# Control of Time-Varying Behavior

Proportional-Derivative (PD) controller: react to the immediate sensory inputs

- E.g.: yaw control
- Need a reference (or “desired”) heading

Where does this reference come from?

# Control of Time-Varying Behavior

Where does the reference come from?

- Determined by what our task is (or subtask)

- E.g.: at the current state of a mission, it may be appropriate to orient the craft in a particular direction so that it can fly back "home"

# Control of Time-Varying Behavior

Can often express a “mission” in terms of a sequence of sub-tasks (or a plan)

- But: we also want to handle contingencies when they arrive

Finite state machines are a simple way of expressing such plans and contingencies

# Finite State Machines (FSMs)

Pure FSM form is composed of:

- A set of states
- A set of possible inputs (or events)
- A set of possible outputs (or actions)
- A transition function:
  - Given the current state and an input: defines the output and the next state

# Finite State Machines (FSMs)

States:

- Represent all possible “situations” that must be distinguished
- At any given time, the system is in exactly one of the states
- There is a finite number of these states

# Finite State Machines (FSMs)

An example: a 3-bit counter that increments when “count” input is received

- States: ?

# Finite State Machines (FSMs)

An example: a counter

- States: the different combinations of the digits: 000, 001, 010, … 111

- Inputs: ?

# Finite State Machines (FSMs)

An example: a counter

- Inputs (events):
  - Only one: “count”
  - We will call this “C”

- Outputs: ?

# Finite State Machines (FSMs)

An example: a counter

- Outputs: same as the set of states

- Transition function: ?

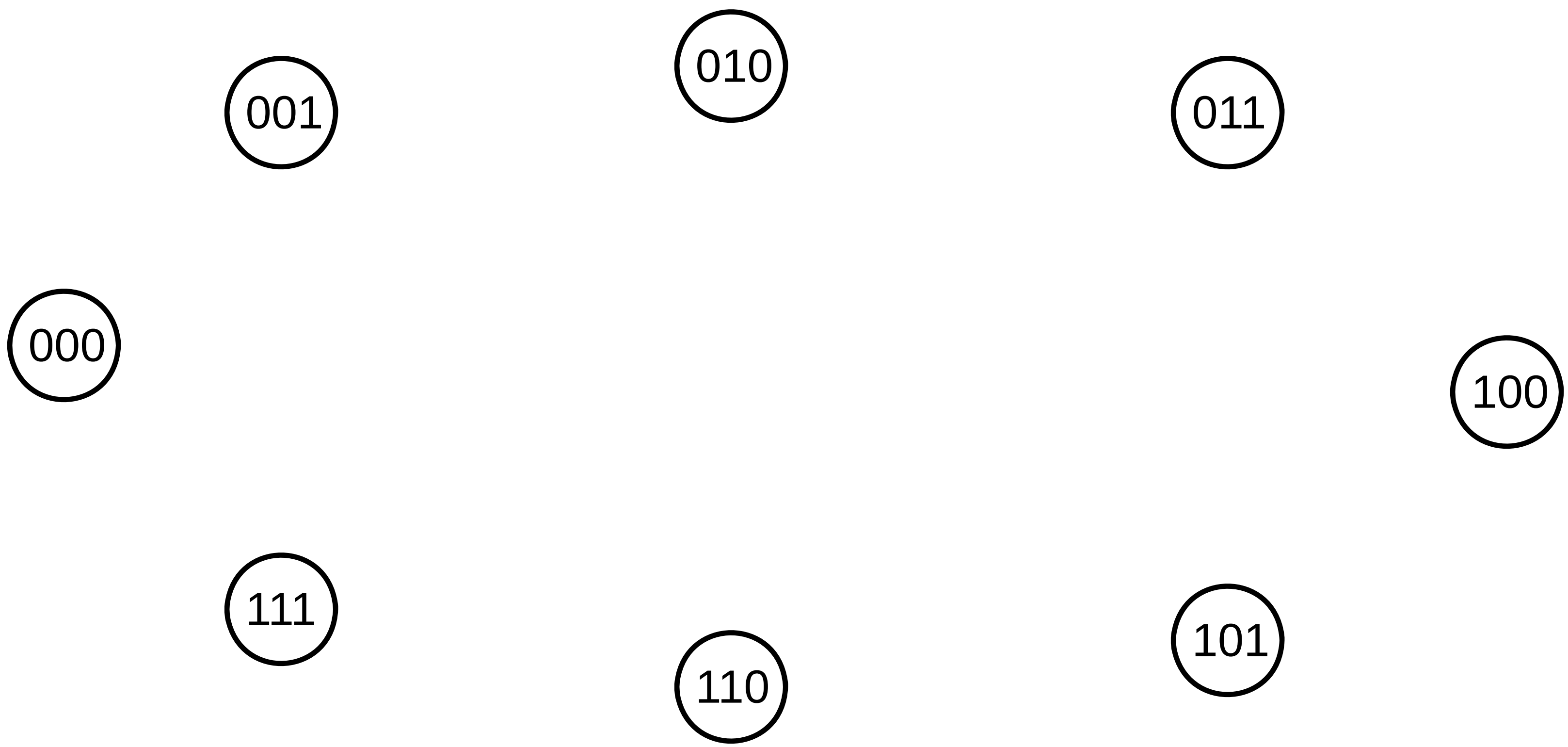
# Finite State Machines (FSMs)

An example: a counter

- Transition function:
  - On the count event, transition to the next highest value

# FSM Example: Synchronous Counter

## A Graphical Representation:

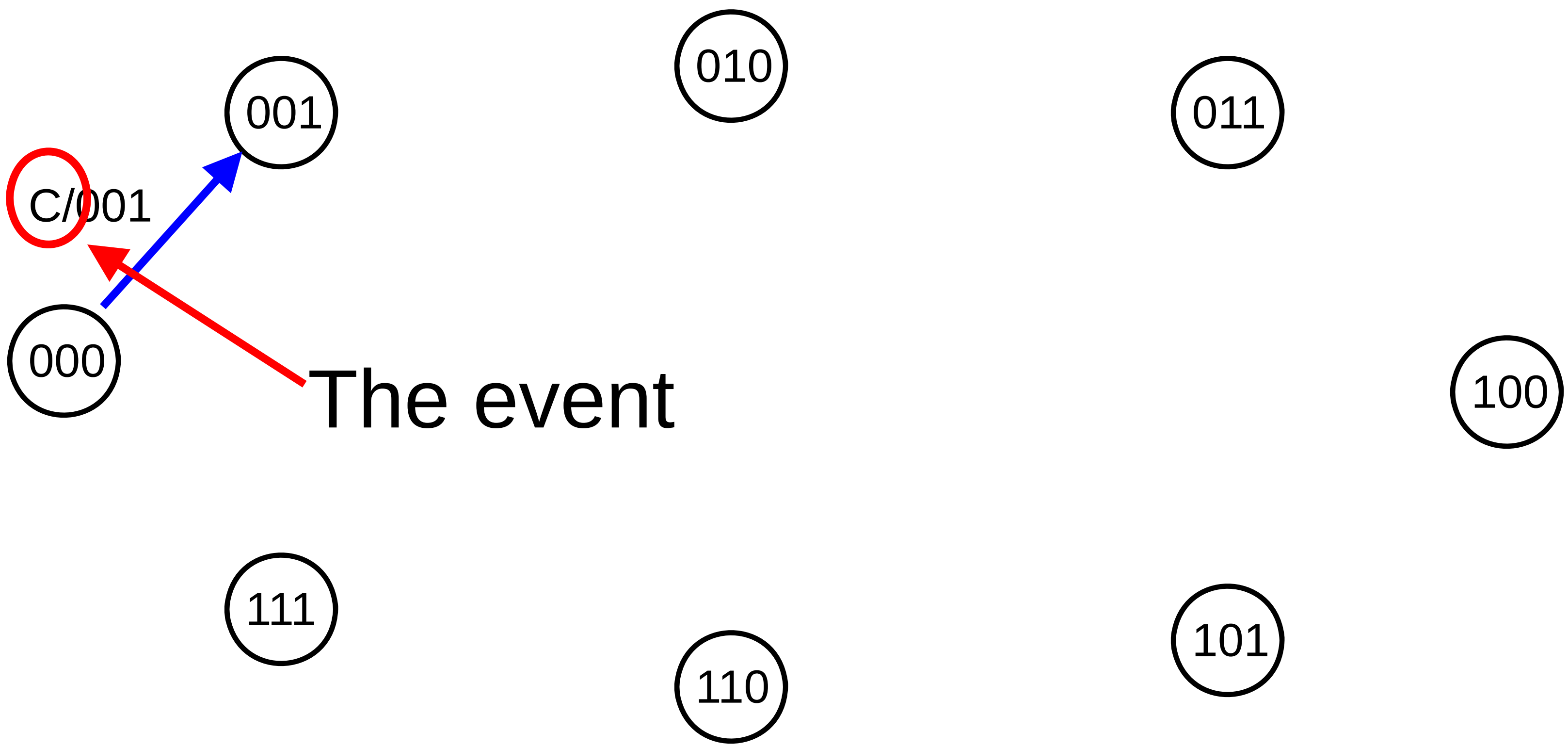



A set of states

# FSM Example: Synchronous Counter

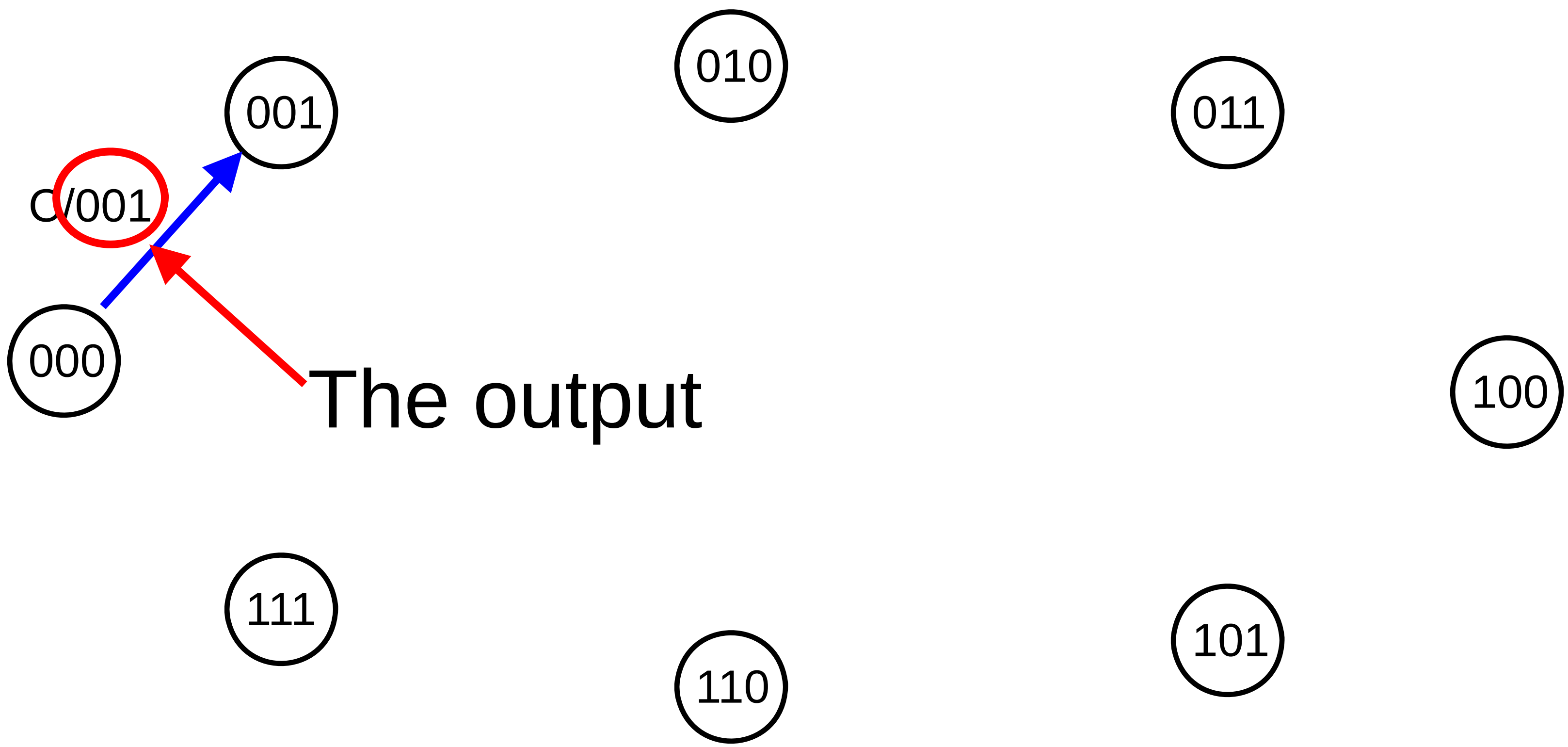
# FSM Example: Synchronous Counter

A transition



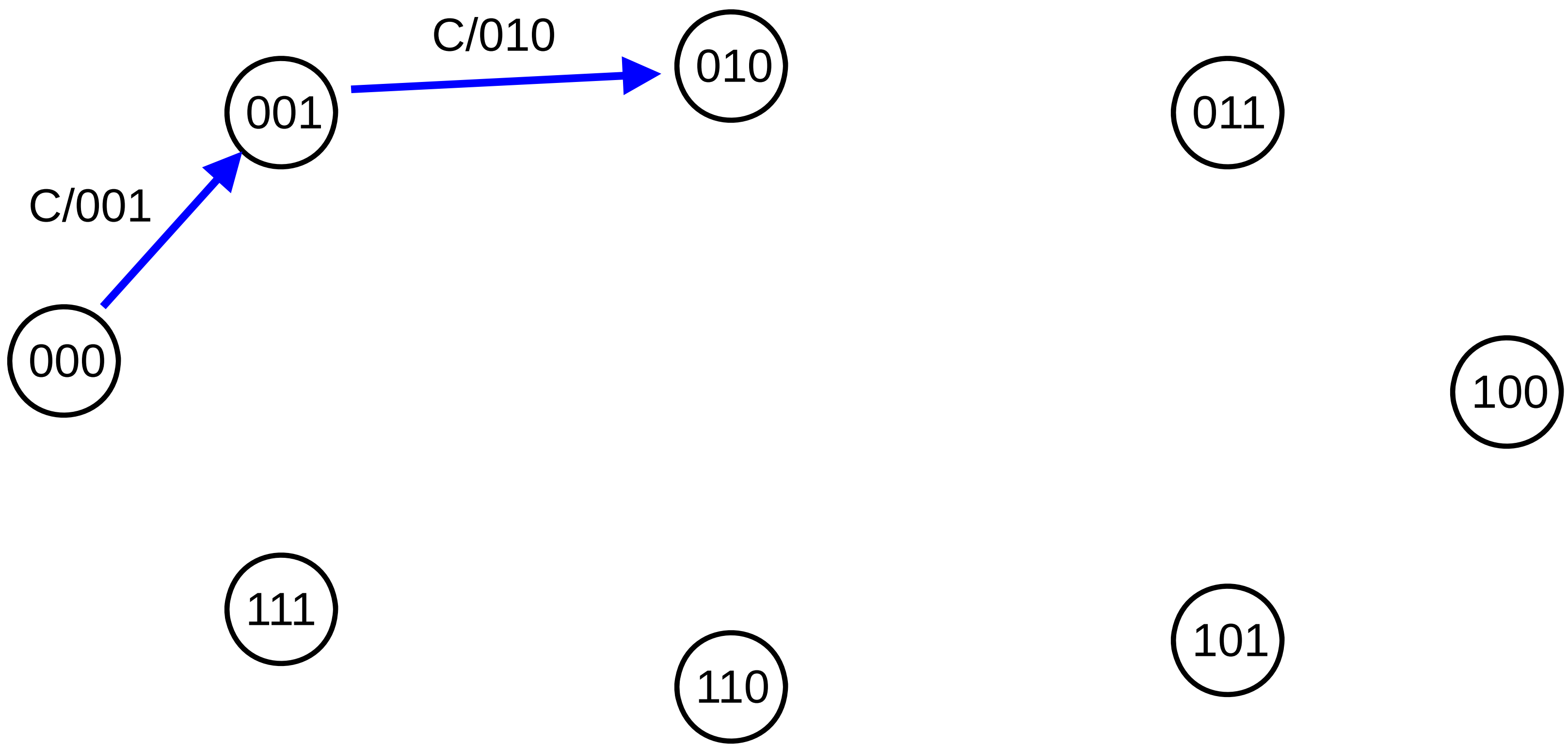
# FSM Example: Synchronous Counter

A transition



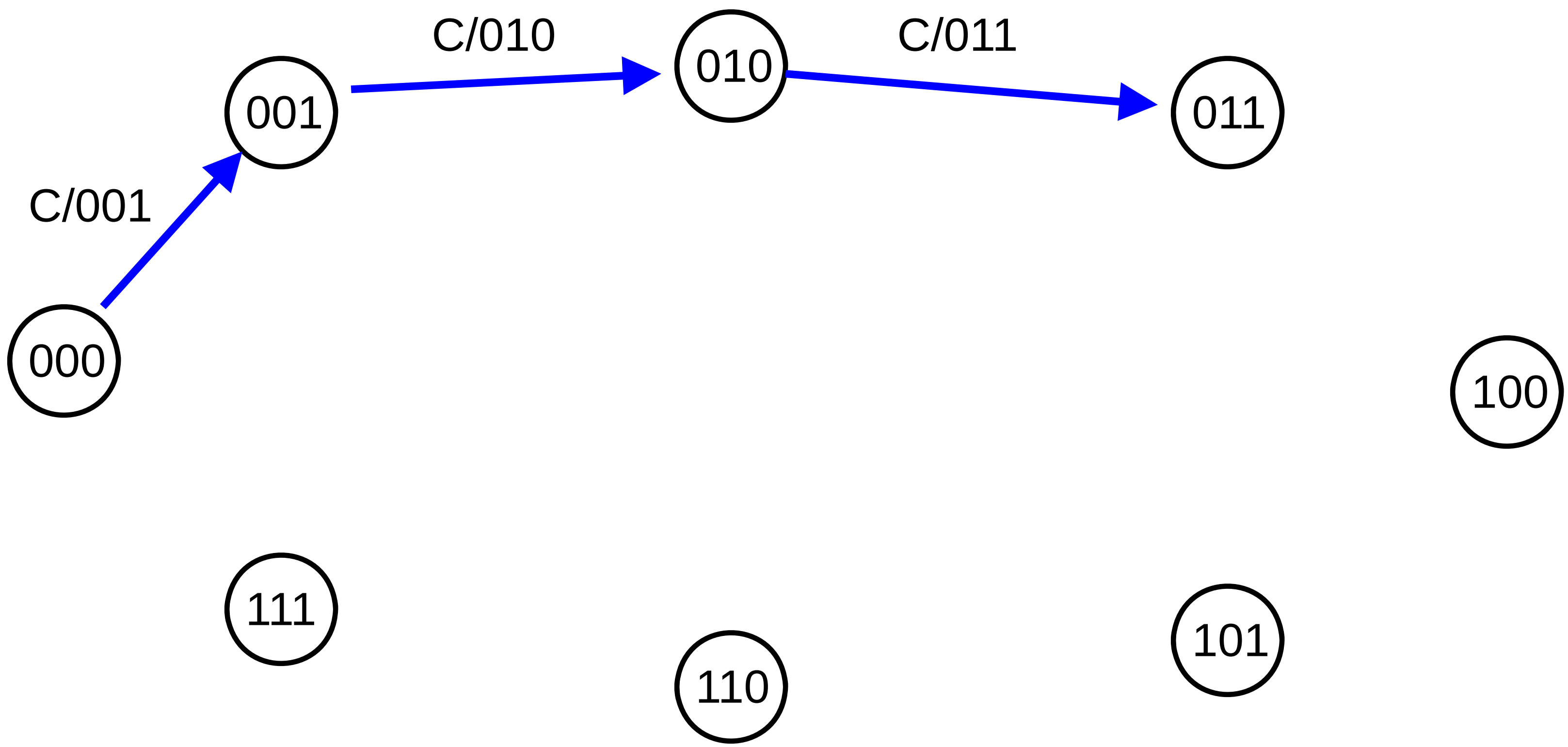
# FSM Example: Synchronous Counter

The next transition



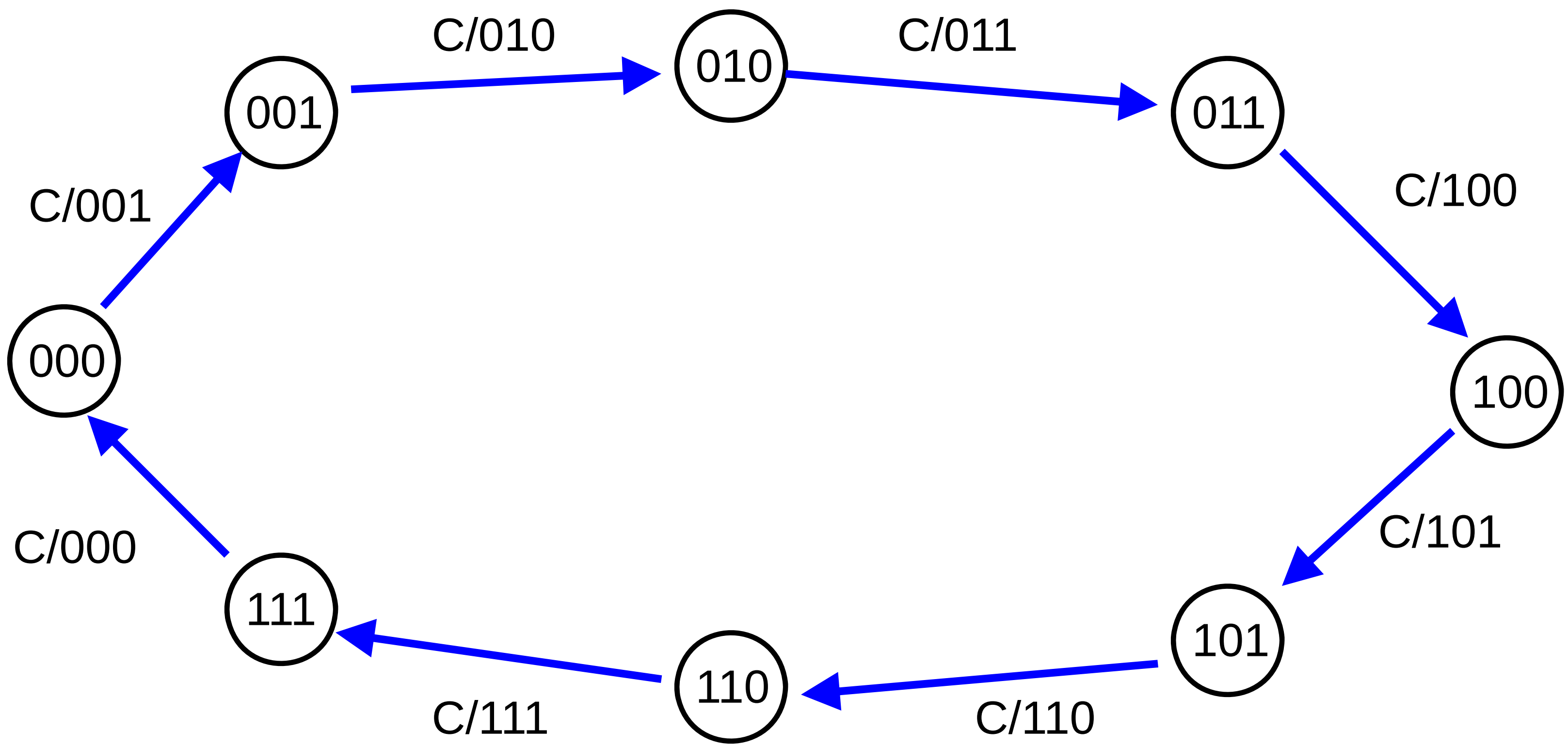
# FSM Example: Synchronous Counter

The next transition

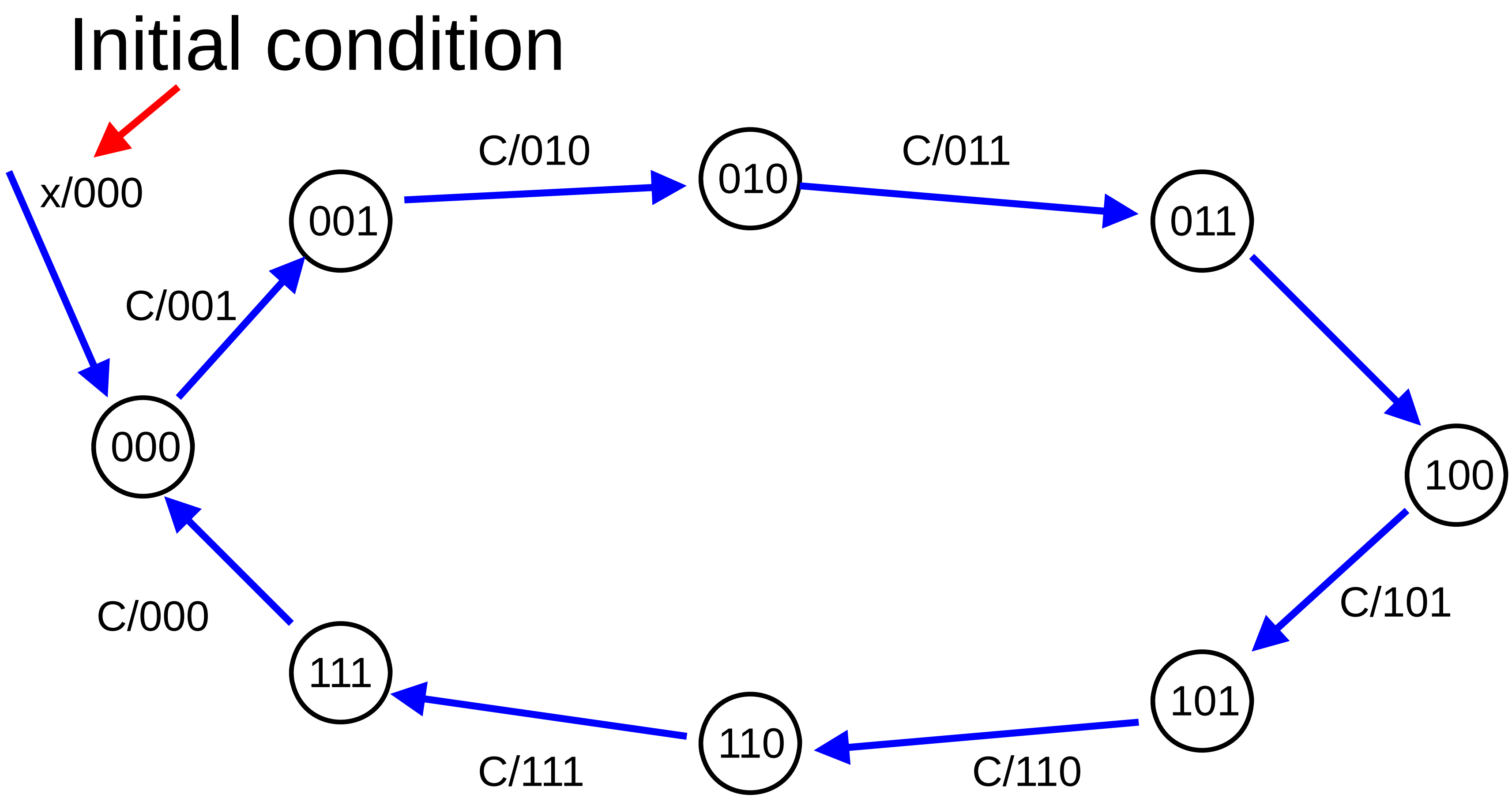


# FSM Example: Synchronous Counter

The full transition set



# FSM Example: Synchronous Counter



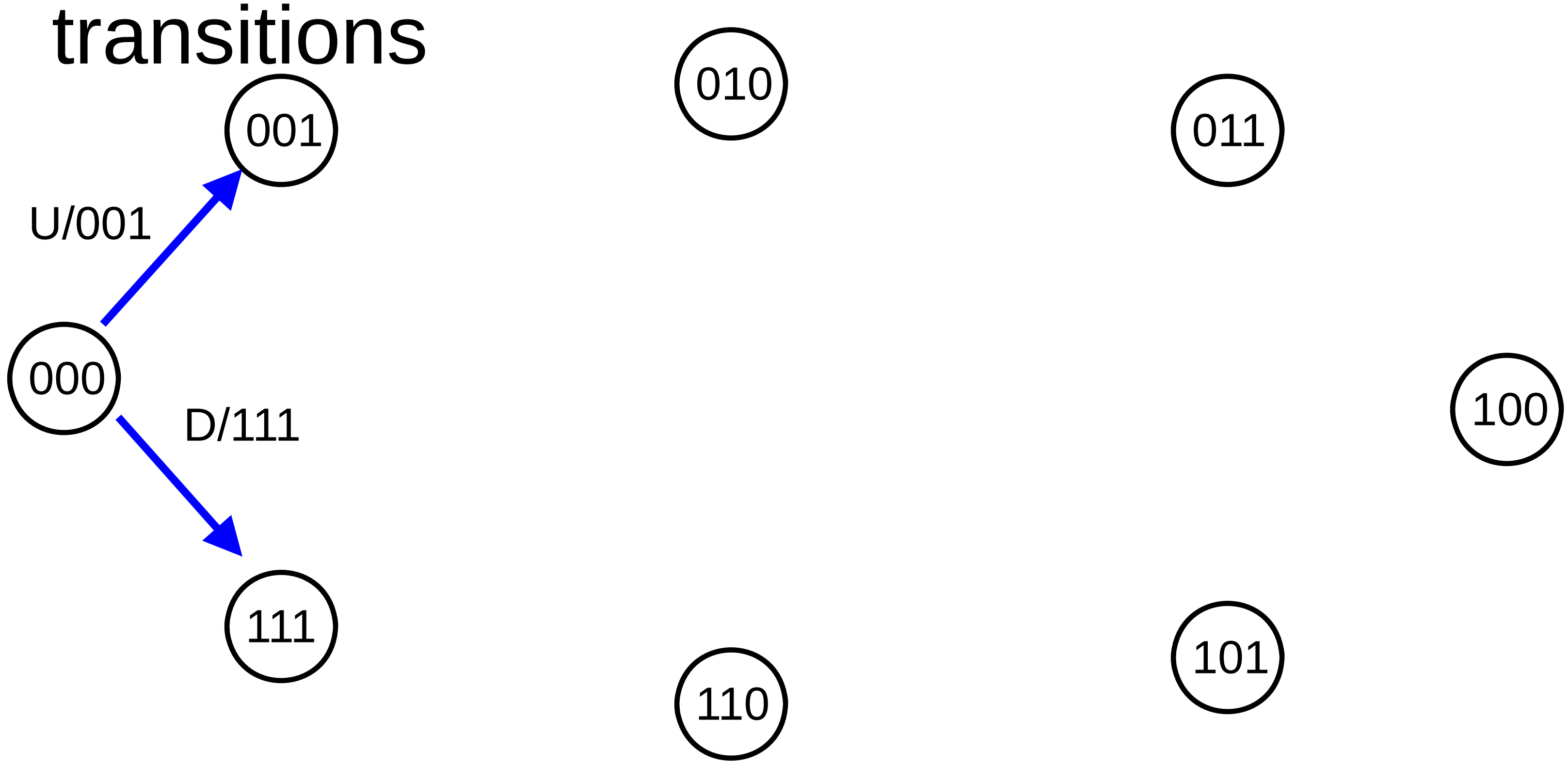
# Example II: An Up/Down Counter

Suppose we have two events (instead of one): Count up and count down

- How does this change our state transition diagram?

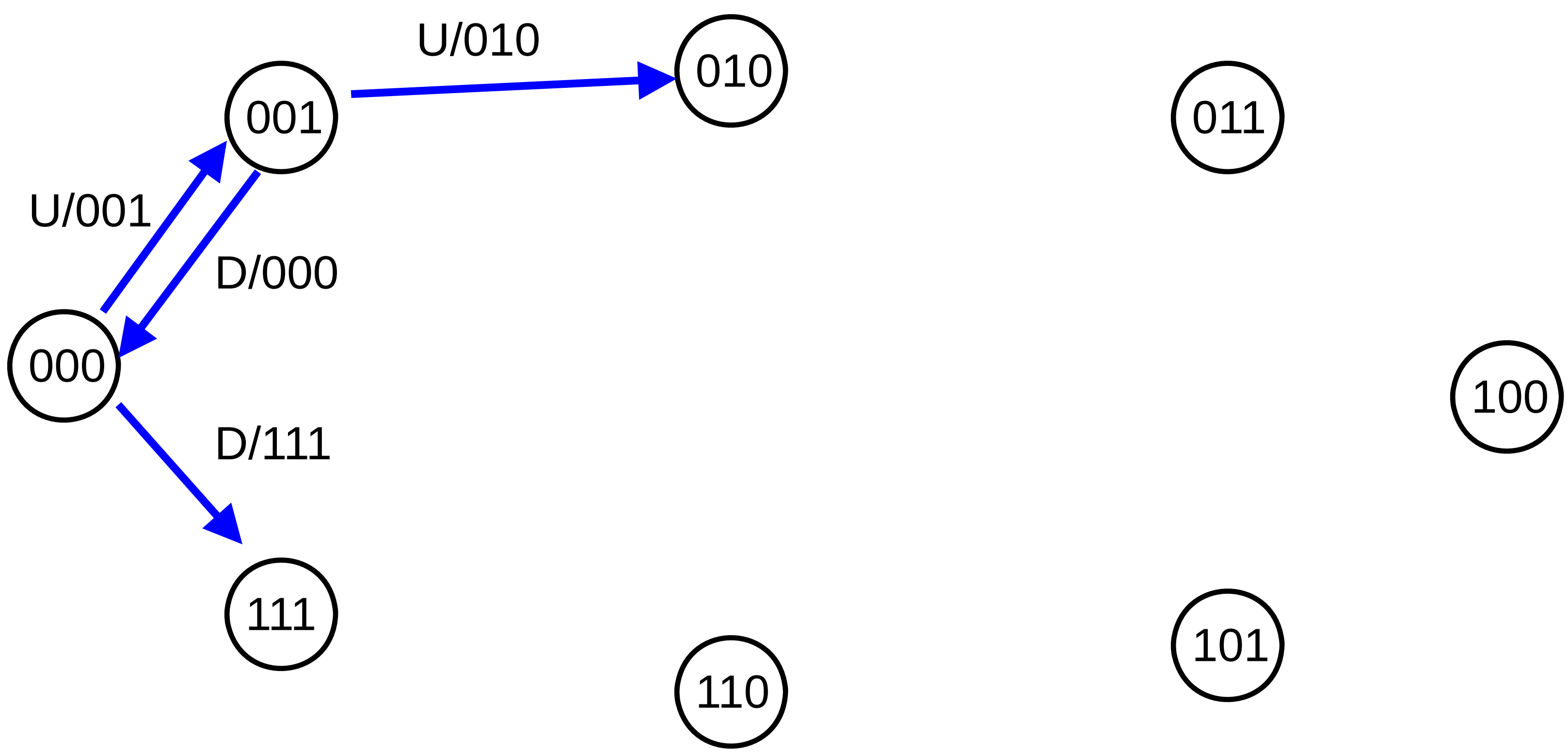
# Example II: An Up/Down Counter

From state 000, there are now two possible transitions



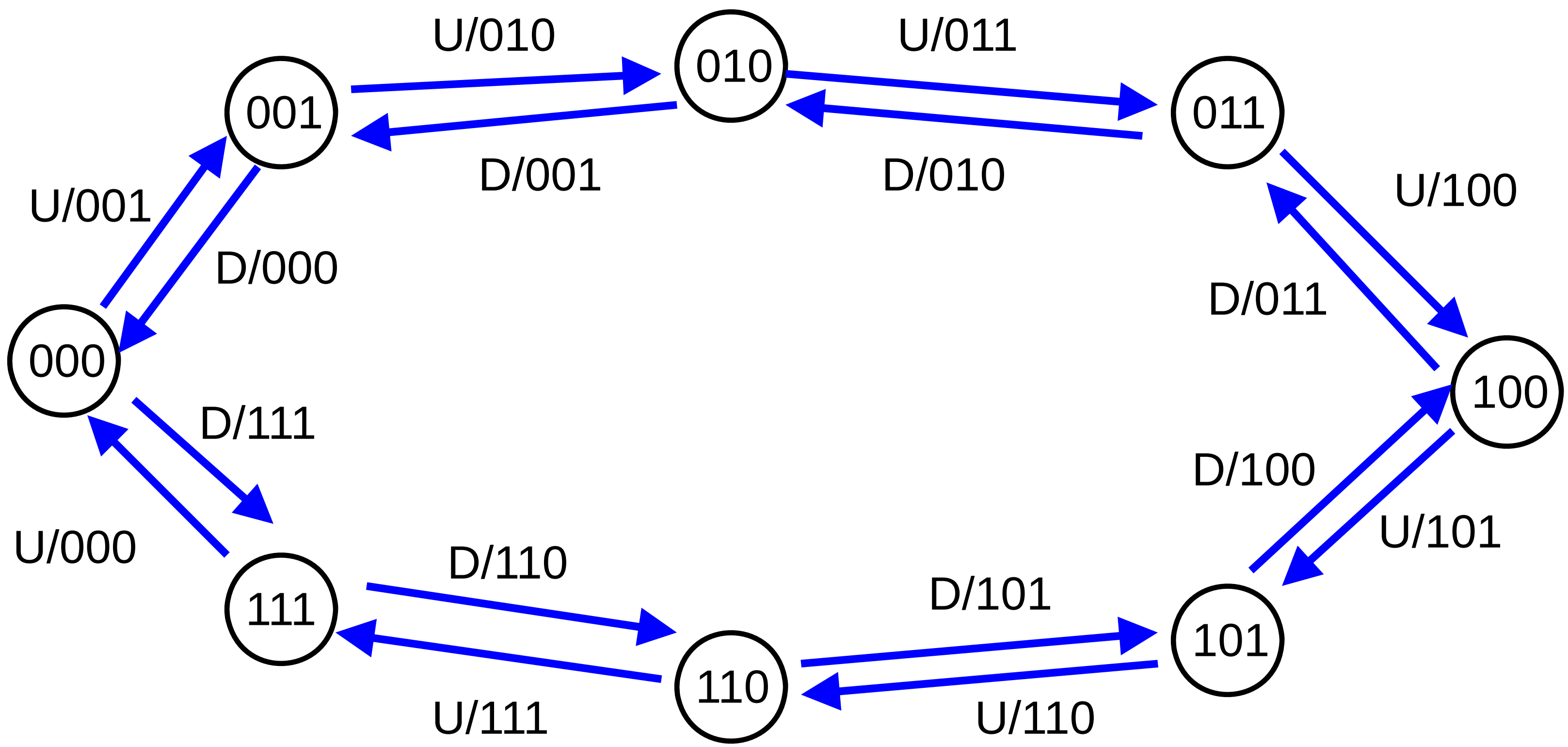
# Example II: An Up/Down Counter

Likewise for state 001…



# Example II: An Up/Down Counter

## The full transition set



# FSMs and Control

How do we relate FSMs to Control?

- States are ?

# FSMs and Control

How do we relate FSMs to Control?

- States are our memory of recent inputs

- Inputs are ?

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How do we relate FSMs to Control?

- States are our memory of recent inputs
- Inputs are some processed representation of what the sensors are observing
- Outputs are ?

# FSMs and Control

How do we relate FSMs to Control?

- States are our memory of recent inputs

- Inputs are some processed representation of what the sensors are observing

- Outputs are the control actions
  - These are typically “high level” actions: e.g., set the goal orientation to 125 degrees

# FSMs: A Control Example

Suppose we have a vending machine:

- Accepts dimes and nickels
- Will dispense one of two things once $.20 has been entered: Jolt or Buzz Water
  - – The “user” requests one of these by pressing a button

- Ignores select if < $.20 has been entered
- Immediately returns any coins above $.20

# Vending Machine FSM

What are the states?

# Vending Machine FSM

What are the states?

- \$0
- \$.05
- \$.10
- \$.15
- \$.20

# Vending Machine FSM

What are the inputs/events?

# Vending Machine FSM

What are the inputs/events?

- Input nickel (N)
- Input dime (D)
- Select Jolt (J)
- Select Buzz Water (BW)

# Vending Machine FSM

What are the outputs?

# Vending Machine FSM

What are the outputs?

- Return nickel (RN)
- Return dime (RD)
- Dispense Jolt (DJ)
- Dispense Buzz Water (DBW)
- Nothing (Z)


# Vending Machine Design

What is the initial state?

# Vending Machine Design

What is the initial state?

- S = \$0

# Vending Machine Design

What can happen from S = $0?

| Event | Next State | Output |
|---|---|---|
| | | |
| | | |
| | | |
| | | |

# Vending Machine Design

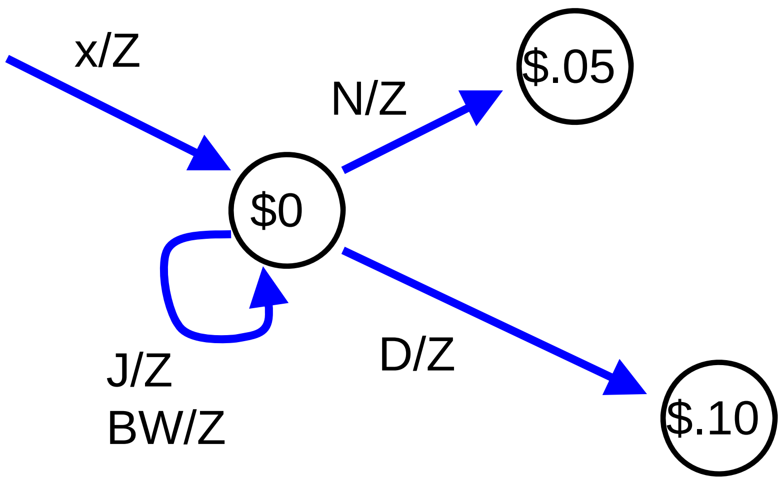
What can happen from S = \$0?

What does this part of the diagram look like?

| Event | Next State | Output |
|---|---|---|
| N | \$.05 | Z |
| D | \$.10 | Z |
| J | \$0 | Z |
| BW | \$0 | Z |

# Vending Machine Design

A piece of the state diagram:



# Vending Machine Design

What can happen from S = $0.05?

| Event | Next State | Output |
|---|---|---|
| | | |
| | | |
| | | |
| | | |

# Vending Machine Design

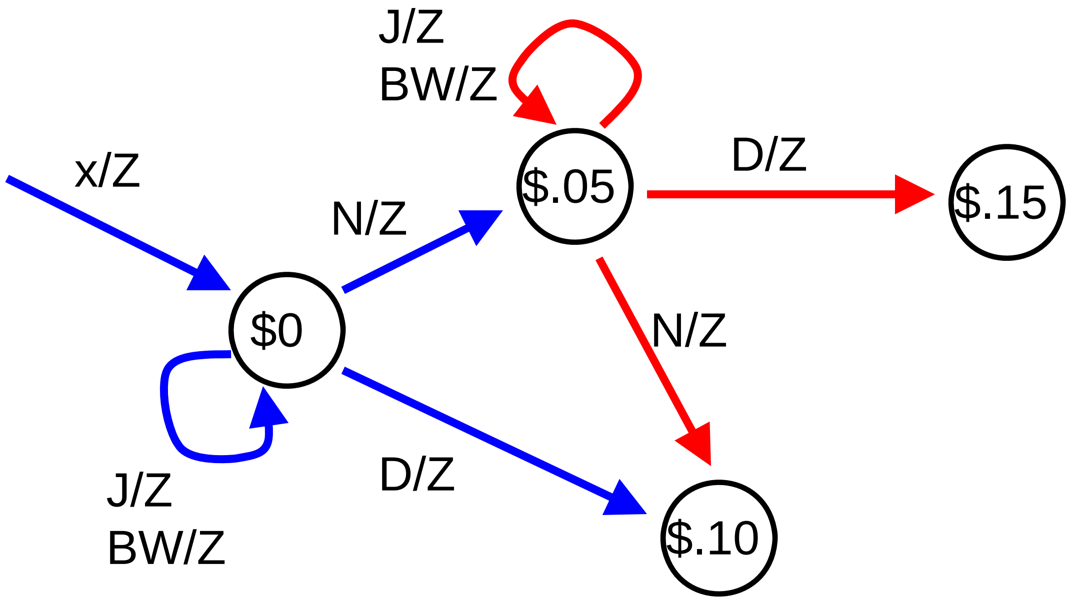
What can happen from S = $0.05?

What does the modified diagram look like?

| Event | Next State | Output |
|---|---|---|
| N | $.10 | Z |
| D | $.15 | Z |
| J | $.05 | Z |
| BW | $.05 | Z |

# Vending Machine Design

A piece of the state diagram:



# Vending Machine Design

What can happen from S = $0.10?

| Event | Next State | Output |
|---|---|---|
| | | |
| | | |
| | | |
| | | |

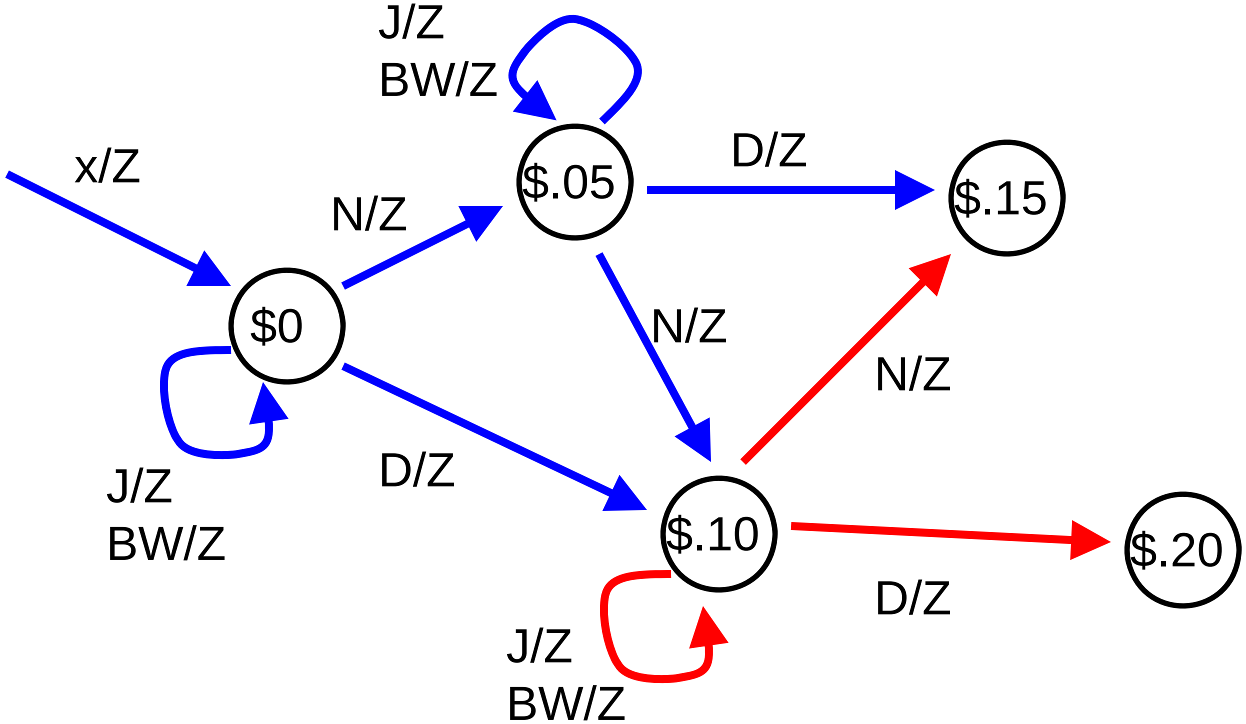
# Vending Machine Design

What can happen from S = $0.10?

| Event | Next State | Output |
|---|---|---|
| N | $.15 | Z |
| D | $.20 | Z |
| J | $.10 | Z |
| BW | $.10 | Z |

# Vending Machine Design

A piece of the state diagram:



# Vending Machine Design

What can happen from S = $0.15?

| Event | Next State | Output |
|---|---|---|
| | | |
| | | |
| | | |
| | | |

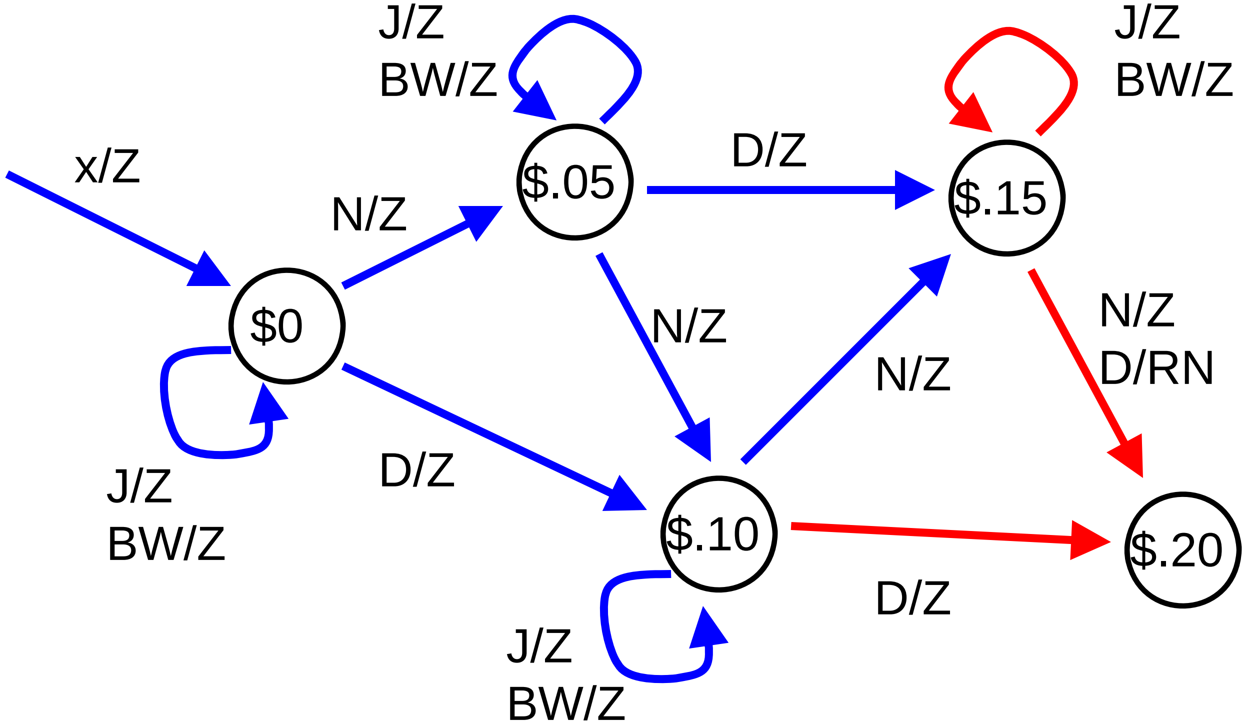
# Vending Machine Design

What can happen from S = $0.15?

| Event | Next State | Output |
|---|---|---|
| N | $.20 | Z |
| D | $.20 | RN |
| J | $.15 | Z |
| BW | $.15 | Z |

# Vending Machine Design

A piece of the state diagram:



# Vending Machine Design

Finally: what can happen from S = \$0.20?

| Event | Next State | Output |
|---|---|---|
| | | |
| | | |
| | | |
| | | |

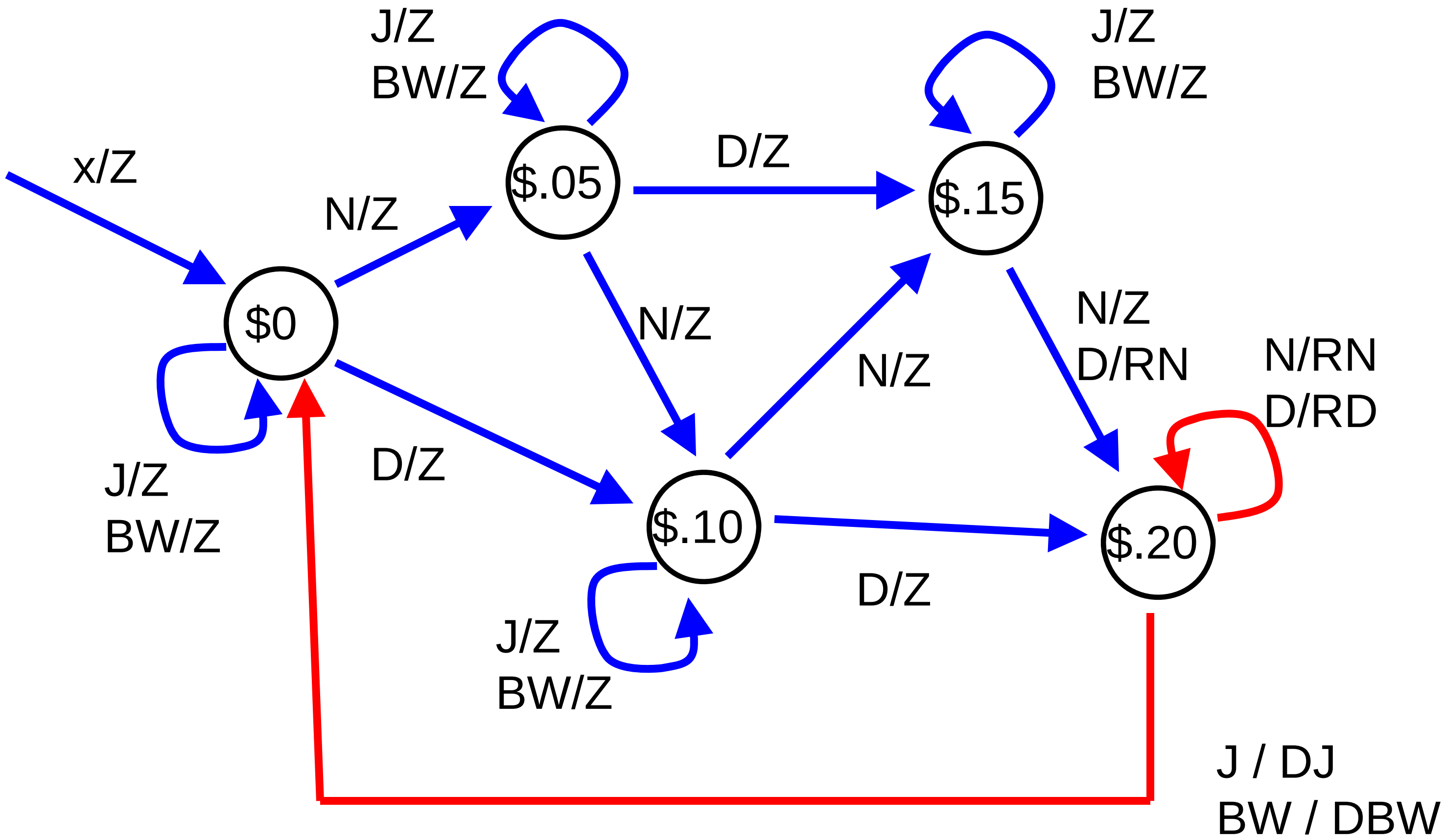
# Vending Machine Design

Finally, what can happen from S = $0.20?

| Event | Next State | Output |
|---|---|---|
| N | $.20 | RN |
| D | $.20 | RD |
| J | $0 | DJ  |
| BW | $0 | DBW  |

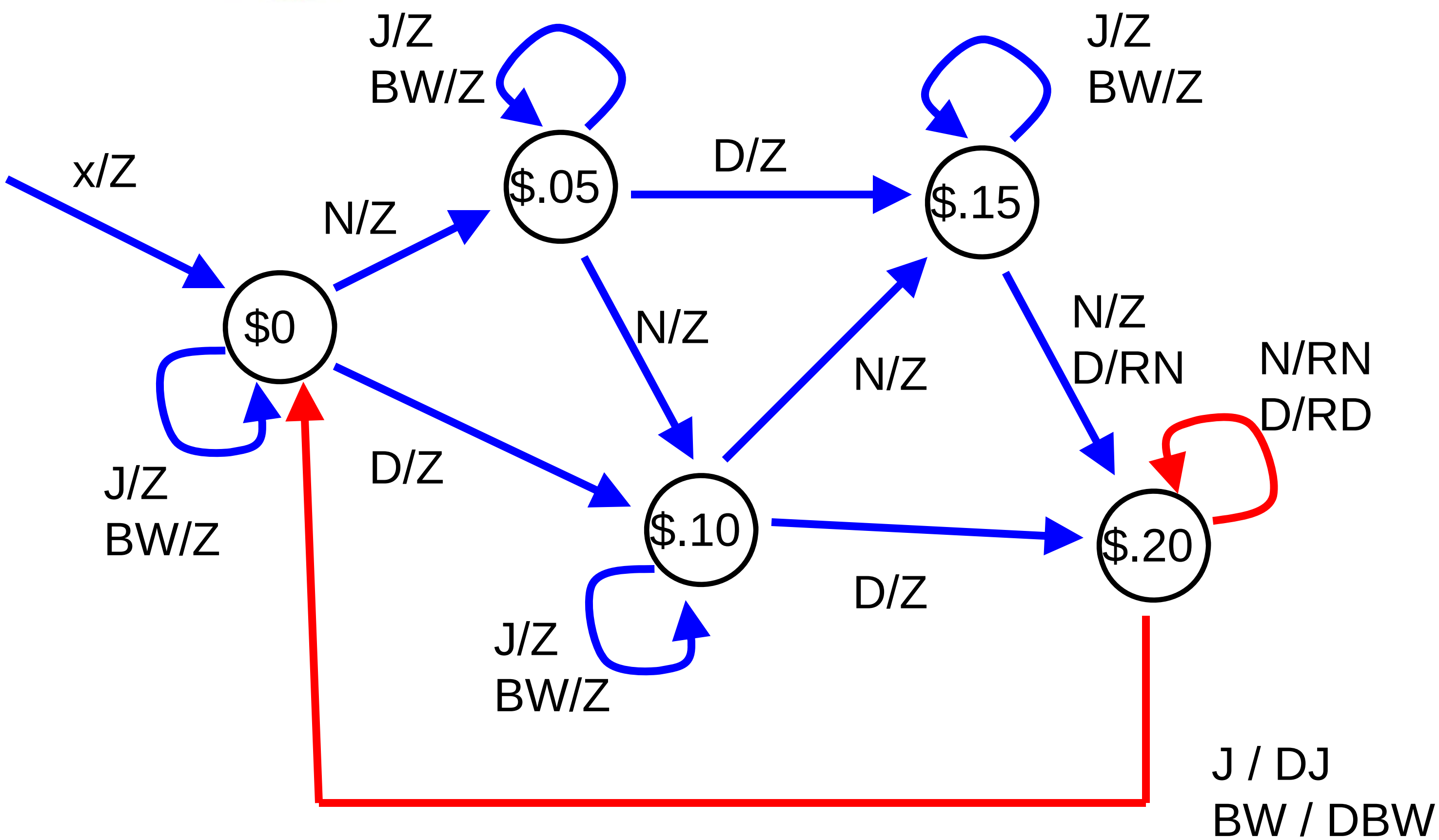
# Vending Machine Design

The complete state diagram:



# Last Time


JOLT
SILVER
CHERRY
COLA
BLUE
RED


x/Z
$0
J/Z
BW/Z
N/Z
D/Z
$.05
J/Z
BW/Z
D/Z
N/Z
$.10
J/Z
BW/Z
N/Z
D/Z
$.15
J/Z
BW/Z
N/Z
D/RN
$.20
N/RN
D/RD
J / DJ
BW / DBW

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- Outputs are the control actions

# A Robot Control Example

Consider the following task:

- The robot is to move toward the first beacon that it "sees"
- The robot searches for a beacon in the following order: right, left, front
- Once beacon is found, move toward it and stop once the beacon is reached

What is the FSM representation?

# Robot Description

Mobile robot with sensor turret on top

- Mobile robot turns take time
- Turret turns are relative to the mobile base and do not take time

# Events

- Turn complete (TC)
- Beacon (B)
- No Beacon (NB)

# Actions

- Look left (LL): turn turret to be facing left (relative to the mobile base)
- Look right (LR)
- Look forward (LF)
- Turn left (TL): turn robot base by 90 degrees to the left
- Turn right (TR)
- Move forward (F)

# Robot Control Example II

Consider the following task:

- The robot must lift off to some altitude
- Translate to some location
- Take pictures
- Return to base
- Land
- At any time: a detected failure should cause the craft to land

What is the FSM representation?

# FSMs As Controllers

Must bridge the gap between the FSM and the low- and mid-level controllers

- Events:
  - Abstraction of sensor or internal state
- Actions:
  - Modify mid- or low-level control behavior

# FSMs in C

```
State state = STATE_0;   // Initial state
while(1) {
  <do some processing of the sensory inputs>
  switch(state) {
      case STATE_0:
            <handle state 0>
            break;
      case STATE_1:
            <handle state 1>
            break;
      case STATE_2: …
  }
}
```

# FSMs in C (some other possibilities)

```
State state = STATE_0;   // Initial state
while(1) {
  <do some processing of the sensory inputs>
  switch(state) {
     case STATE_0:
          <handle state 0>
          break;
        :
     default:
          <handle default case>
          break;
  }
  <do some low-level control>
}
```

# Handling Each State

- You will need to provide code that handles the event processing for each state
- Specifically:
  - You need to handle each event that can occur
  - For each event, you must specify:
    - What action is to be taken
    - What the next state is

# Handling Each State

In our vending machine example:

- Events are easy to describe (only a few things can happen)
- It is convenient in this case to also “switch” on the event

# FSMs in C: Processing for Individual States

```
case STATE_10cents:
   // $.10 has already been deposited
   switch(event) {
        case EVENT_NICKEL:   // Nickel
                state = STATE_15cents;  // Transition to $.15
                break;
        case EVENT_DIME:   // Dime
                state = STATE_20cents;  // Transition to $.2
                break;
        case EVENT_JOLT:   // Select Jolt
        case EVENT_BUZZ:   // Select Buzzwater
                display_NOT_ENOUGH();
                break;

        case EVENT_NONE:   // No event
                break;           // Do nothing

   };
   break;
```

# Handling Each State

Some events do not fall neatly into one of several categories

- This precludes the use of the “switch” construct for events
- For example: an event that occurs when our hovercraft reaches a goal orientation
- For these continuous situations, we typically use an “if” construct …

# FSMs in C: Processing for Individual States

```
:
:
case STATE_MISSION_PHASE_3:
     if(heading_error < 100 &&
          heading_error > -100)
     {
          // Accelerate forward!
          forward_thrust = 126;
          state = STATE_MISSION_PHASE_4;
     };
  break;
:
:
```

# FSMs in C: Processing for Individual States

```
:
case STATE_MISSION_PHASE_4:
     if(distance_left < 200 ||
          distance_right < 200)
     {
          // Brake!
          forward_thrust = 0;
          middle_thrust_magnitude(300);
          middle_thrust_dir(BRAKE);
          state = STATE_MISSION_PHASE_5;
          counter = 0;    // Reset the clock
     };
  break;
:
```

# FSMs in C: Processing for Individual States

```
:
case STATE_MISSION_PHASE_5:
      if(counter > 20)
      {
            // One second has gone by since we
            //   started the brake: Stop the brake

            middle_thrust_magnitude(100);
            middle_thrust_dir(HOVER);
            forward_thrust = 100;
            heading_goal = -900;
            state = STATE_MISSION_PHASE_6;
      };
  break;
:
```

```
REMEMBER: counter is being incremented once per control
  cycle (outside of the FSM code)
```

# FSM Implementation Notes

- FSM code should not contain delays or waits
  - No delay_ms() or while(…){}
  - Remember that your FSM code will be called once per control cycle: use “if” to check for an event during that control cycle
- Use LEDs and/or fprintf() to indicate current state
- Implement and test incrementally

# FSM Implementation Notes

For your project: use an enumerated data type to represent your set of states.