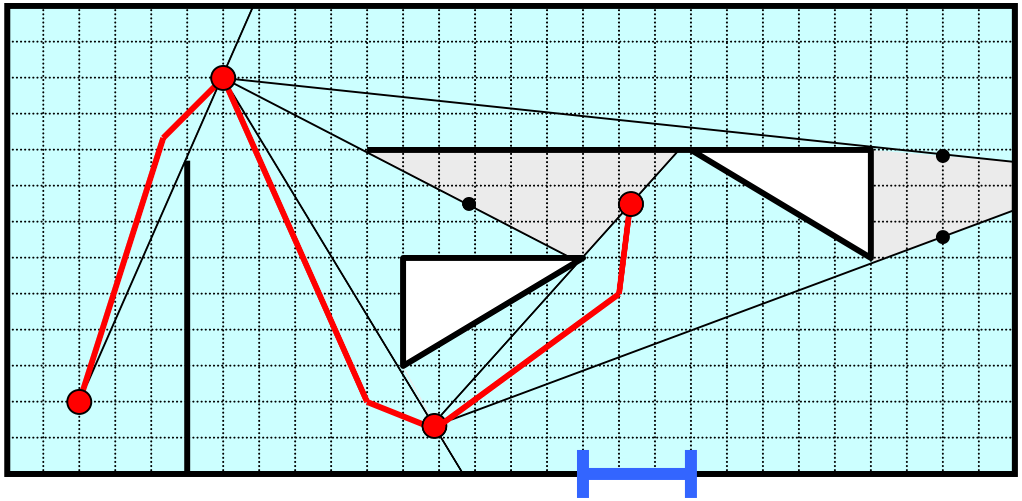
Control for Mobile Robots

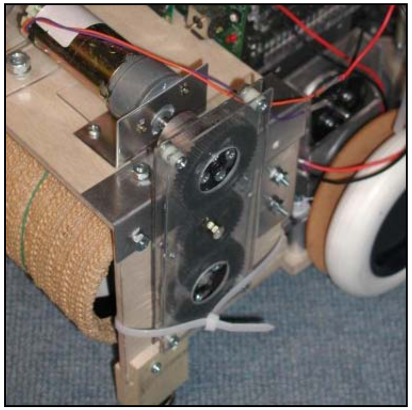


Christopher Batten

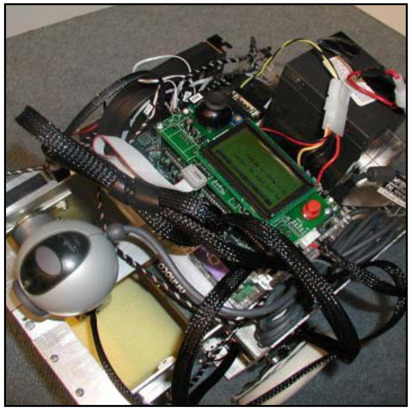
Maslab IAP Robotics Course
January 7, 2005

Building a control system for a mobile robot can be very challenging

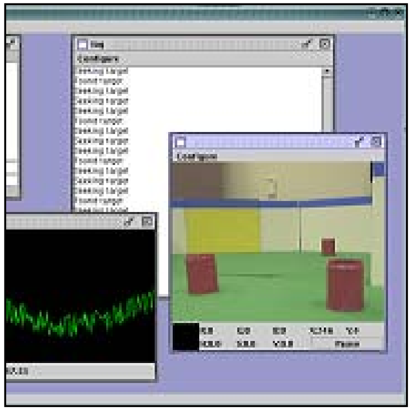
Mobile robots are very complex and involve many interacting components



Mechanical



Electrical



Software

Your control system must integrate these components so that your robot can achieve the desired goal

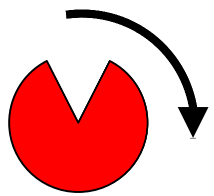
Building a control system for a mobile robot can be very challenging

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

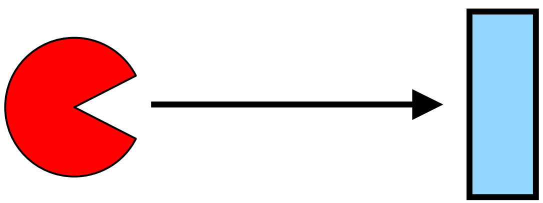
- How will you debug and test your robot?
- What are the performance requirements?
- Can you easily improve aspects of your robot?
- Can you easily integrate new functionality?

Basic primitive of a control system is a behavior

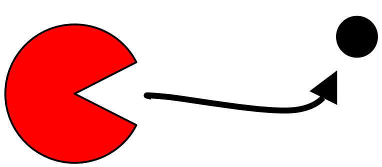
Behaviors should be well-defined, self-contained, and independently testable



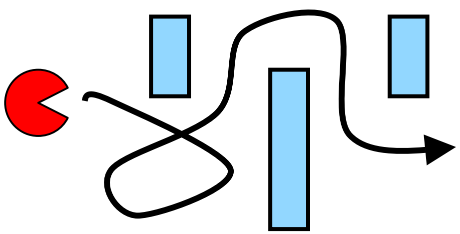
Turn right 90°



Go forward until reach obstacle

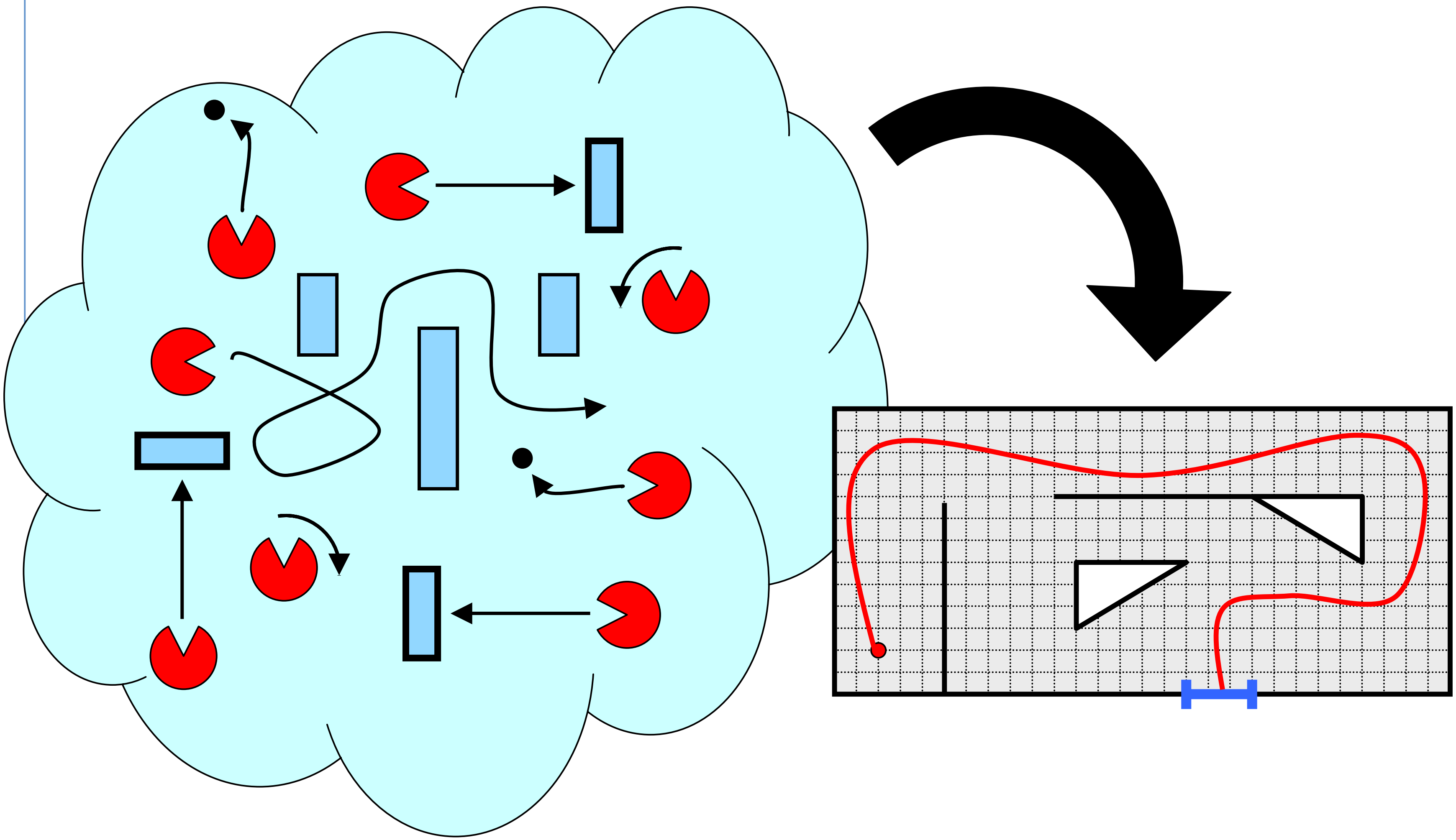


Capture a ball



Explore playing field

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

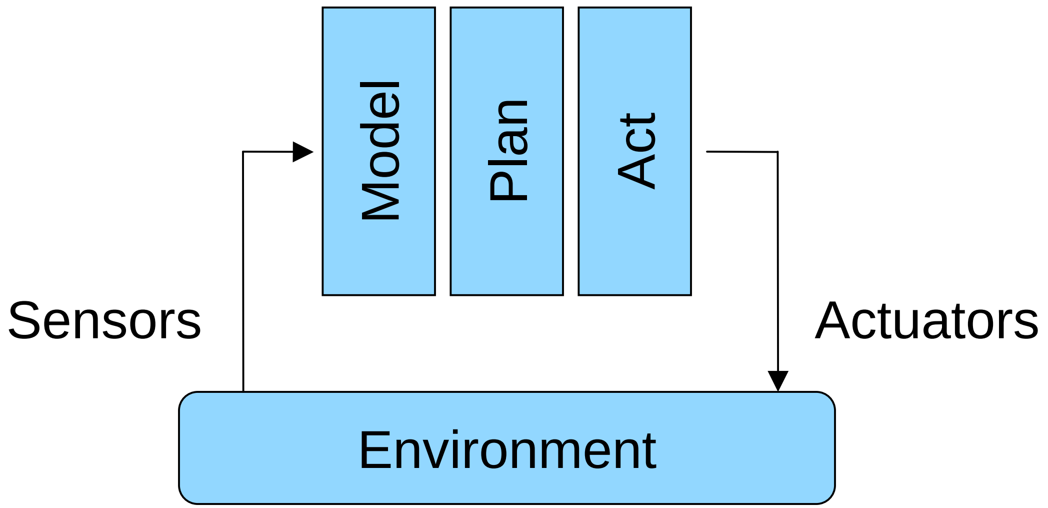


Outline



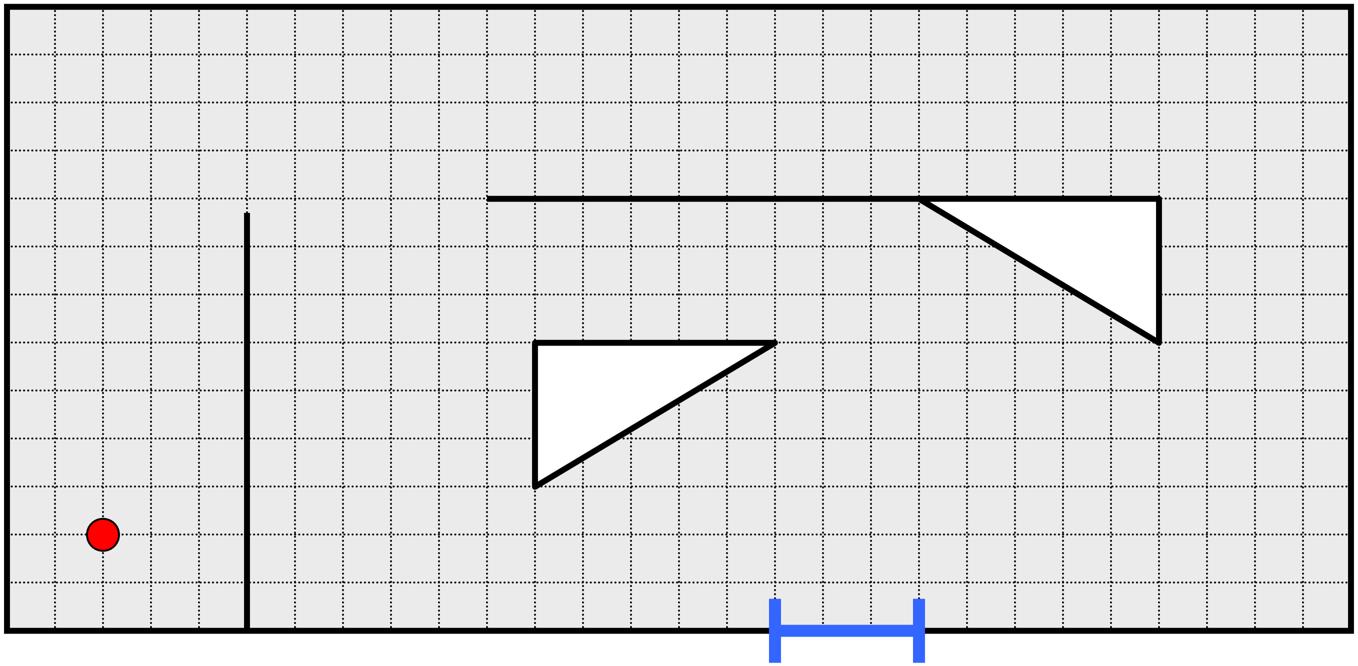
- High-level control system paradigms
  - Model-Plan-Act Approach
  - Behavioral Approach
  - Finite State Machine Approach
- Low-level control loops
  - PID controller for motor velocity
  - PID controller for robot drive system

Model-Plan-Act Approach



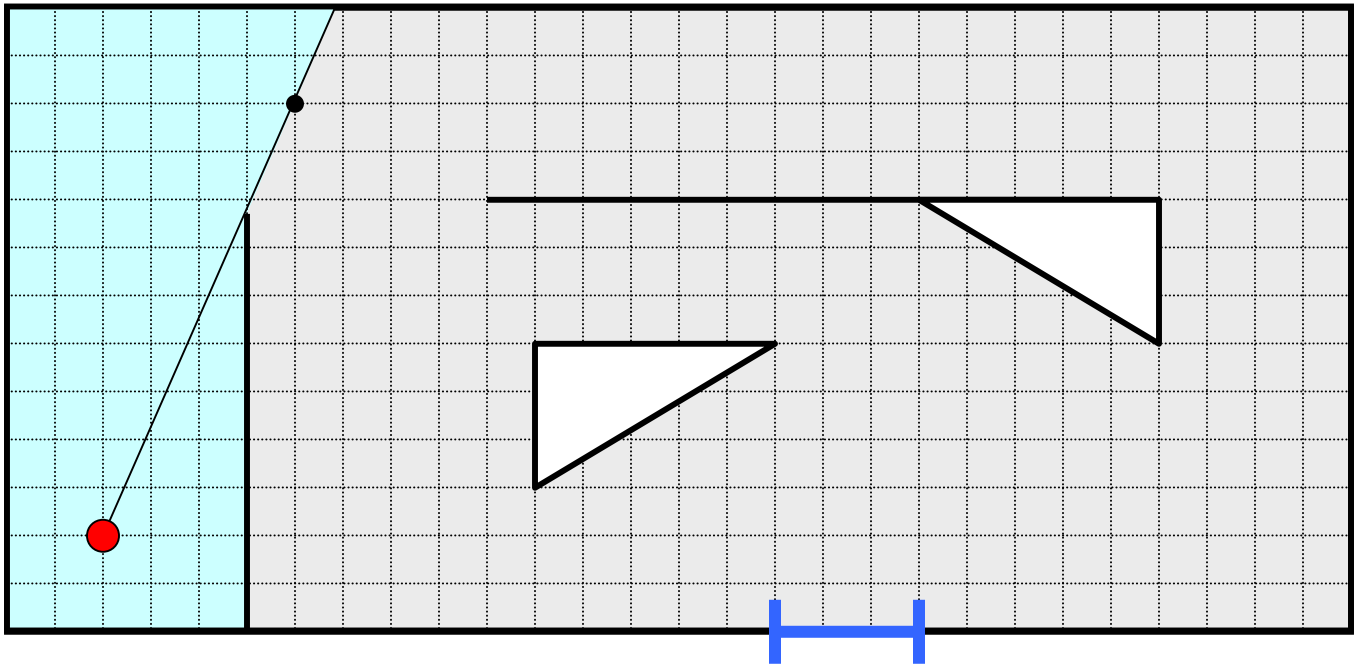
1. Use sensor data to create model of the world
2. Use model to form a sequence of behaviors which will achieve the desired goal
3. Execute the plan

Exploring the playing field using model-plan-act approach



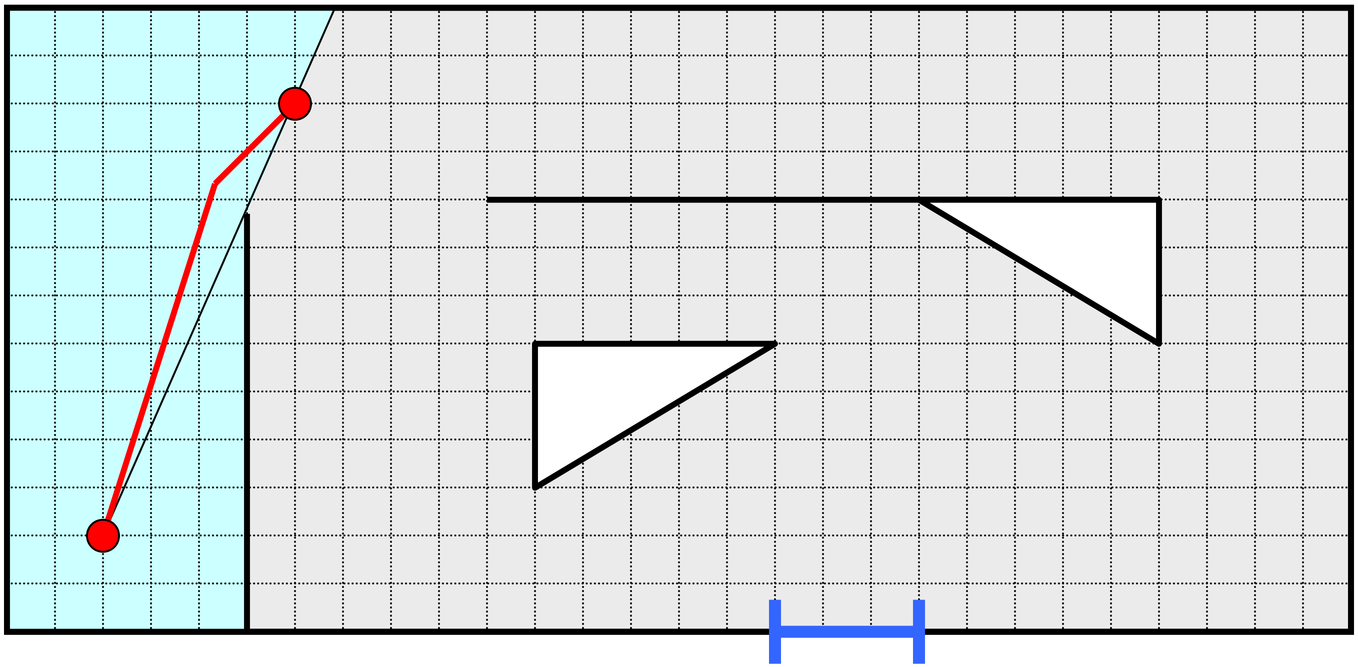
Red dot is the mobile robot
while the blue line is the mousehole

Exploring the playing field using model-plan-act approach



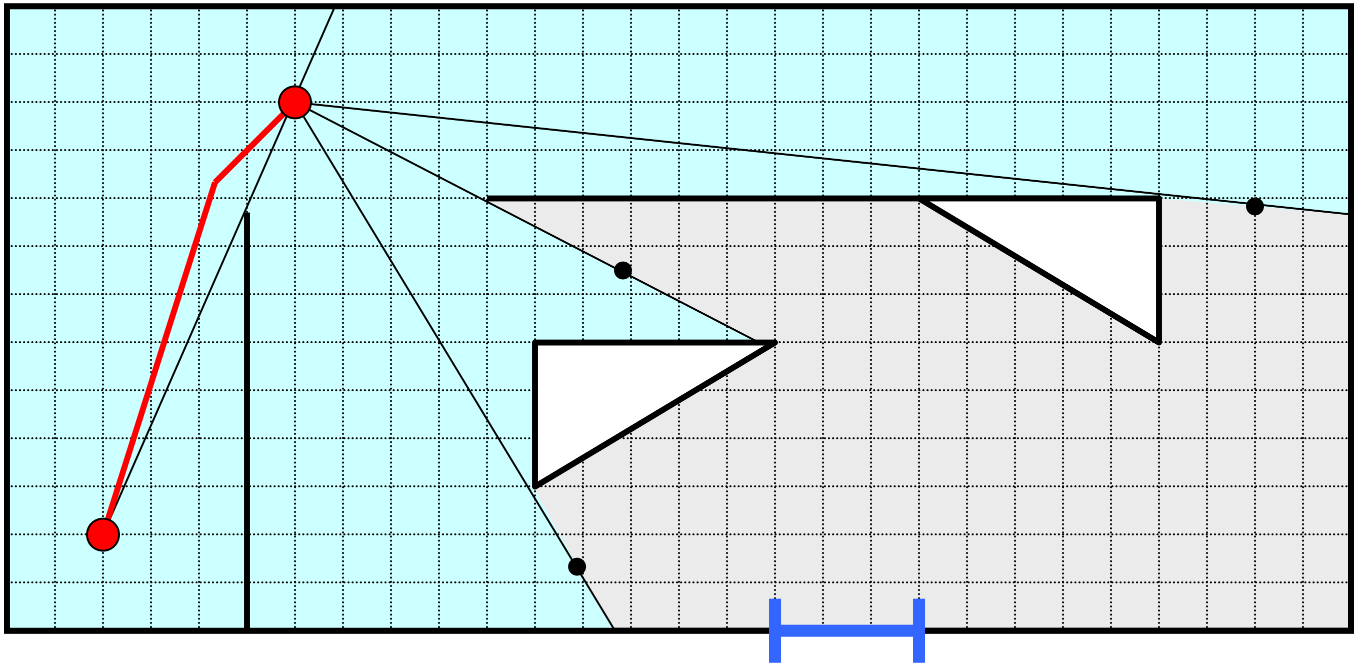
Robot uses sensors to create local map of the world and identify unexplored areas

Exploring the playing field using model-plan-act approach



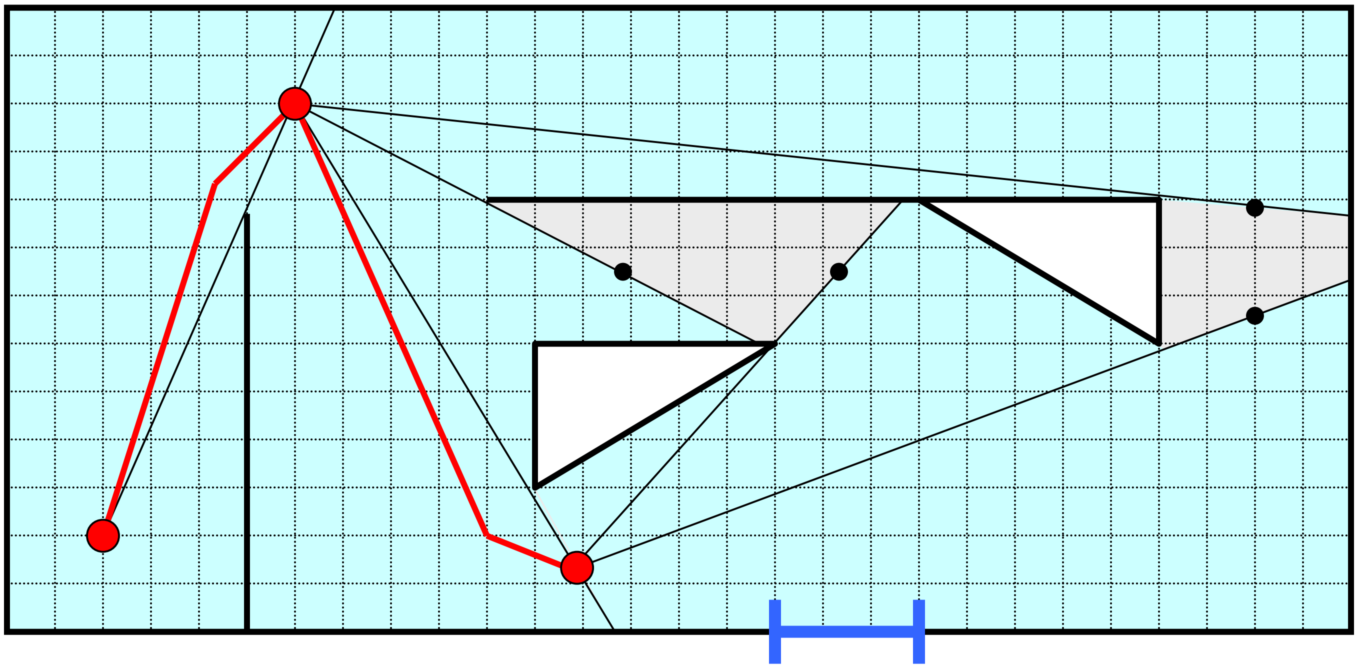
Robot moves to midpoint of unexplored boundary

Exploring the playing field using model-plan-act approach



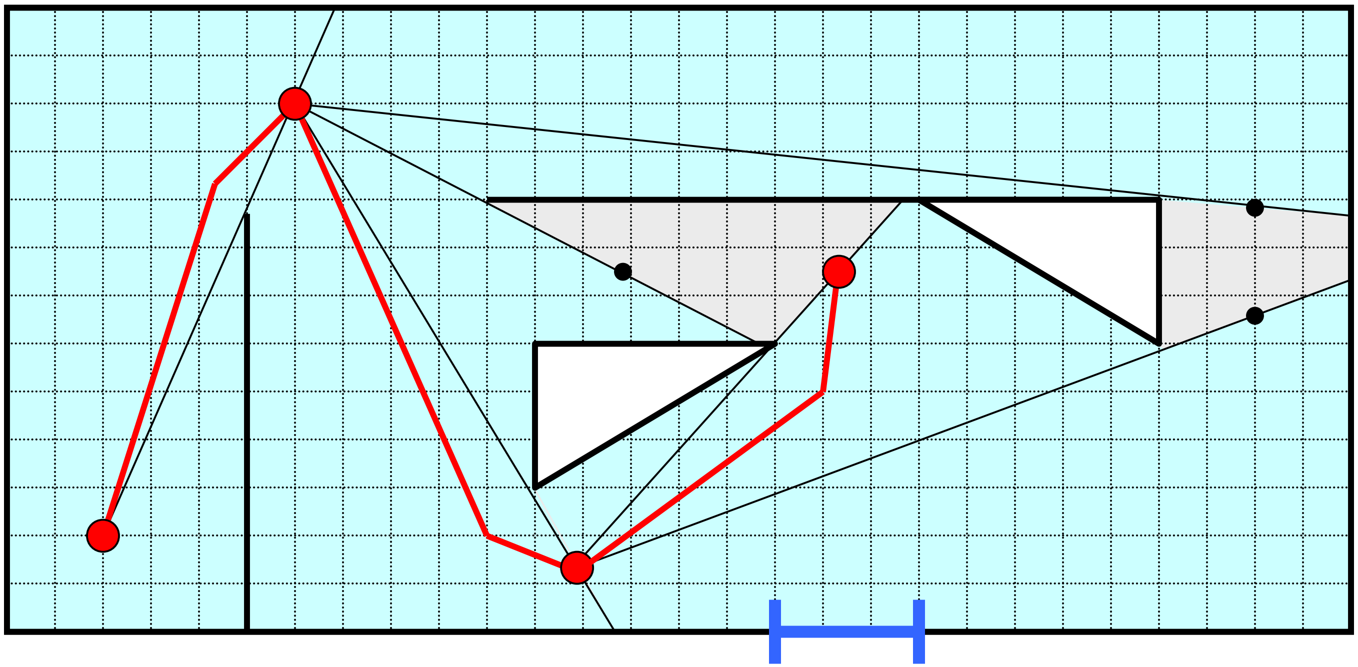
Robot performs a second sensor scan and must align the new data with the global map

Exploring the playing field using model-plan-act approach



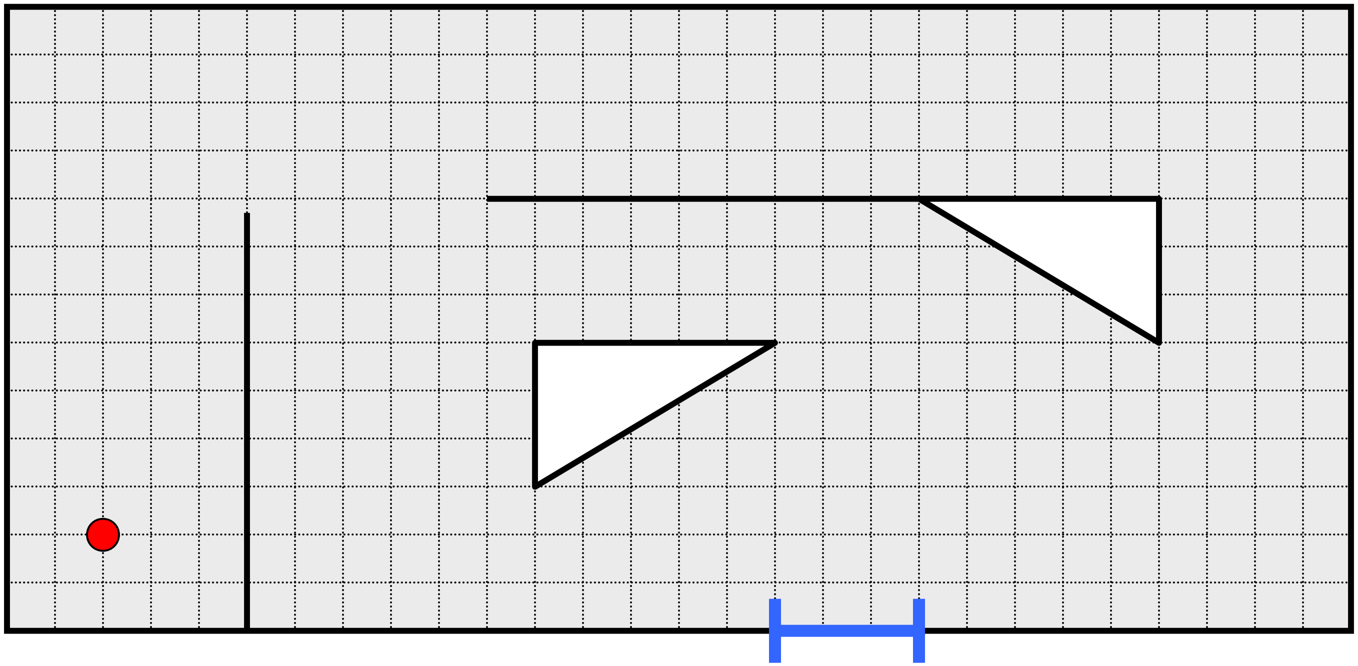
Robot continues to explore the playing field

Exploring the playing field using model-plan-act approach



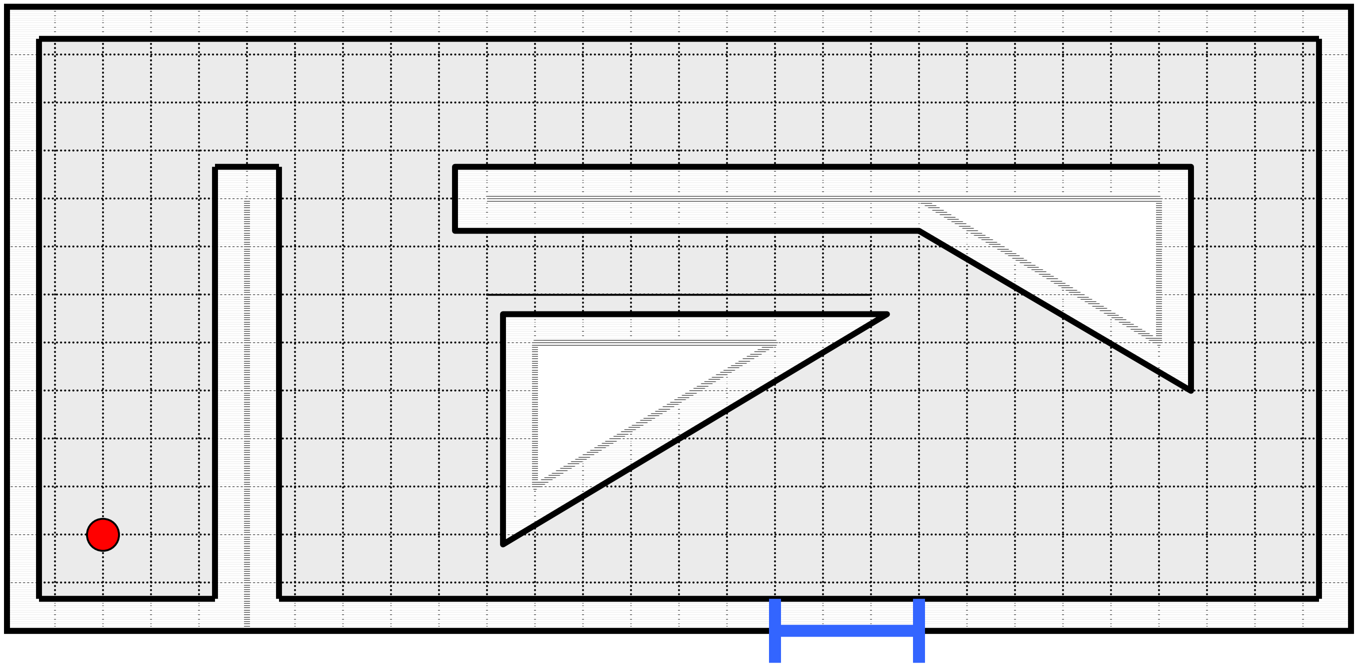
Robot must recognize when it starts to see areas which it has already explored

Finding a mousehole using model-plan-act approach



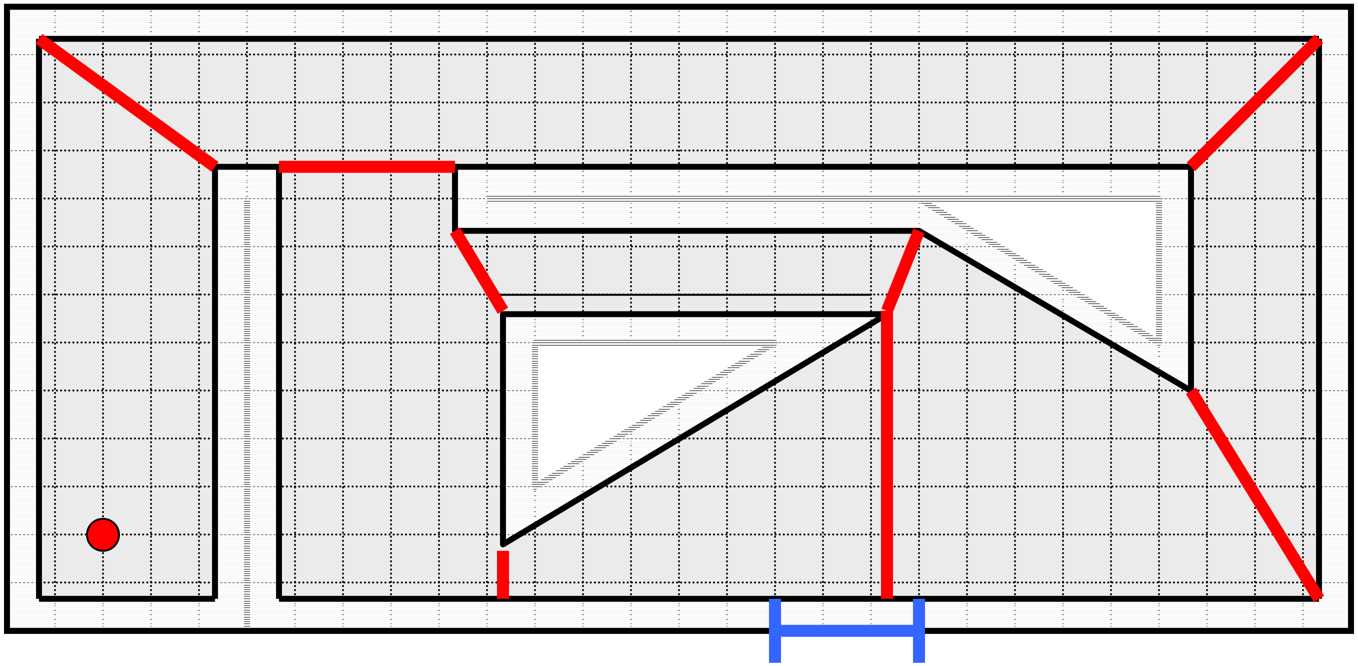
Given the global map,
the goal is to find the mousehole

Finding a mousehole using model-plan-act approach



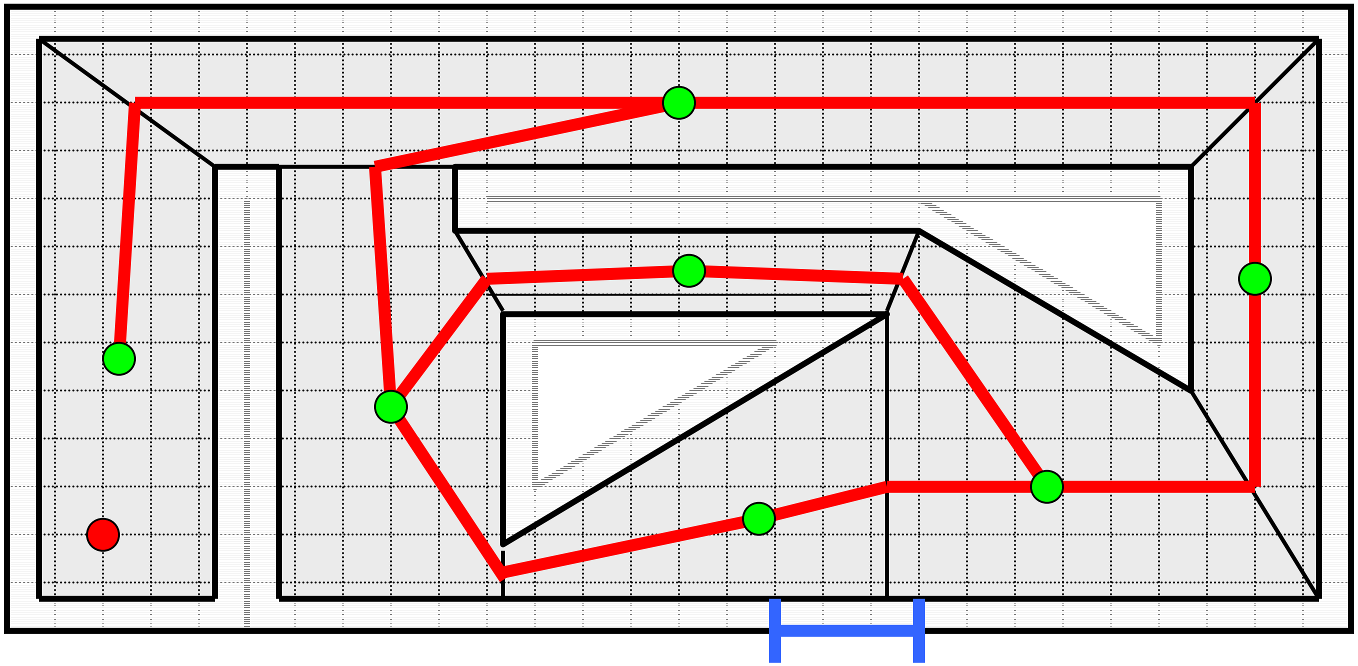
Transform world into configuration space by convolving robot with all obstacles

Finding a mousehole using model-plan-act approach



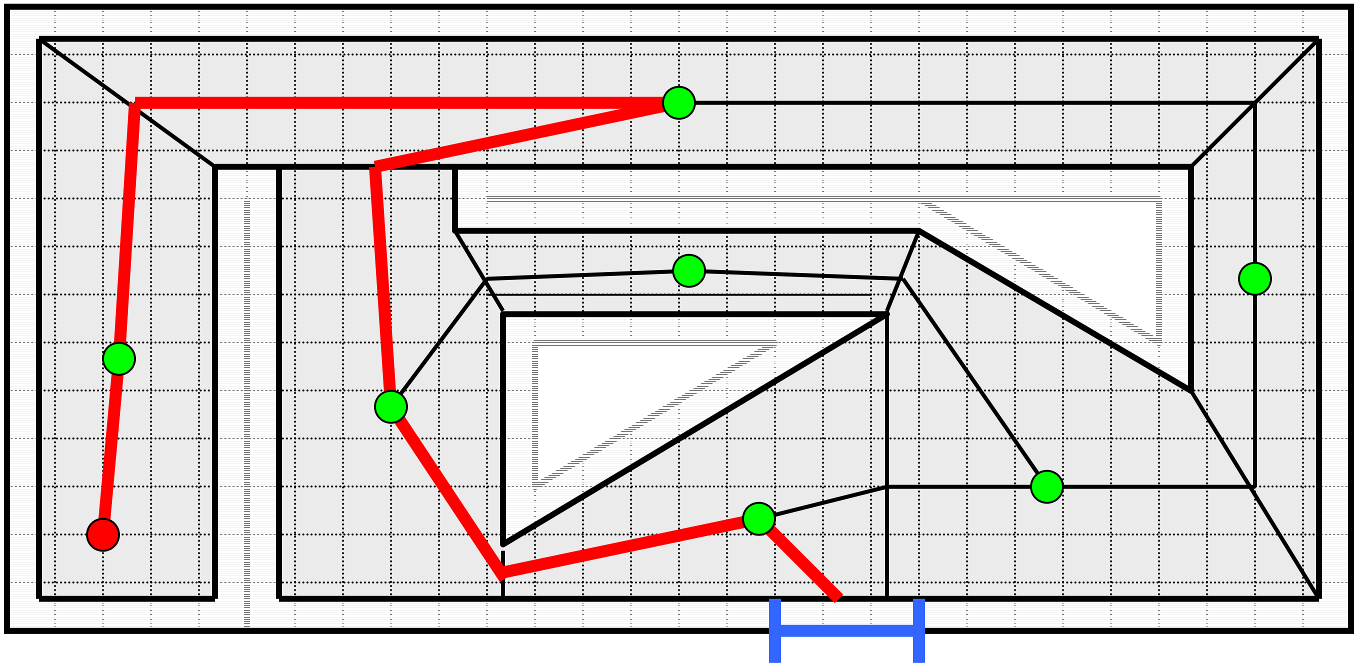
Decompose world into convex cells
Trajectory within any cell is free of obstacles

Finding a mousehole using model-plan-act approach



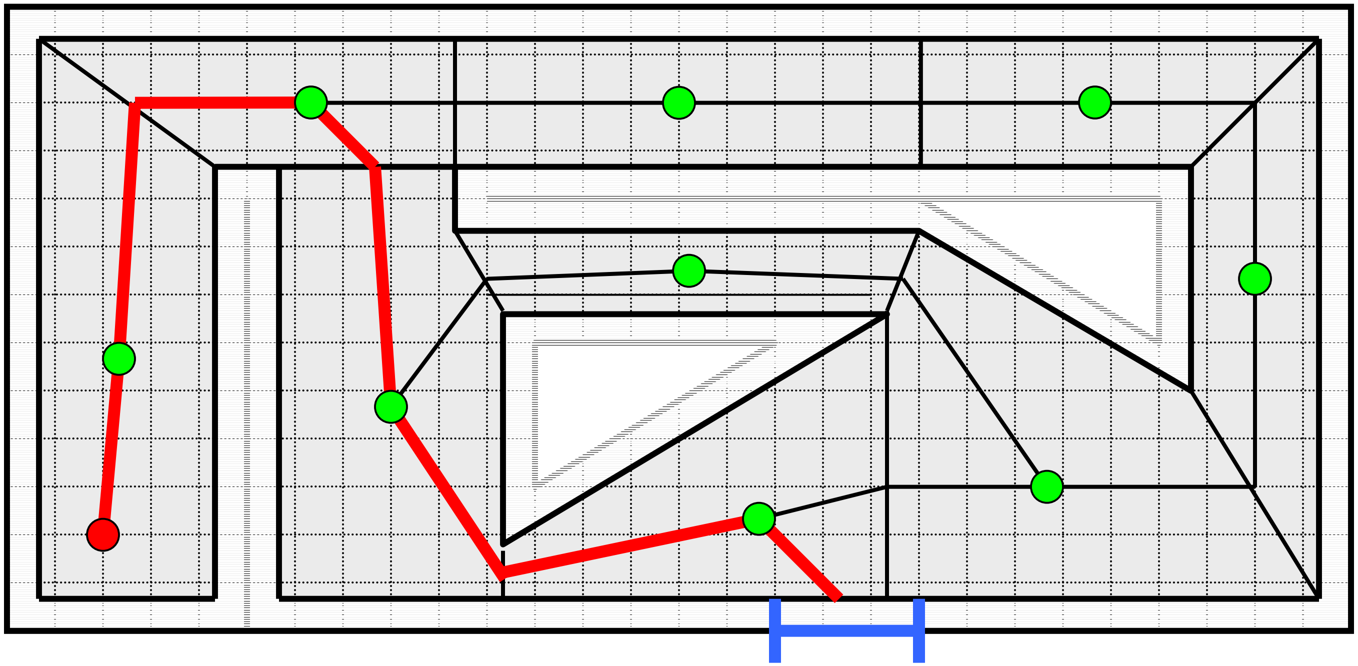
Connect cell edge midpoints and centroids to get graph of all possible paths

Finding a mousehole using model-plan-act approach



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

Finding a mousehole using model-plan-act approach

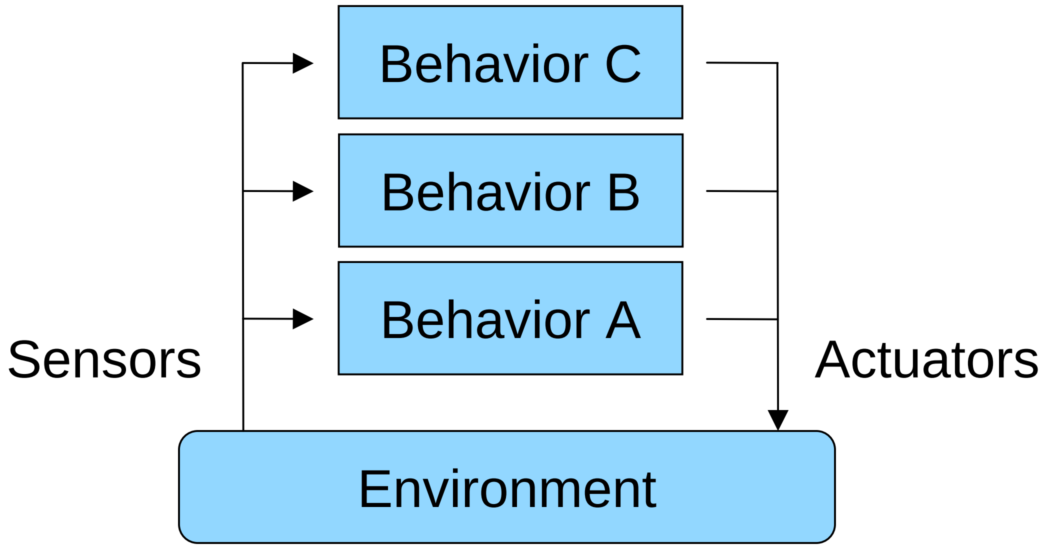


The choice of cell decomposition can greatly influence results

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

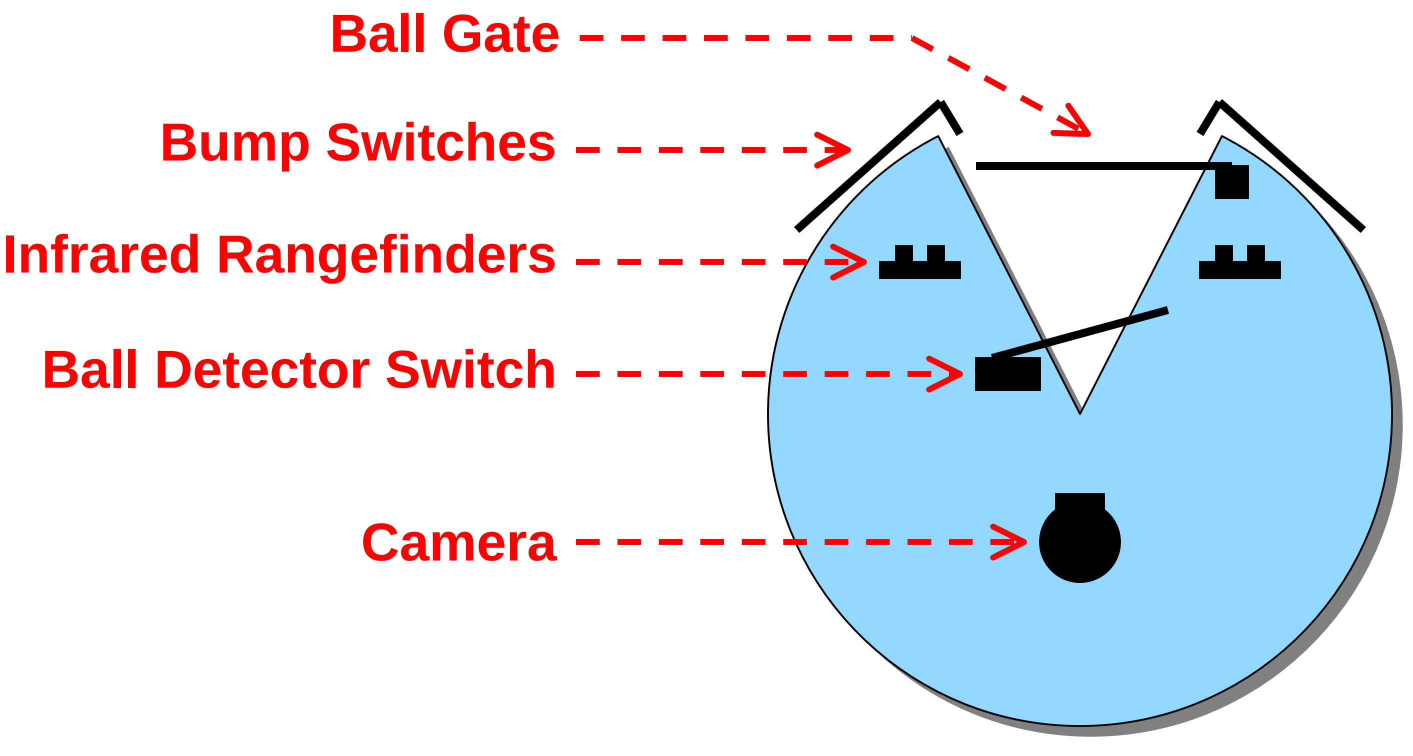
Behavioral Approach



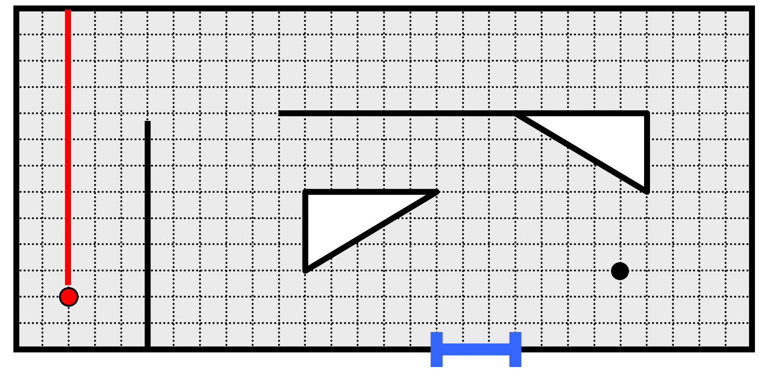
As in simple biological systems,
behaviors directly couple sensors and actuators

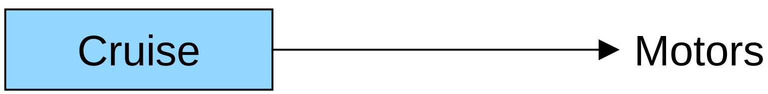
Higher level behaviors are layered
on top of lower level behaviors

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



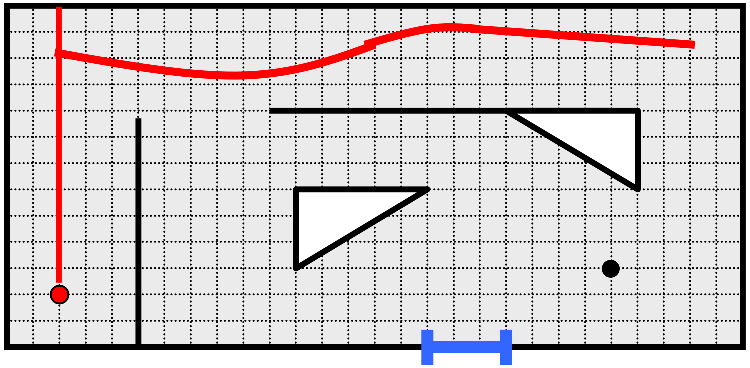
Layering simple behaviors can create much more complex emergent behavior

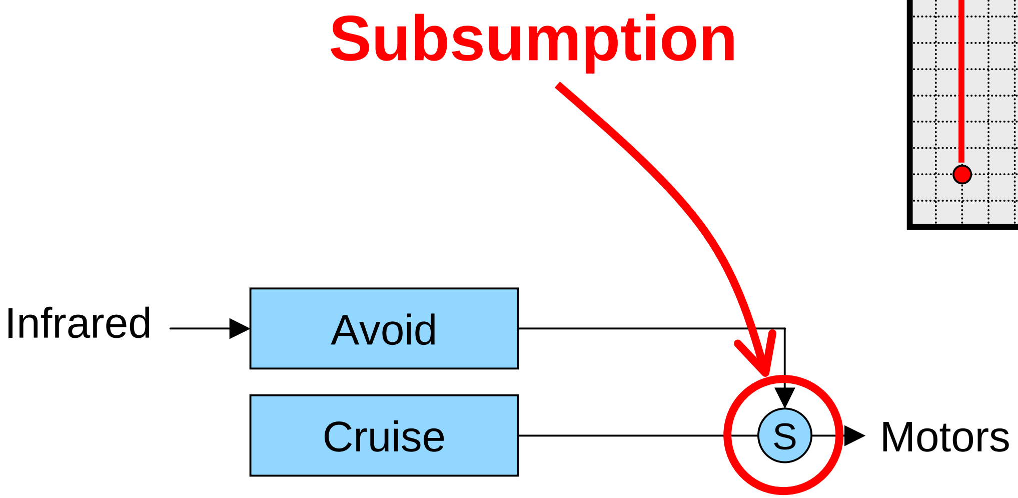




Cruise behavior simply moves robot forward

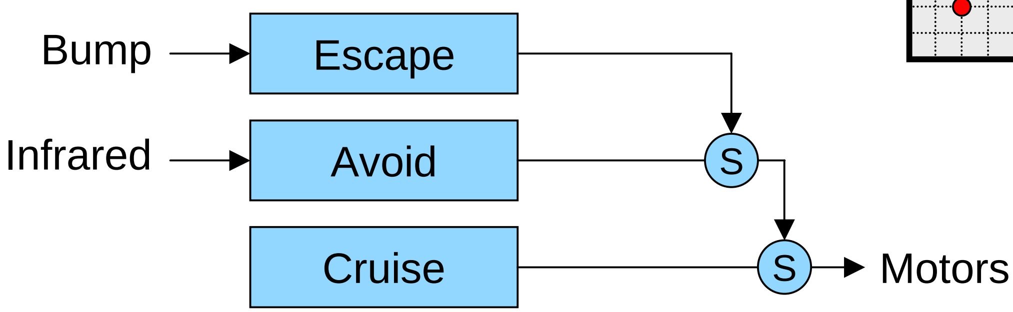
Layering simple behaviors can create much more complex emergent behavior

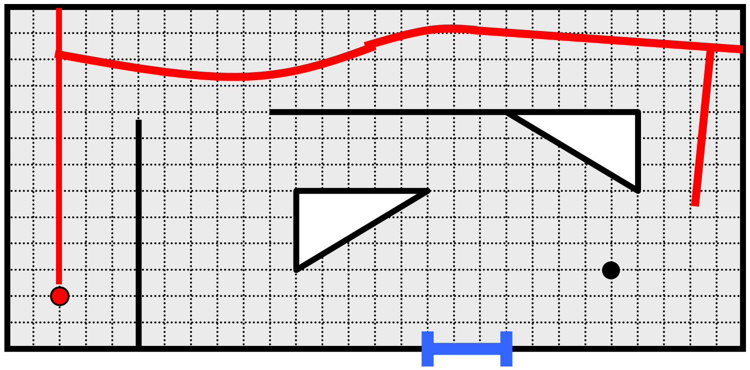




Left motor speed inversely proportional to left IR range
Right motor speed inversely proportional to right IR range
If both IR < threshold stop and turn right 120 degrees

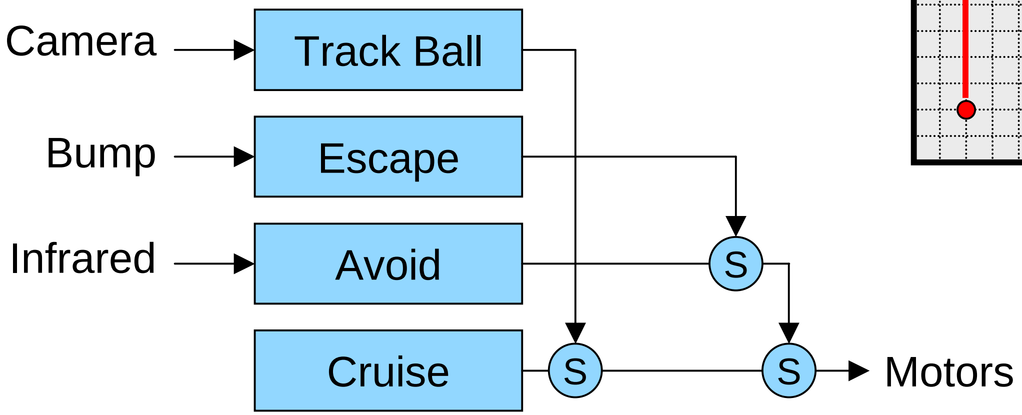
Layering simple behaviors can create much more complex emergent behavior

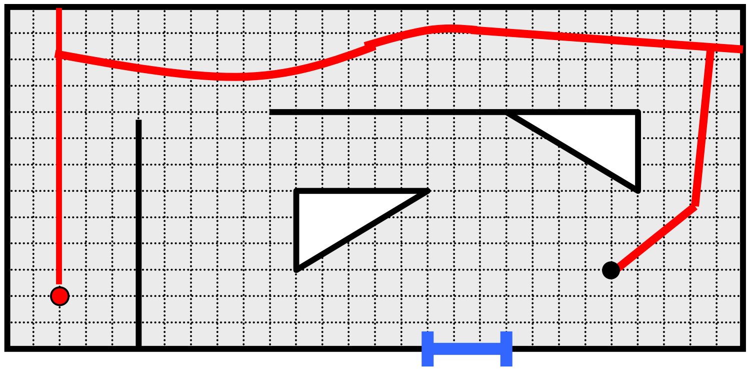




Escape behavior stops motors,
backs up a few inches, and turns right 90 degrees

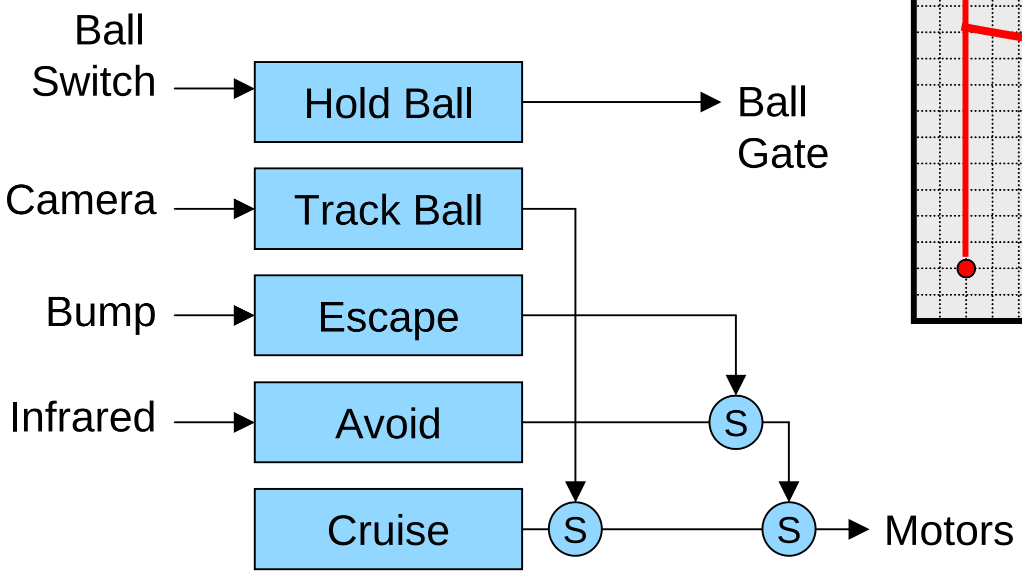
Layering simple behaviors can create much more complex emergent behavior

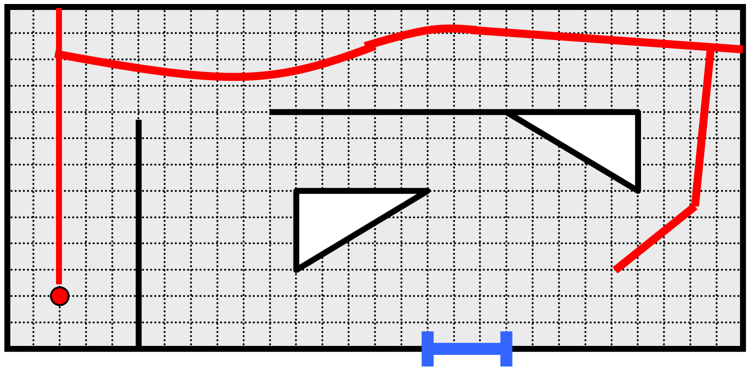




The track ball behavior adjusts the
motor differential to steer the robot towards the ball

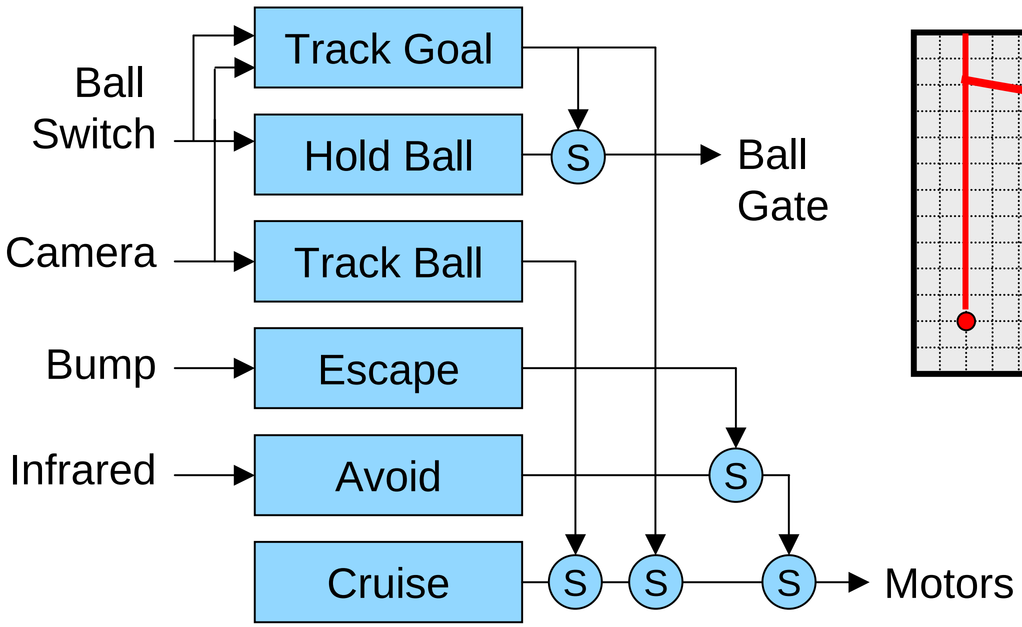
Layering simple behaviors can create much more complex emergent behavior

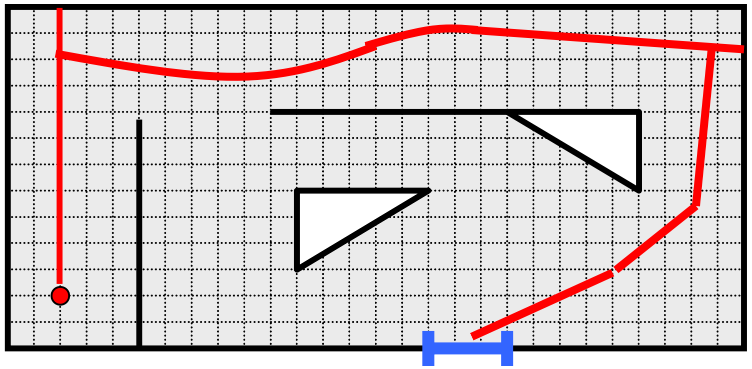




Hold ball behavior simply closes ball gate when ball switch is depressed

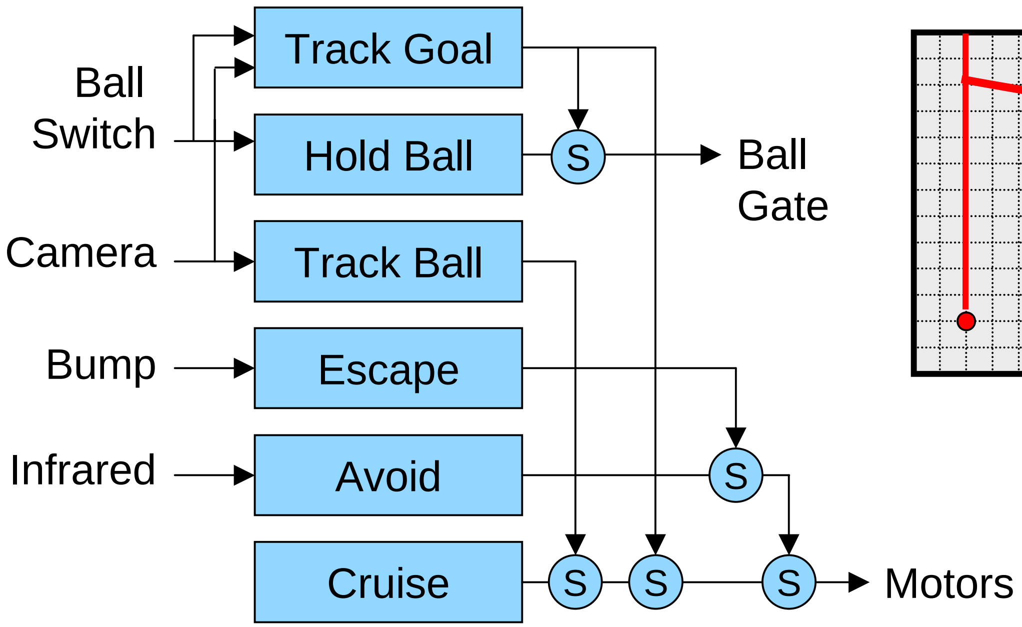
Layering simple behaviors can create much more complex emergent behavior

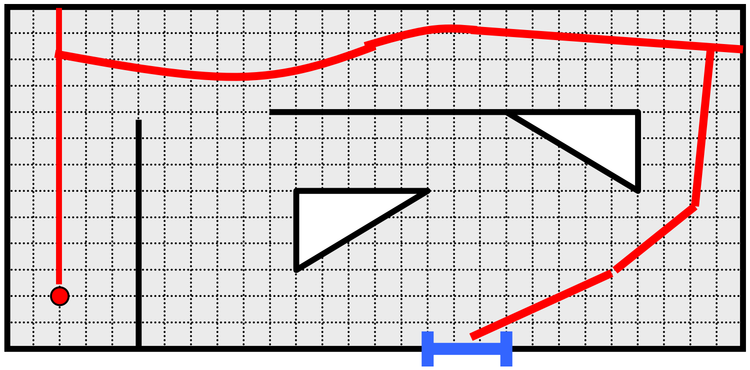




The track goal behavior opens the ball gate and adjusts the motor differential to steer the robot towards the goal

Layering simple behaviors can create much more complex emergent behavior



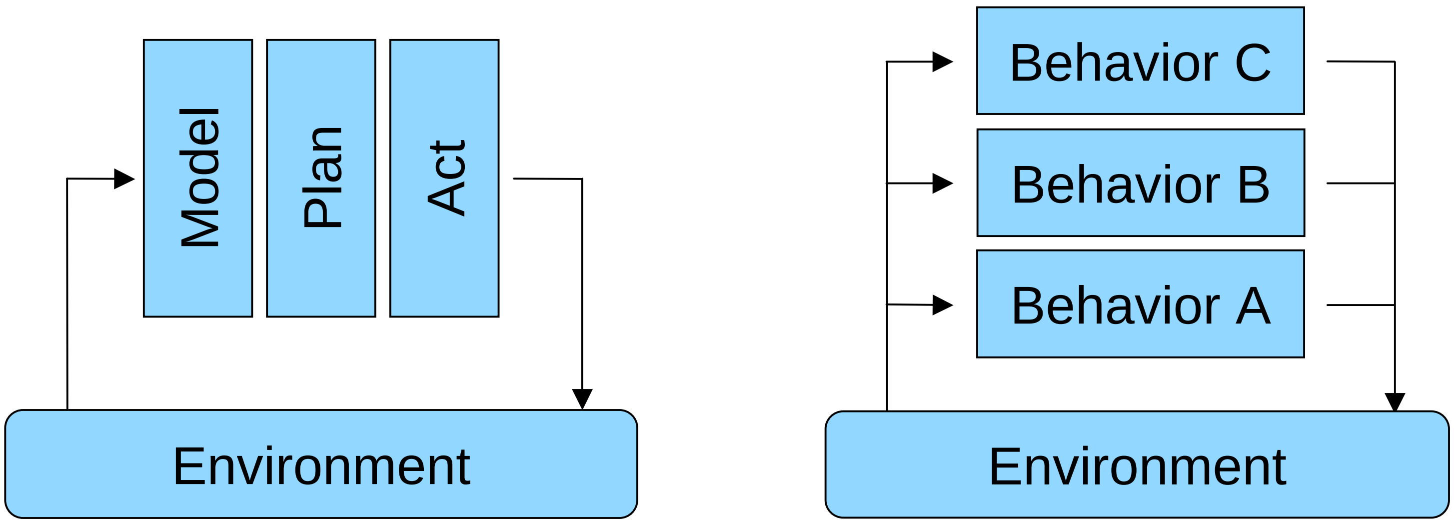


All behaviors are always running in parallel and an arbiter is responsible for picking which behavior can access the actuators

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

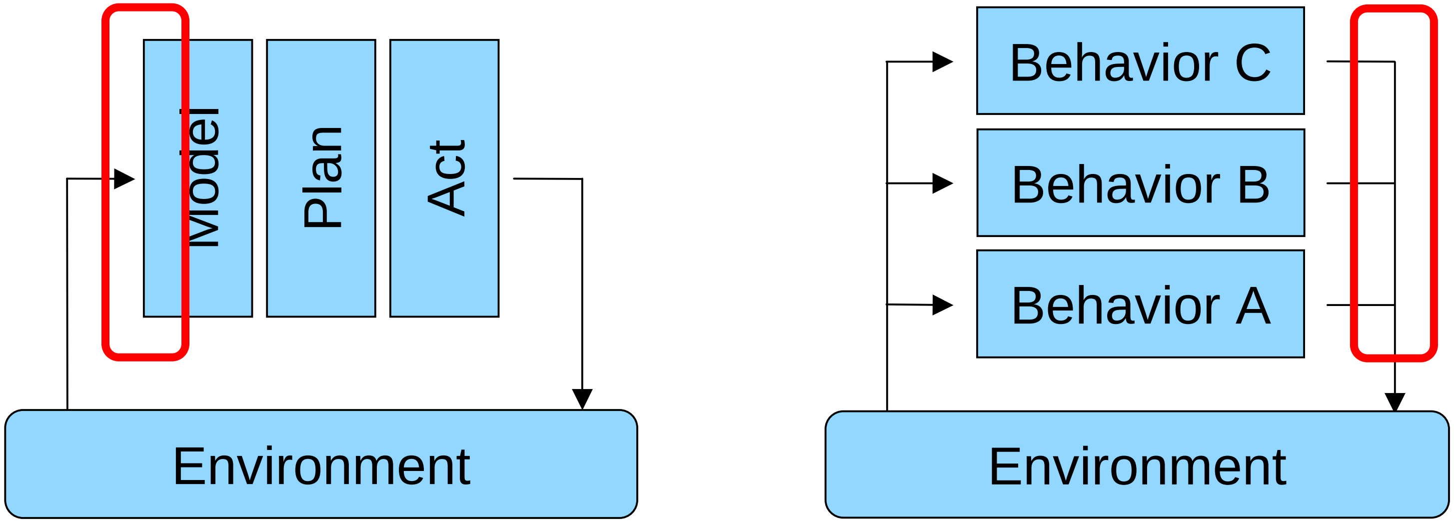
Model-plan-act fuses sensor data, while behavioral fuses behaviors



Model-Plan-Act
(Fixed Plan of Behaviors)

Behavioral
(Layered Behaviors)

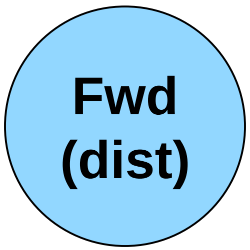
Model-plan-act fuses sensor data, while behavioral fuses behaviors



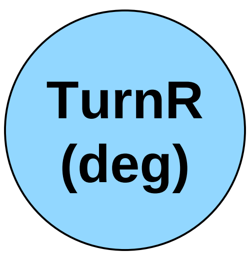
Model-Plan-Act
(Sensor Fusion)

Behavioral
(Behavior Fusion)

Finite State Machines offer another alternative for combining behaviors

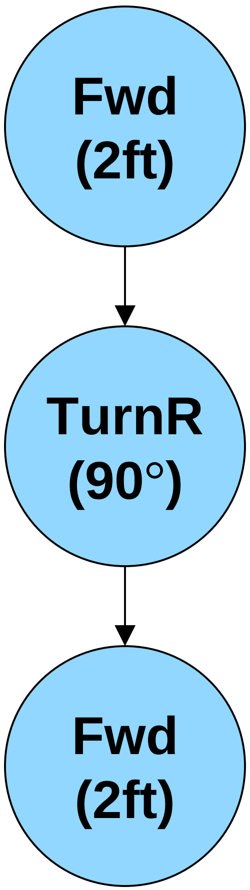


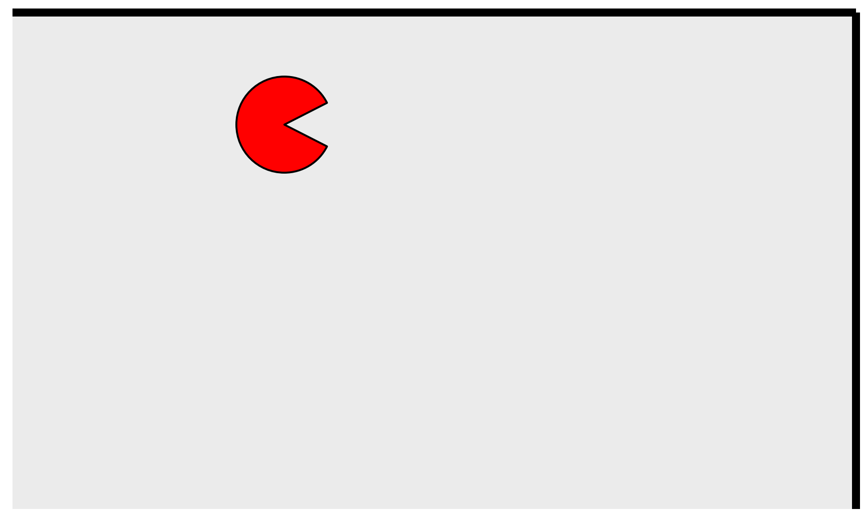
Fwd behavior moves robot straight forward a given distance



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

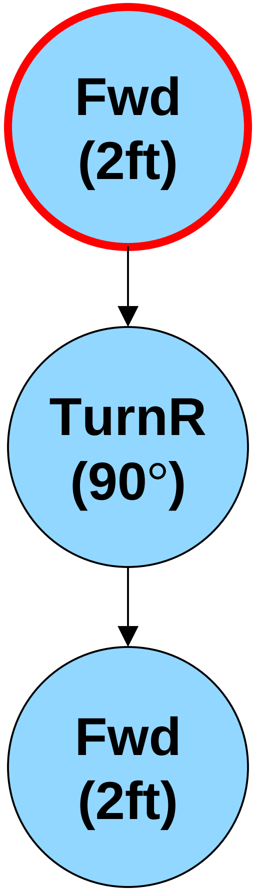
Finite State Machines offer another alternative for combining behaviors

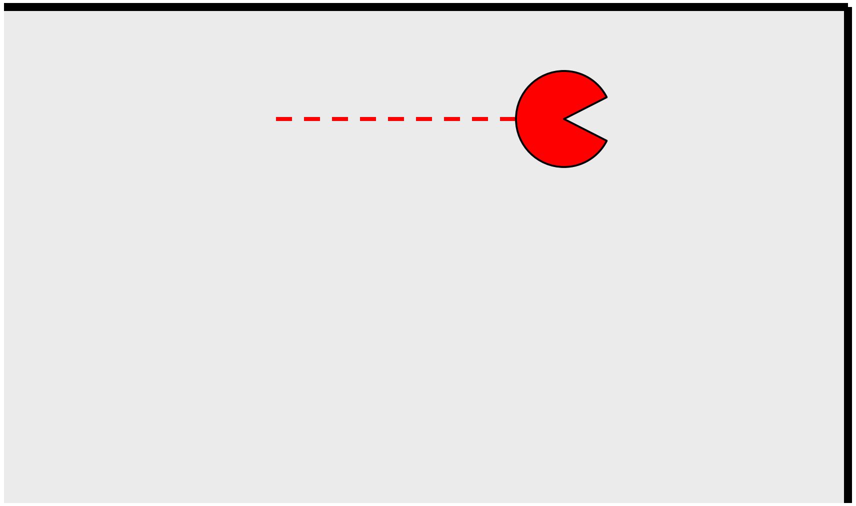




Each state is just a behavior and we can easily link them together to create an open loop control system

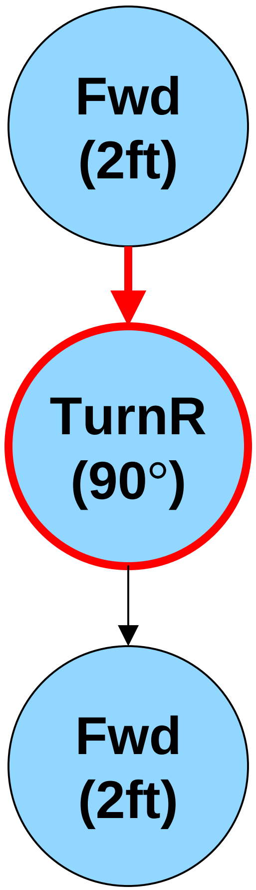
Finite State Machines offer another alternative for combining behaviors

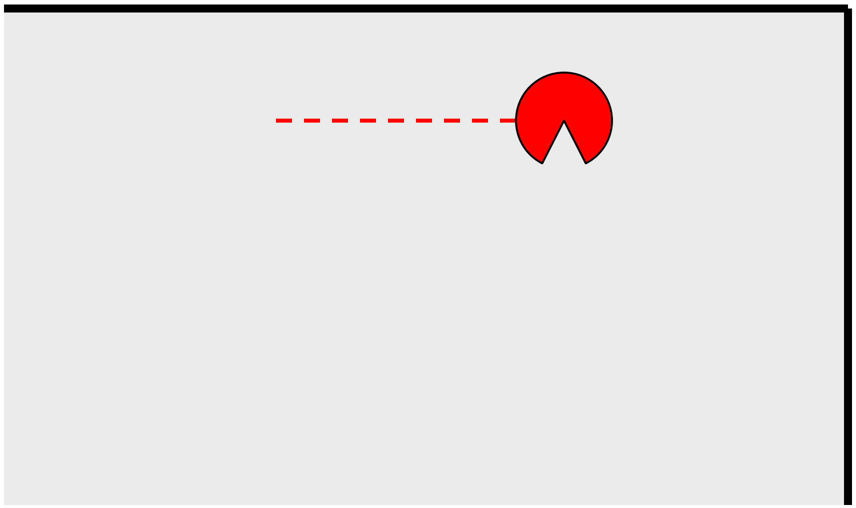




Each state is just a behavior and we can easily link them together to create an open loop control system

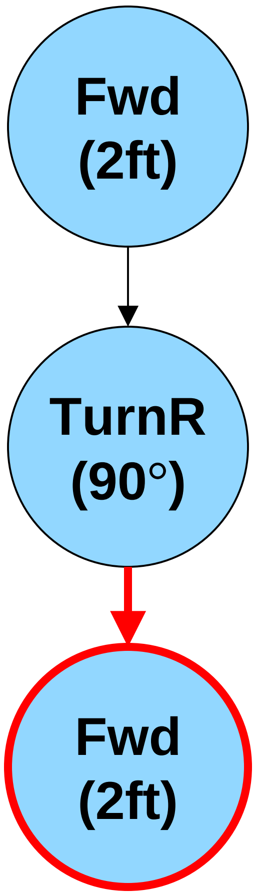
Finite State Machines offer another alternative for combining behaviors

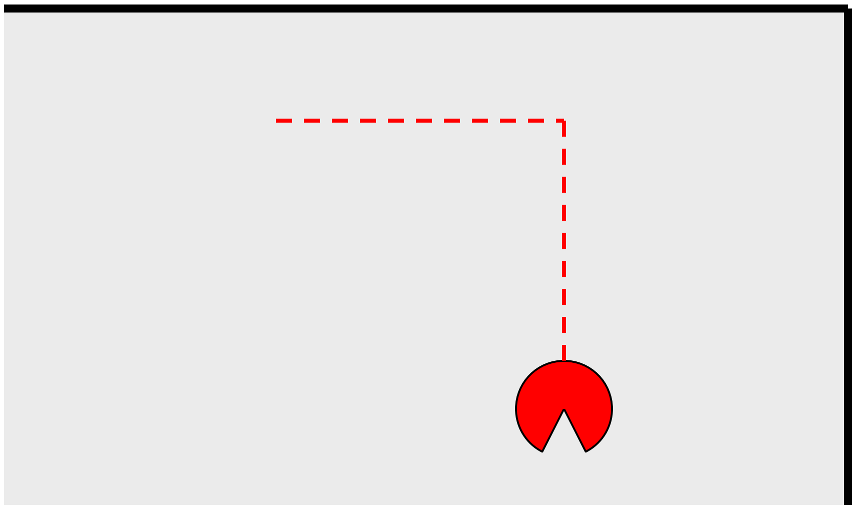




Each state is just a behavior and we can easily link them together to create an open loop control system

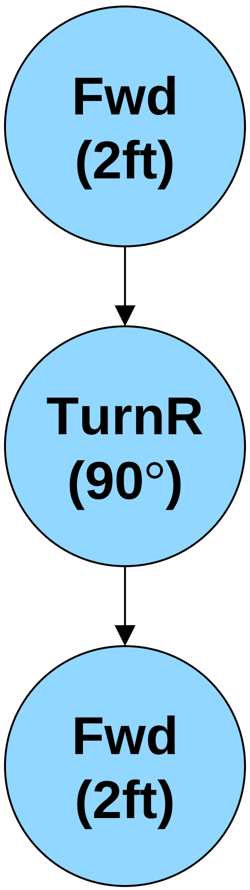
Finite State Machines offer another alternative for combining behaviors

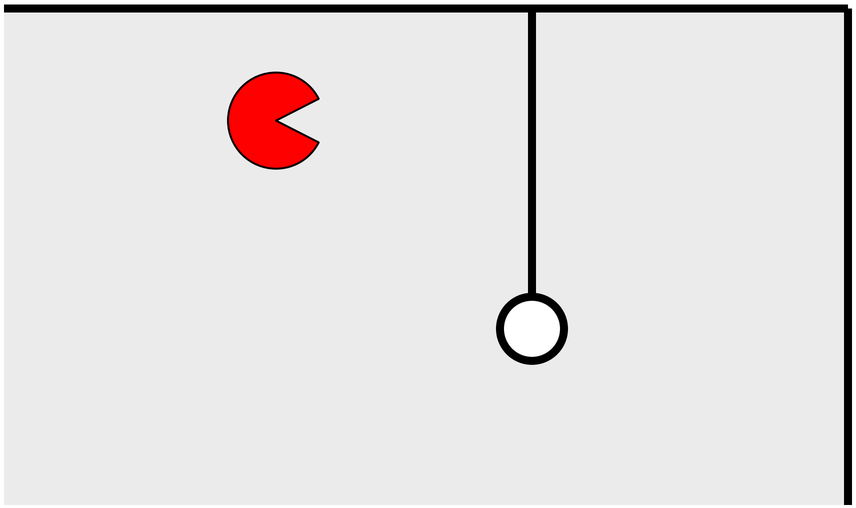




Each state is just a behavior and we can easily link them together to create an open loop control system

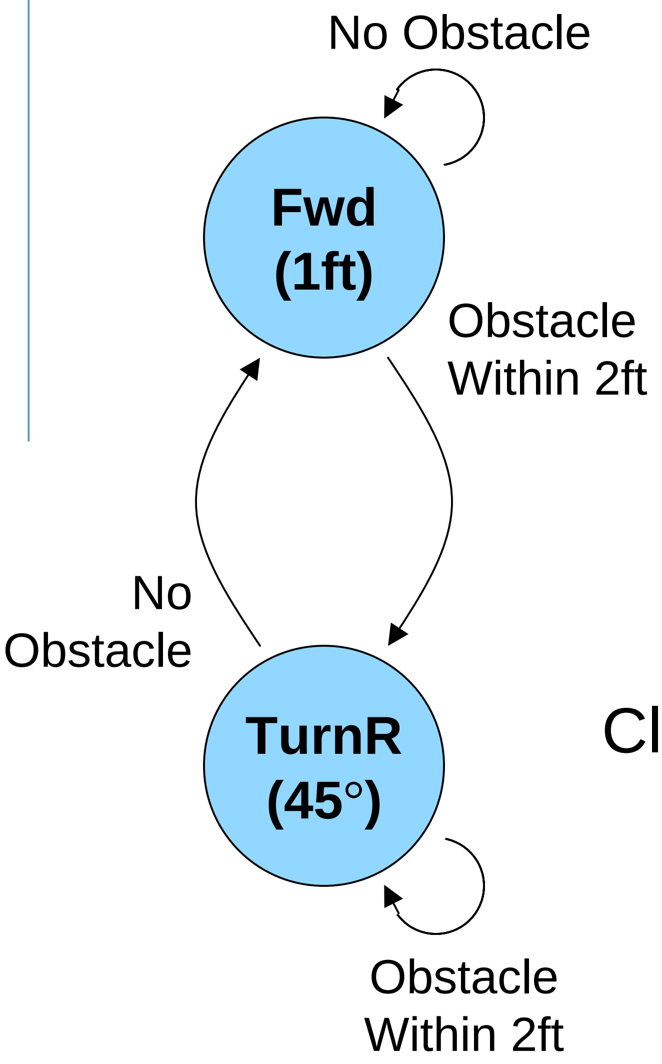
Finite State Machines offer another alternative for combining behaviors

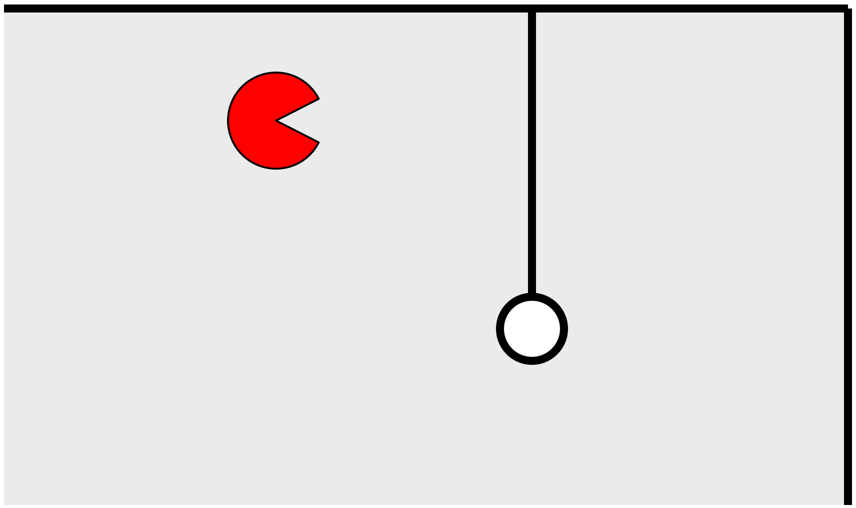




Since the Maslab playing field is unknown, open loop control systems have no hope of success!

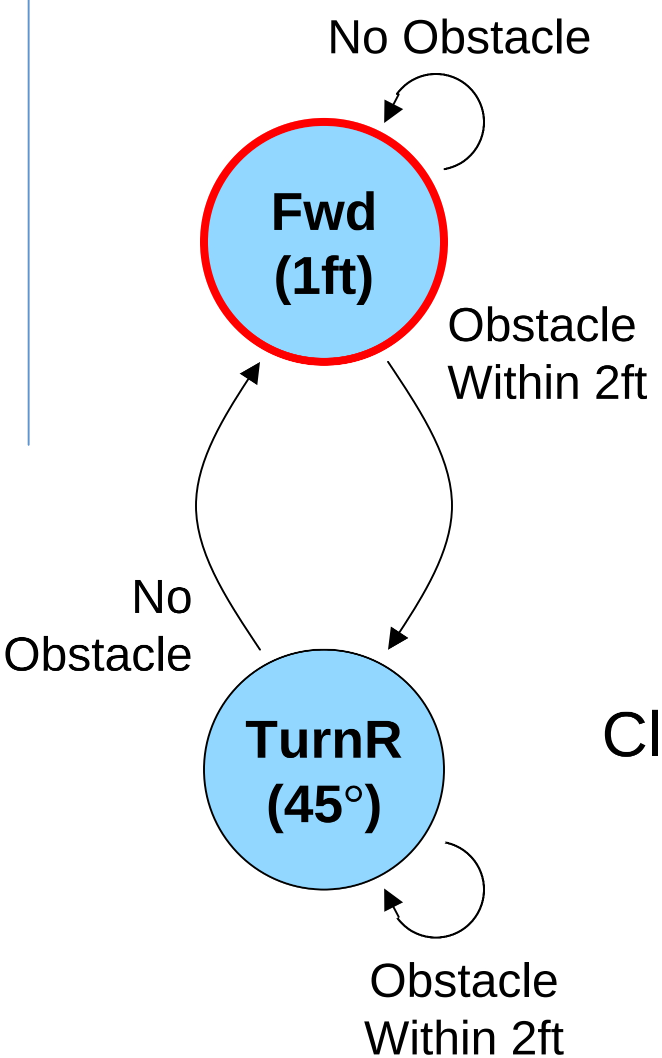
Finite State Machines offer another alternative for combining behaviors

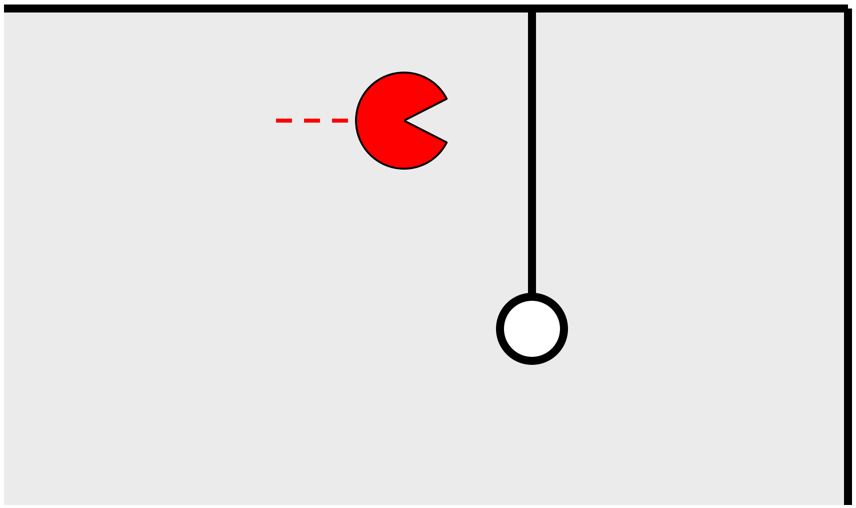




Closed loop finite state machines use sensor data as feedback to make state transitions

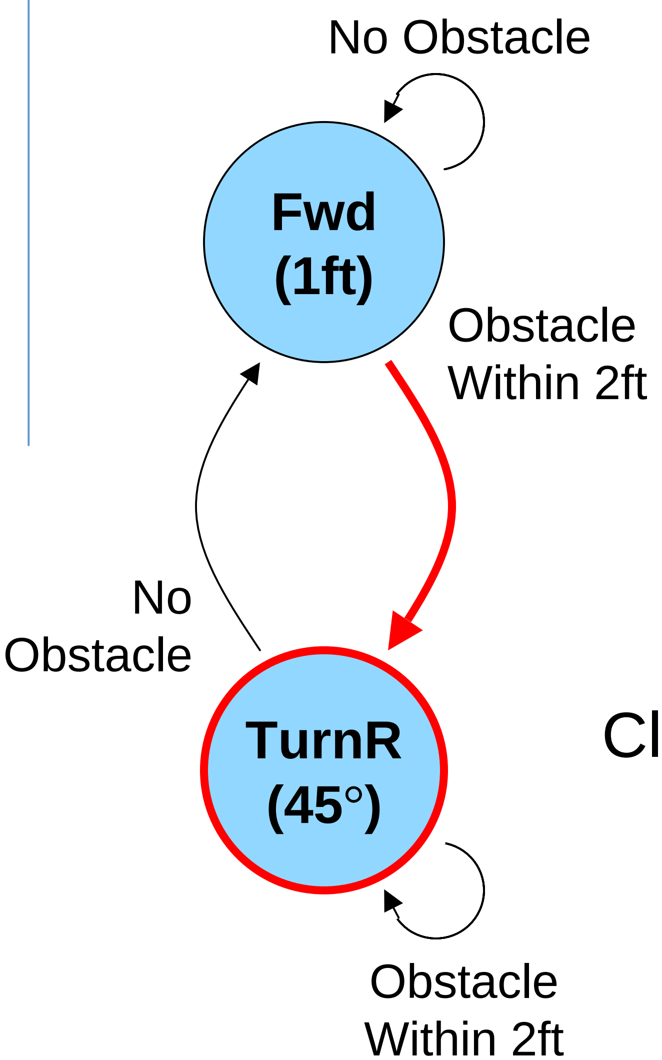
Finite State Machines offer another alternative for combining behaviors

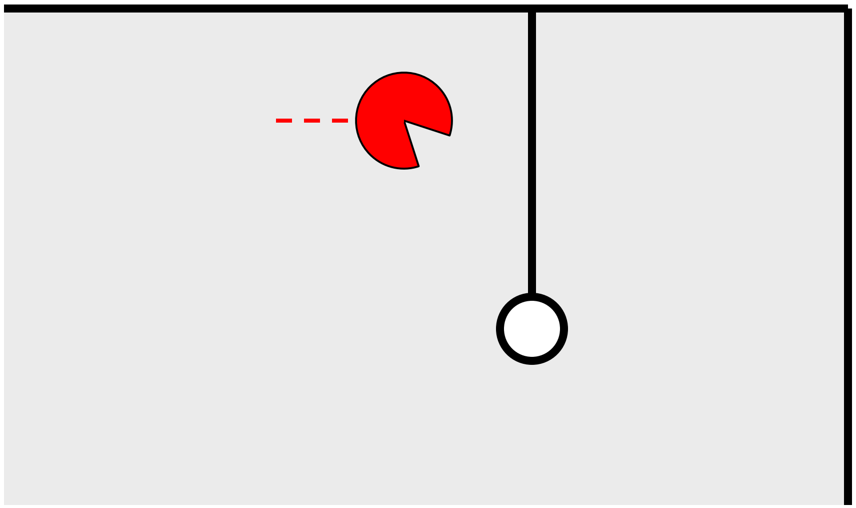




Closed loop finite state machines use sensor data as feedback to make state transitions

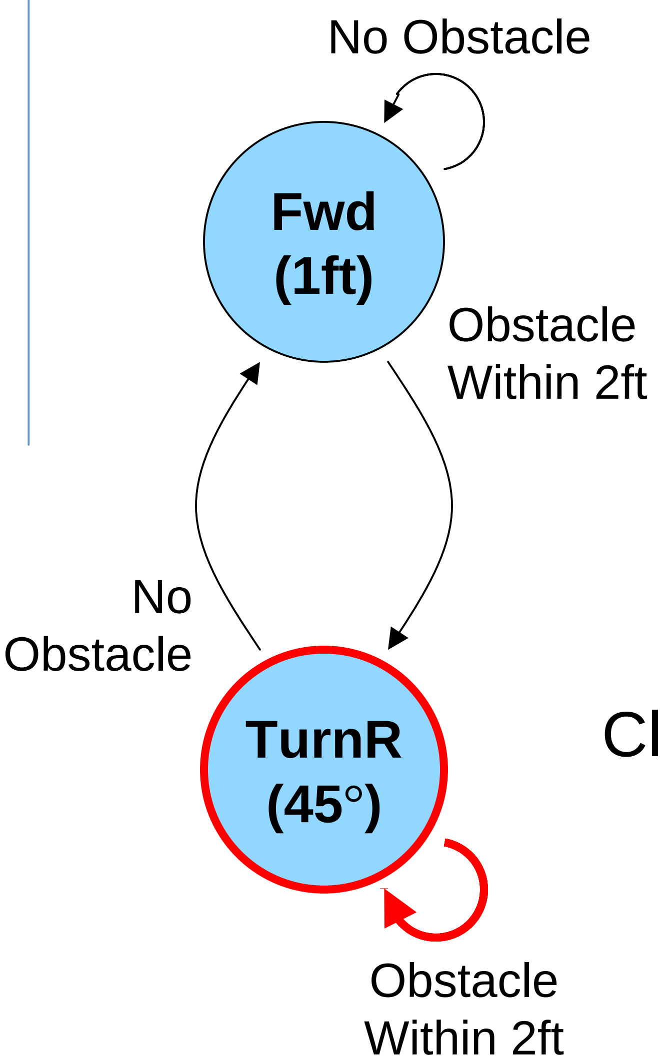
Finite State Machines offer another alternative for combining behaviors

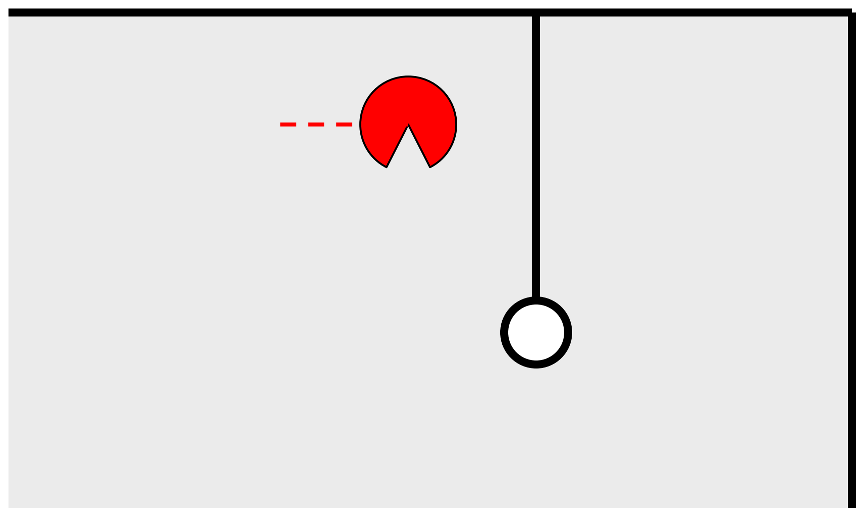




Closed loop finite state machines use sensor data as feedback to make state transitions

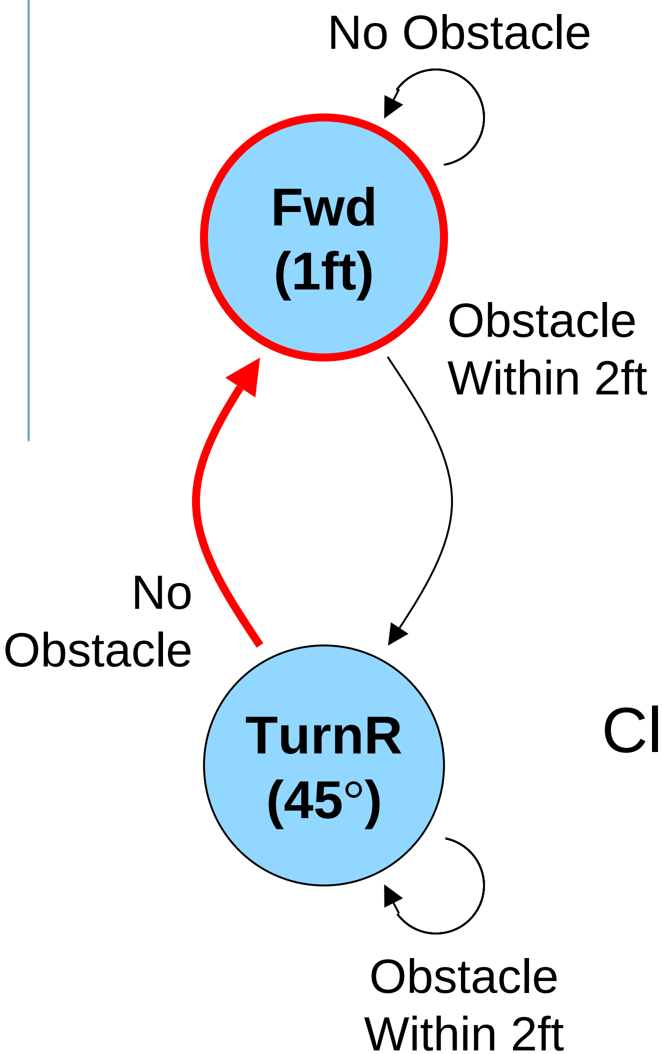
Finite State Machines offer another alternative for combining behaviors

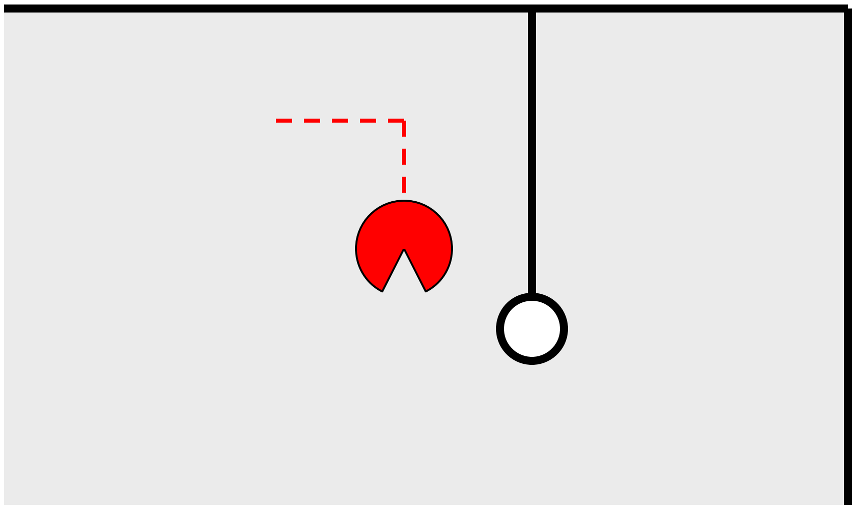




Closed loop finite state machines use sensor data as feedback to make state transitions

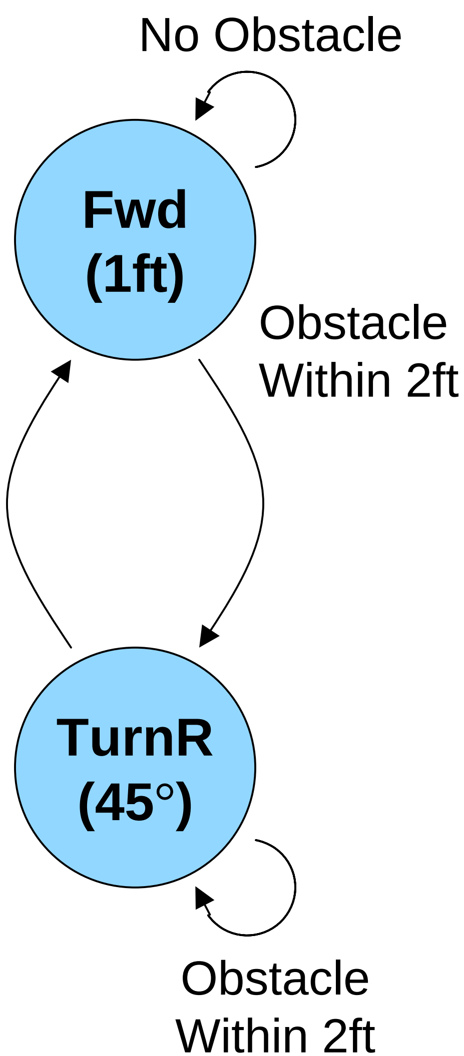
Finite State Machines offer another alternative for combining behaviors





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

Implementing a FSM in Java



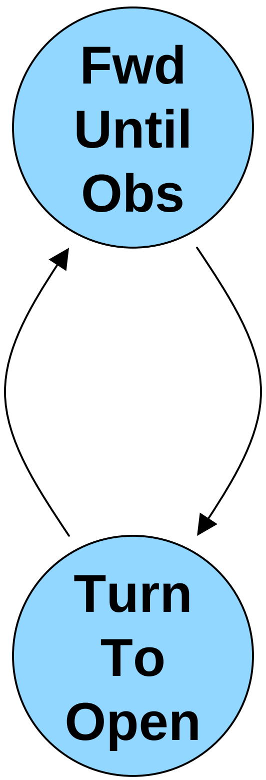

```java
// State transitions
switch ( state ) {

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

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

}

// State outputs
switch ( state ) {

  case States.Fwd_1 :
    moveFoward(1); break;

  case States.TurnR_45 :
    turnRight(45); break;

}
```

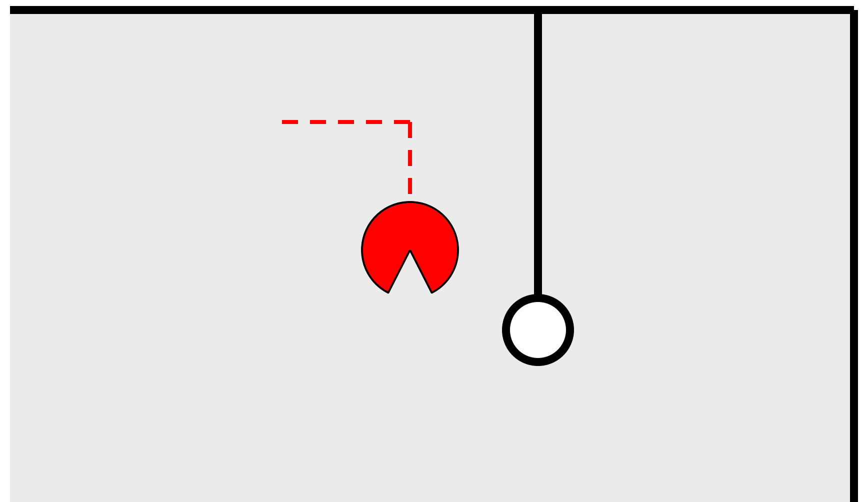
Implementing a FSM in Java

- Implement behaviors as parameterized functions
- First switch statement handles state transitions
- Second switch statement executes behaviors associated with each state
- Use enums for state variables

```
// State transitions
switch ( state ) {

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

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

}

// State outputs
switch ( state ) {

  case States.Fwd_1 :
    moveFoward(1); break;

  case States.TurnR_45 :
    turnRight(45); break;

}
```

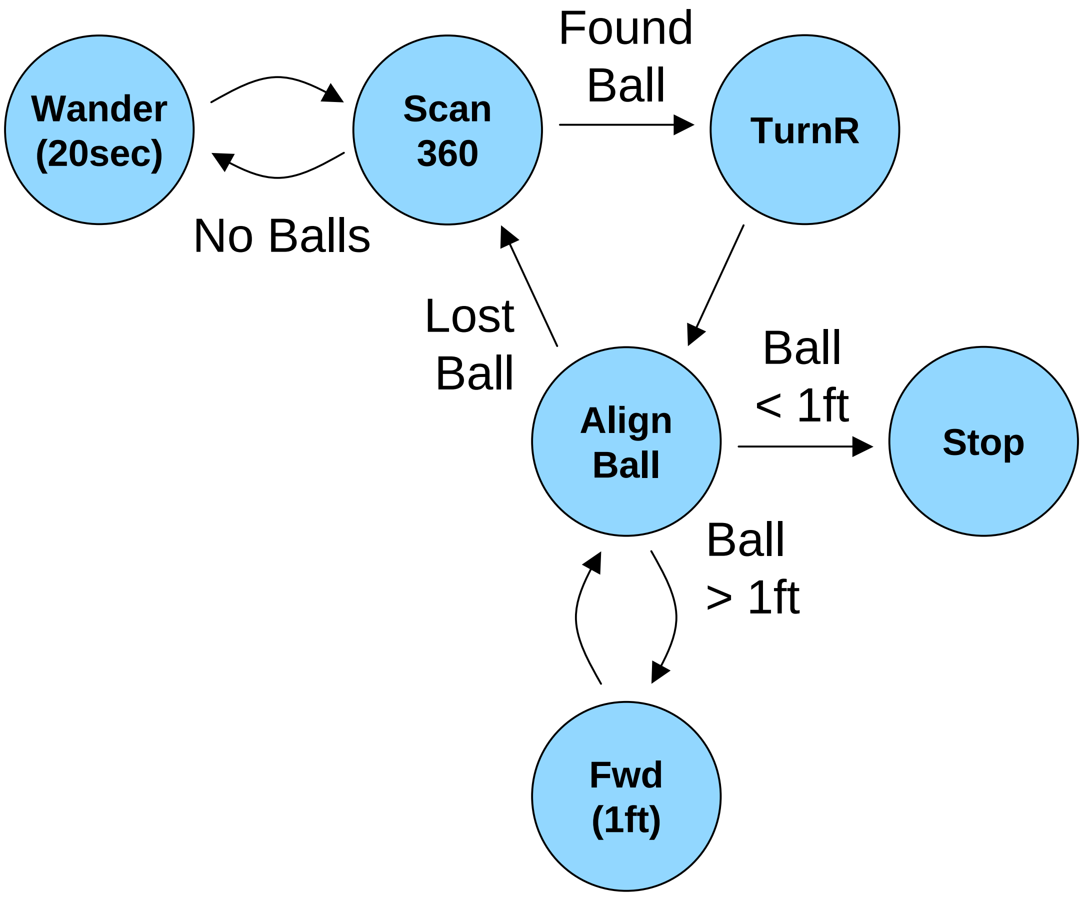
Finite State Machines offer another alternative for combining behaviors



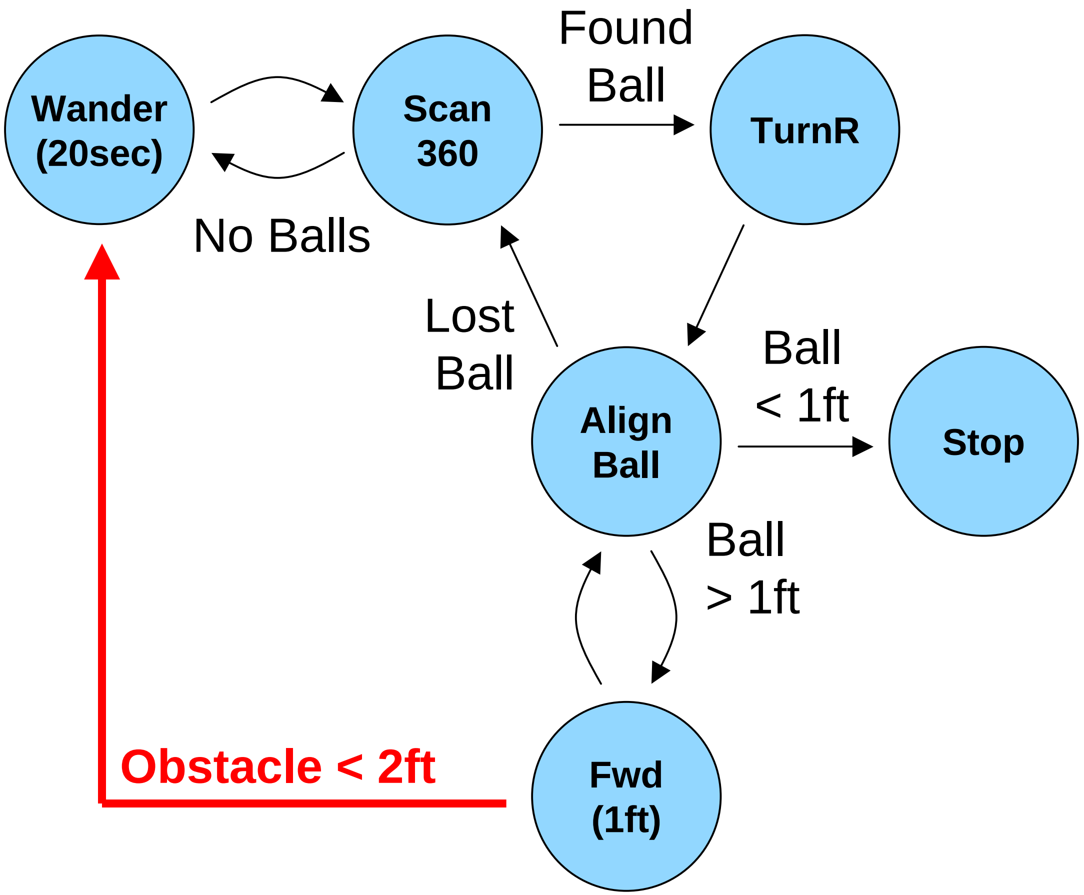


Can also fold closed loop feedback into the behaviors themselves

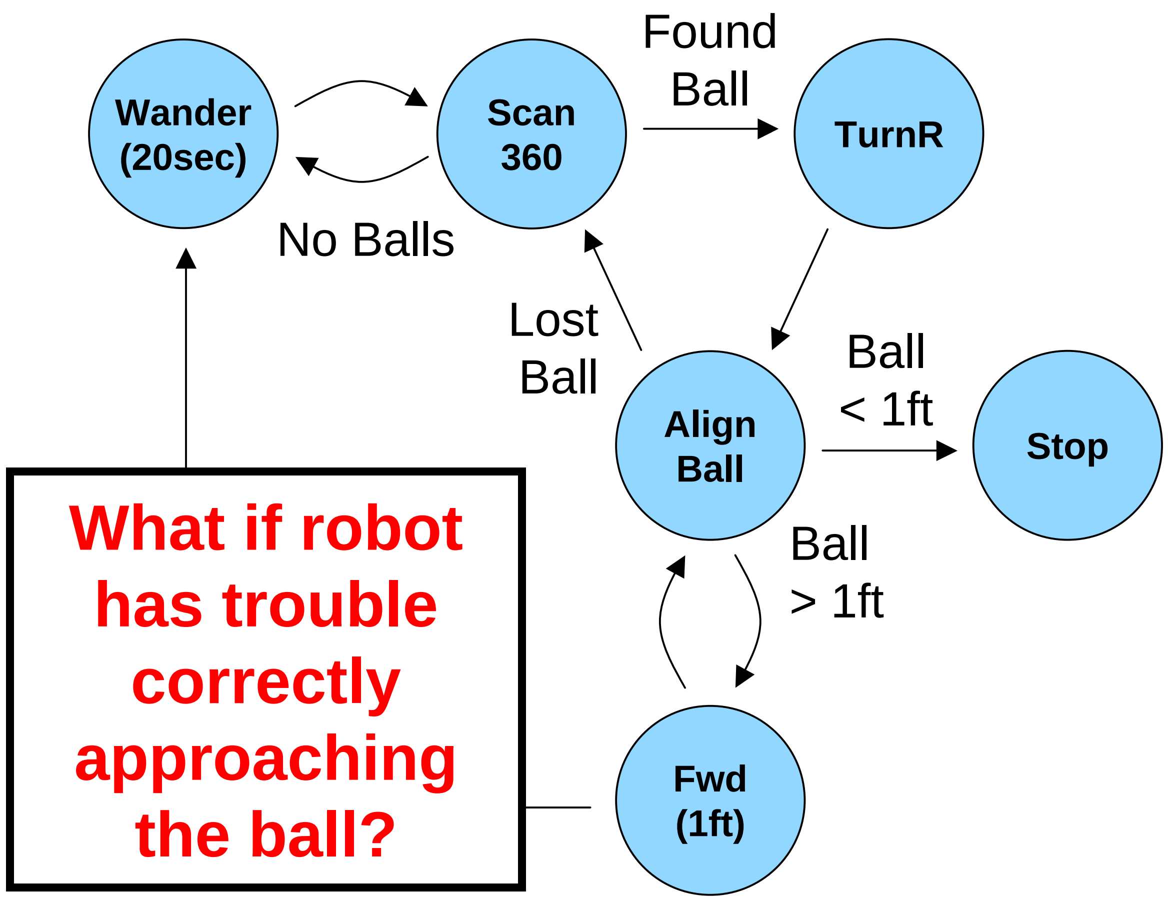
Simple finite state machine to locate red balls



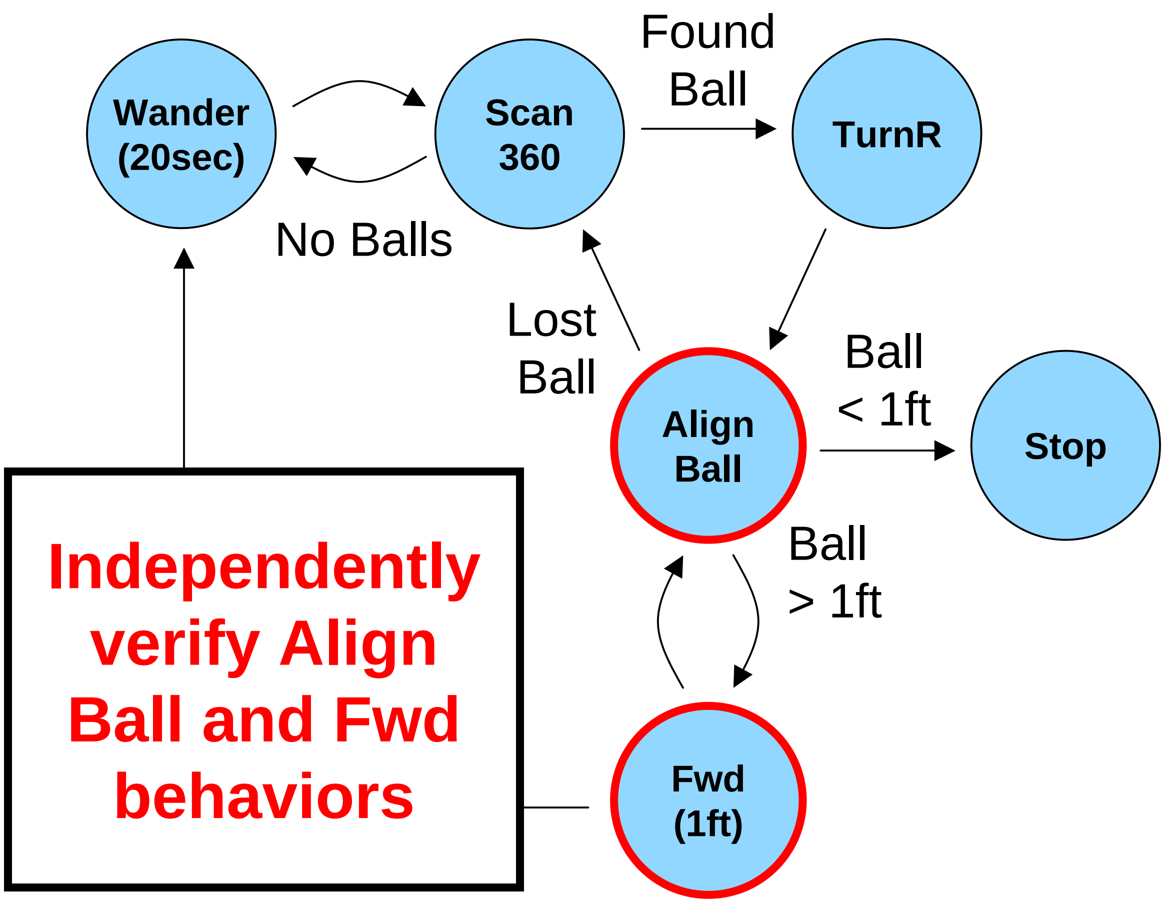
Simple finite state machine to locate red balls



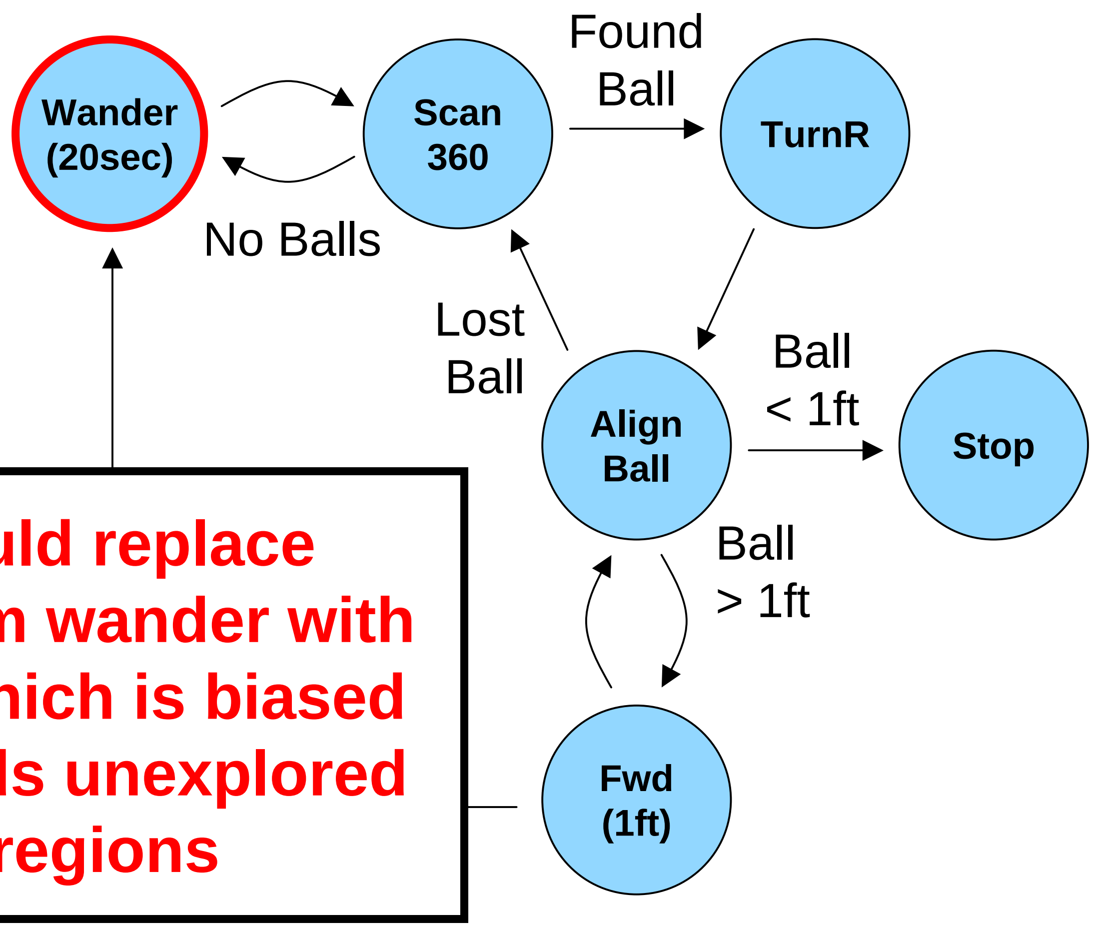
To debug a FSM control system verify behaviors and state transitions



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

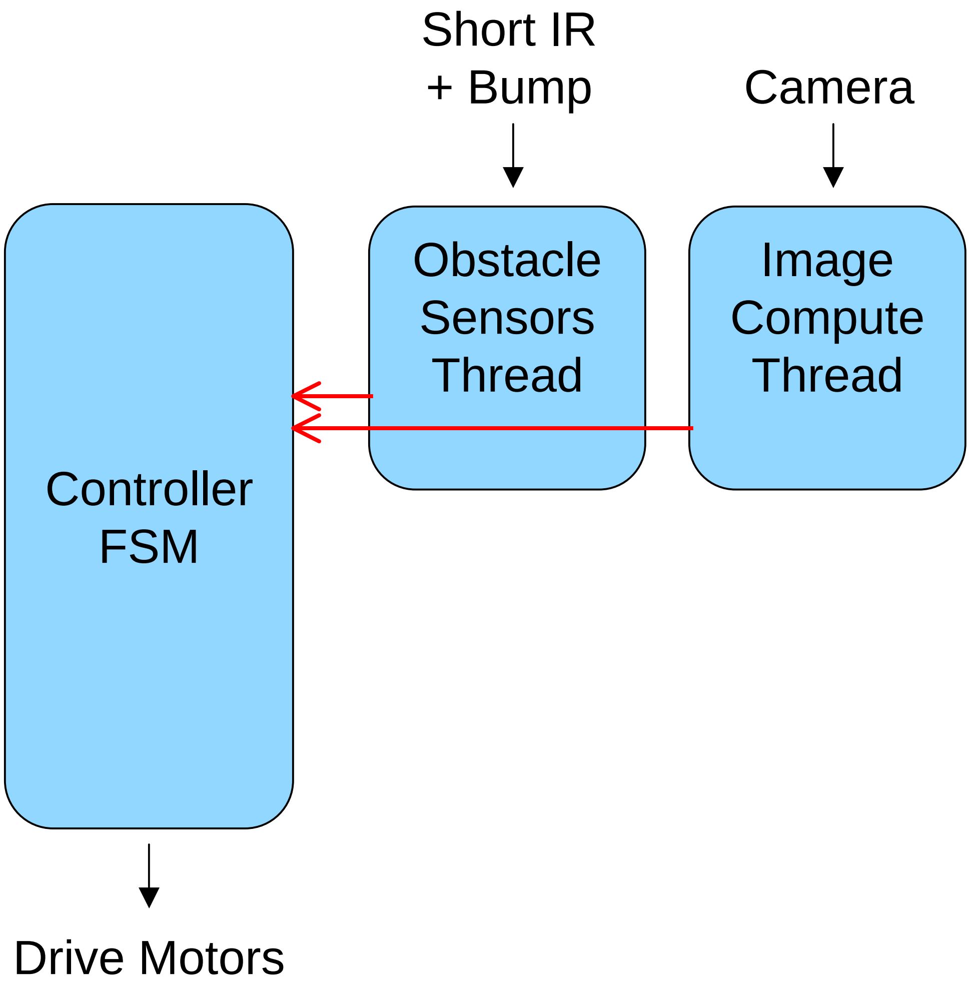
Improve FSM control system by replacing a state with a better implementation

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

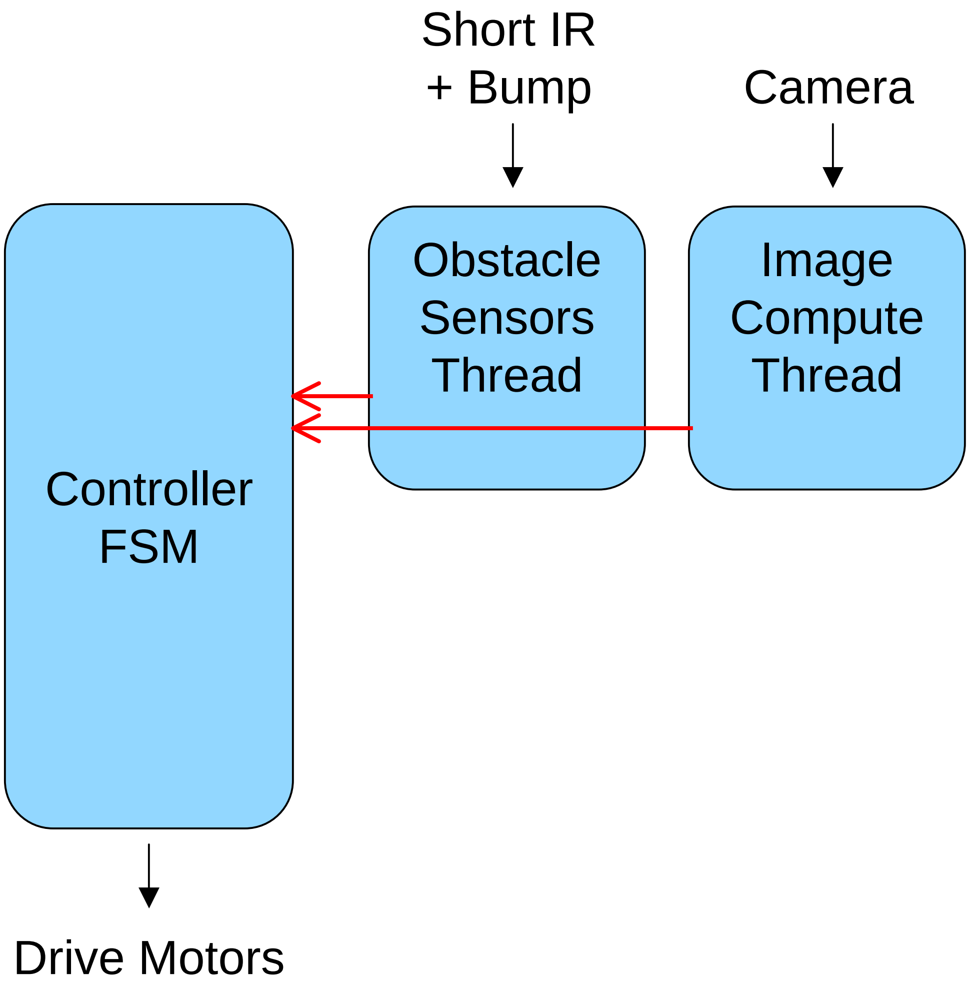
- Image processing is time consuming so might not check for obstacles until too late
- Not checking camera when rotating
- Wander behavior begins to become monolithic

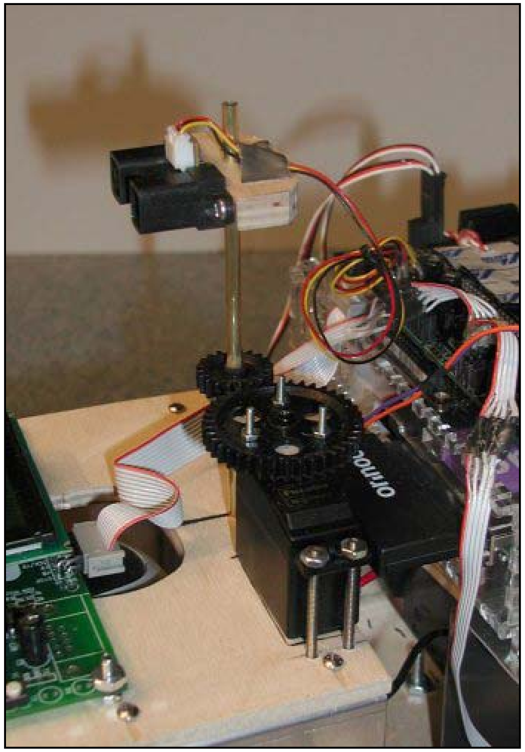
```
ball = false
turn both motors on
while ( !timeout and !ball )
  capture and process image
  if ( red ball ) ball = true

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

endwhile
```

Multi-threaded finite state machine control systems

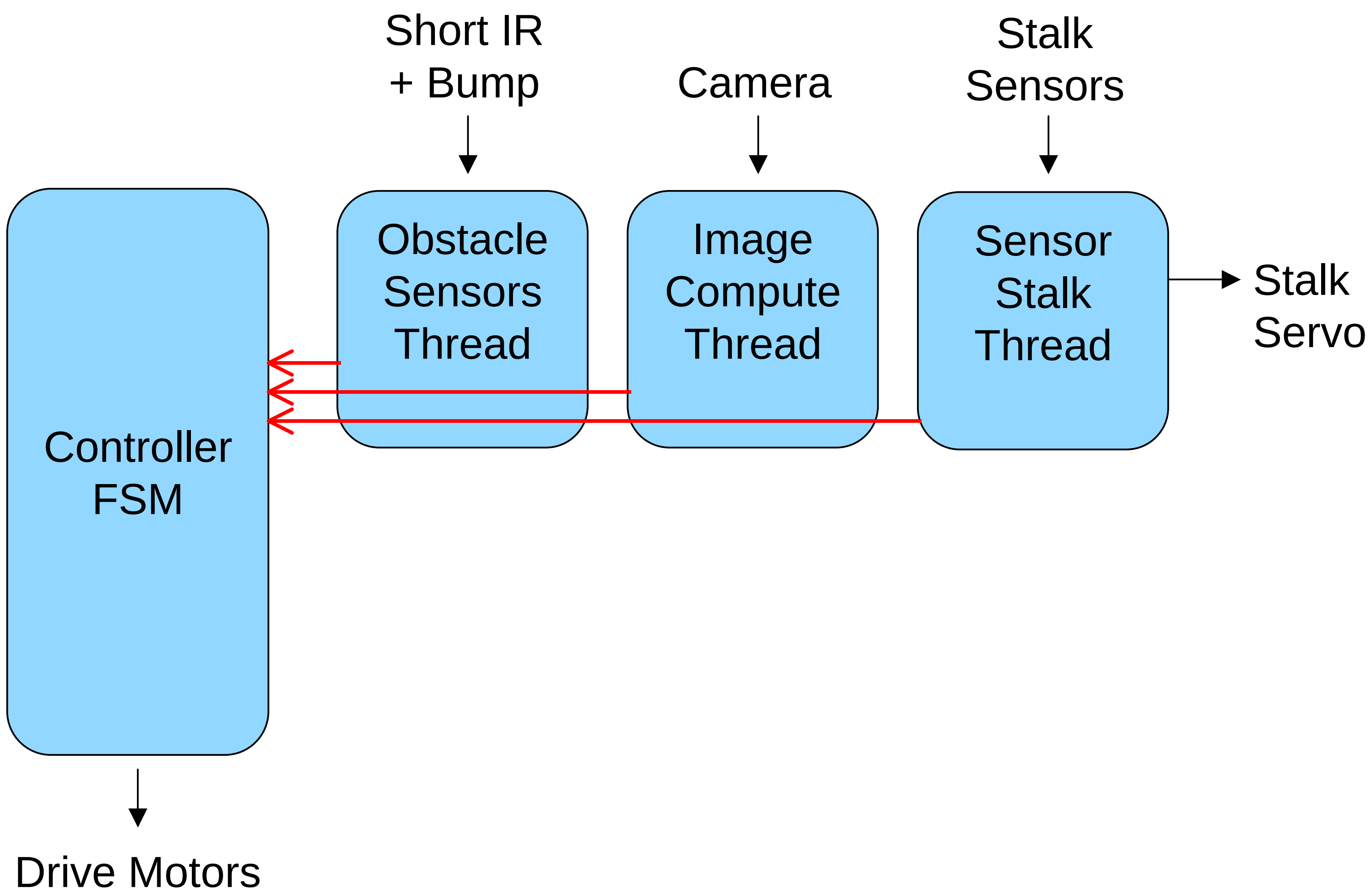


Multi-threaded finite state machine control systems

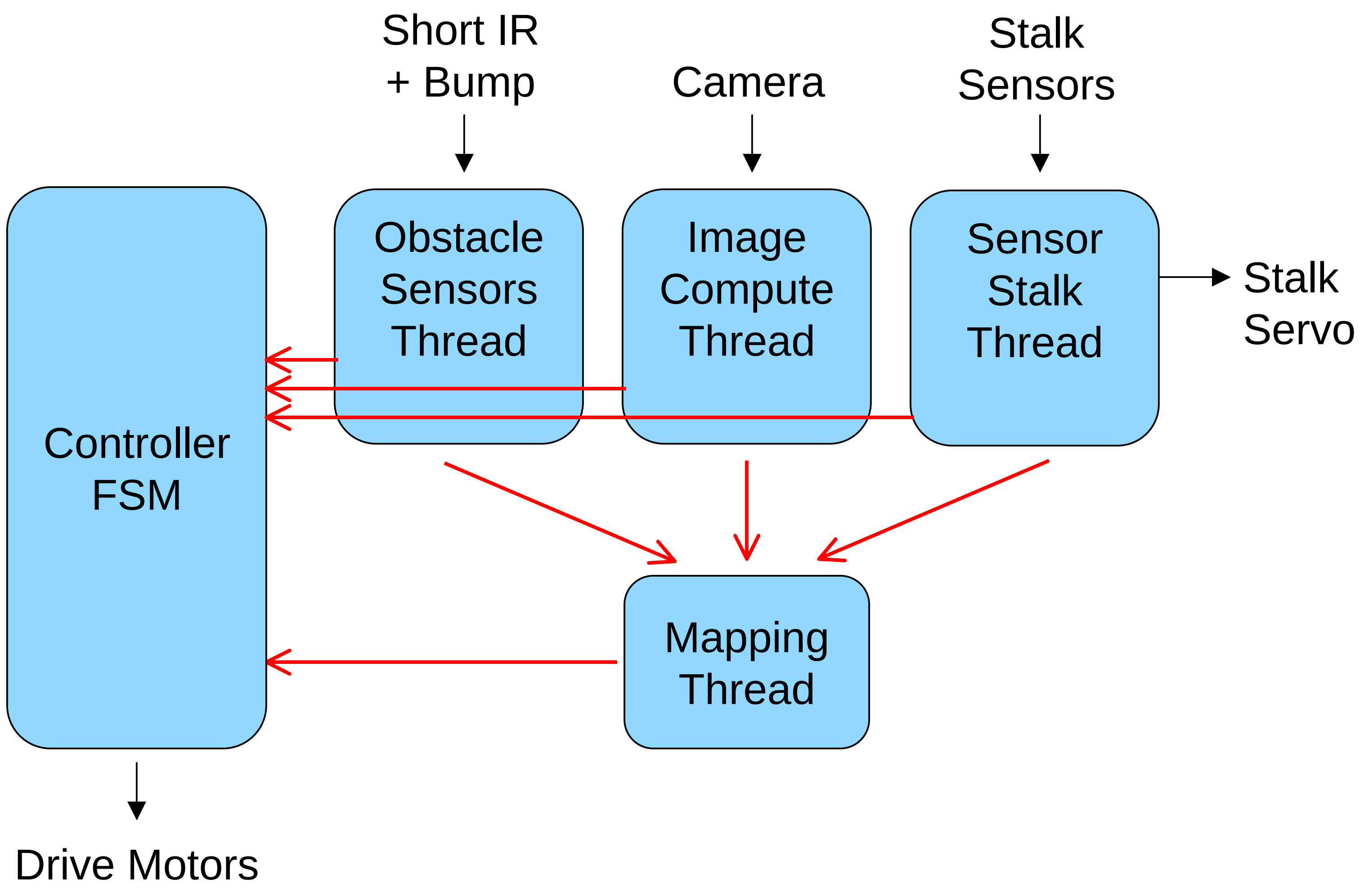




Multi-threaded finite state machine control systems



Multi-threaded finite state machine control systems



FSMs in Maslab

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

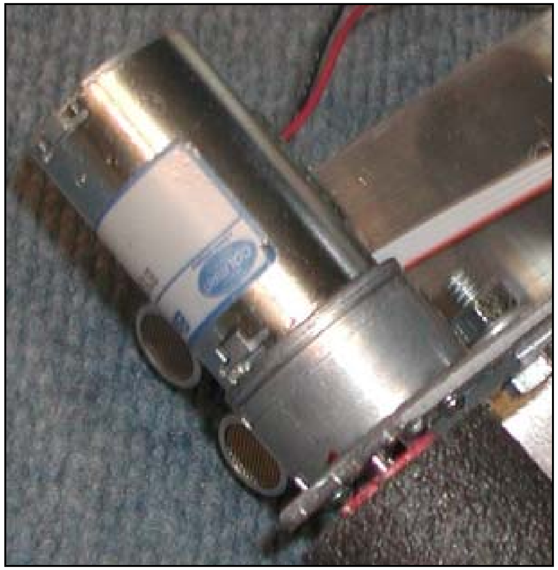
Outline

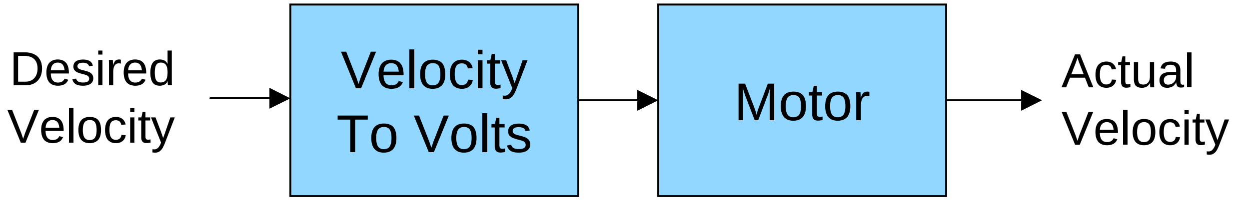
- High-level control system paradigms
  - Model-Plan-Act Approach
  - Behavioral Approach
  - Finite State Machine Approach
- **Low-level control loops**
  - **PID controller for motor velocity**
  - **PID controller for robot drive system**

Problem: How do we set a motor to a given velocity?

Open Loop Controller

- Use trial and error to create some kind of relationship between velocity and voltage
- Changing supply voltage or drive surface could result in incorrect velocity



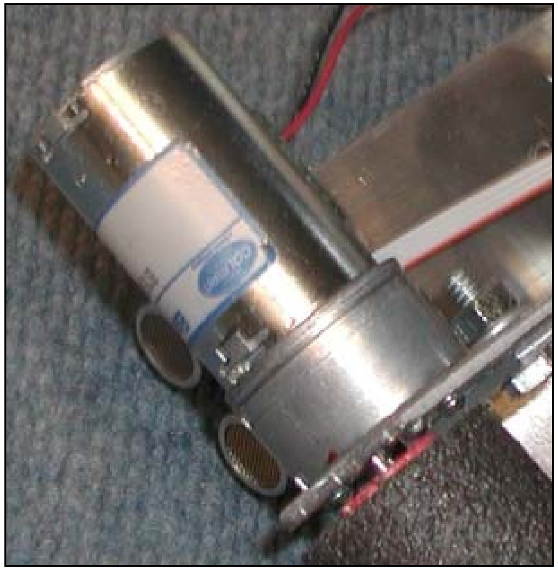


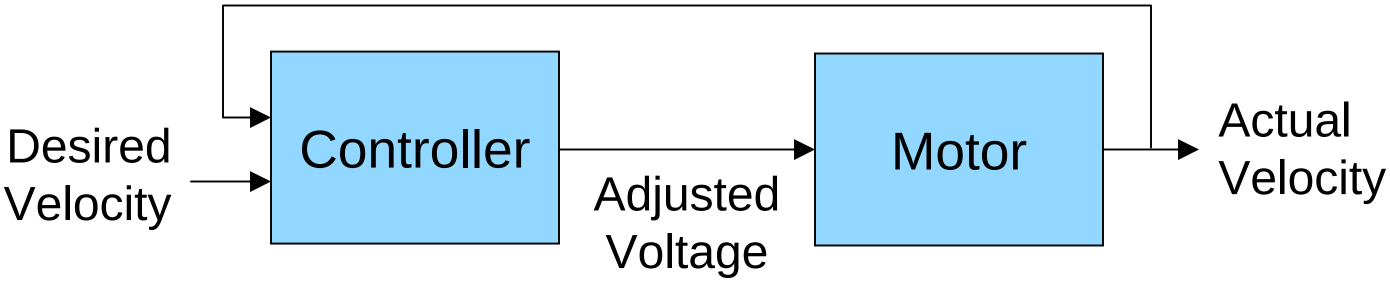
Problem: How do we set a motor to a given velocity?

Closed Loop Controller

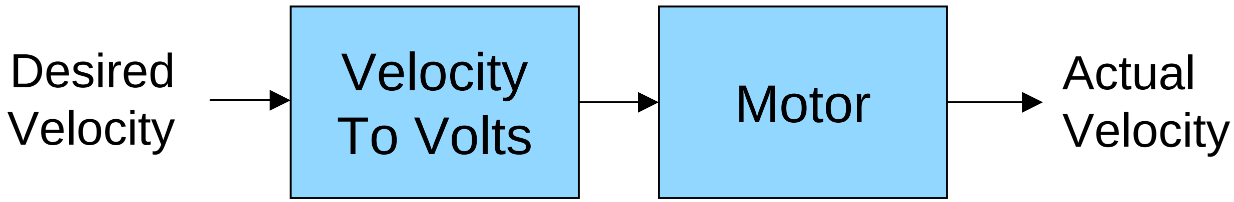
– Feedback is used to adjust the voltage sent to the motor so that the actual velocity equals the desired velocity

– Can use an optical encoder to measure actual velocity



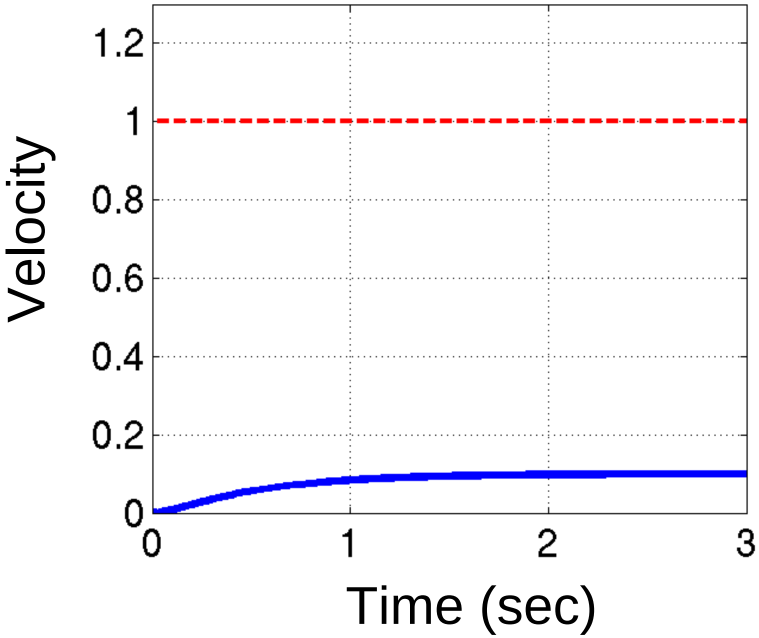


Step response with no controller

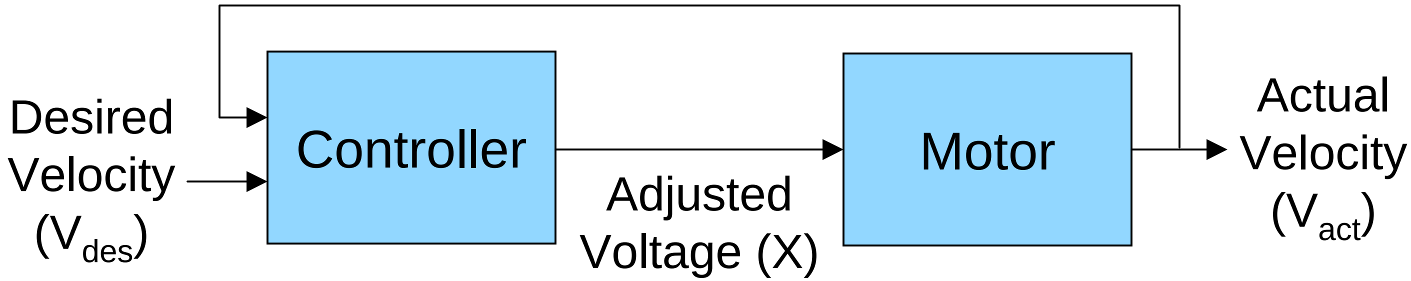


- Naive velocity to volts
- Model motor with several differential equations

- Slow rise time
- Stead-state offset

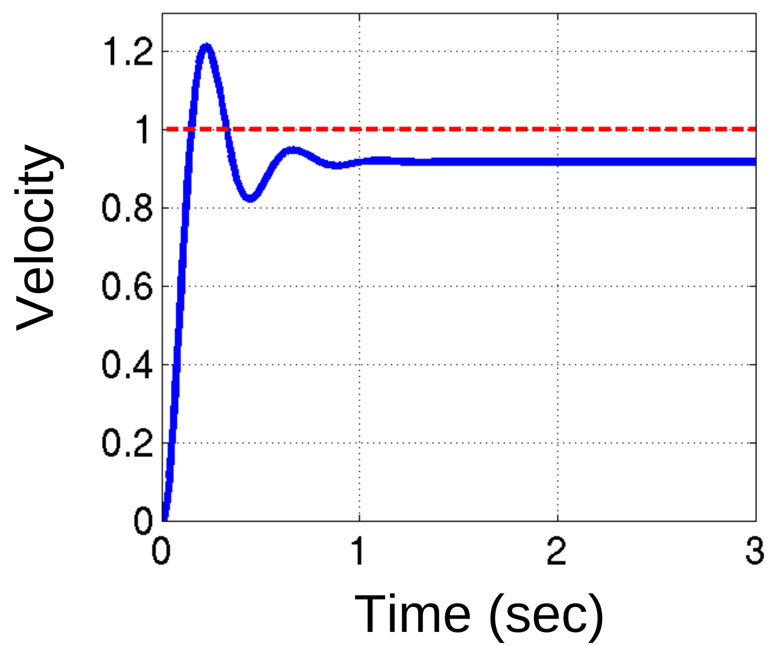


Step response with proportional controller

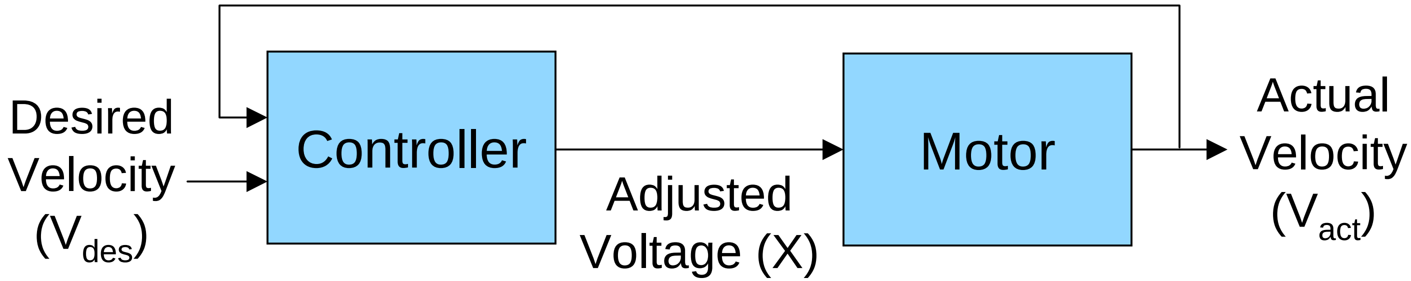


$$X = V_{des} + K_P \cdot \left(V_{des} - V_{act}\right)$$

- Big error big = big adj
- Faster rise time
- Overshoot
- Stead-state offset

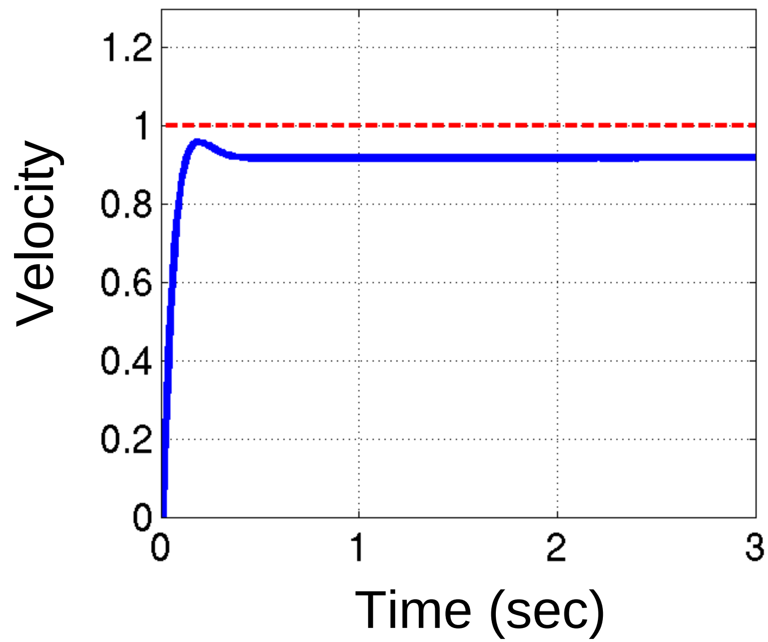


Step response with proportional-derivative controller

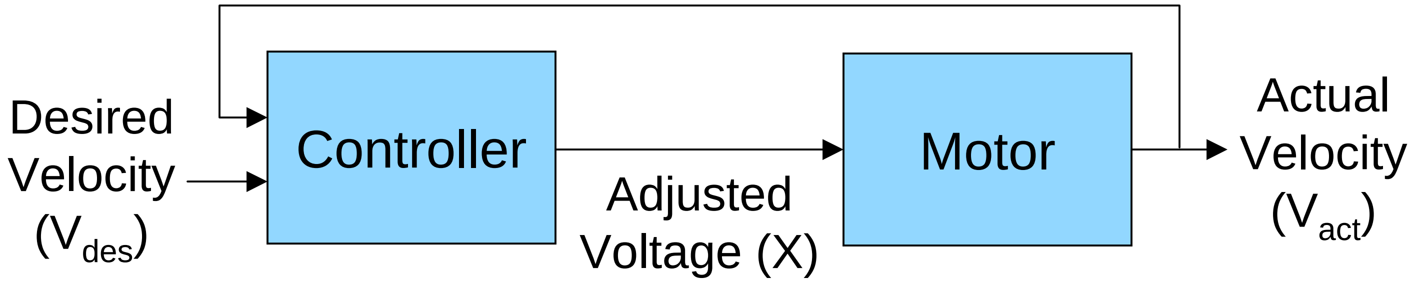


$$X = V_{des} + K_P e(t) - K_D \frac{de(t)}{dt}$$

- When approaching desired velocity quickly, de/dt term counteracts proportional term slowing adjustment
- Faster rise time
- Reduces overshoot

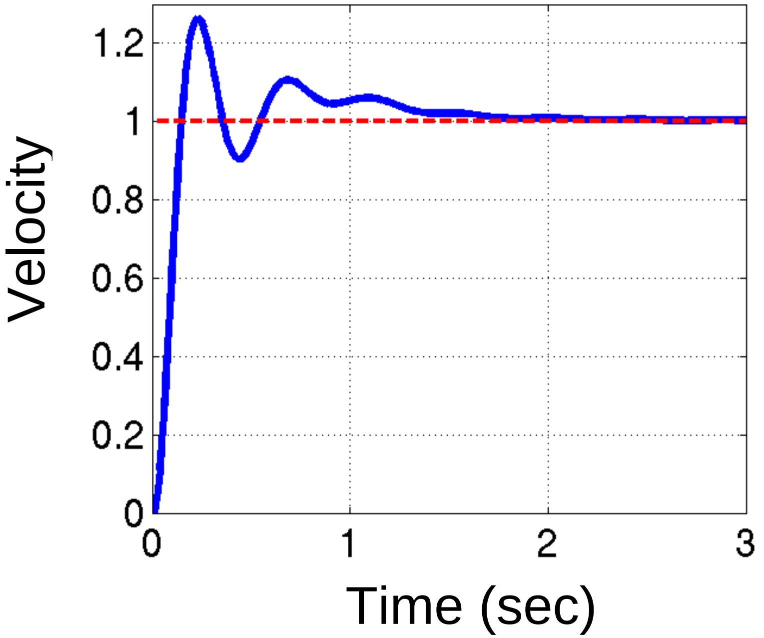


Step response with proportional-integral controller

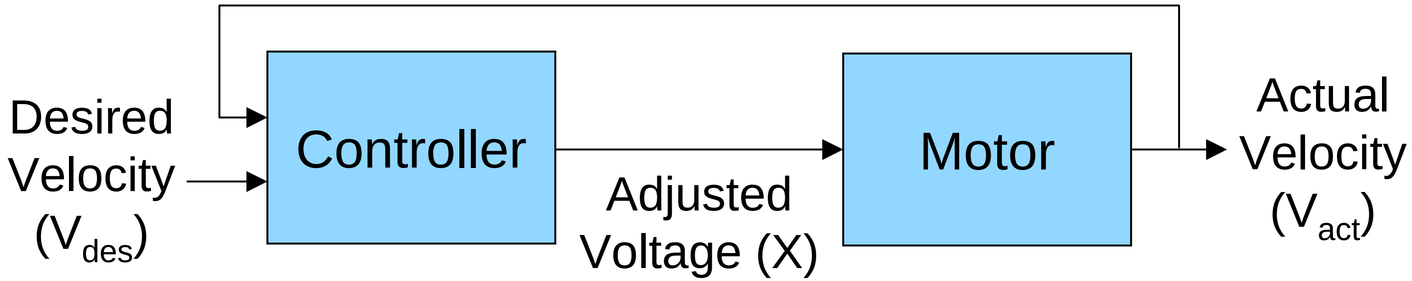


$$X = V_{des} + K_P e(t) - K_I \int e(t)\, dt$$

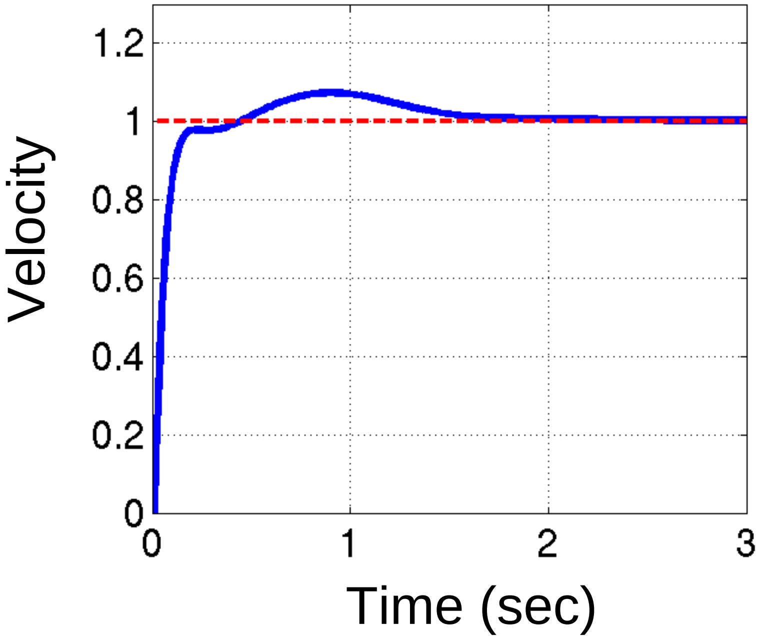
- Integral term eliminates accumulated error
- Increases overshoot



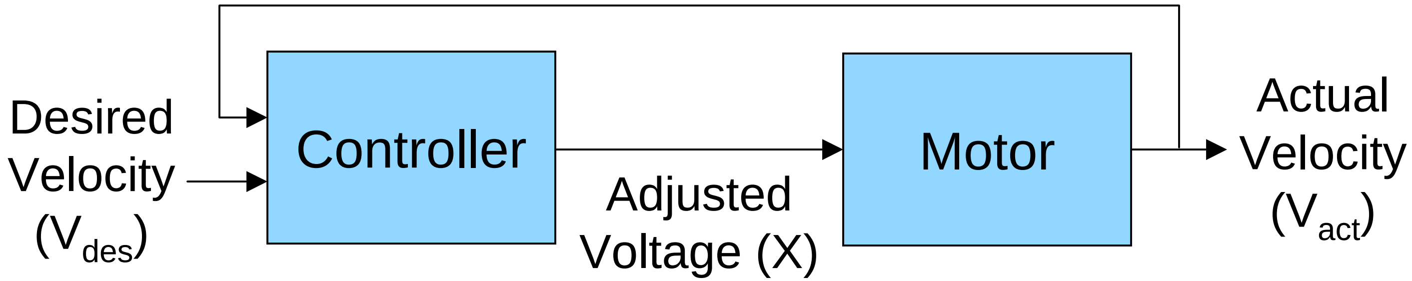
Step response with PID controller



$$X = V_{des} + K_P e(t) + K_I \int e(t)\, dt - K_D \frac{de(t)}{dt}$$

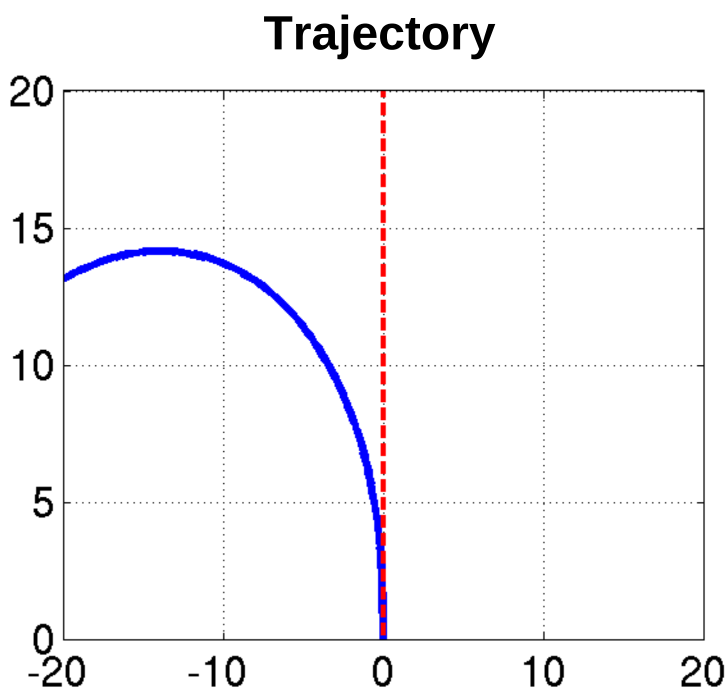


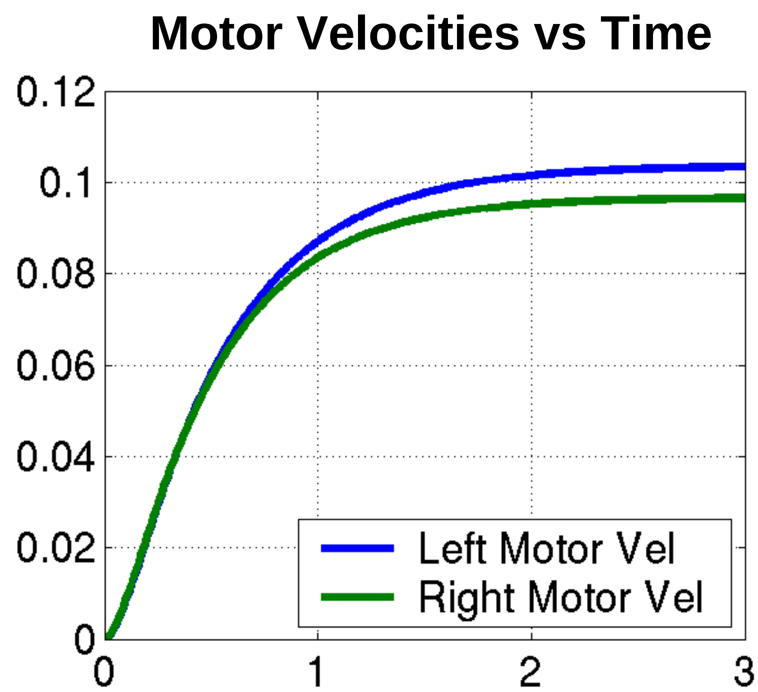
Choosing and tuning a controller



- Use the simplest controller which achieves the desired result
- Tuning PID constants is very tricky, especially for integral constants
- Consult the literature for more controller tips and techniques

Problem: How do we make our robots go in a nice straight line?

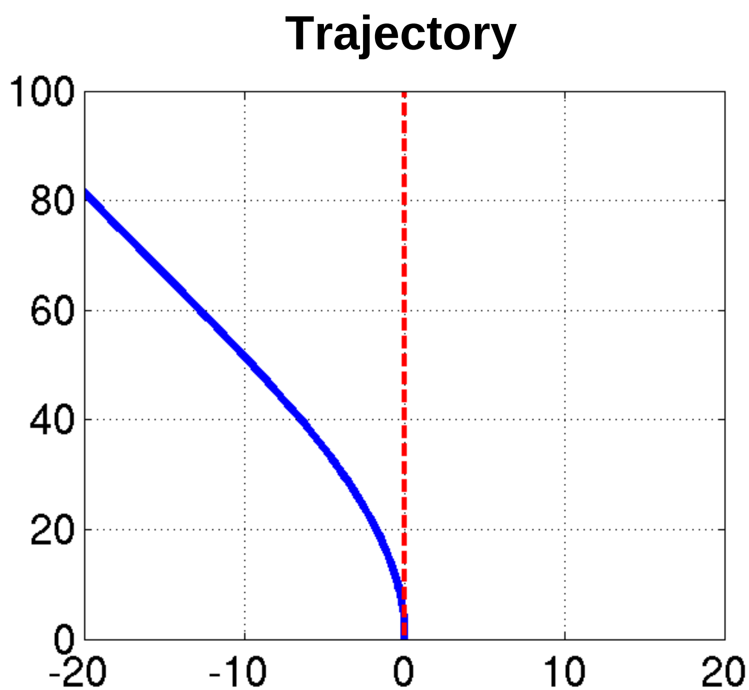


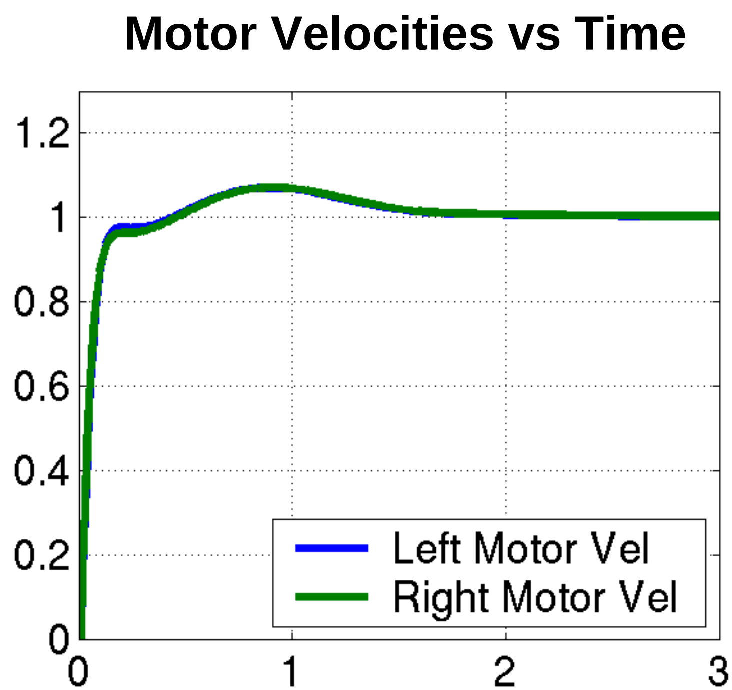


Model differential drive with slight motor mismatch

With an open loop controller, setting motors to same velocity results in a less than straight trajectory

Problem: How do we make our robots go in a nice straight line?

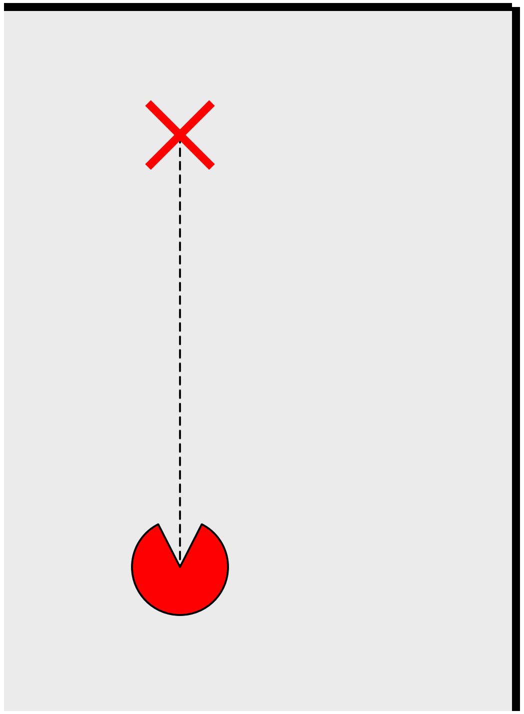




With an independent PID controller for each motor, setting motors to same velocity results in a straight trajectory but not necessarily straight ahead!

Problem: How do we make our robots go in a nice straight line?

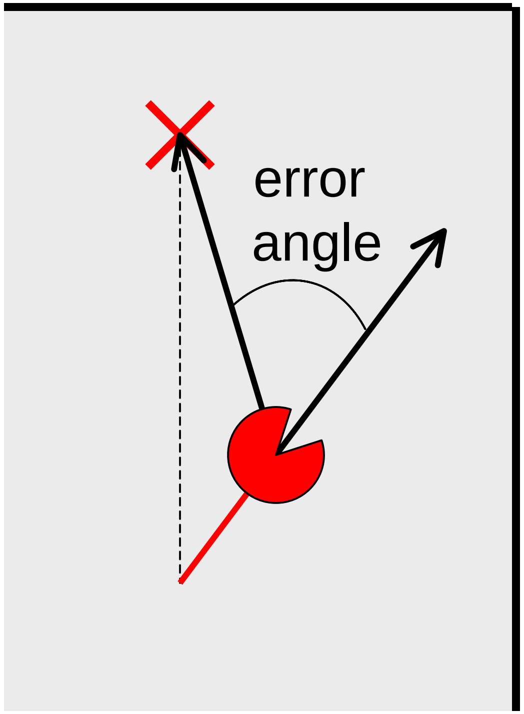
- Need to couple drive motors
  - Use low-level PID controllers to set motor velocity and a high-level PID controller to couple the motors
  - Use one high-level PID controller which uses odometry or even image processing to estimate error



Problem: How do we make our robots go in a nice straight line?

Need to couple drive motors

- Use low-level PID controllers to set motor velocity and a high-level PID controller to couple the motors
- Use one high-level PID controller which uses odometry or even image processing to estimate error



Take Away Points

- Integrating **feedback** into your control system "closes the loop" and is essential for creating robust robots
- Simple **finite state machines** make a solid starting point for your Maslab control systems
- Spend time this weekend **designing behaviors** and deciding how you will **integrate** these behaviors to create your control system