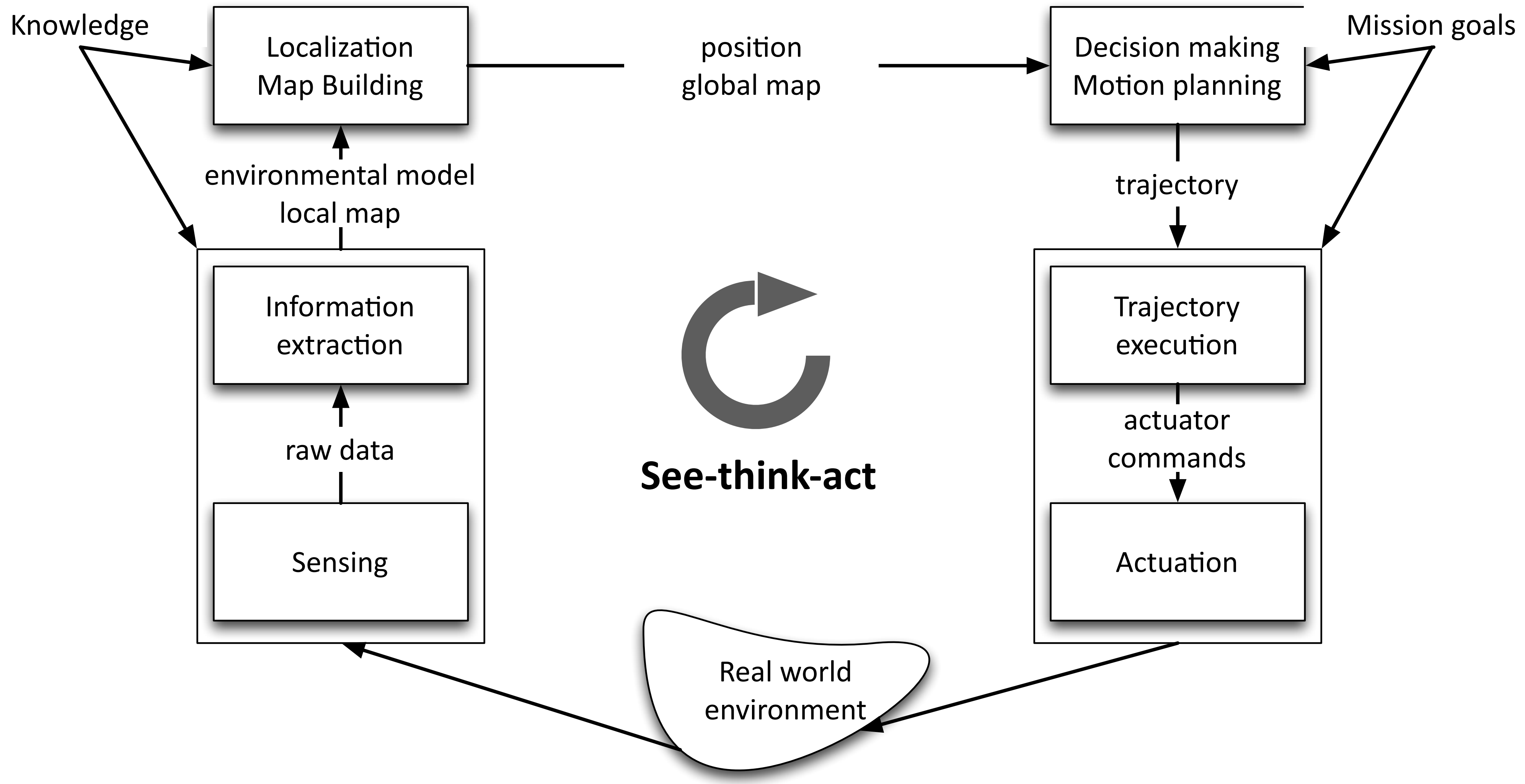
Principles of Robot Autonomy I

Finite state machines

IPRL

Autonomous Systems Lab

The see-think-act cycle

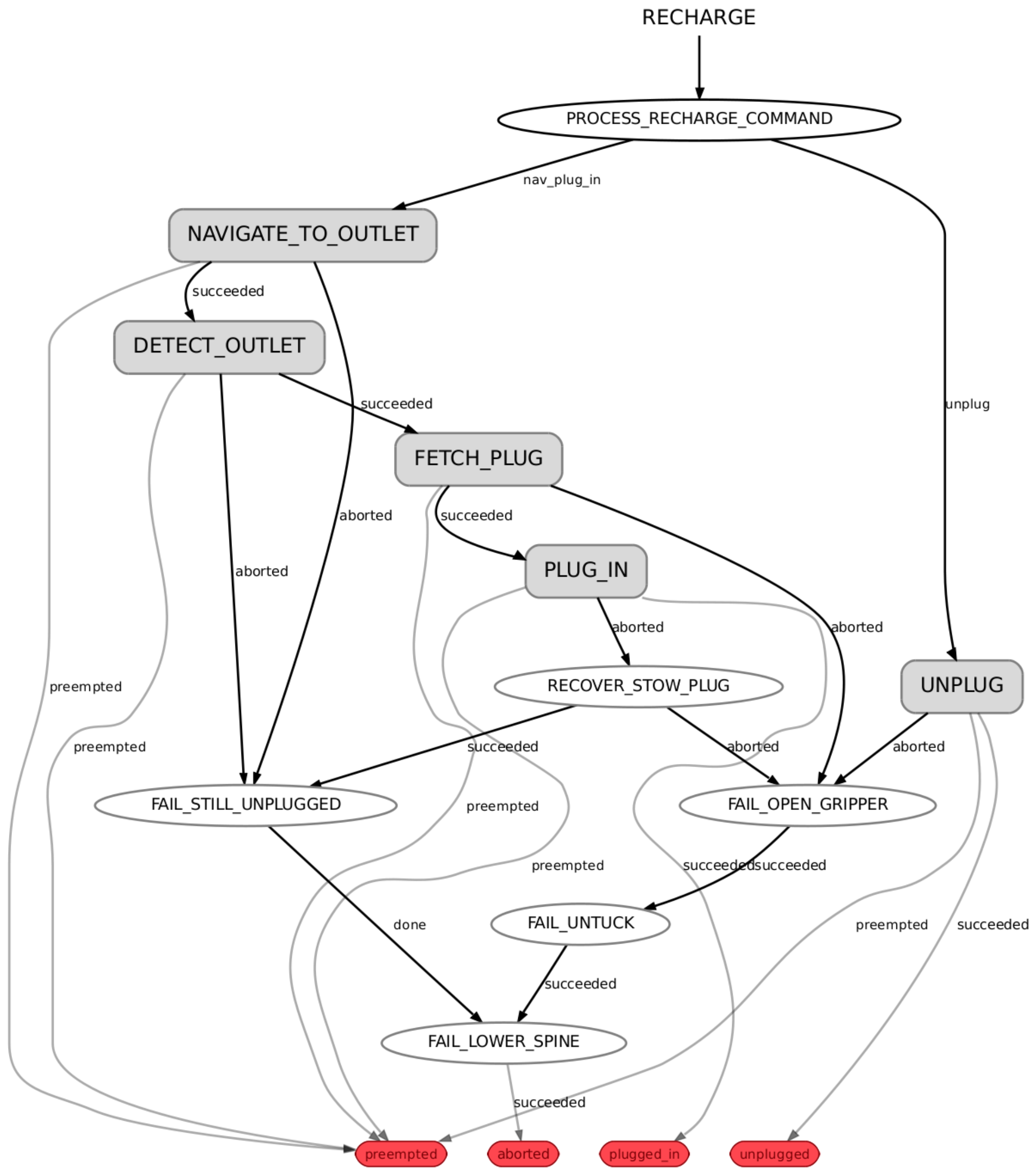


Today’s lecture

- Aim
  - Introduce and formalize the concept of Finite State Machines (FSMs)
  - Discuss their relevance, strengths and limitations
  - Introduce tools to allow you to use them effectively

- Readings
  - Chapter 4 of Leslie Kaelbling, Jacob White, Harold Abelson, Dennis Freeman, Tomás Lozano-Pérez, and Isaac Chuang. *6.01SC Introduction to Electrical Engineering and Computer Science I.* Spring 2011. Massachusetts Institute of Technology: MIT OpenCourseWare.

Motivation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PROCESS_RECHARGE_COMMAND
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NAVIGATE_TO_OUTLET
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unplugged

Finite State Machines

Definition*: A computational model for systems whose output depends on the **entire history** of their inputs.*

A finite state machine is a modeling framework, NOT an algorithm (similar to Markov decision processes, probability densities, factor graphs etc.)

Finite State Machines in practice

- In practice, used in many different ways
  - Synthetically (specifies a program)
    - E.g. a product manager and an engineer specifies how an ATM machine should "behave" before starting its implementation
  - Analytically (describe the behavior of a combination of systems)
    - E.g. two self-driving cars could be modeled as FSMs. An engineer could try to see if they might end up stuck in some infinite loop at an intersection
  - Predictively (to predict interaction with an environment)
    - A self-driving car could have an internal model of a pedestrian as an FSM and use it to figure out how it should behave around it

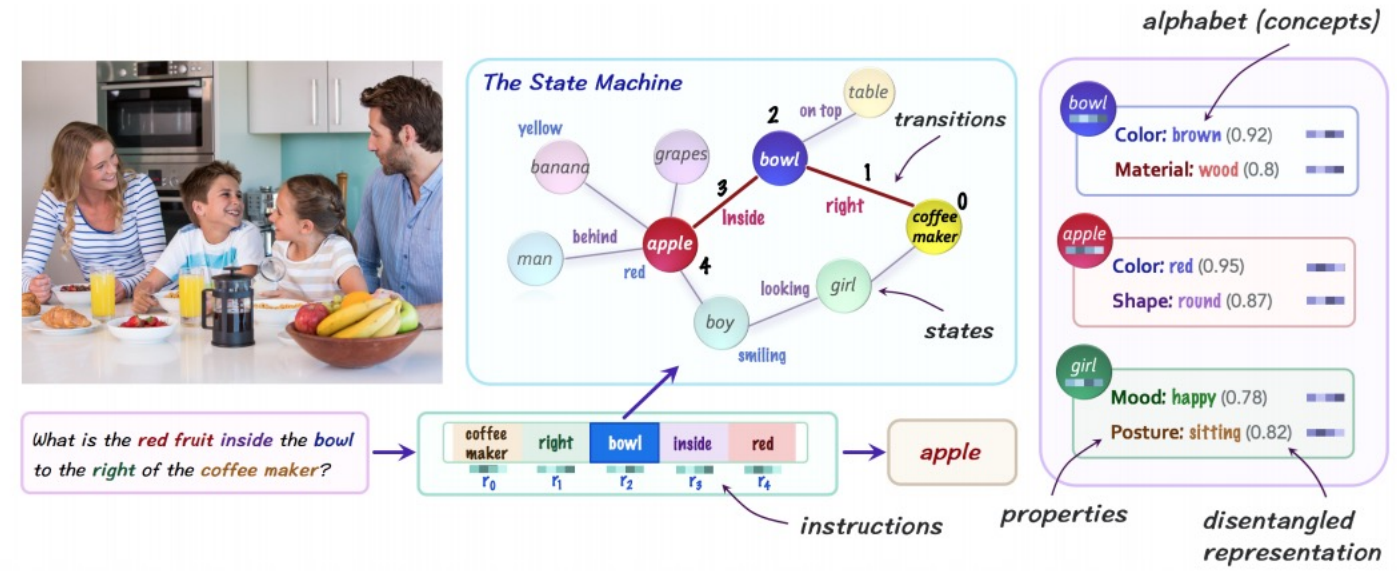
Why are we teaching FSMs?

- For the practitioner: designing the extremely complex state machines required to fly drones, drive self-driving cars or operate warehouse robots is still one of the most time-consuming/difficult tasks faced by companies…

- How do we handle the failure of a combination of sensors gracefully?
- How do we negotiate an intersection?
- How do I get my turtlebot to start backtracking after a collision?

Why are we teaching FSMs?

- For the researcher: It's a fundamental building block of how we understand computation, and still relevant to research today...



Hudson, Drew A., and Christopher D. Manning. "Learning by abstraction: The neural state machine." *arXiv preprint arXiv:1907.03950* (2019).

Mathematical definition

- Sets:
  - A set of states S
  - A set of inputs I, called the input vocabulary
  - A set of outputs O, called the output vocabulary
- Maps:
  - Next-state function that maps input and the state to the next state $n(i_t, s_t) \to s_{t+1}$
  - Output function $o(i_t, s_t) \to o_t$
- An initial state s_0

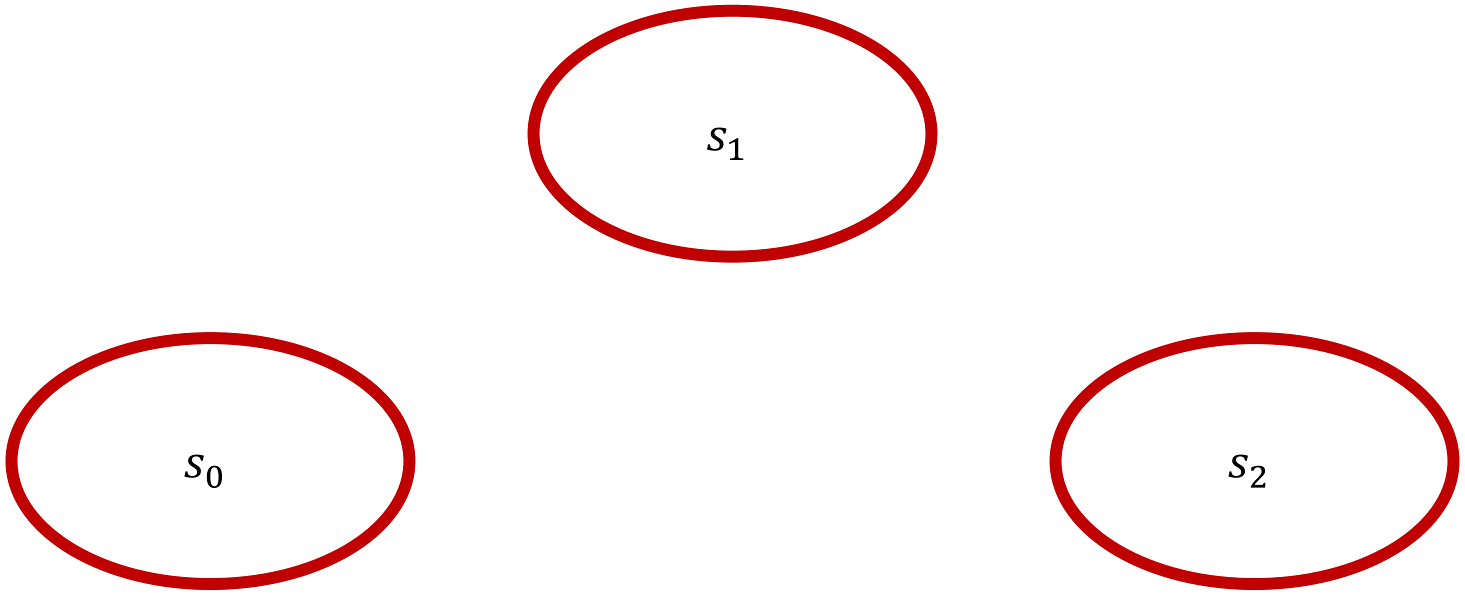
Graphical representation

- Given the sets (S, I, O), it is common to express the maps (n, o) by using a graph

$S: \{s_0, s_1, s_2\}$

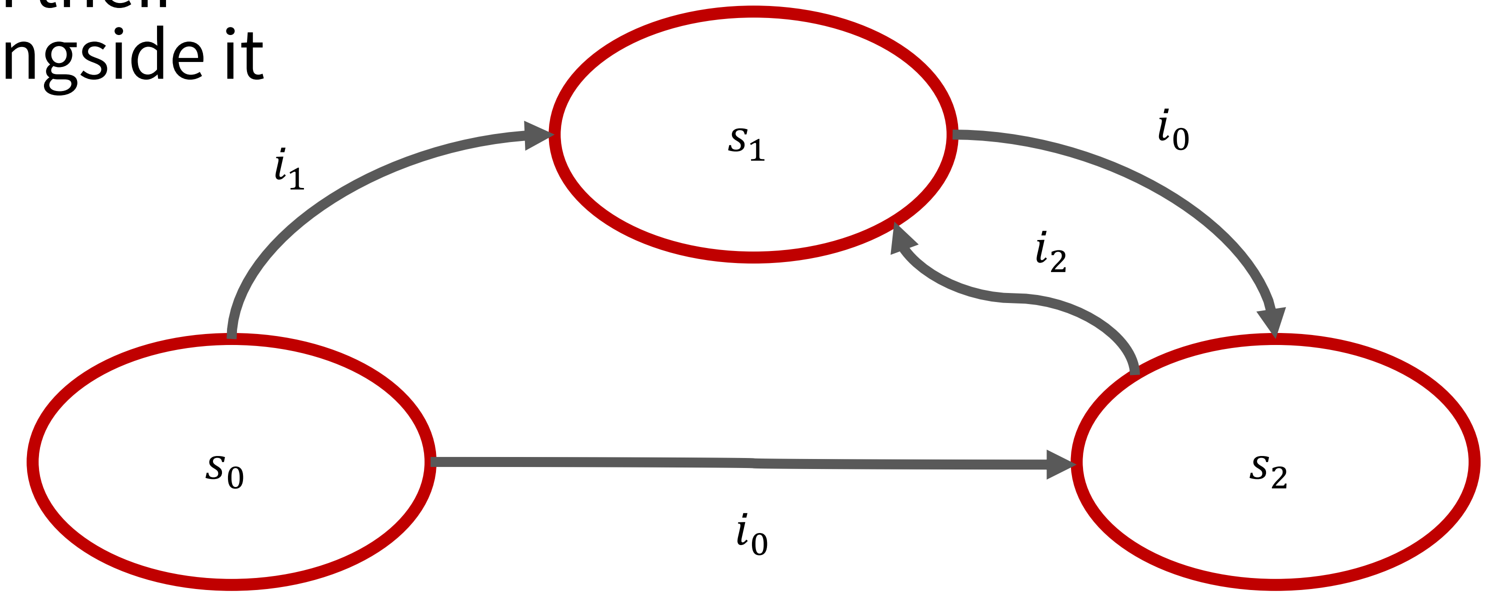
I: $\{i_0, i_1, i_2\}$

O: $\{o_0, o_1\}$



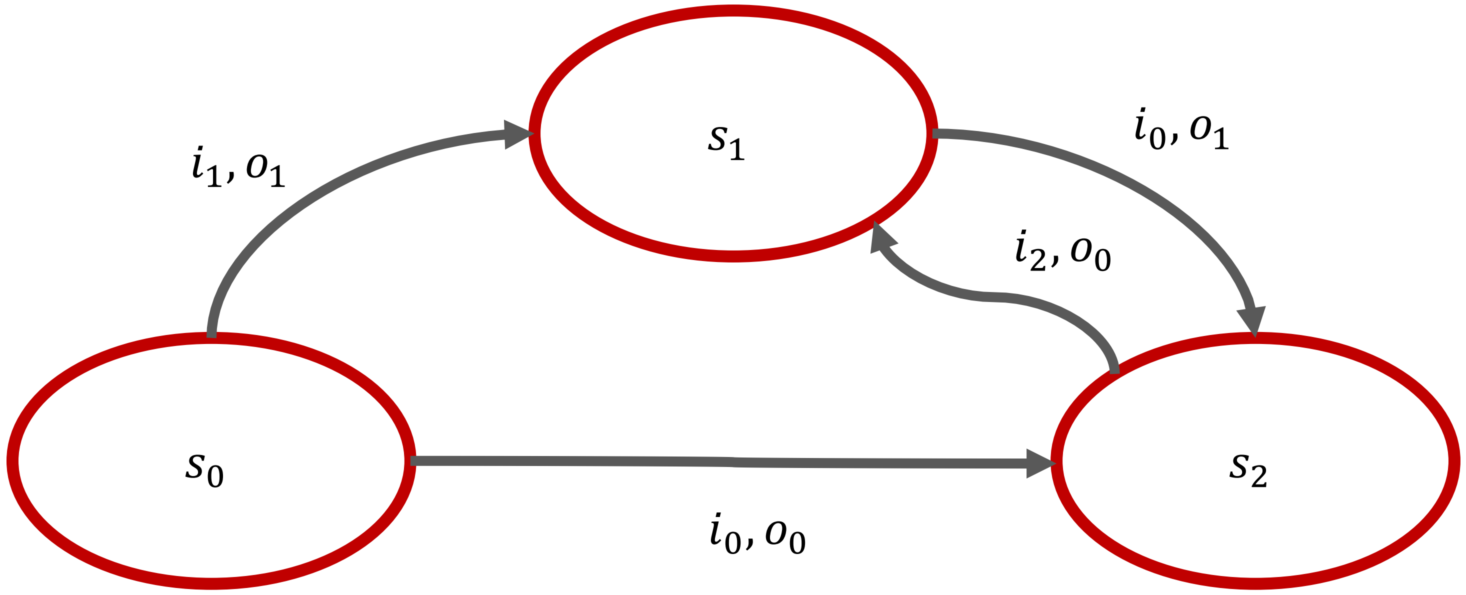
Graphical representation

The transition (next-state) map is represented by arrows between states, with their associated input alongside it



Graphical representation

The output map is written alongside each transition



$$\begin{tikzcd} & s_1 \arrow[dr, bend left, "{i_0, o_1}"] & \\ s_0 \arrow[ur, bend left, "{i_1, o_1}"] \arrow[rr, "{i_0, o_0}"'] & & s_2 \arrow[ul, bend left, "{i_2, o_0}"] \end{tikzcd}$$

Example: parking gate control

The gate can be in one of three positions: ‘top’, ‘middle’ or ‘bottom’

A sensor tells the gate if a car is waiting in front of it

A sensor tells the gate if a car has just passed through it

The gate can take the following actions: raise the gate, lower the gate, no operation (nop).

We want the following behavior:

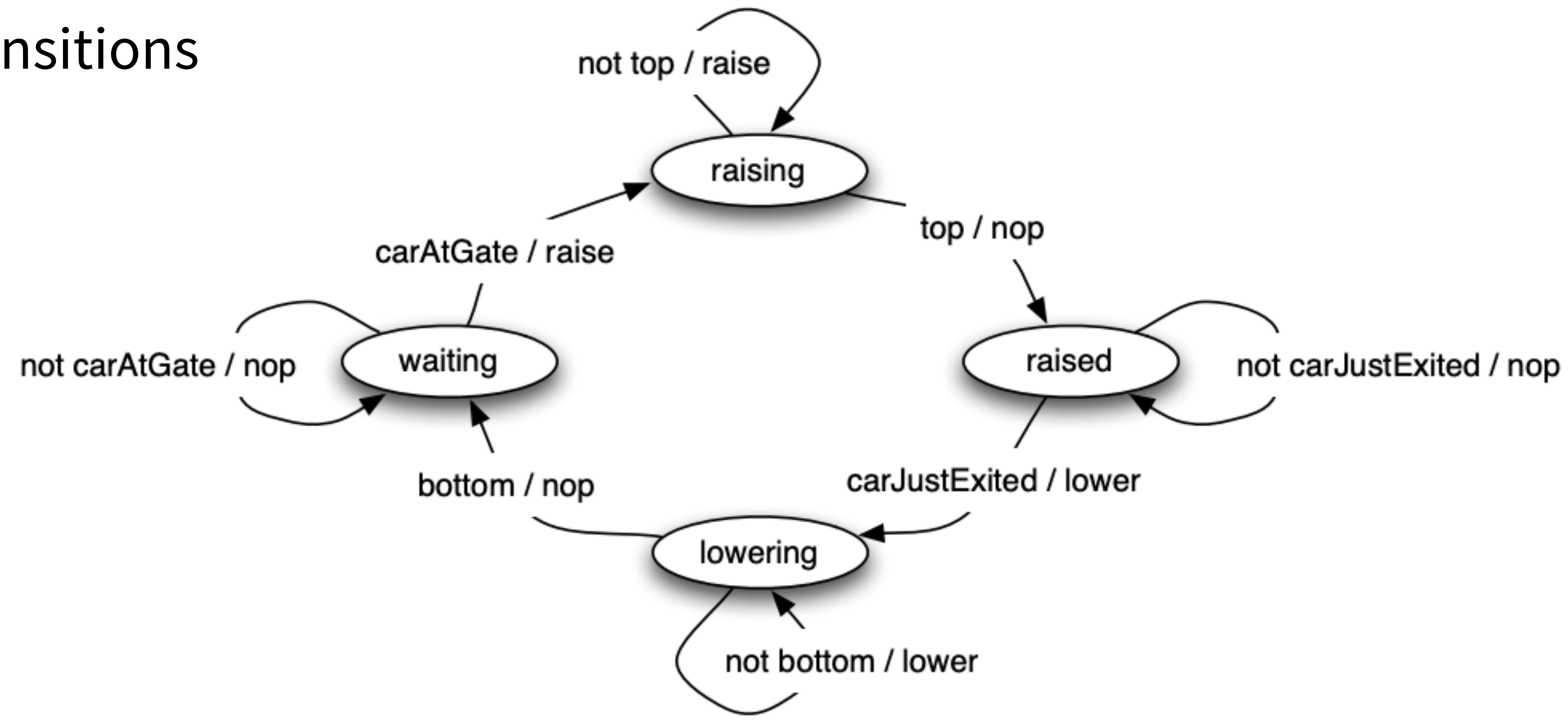
- If a car wants to come through, need to raise the arm to ‘top’ position
- The gate has to stay there until the car has driven though the gate
- The gate has to go back down after the car has gone through

Example: parking gate control

- States: ‘waiting’, ‘raising’, ‘raised’, ‘lowering’
- Input: ‘no car at gate’, ‘car at gate’, ‘gate at top’, ‘not gate at top’, ‘gate at bottom’, ‘not gate at bottom’, ‘car just exited’, ‘not car just existed’
- Output: ‘raise’, ‘lower’, ‘nop’

Example: parking gate control

- Transitions

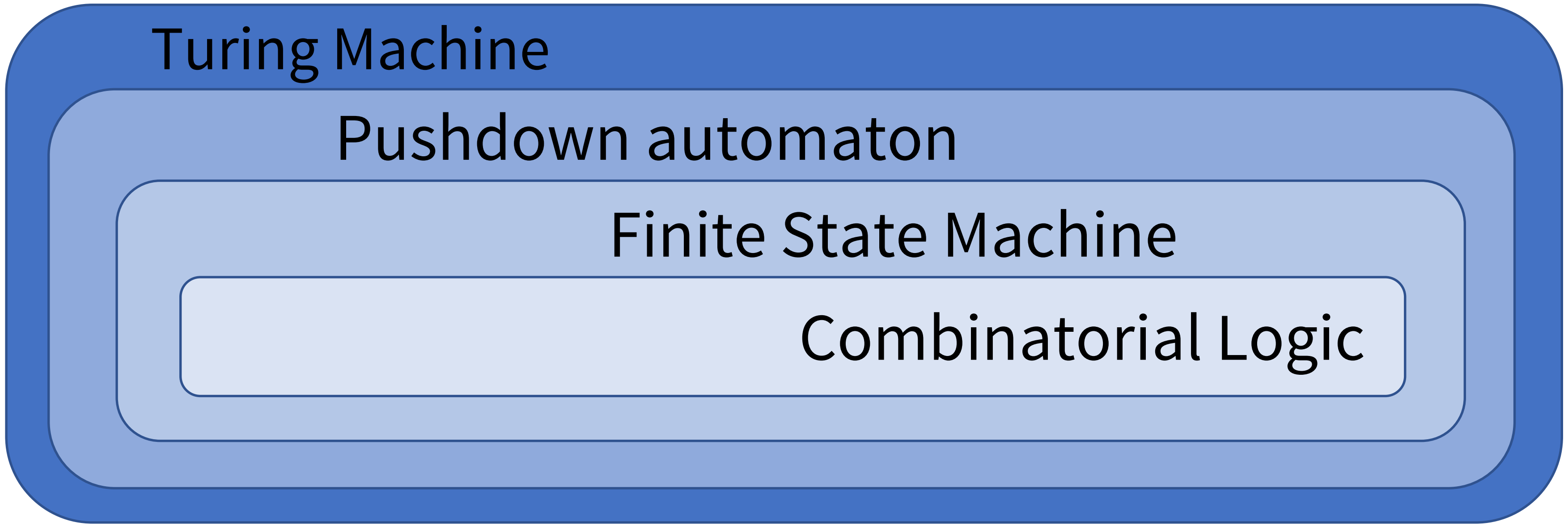


Example: parentheses balancing

- We want to design an automata that can read a string of text of any length and say whether or not the parentheses in the string are balanced or not
  - Balanced: ”1 + (2 + 3 – (4 * 5))”
  - Not balanced: “1 + (2 + 3 – 4 * 5))”
- “… a string of text of **any length**…”
- A robot that can accomplish such a task would need an infinite number of states… and cannot therefore be represented by a **finite** state machine

FSM in the bigger picture of computation

- In terms of computational power, (deterministic) finite state machines are actually somewhat low on the totem pole of automata… with Turing Machines somewhere close to the top.



A Turing Machine could solve our parentheses balancing problem!

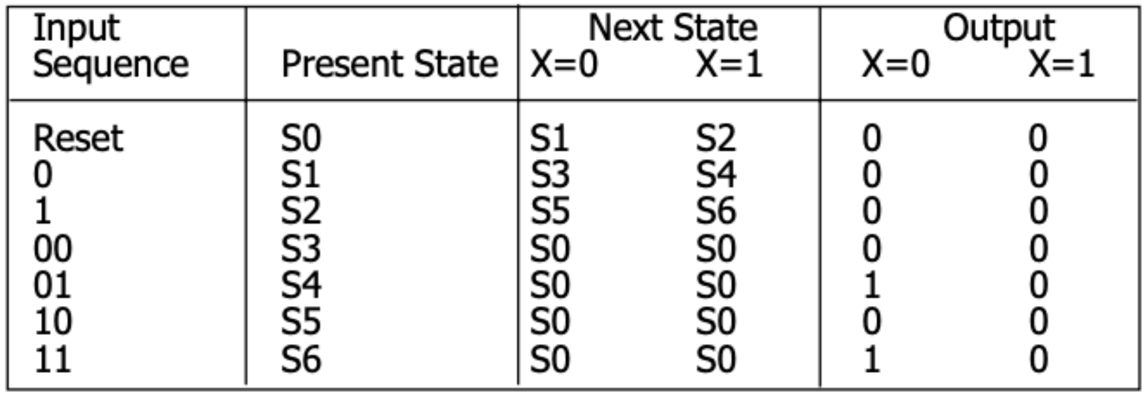
Architecture

- The architecture of finite state machines can become quite complex
- Additional states can generate an exponential number of transitions
- Strategies to keep the architecture tractable:
    1. Reduction of redundant states
    2. Hierarchical finite state machines
    3. Composition using common patterns

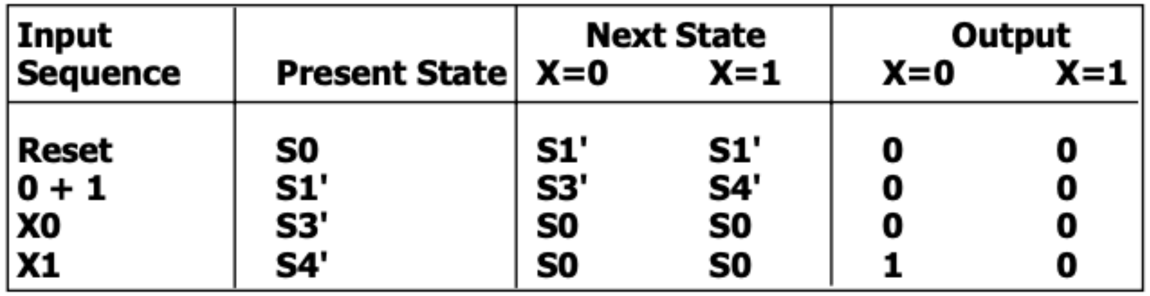
Finite State Machine optimization

- Algorithms exist to identify and combine states that have equivalent behavior
- Equivalent states:
  - Same output
  - For all input combinations, state transition to same or equivalent states
- Sketch of polynomial time algorithm:
  - Place all states in one set
  - Initially partition set based on output behavior
  - Successively partition resulting subsets based on next state transitions
  - Repeat until no further partitioning

Finite State Machine optimization



Input Sequence	Present State	Next State		Output	
		X=0	X=1	X=0	X=1
Reset	S0	S1	S2	0	0
0	S1	S3	S4	0	0
1	S2	S5	S6	0	0
00	S3	S0	S0	0	0
01	S4	S0	S0	1	0
10	S5	S0	S0	0	0
11	S6	S0	S0	1	0



Input Sequence	**Present State**	**Next State**		**Output**	
		X=0	**X=1**	**X=0**	**X=1**
Reset	**S0**	**S1'**	**S1'**	**0**	**0**
0 + 1	**S1'**	**S3'**	**S4'**	**0**	**0**
X0	**S3'**	**S0**	**S0**	**0**	**0**
X1	**S4'**	**S0**	**S0**	**1**	**0**

Sequence detector for 010 or 110

(S0 S1 S2 S3 S4 S5 S6)

(S0 S1 S2 S3 S5) (S4 S6)

(S0 S3 S5) (S1 S2) (S4 S6)

(S0) (S3 S5) (S1 S2) (S4 S6)

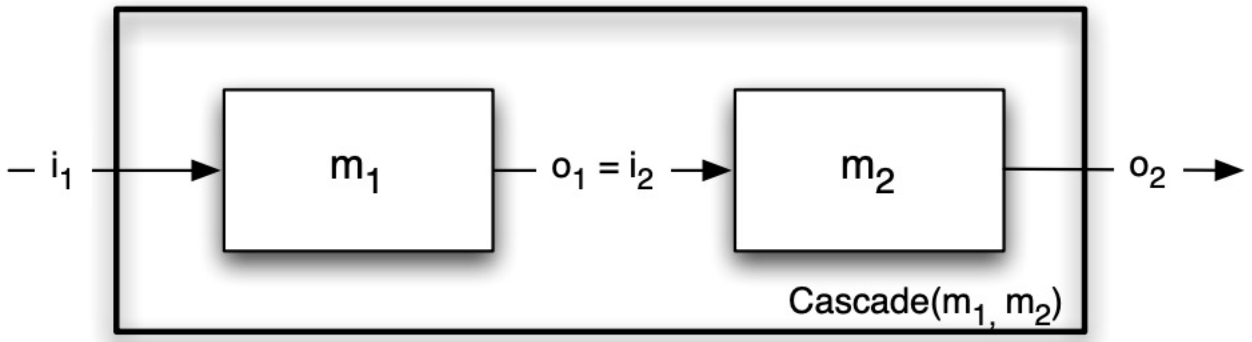
Hierarchical Finite State Machines

- Some states might not be equivalent, but it might still be beneficial to group closely related ones together

- This leads to the following two concepts:
  - Super-states (groups of states)
  - Generalized transitions (transitions between super-states)

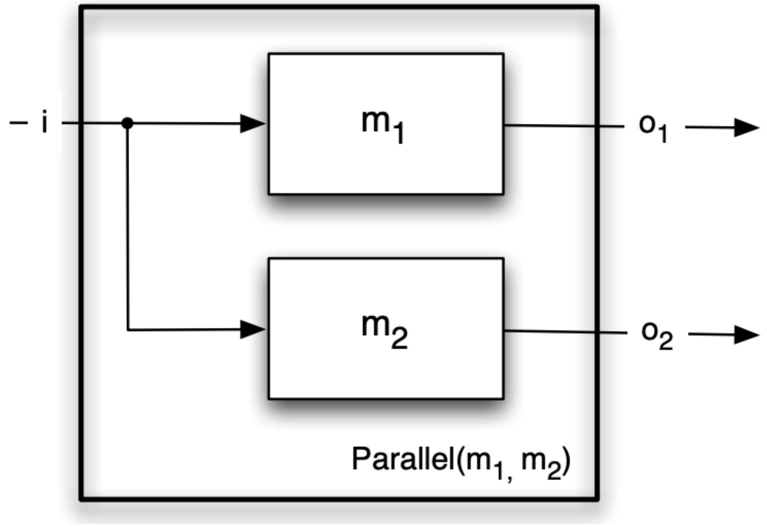
Composition

- Cascade
  - Requirement: output vocabulary of m1 must match input vocabulary of m2
  - Resulting state: concatenation of states
  - Resulting input: input of m1
  - Resulting output: output of m2



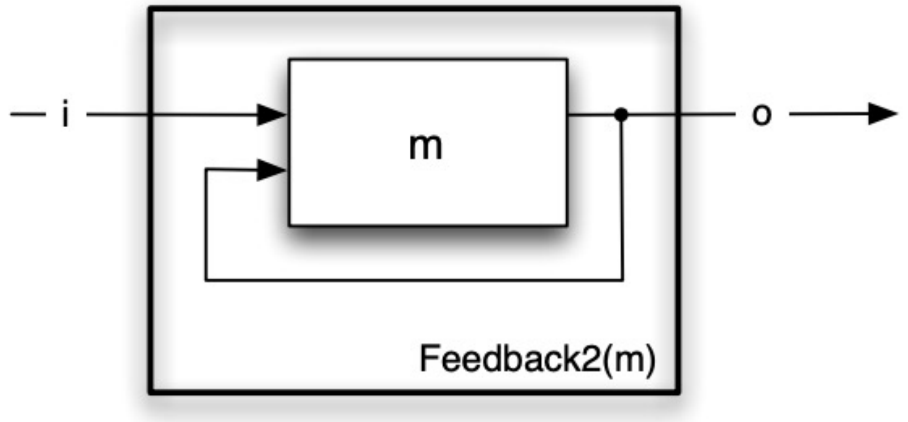
Composition

- Parallel
  - Requirement: Input vocabularies must be the same
  - Resulting state: concatenation of states
  - Resulting input: same as input vocabulary of component machines
  - Resulting output: concatenation of outputs



Composition

- Feedback
  - Requirement: Input and output vocabularies must be the same
  - Resulting state: same
  - Resulting input: partial input
  - Resulting output: same



Implementation

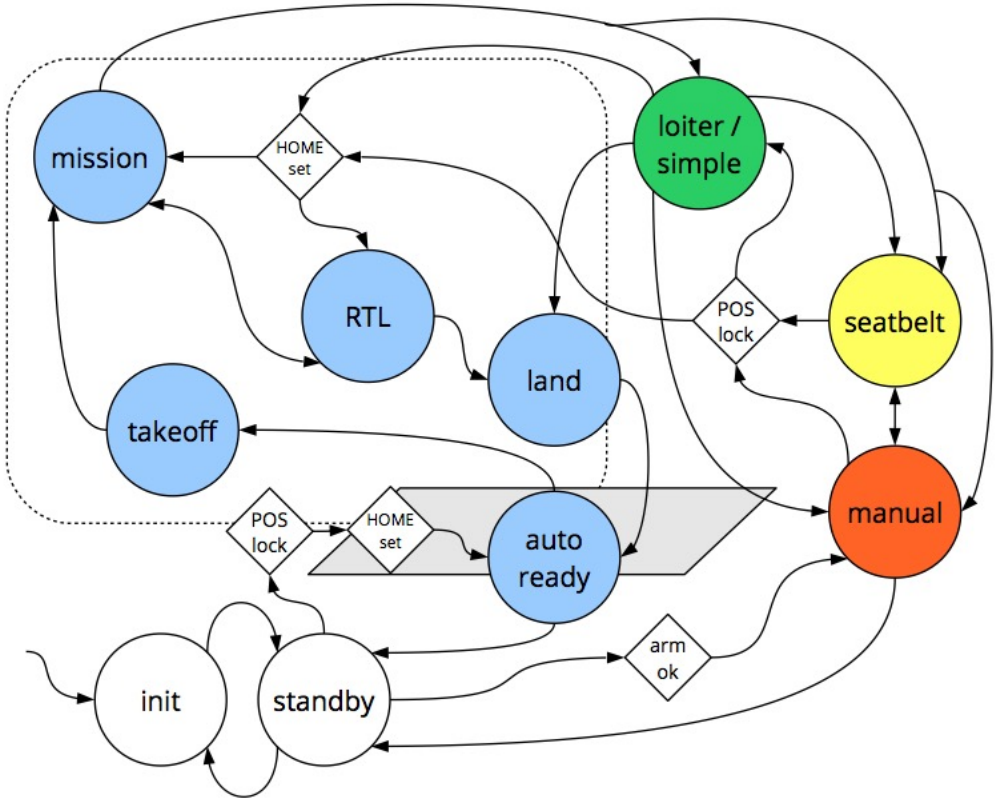
- Aim of this section
    - Understand that you do NOT have to use anything in particular in order to implement a FSM
    - Understand that there are however common ways to implement finite state machines
    - Grow awareness of tools available to help you build and analyze them

Implementation

- A common strategy is to exploit Object Oriented Programming (OOP) and implement a class that corresponds to your finite state machine
- The class keeps track of which state the FSM is in (e.g. in a variable)
- A loop repeats at some fixed rate
- Each loop, the FSM input is read (e.g. sensors, clock)
- The current state is executed (as an if/else block)
    - Actions that need to be taken (e.g. set actuator setpoints)
    - Transition to next state (e.g. state variable updated)

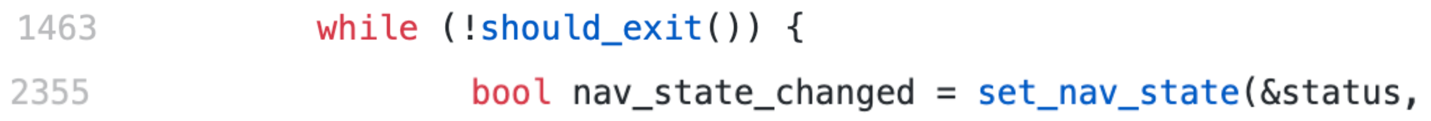
Example implementation

- PX4: in many ways the leading open source flight software for drones



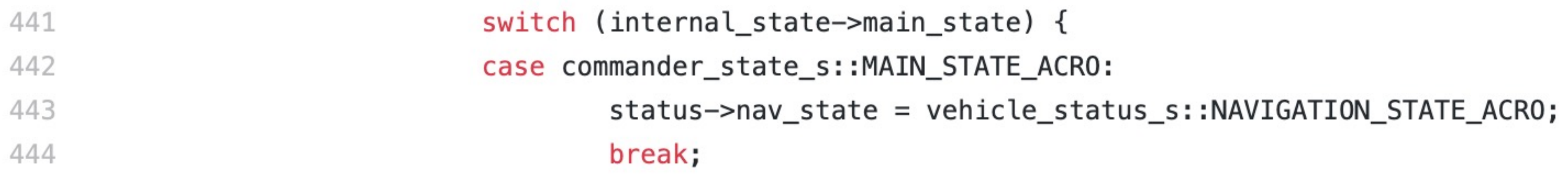
Example implementation

- Commander.cpp



```
	while (!should_exit()) {
		bool nav_state_changed = set_nav_state(&status,
```

- state_machine_helper.cpp



```
	switch (internal_state->main_state) {
	case commander_state_s::MAIN_STATE_ACRO:
		status->nav_state = vehicle_status_s::NAVIGATION_STATE_ACRO;
		break;
```

Example implementation

- Your very own navigator.py!

```python
# STATE MACHINE LOGIC
# some transitions handled by callbacks
if self.mode == Mode.IDLE:
    pass
elif self.mode == Mode.ALIGN:
    if self.aligned():
        self.current_plan_start_time = rospy.get_rostime()
        self.switch_mode(Mode.TRACK)
elif self.mode == Mode.TRACK:
    if self.near_goal():
        self.switch_mode(Mode.PARK)
    elif not self.close_to_plan_start():
        rospy.loginfo("replanning because far from start")
        self.replan()
    elif (rospy.get_rostime() - self.current_plan_start_time).to_sec() > self.current_plan_duration:
        rospy.loginfo("replanning because out of time")
        self.replan() # we aren't near the goal but we thought we should have been, so replan
elif self.mode == Mode.PARK:
    if self.at_goal():
        # forget about goal:
        self.x_g = None
        self.y_g = None
        self.theta_g = None
        self.switch_mode(Mode.IDLE)

self.publish_control()
rate.sleep()
```

ROS State Machines: SMACH

- A ROS tool that allows you to synthesize FSMs more easily
- Provides visualization tools
- Support hierarchical state machines
- Enables easy composition
- See http://wiki.ros.org/smach/Tutorials/Getting%20Started

SMACH: Basic Syntax

- Two main components:
  - SMACH State
  - SMACH Container (e.g. FSM)

SMACH: Basic Syntax

- SMACH State
  - The basic state abstraction. Corresponds 1:1 with the FSM states described earlier
  - Inherit from `smach.State` and must implement two functions:
    - `__init__`
    - `execute`
  - `execute` should return ‘`outcomes`’

SMACH: Basic Syntax

```python
class Foo(smach.State):
   def __init__(self, outcomes=['outcome1', 'outcome2']):
     # Your state initialization goes here

   def execute(self, userdata):
      # Your state execution goes here
      if xxxx:
          return 'outcome1'
      else:
          return 'outcome2'
```

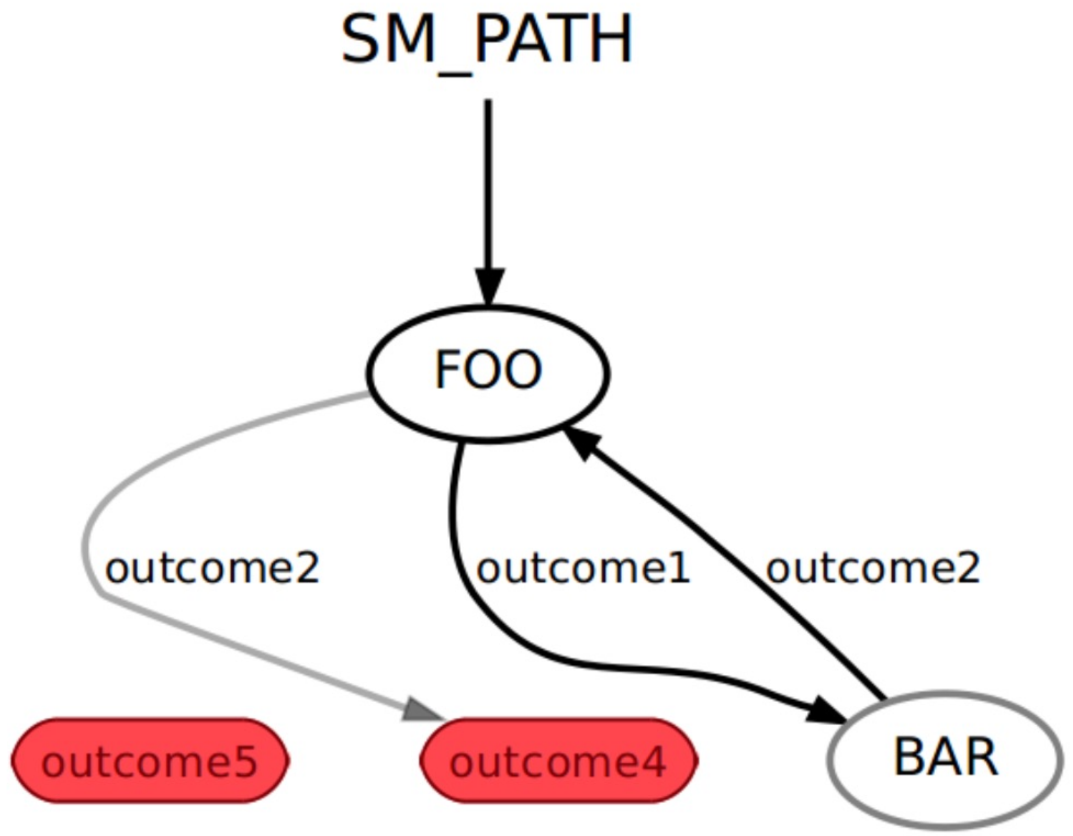
SMACH: Basic Syntax

- SMACH Container
  - Roughly corresponds to the idea of a finite state machine, with variations.
  - You are most likely to use the container `smach.StateMachine`
  - States can be added to containers
  - Containers can be composed

SMACH: Basic Syntax

```python
sm = smach.StateMachine(outcomes=['outcome4','outcome5'])
with sm:
   smach.StateMachine.add('FOO', Foo(),
                          transitions={'outcome1':'BAR',
                                       'outcome2':'outcome4'})
   smach.StateMachine.add('BAR', Bar(),
                          transitions={'outcome2':'FOO'})
```

SMACH: Basic Example



SMACH: Basic Example

```python
# define state Foo
class Foo(smach.State):
    def __init__(self):
        smach.State.__init__(self, outcomes=['outcome1','outcome2'])
        self.counter = 0

    def execute(self, userdata):
        rospy.loginfo('Executing state FOO')
        if self.counter < 3:
            self.counter += 1
            return 'outcome1'
        else:
            return 'outcome2'
```

SMACH: Basic Example

```python
# define state Bar
class Bar(smach.State):
    def __init__(self):
        smach.State.__init__(self, outcomes=['outcome2'])

    def execute(self, userdata):
        rospy.loginfo('Executing state BAR')
        return 'outcome2'
```

SMACH: Basic Example

```python
# main
def main():
    rospy.init_node('smach_example_state_machine')

    # Create a SMACH state machine
    sm = smach.StateMachine(outcomes=['outcome4', 'outcome5'])

    # Open the container
    with sm:
        # Add states to the container
        smach.StateMachine.add('FOO', Foo(),
                               transitions={'outcome1':'BAR',
                                            'outcome2':'outcome4'})
        smach.StateMachine.add('BAR', Bar(),
                               transitions={'outcome2':'FOO'})

    # Execute SMACH plan
    outcome = sm.execute()
```

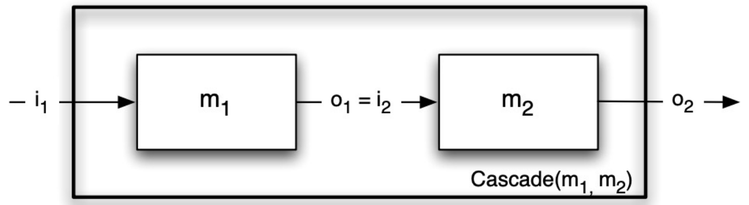
SMACH: Composition

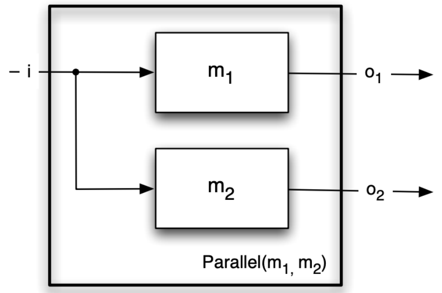
- The composition operations described earlier (cascade, parallel, feedback) are also possible in SMACH

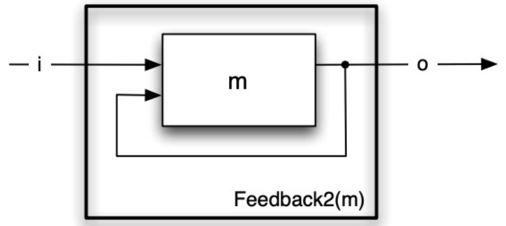
Cascade -> `smach.Sequence`

Parallel -> `smach.Concurrence`

Feedback -> `smach.Iterator`

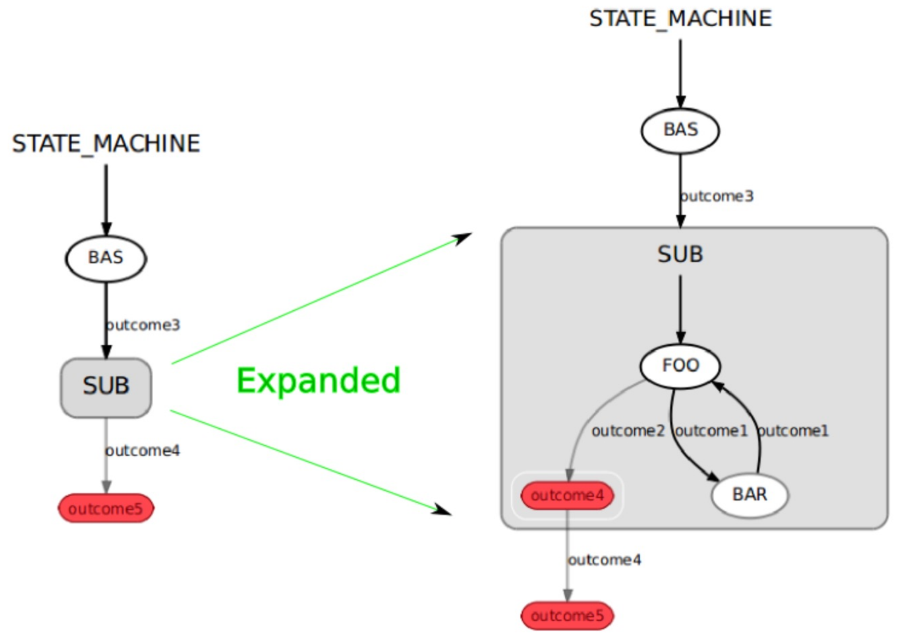






SMACH: Visualization

- The package `smach_visualizer` allows you to easily inspect and monitor your state machine



Thanks for a great quarter!