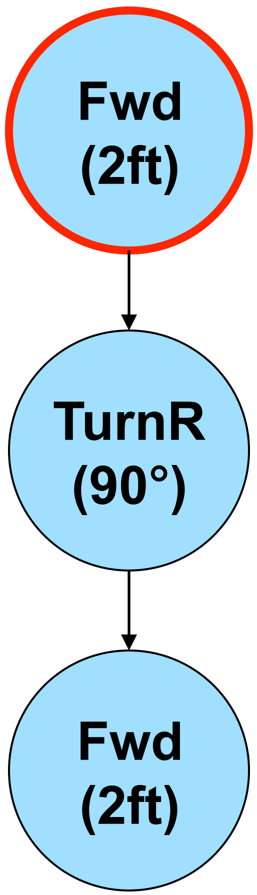

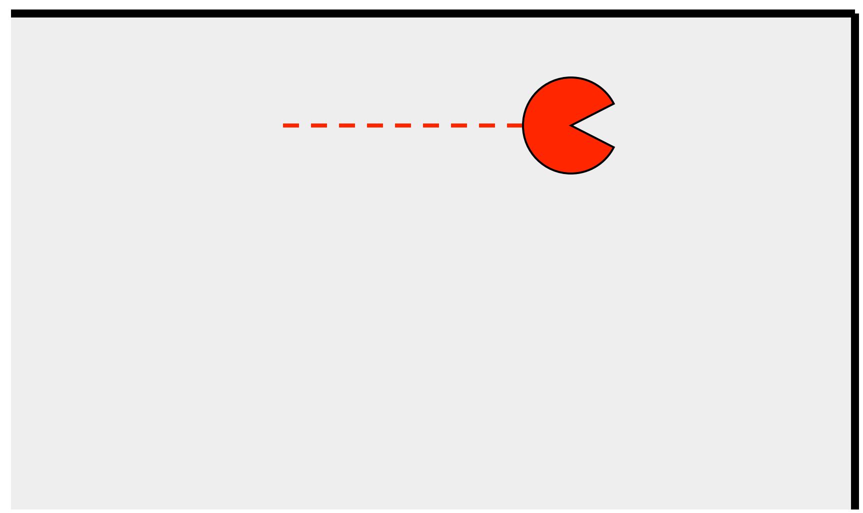

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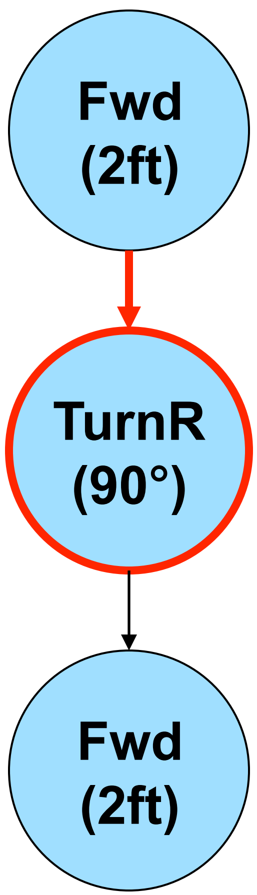

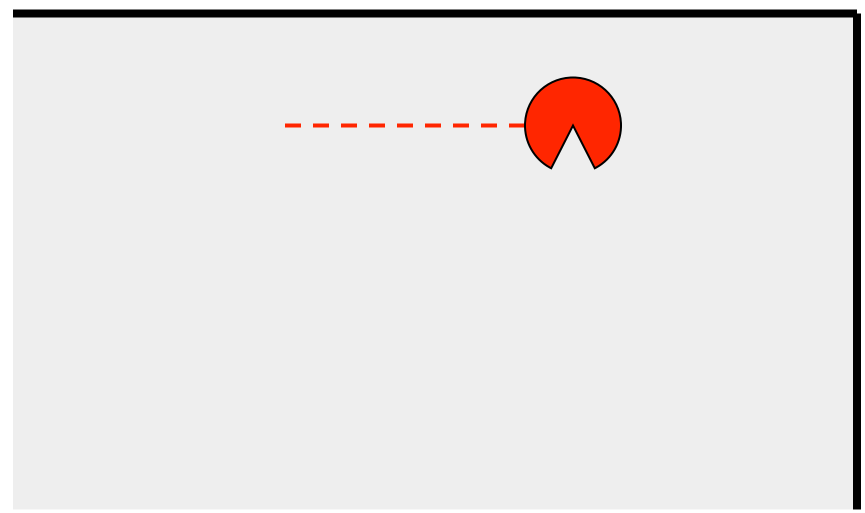

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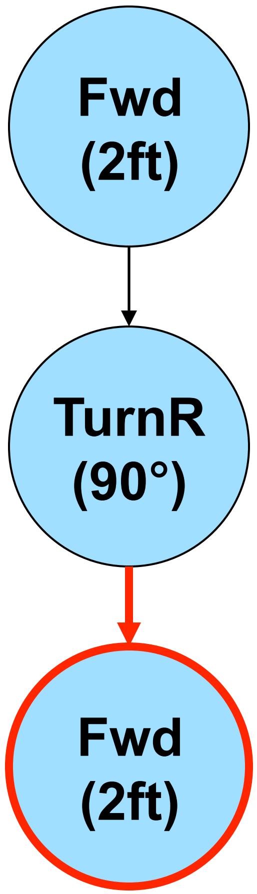

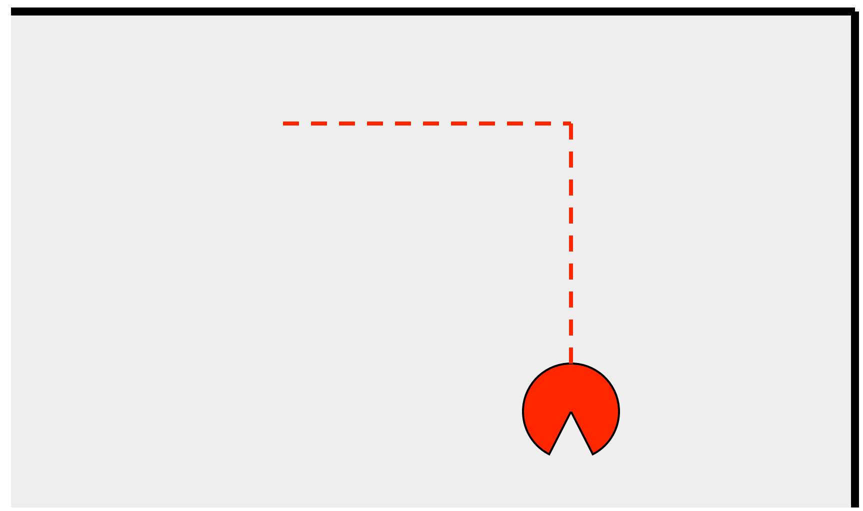

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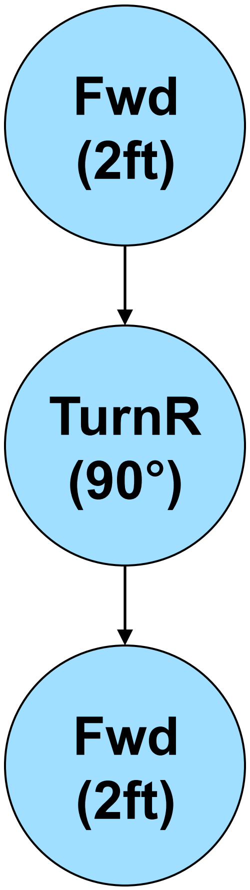
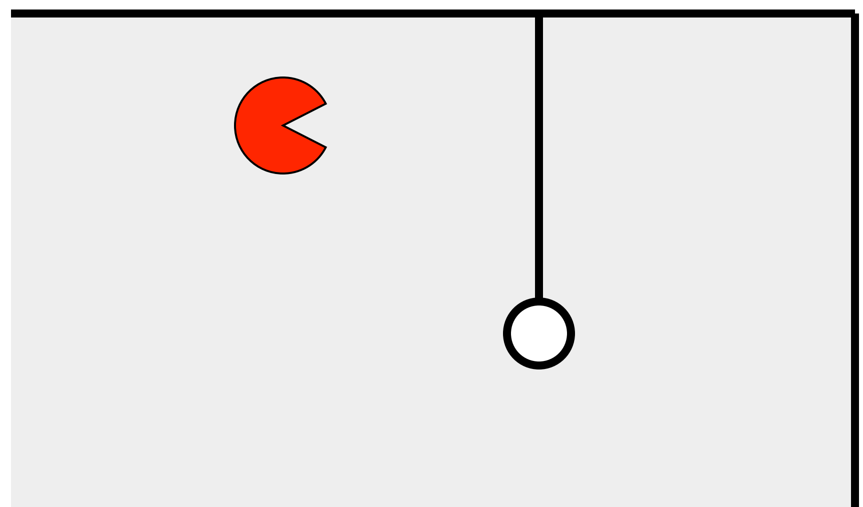
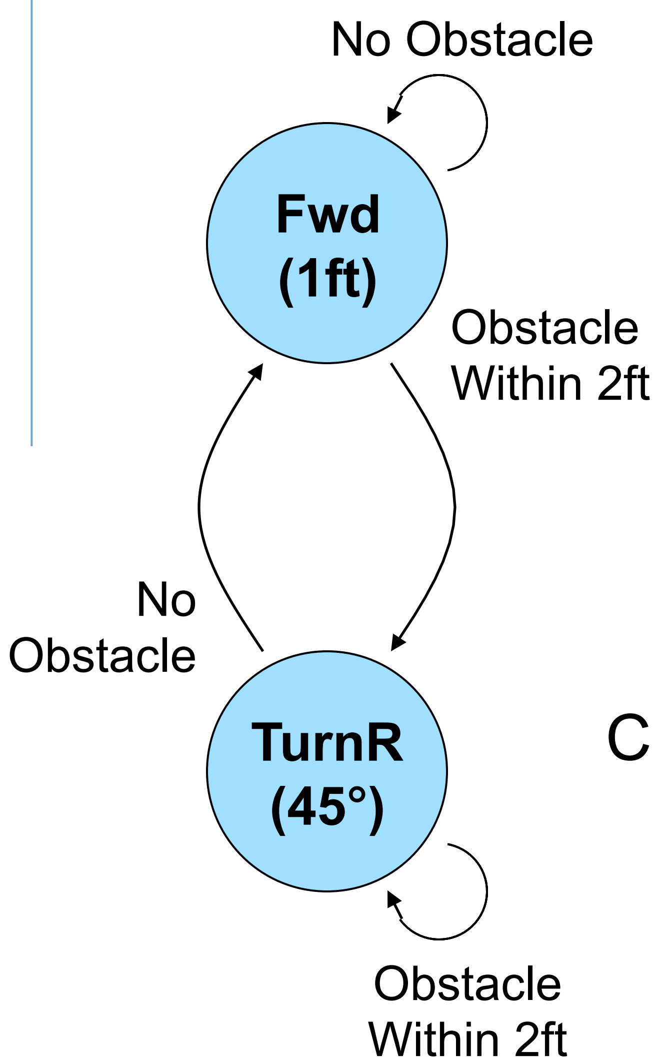
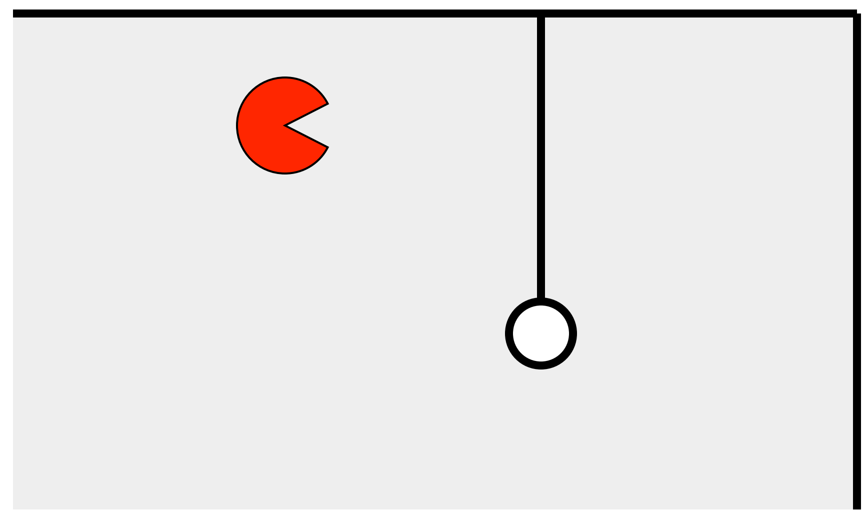




Since the Maslab playing field is unknown, open loop control systems have no hope of success!

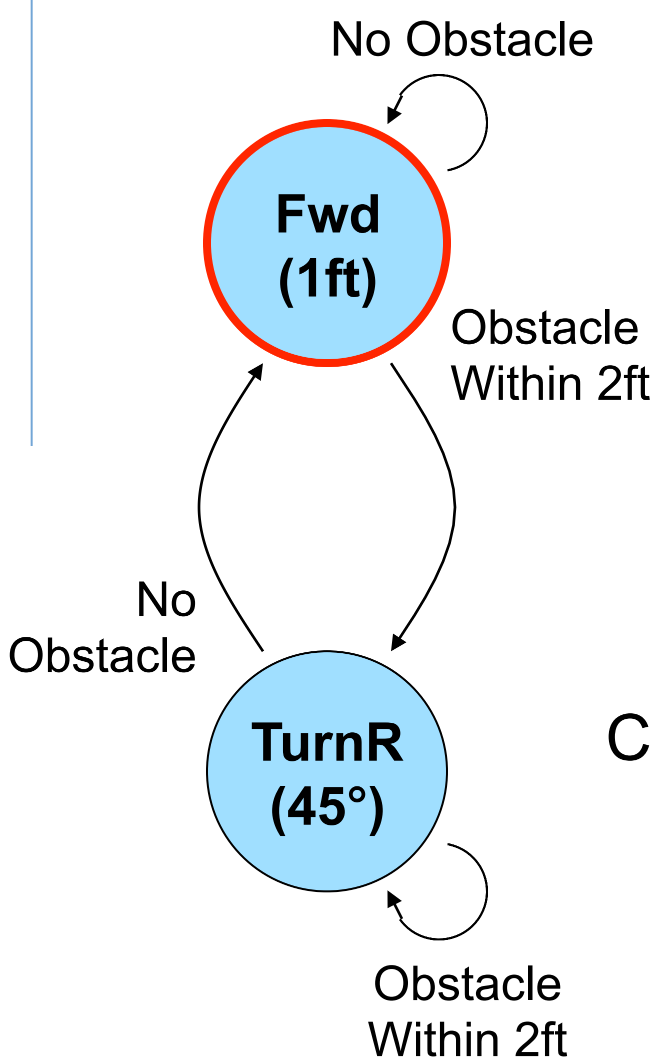
Finite State Machines offer another alternative for combining behaviors

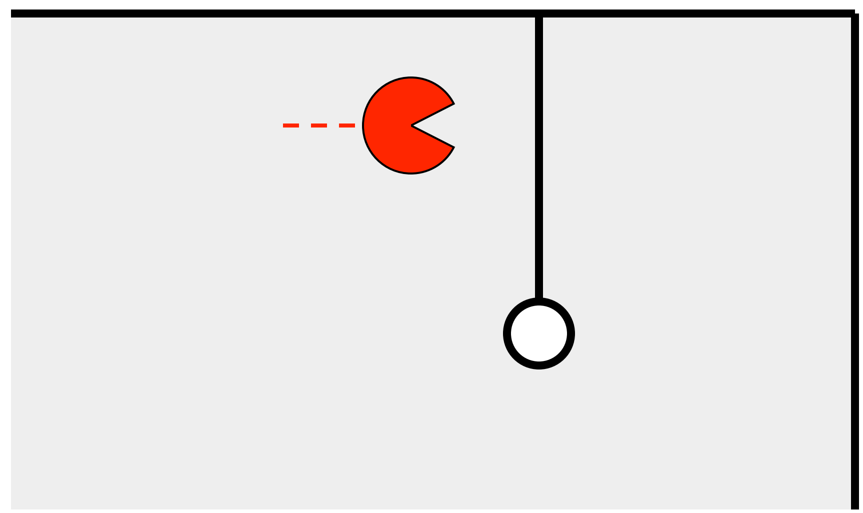




Closed loop finite state machines use sensor data as feedback to make state transitions

Finite State Machines offer another alternative for combining behaviors





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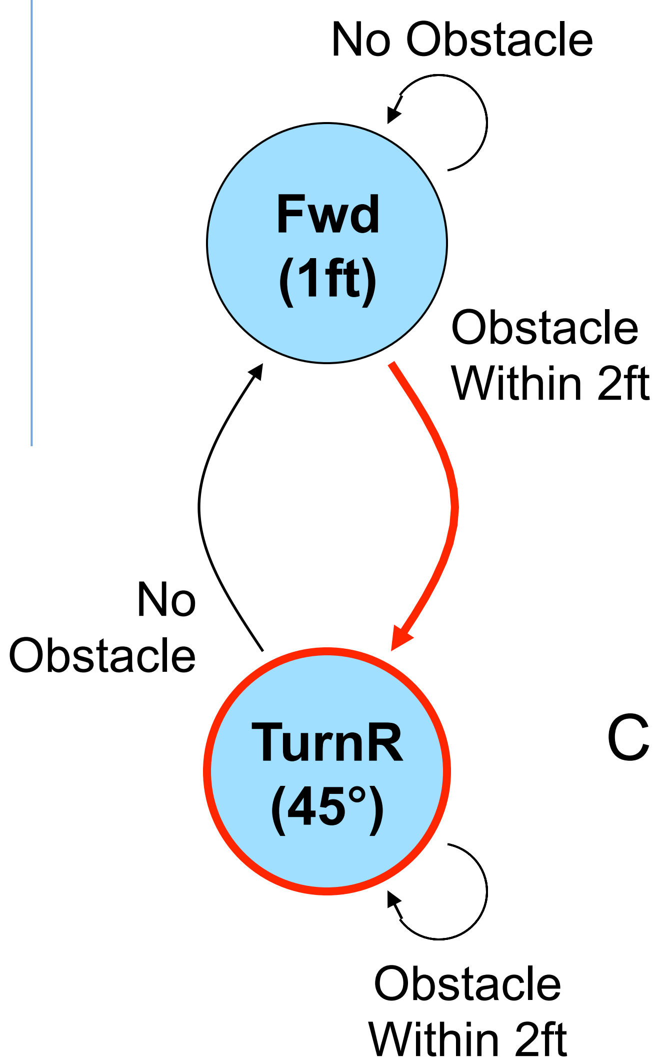

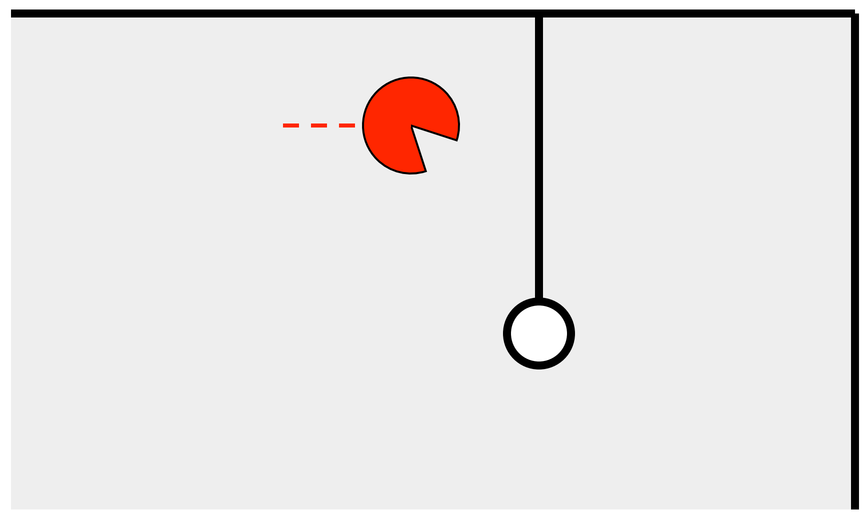

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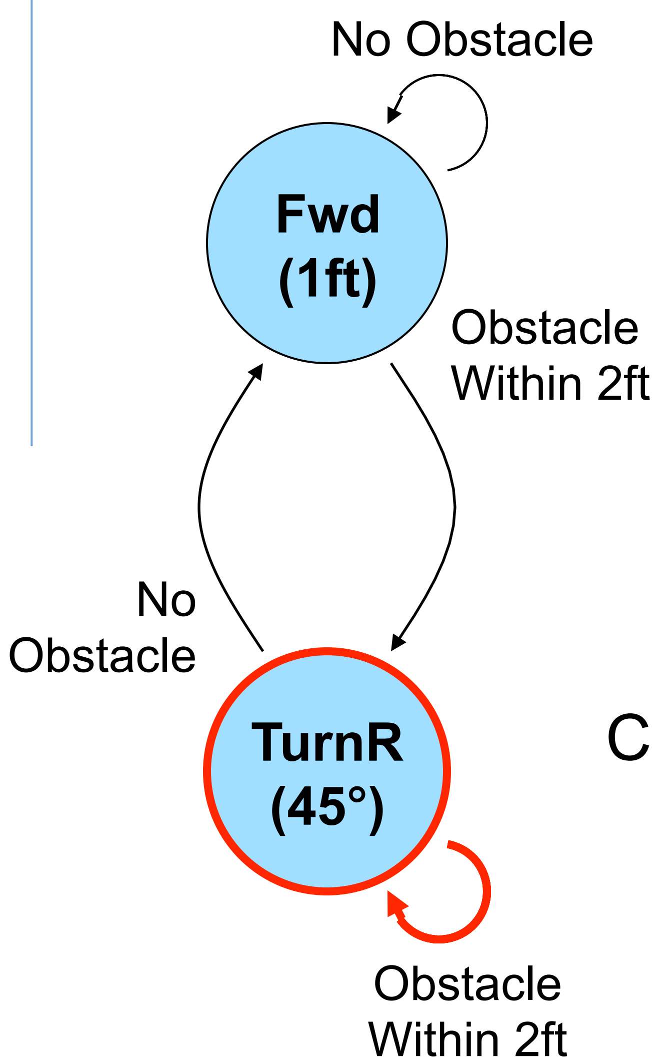

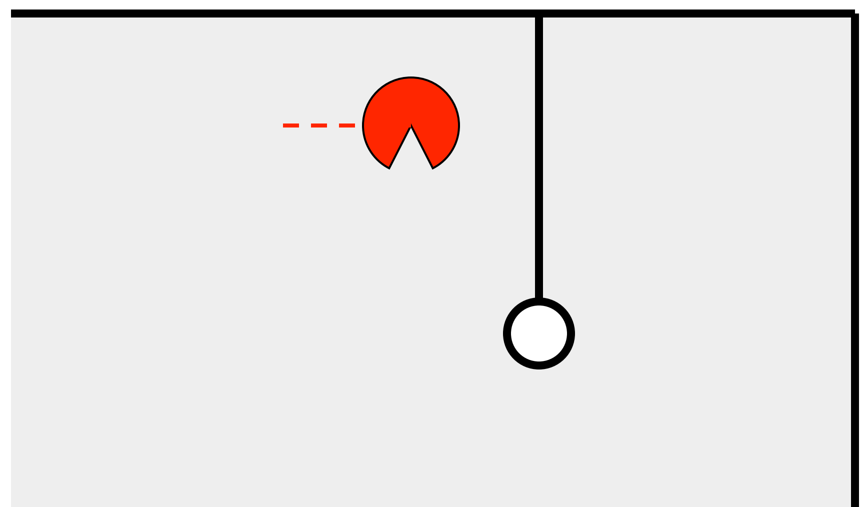

Closed loop finite state machines use sensor data as feedback to make state transitions

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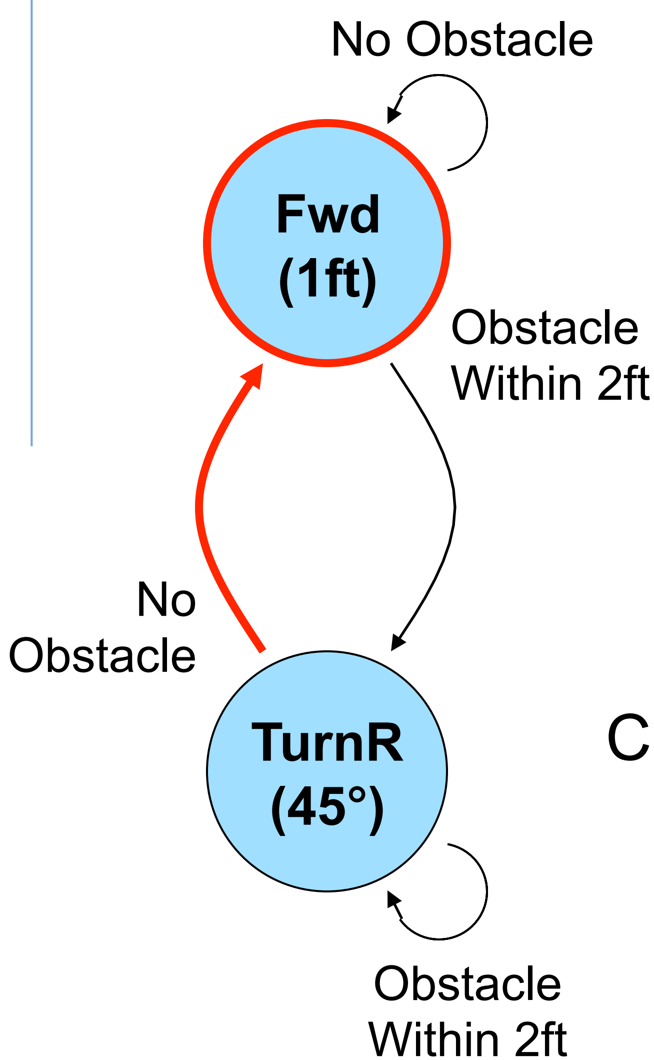
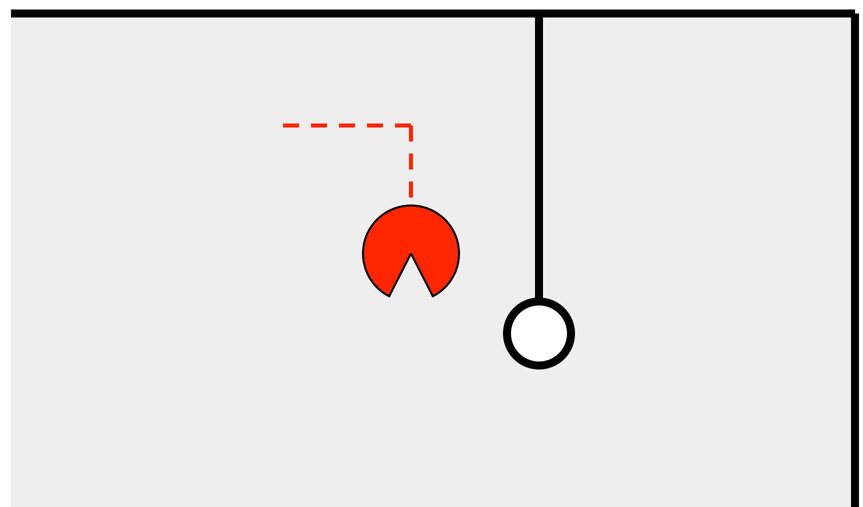
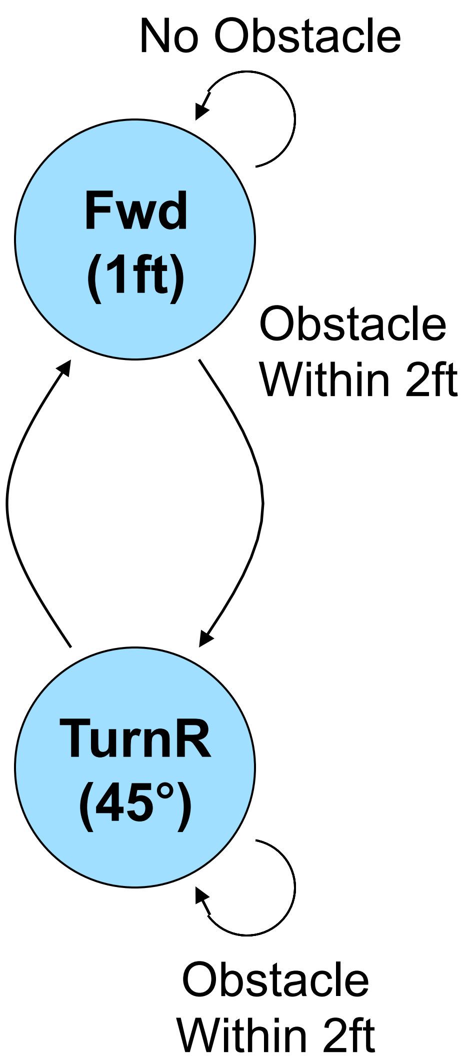




Closed loop finite state machines use sensor data as feedback to make state transitions

Implementing a Finite State Machine in Java



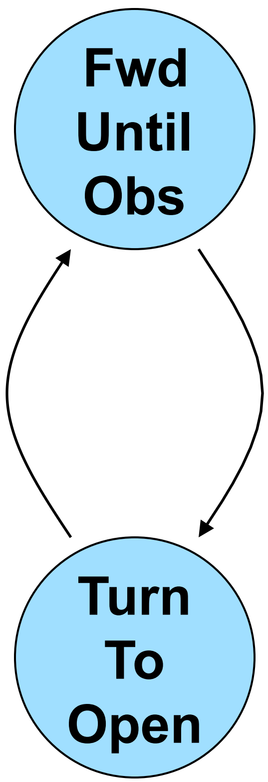

```
switch ( state ) {

  case States.Fwd_1 :
    moveFoward(1);
    if ( distanceToObstacle() < 2 )
      state = TurnR_45;
    break;

  case States.TurnR_45 :
    turnRight(45);
    if ( distanceToObstacle() >= 2 )
      state = Fwd_1;
    break;

}
```

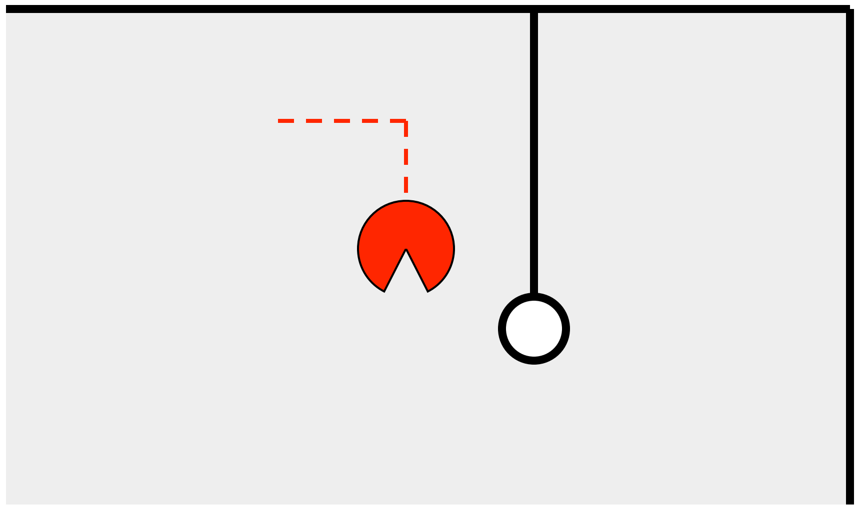
Implementing a FSM in Java

- Implement behaviors as parameterized functions
- Each case statement includes behavior instance and state transition
- Use enums for state variables

```
switch ( state ) {

  case States.Fwd_1 :
    moveFoward(1);
    if ( distanceToObstacle() < 2 )
      state = TurnR_45;
    break;

  case States.TurnR_45 :
    turnRight(45);
    if ( distanceToObstacle() >= 2 )
      state = Fwd_1;
    break;

}
```

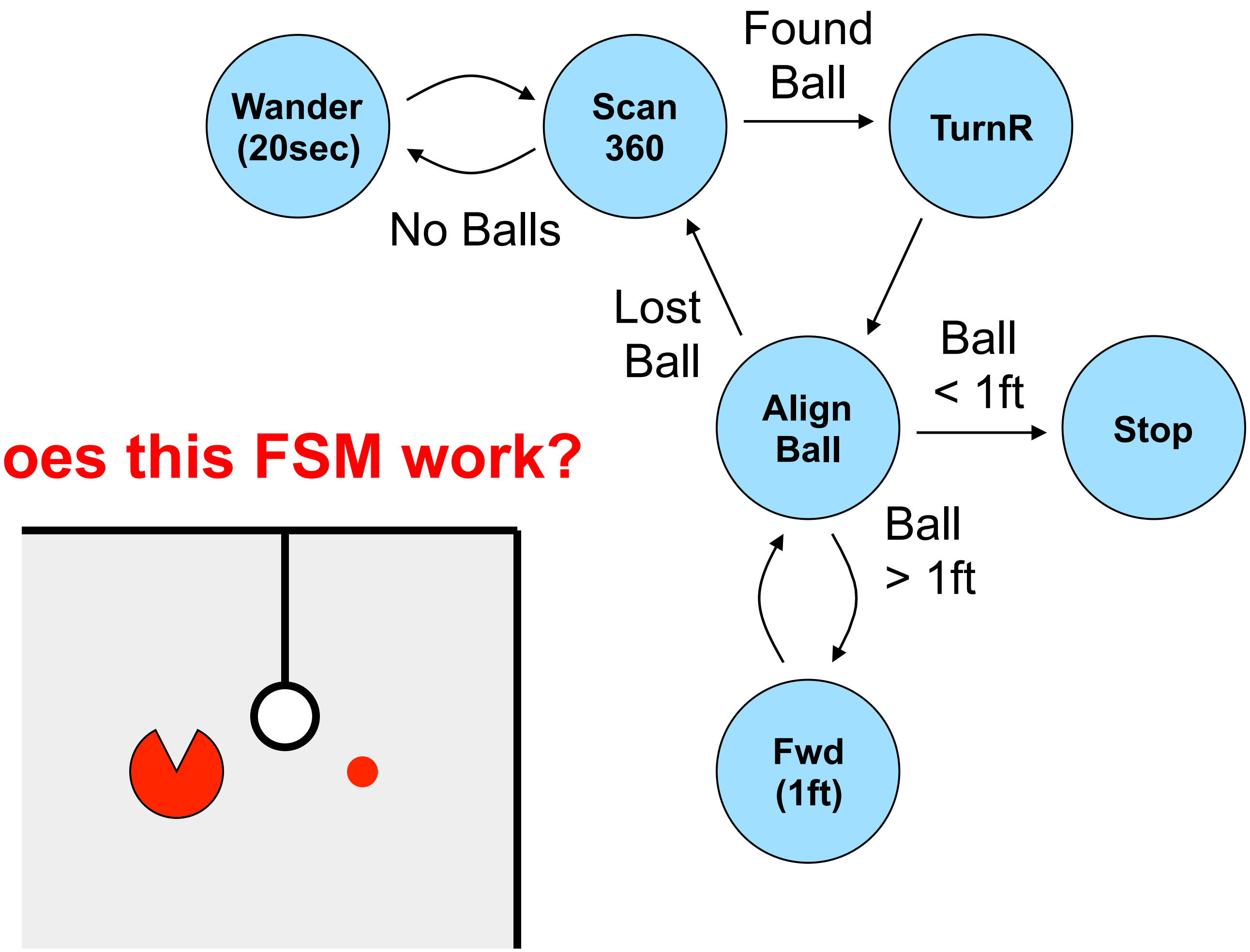
Finite State Machines offer another alternative for combining behaviors





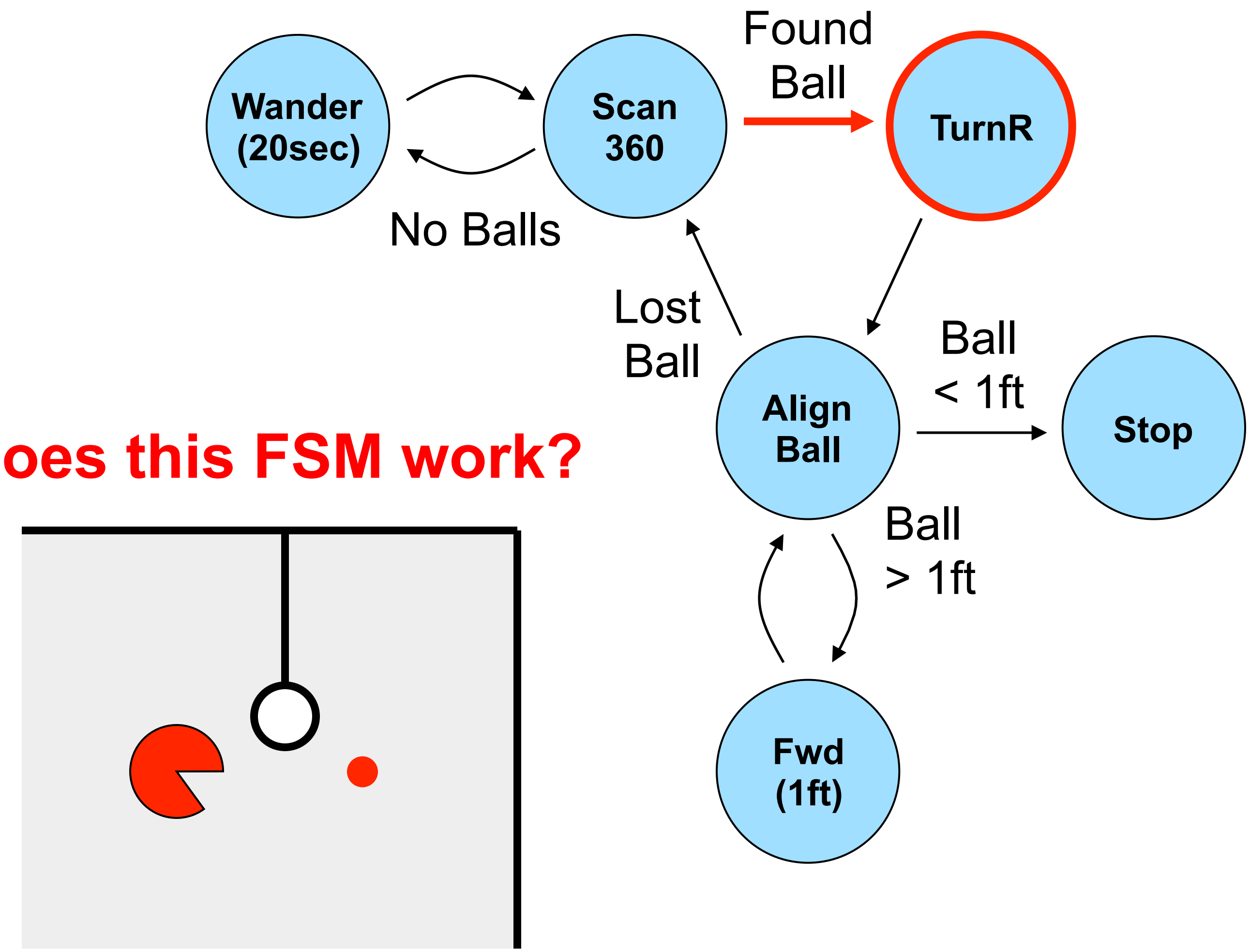
Can also fold closed loop feedback into the behaviors themselves

Simple finite state machine to locate red balls



Does this FSM work?

Simple finite state machine to locate red balls



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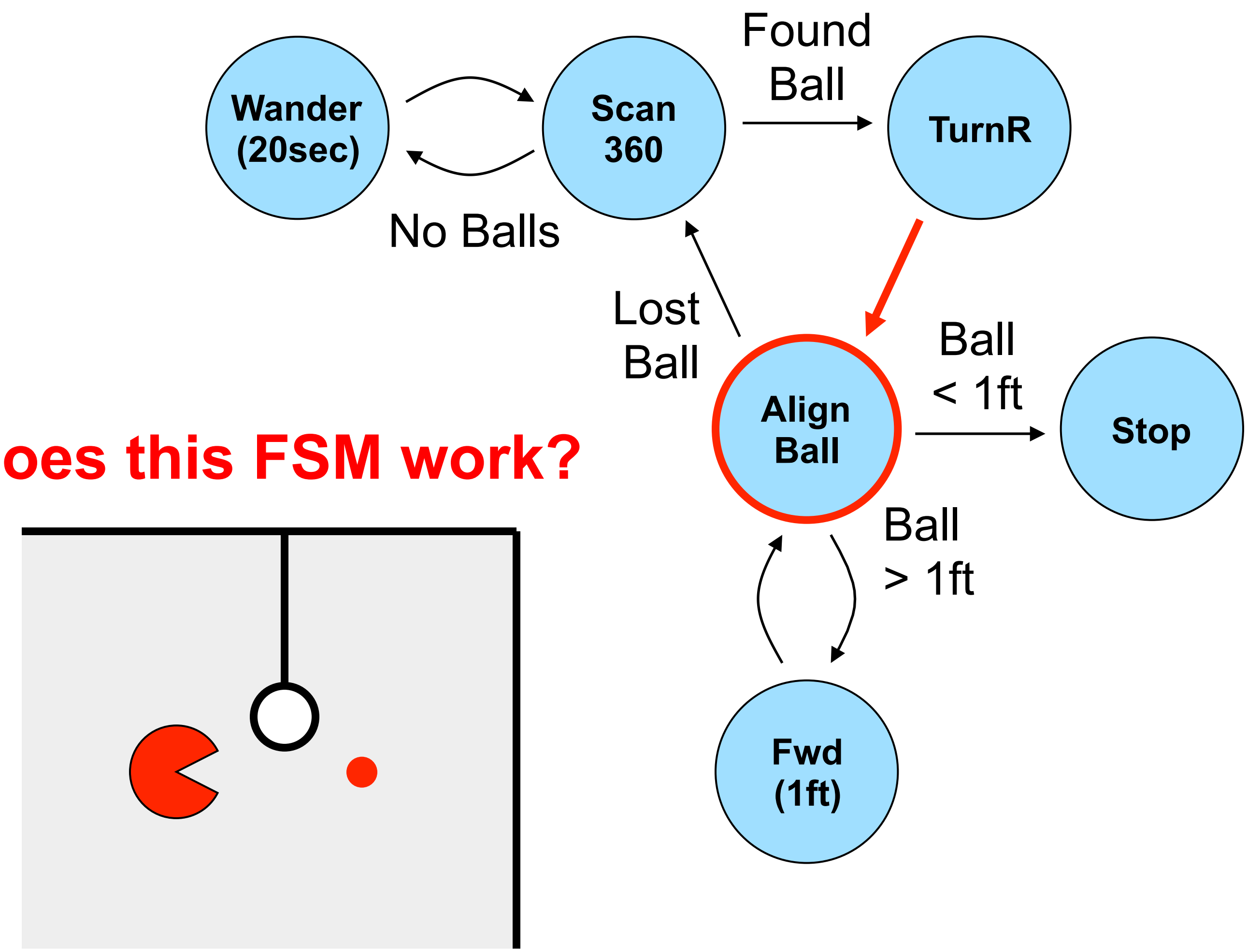

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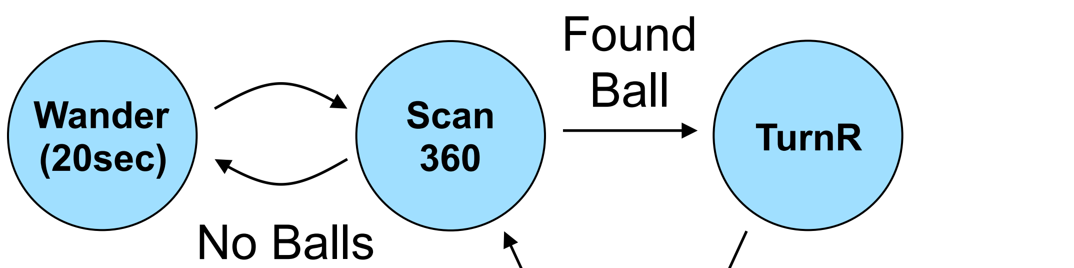
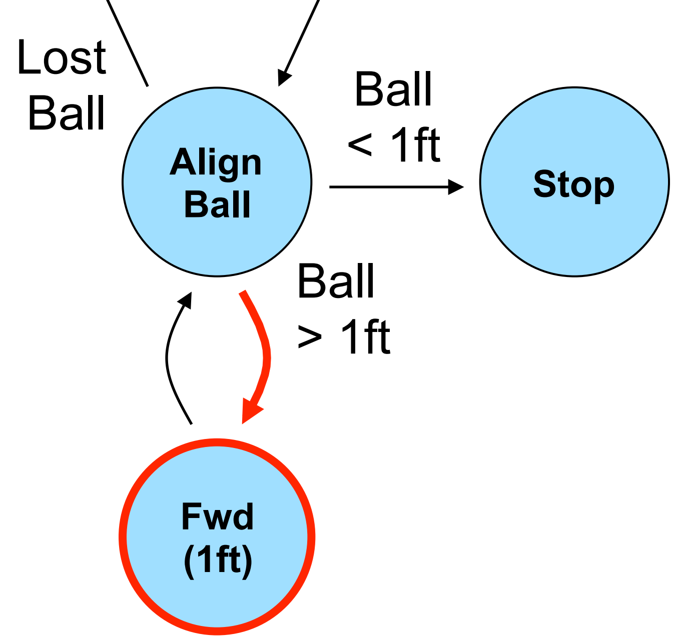

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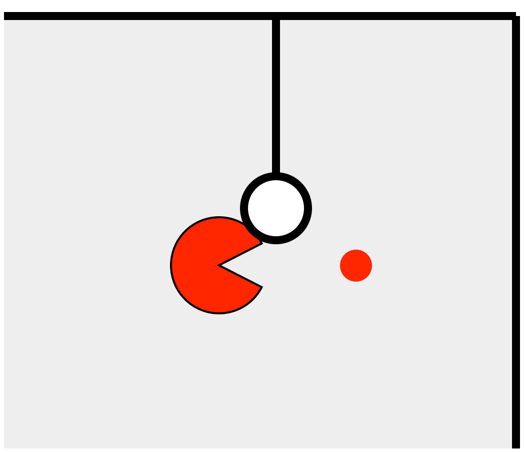

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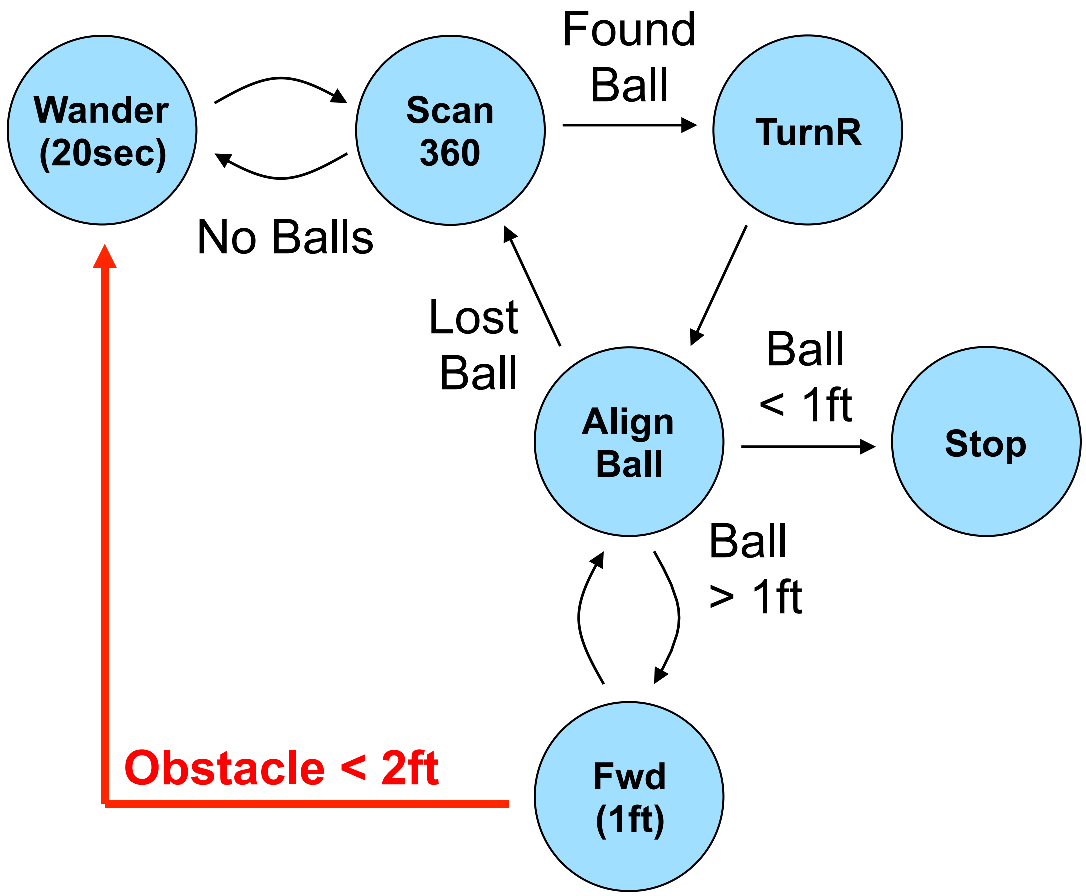
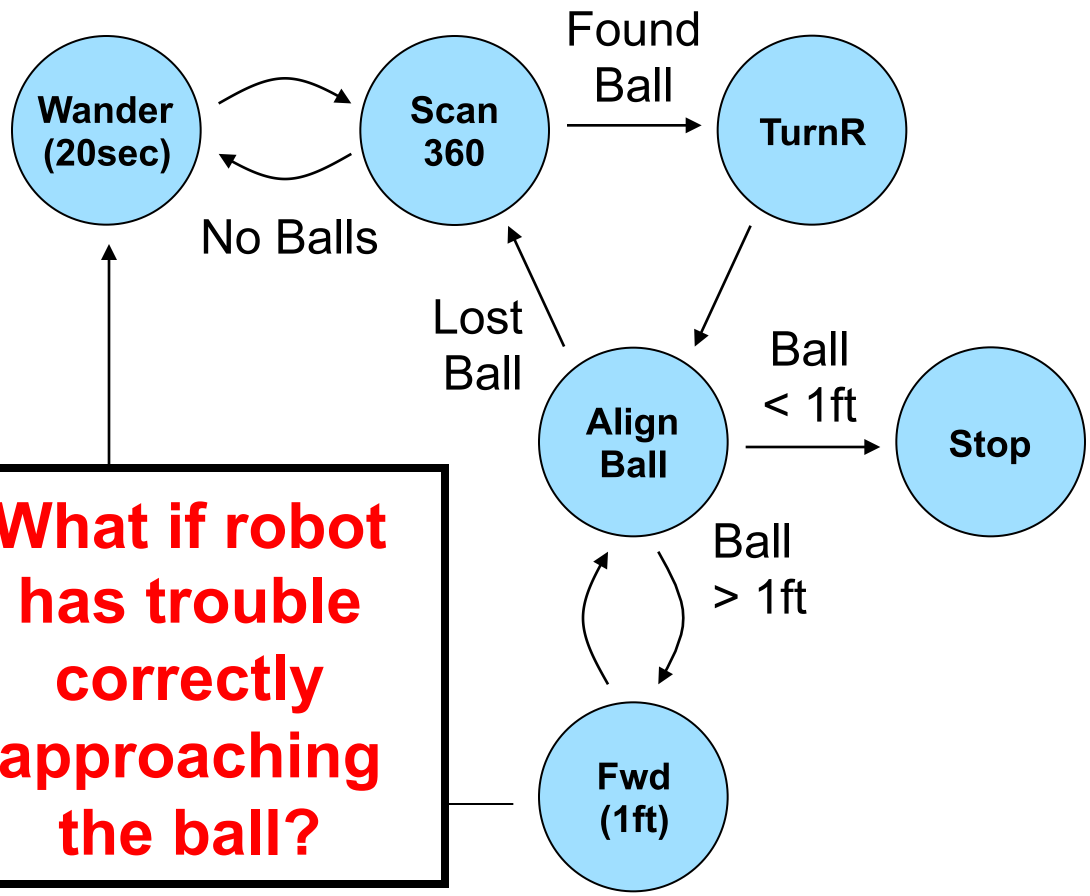
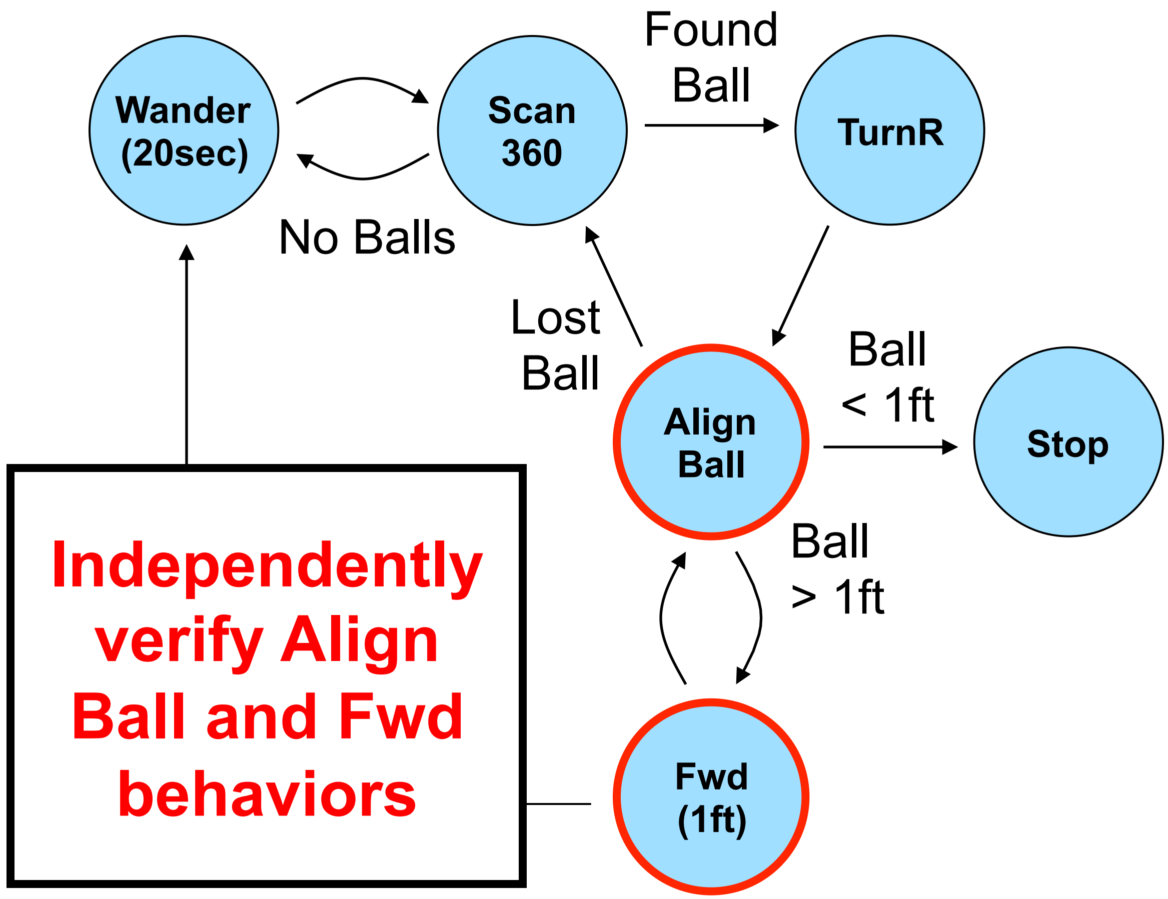


To debug a FSM control system verify behaviors and state transitions

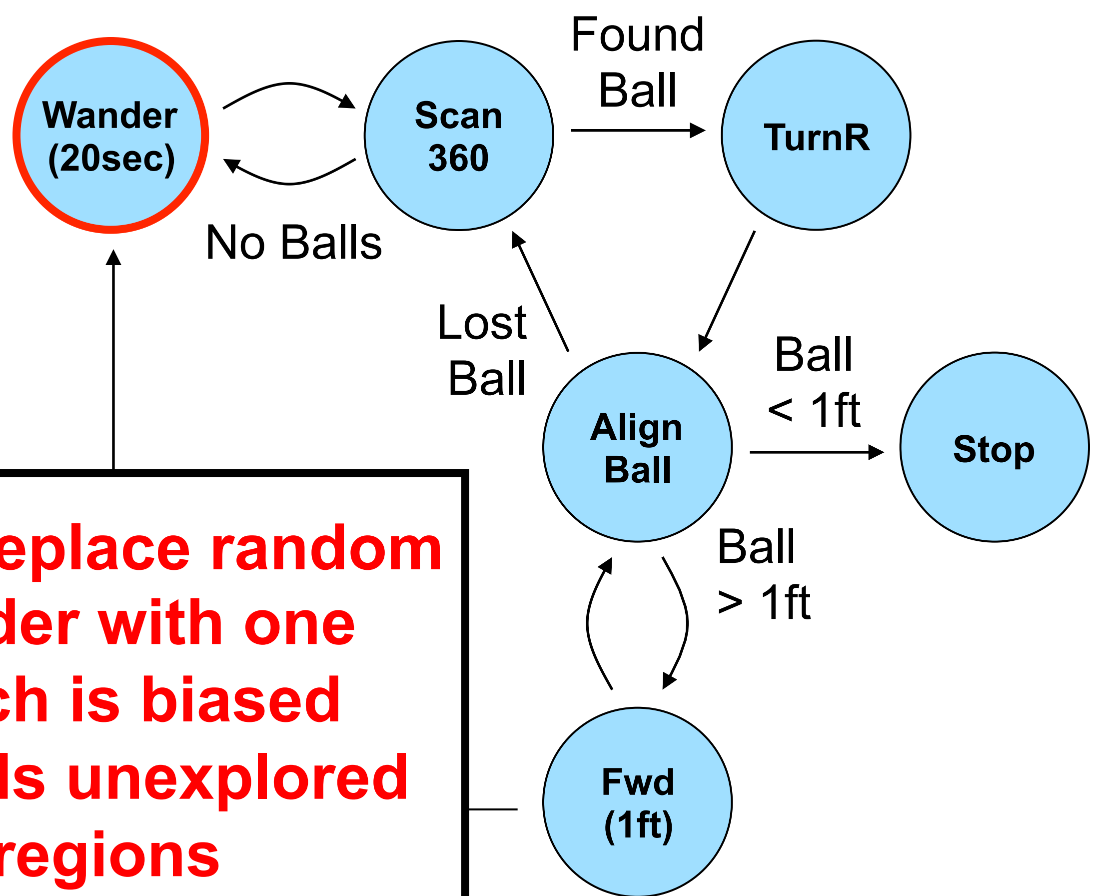


What if robot has trouble correctly approaching the ball?

To debug a FSM control system verify behaviors and state transitions



Improve FSM control system by replacing a state with a better implementation



Could replace random wander with one which is biased towards unexplored regions

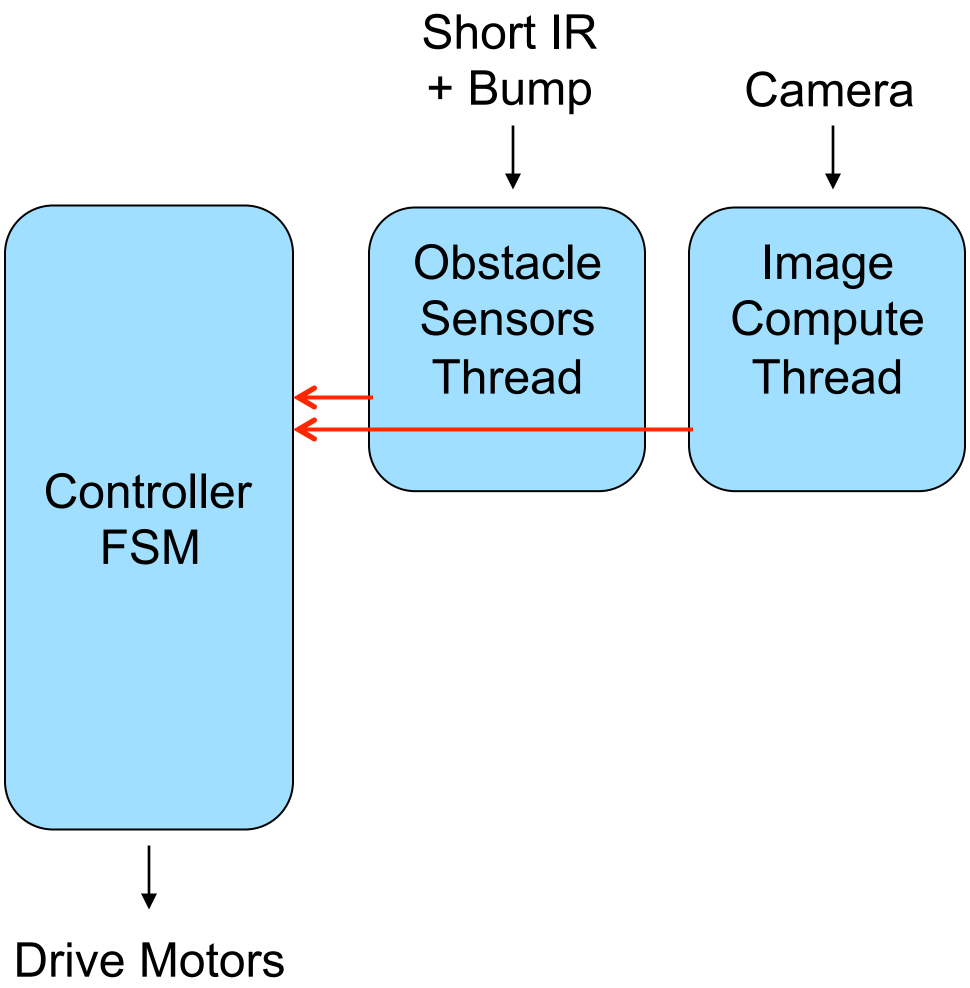
Improve FSM control system by replacing a state with a better implementation

What about integrating camera code into wander behavior so robot is always looking for red balls?

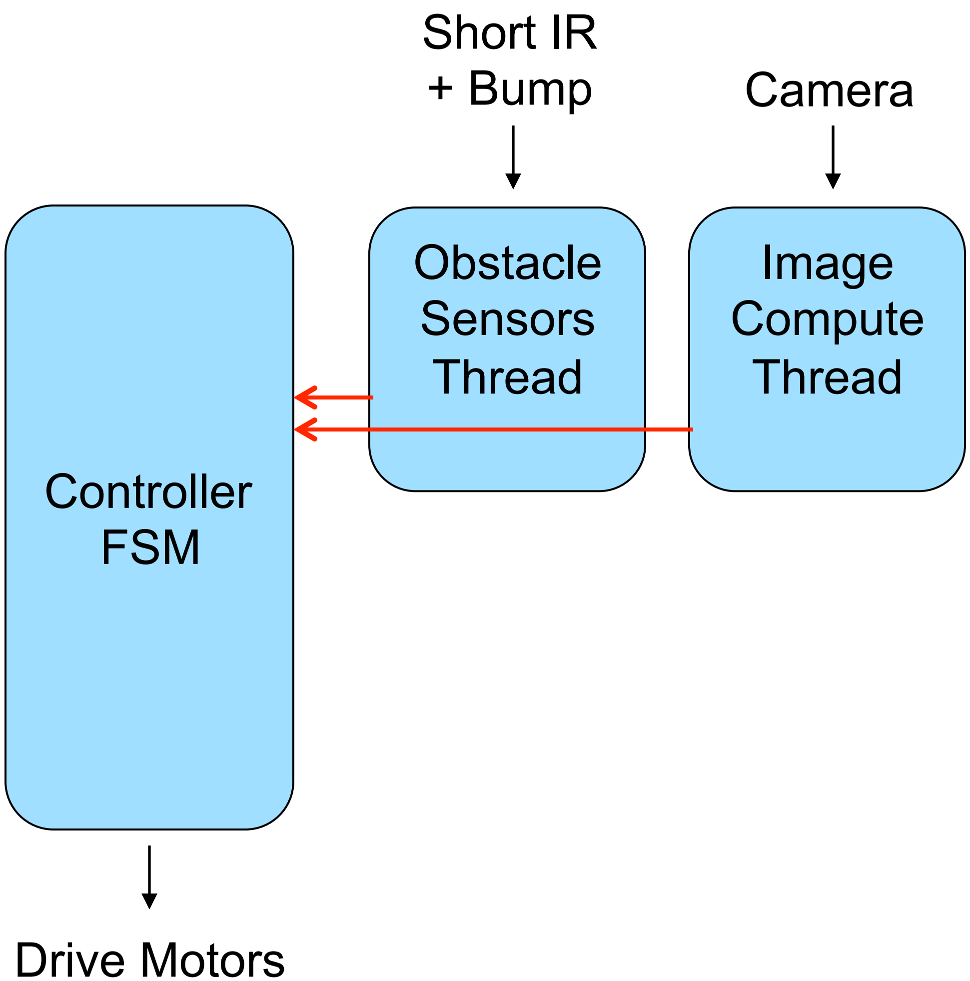
- Image processing is time consuming so might not check for obstacles until too late
- Not checking camera when rotating
- Wander behavior begins to become monolithic

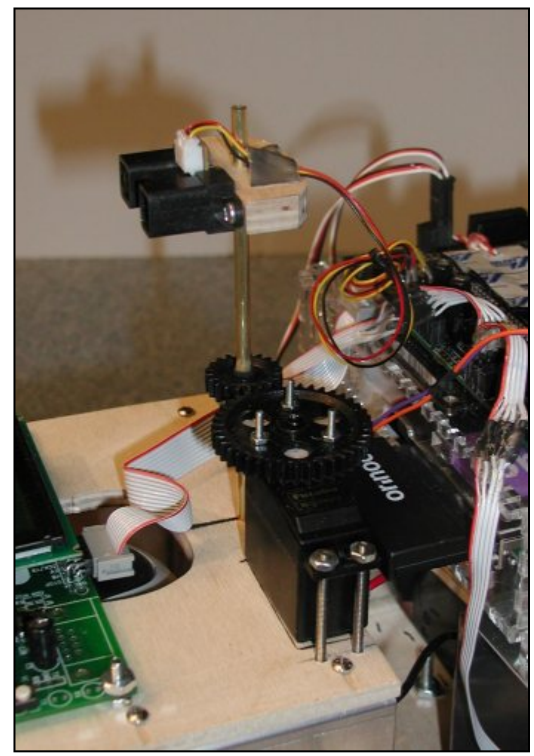
```
ball = false
turn both motors on
while ( !timeout and !ball )
  capture and process image
  if ( red ball ) ball = true

  read IR sensor
  if ( IR < thresh )
    stop motors
    rotate 90 degrees
    turn both motors on
  endif

endwhile
```

Multi-threaded finite state machine control systems

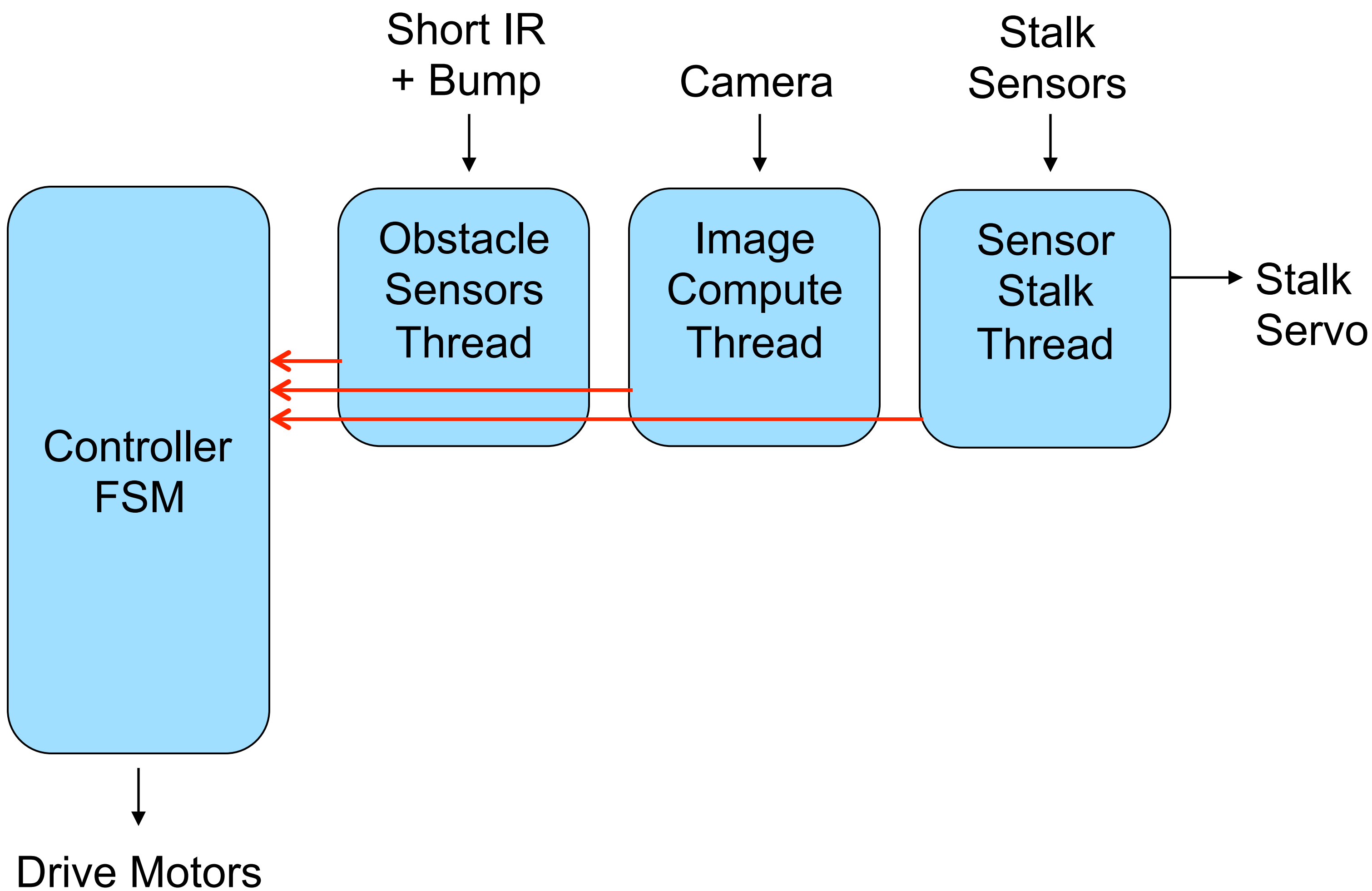


Multi-threaded finite state machine control systems

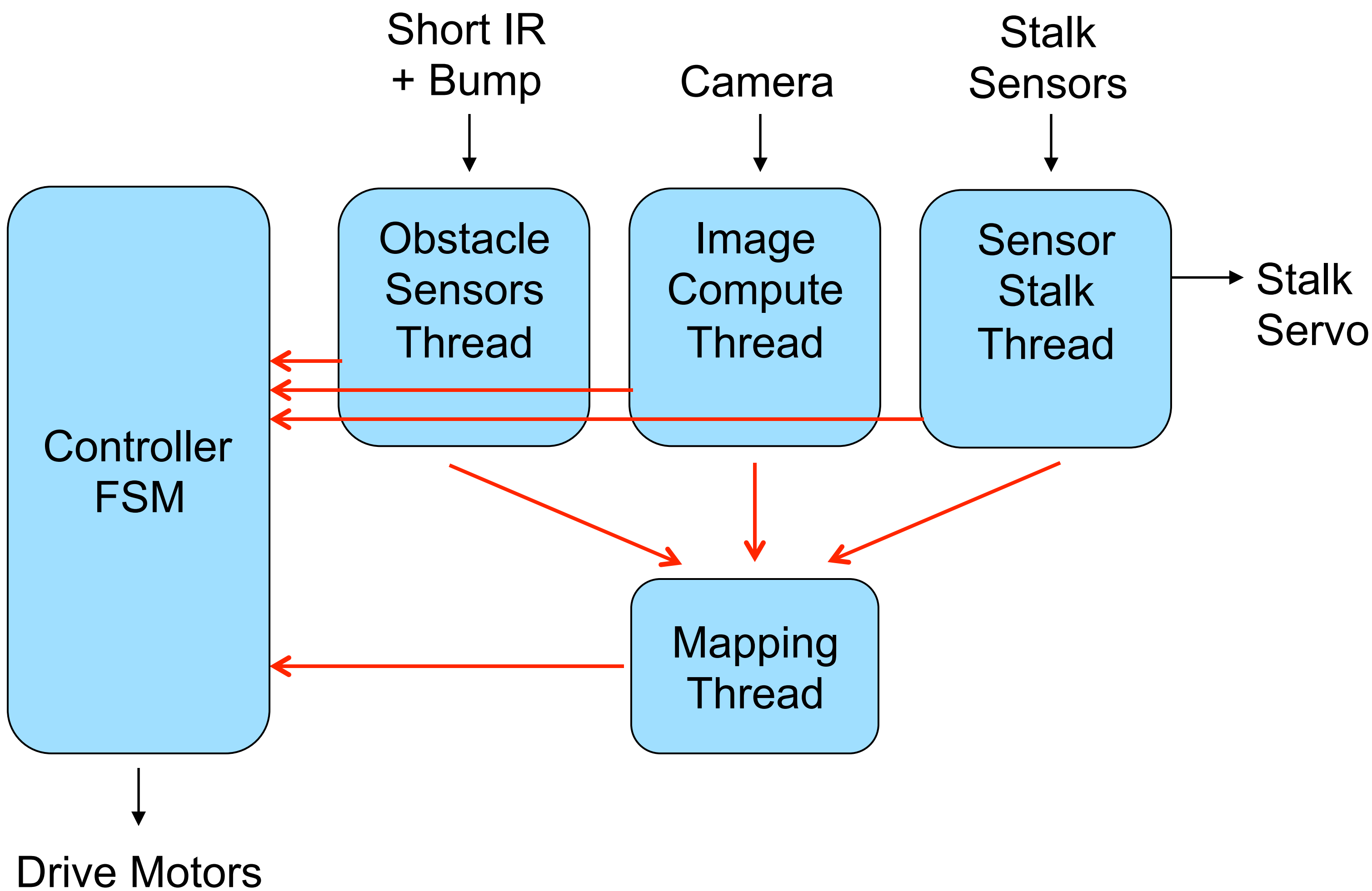




Multi-threaded finite state machine control systems



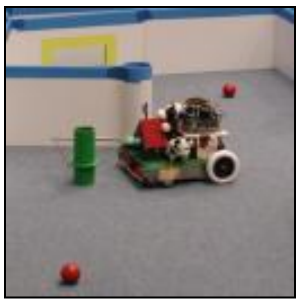
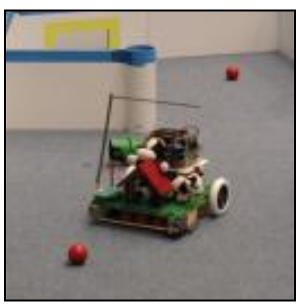
Multi-threaded finite state machine control systems



FSMs in Maslab

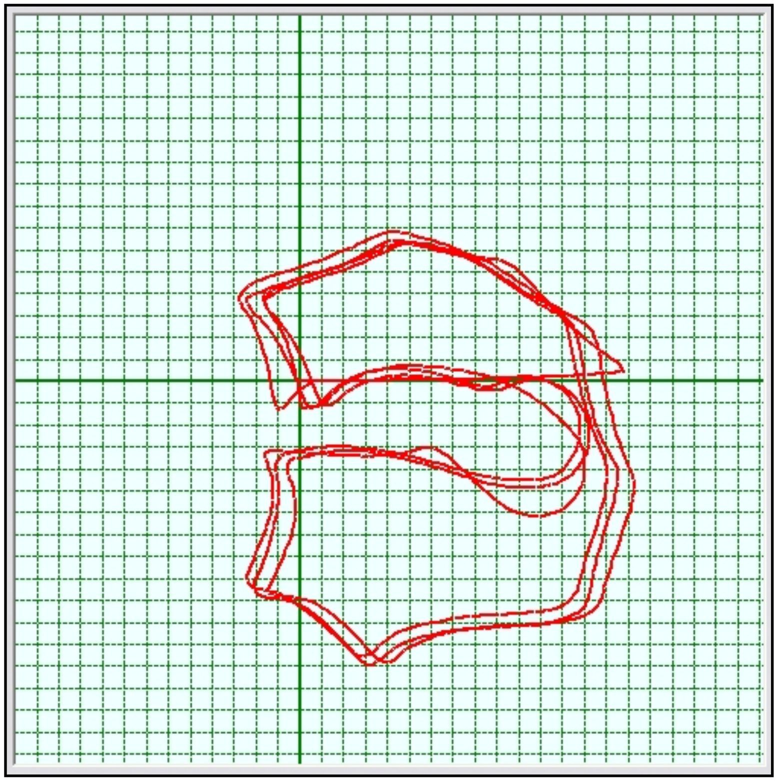
Finite state machines can combine the model-plan-act and emergent approaches and are a good starting point for your Maslab robotic control system

Outline

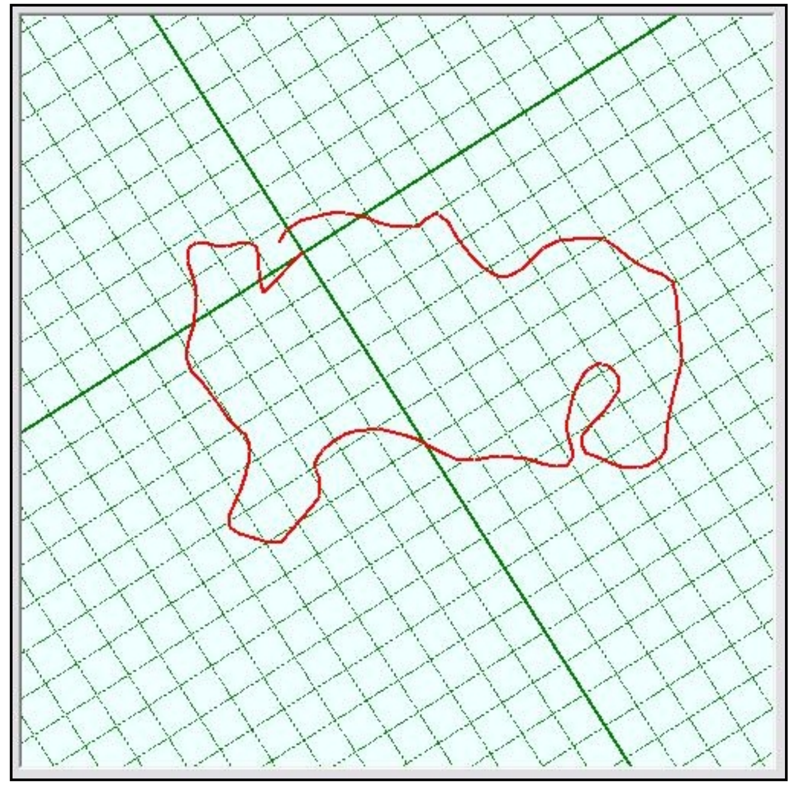




- High-level control system paradigms
  - Model-Plan-Act Approach
  - Behavioral Approach
  - Finite State Machine Approach
- Low-level control loops
  - PID controller for motor velocity
  - PID controller for robot drive system
- **Examples from past years**

Team 15 in 2005 used a map-plan-act approach (well at least in spirit)

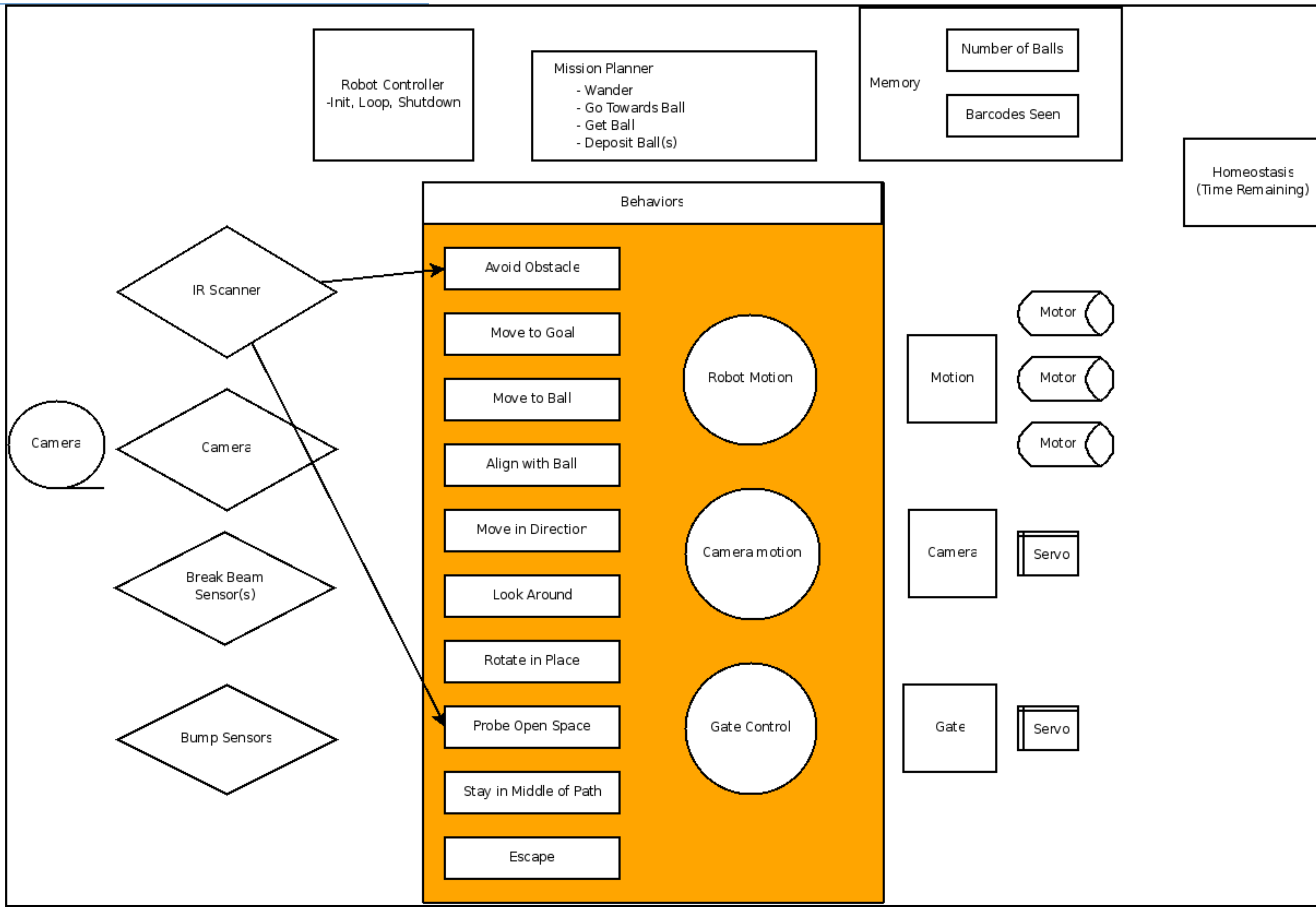


Multiple runs around
a mini-playing field

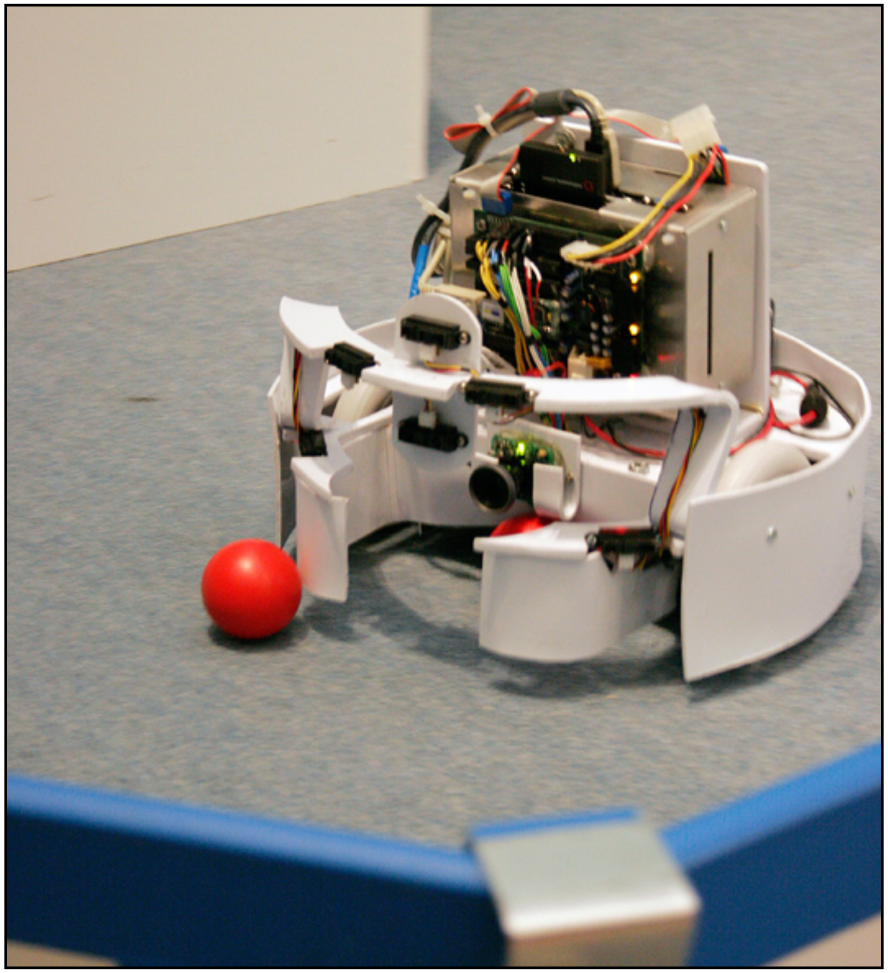


Odometry data from
exploration round of contest

Team 14 in 2008 used an FSM-like architecture with reactive behaviors

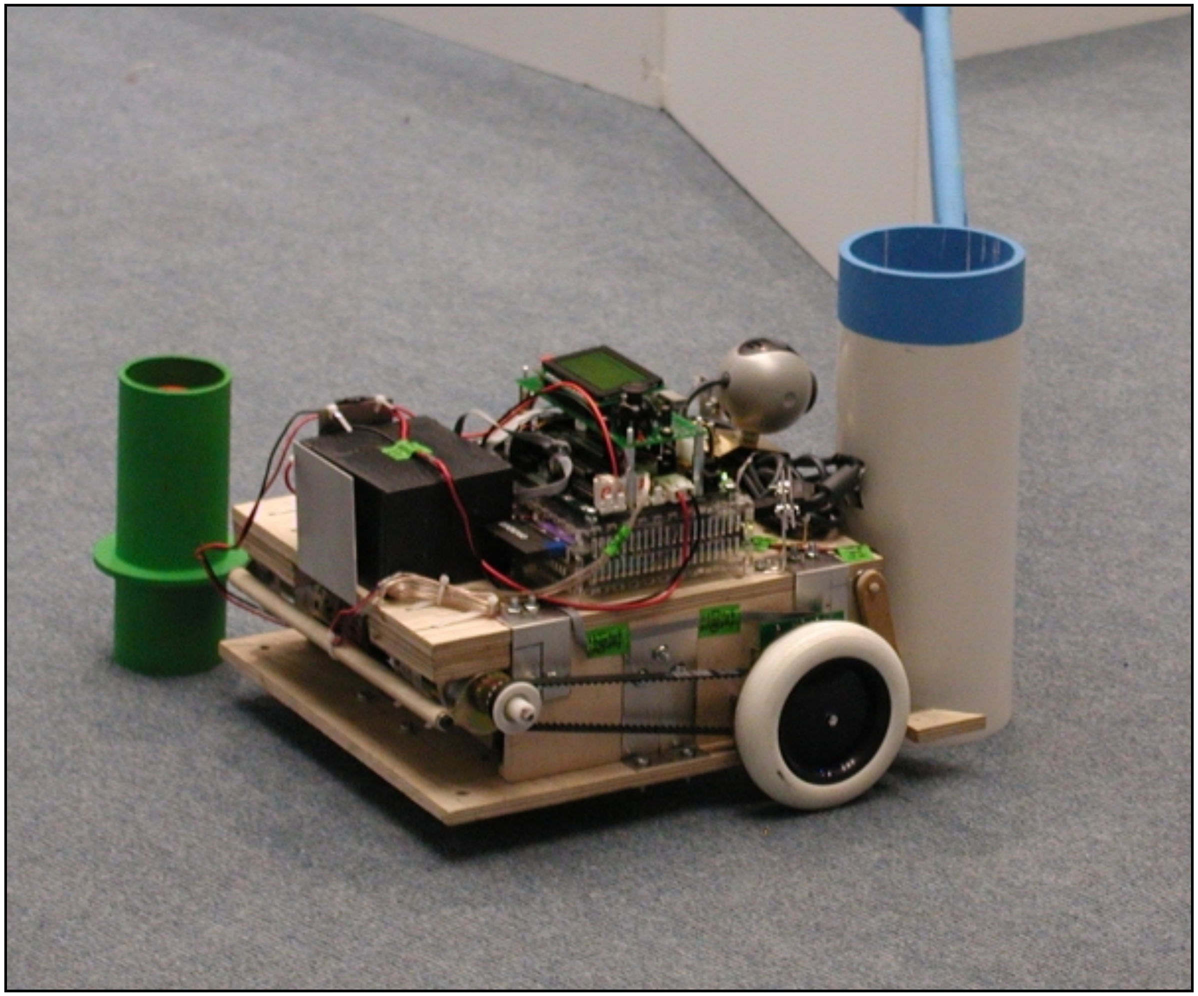


Team 4 in 2005 used an emergent approach with four layered behaviors



- **Boredom:** If image doesn't change then move randomly
- **ScoreGoals:** If image contains a goal the drive straight for it
- **ChaseBalls:** If image contains a ball then drive towards ball
- **Wander:** Turn away from walls or move to large open areas

Team 12 in 2004 learned the hard way how hard building a controller can be!



Take Away Points

- You cannot just hack together a robot controller, you must **design** a robot controller
- Design simple, module behaviors and then decide how to compose these behaviors to achieve the desired task
- Simple **finite state machines** make a solid starting point for your Maslab control systems
- Integrating **feedback** into your control system "closes the loop" and is essential for creating robust robots