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: our synchronous counter

- States: ?

Finite State Machines (FSMs)

An example: our synchronous counter

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

- Inputs: ?

Finite State Machines (FSMs)

An example: our synchronous counter

- Inputs:
  - Really only one: the event associated with the clock transitioning from high to low
  - We will call this "C"

- Outputs: ?

Finite State Machines (FSMs)

An example: our synchronous counter

- Outputs: same as the set of states

- Transition function: ?

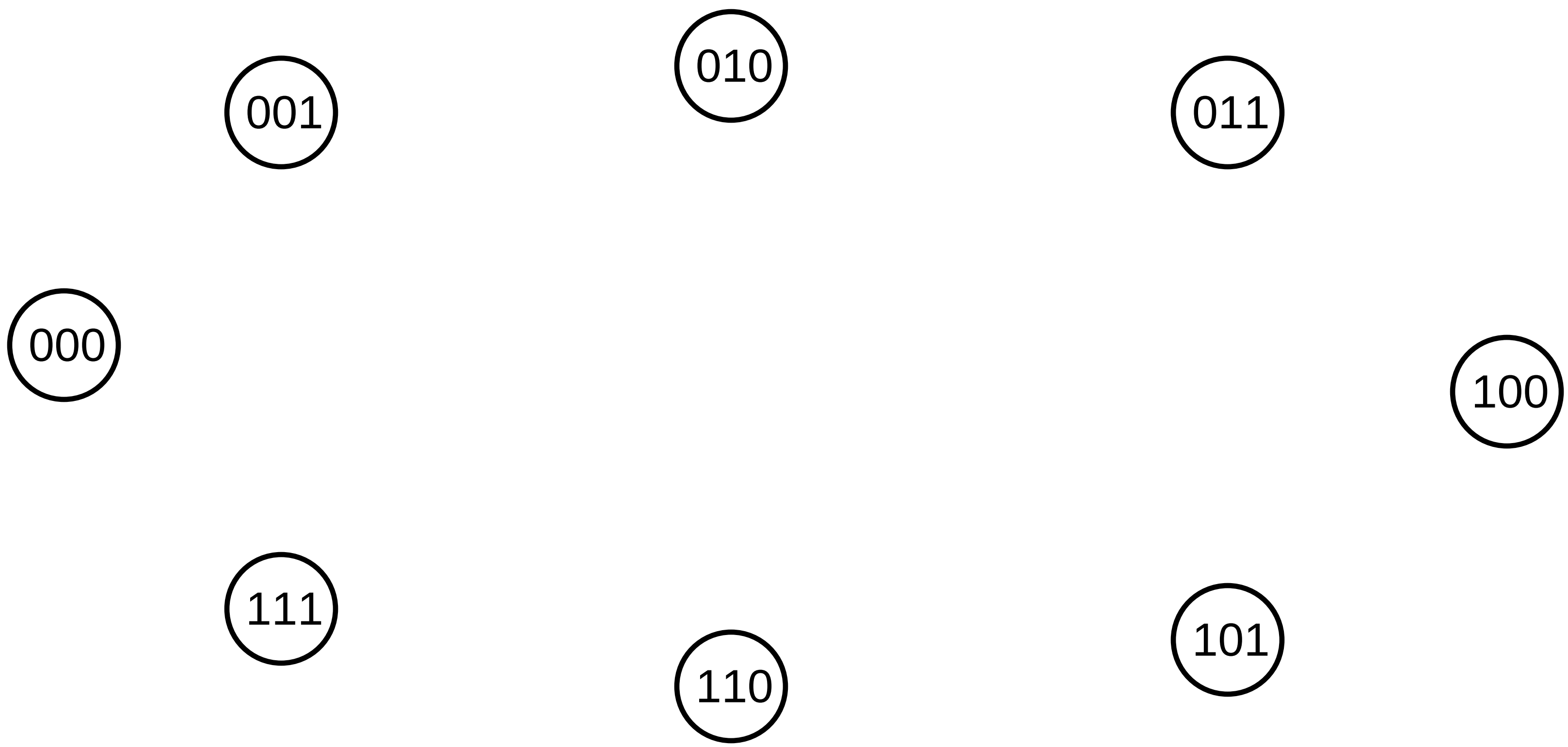
Finite State Machines (FSMs)

An example: our synchronous counter

- Transition function:
  - On the clock event, transition to the next state in the sequence

FSM Example: Synchronous Counter

A Graphical Representation:

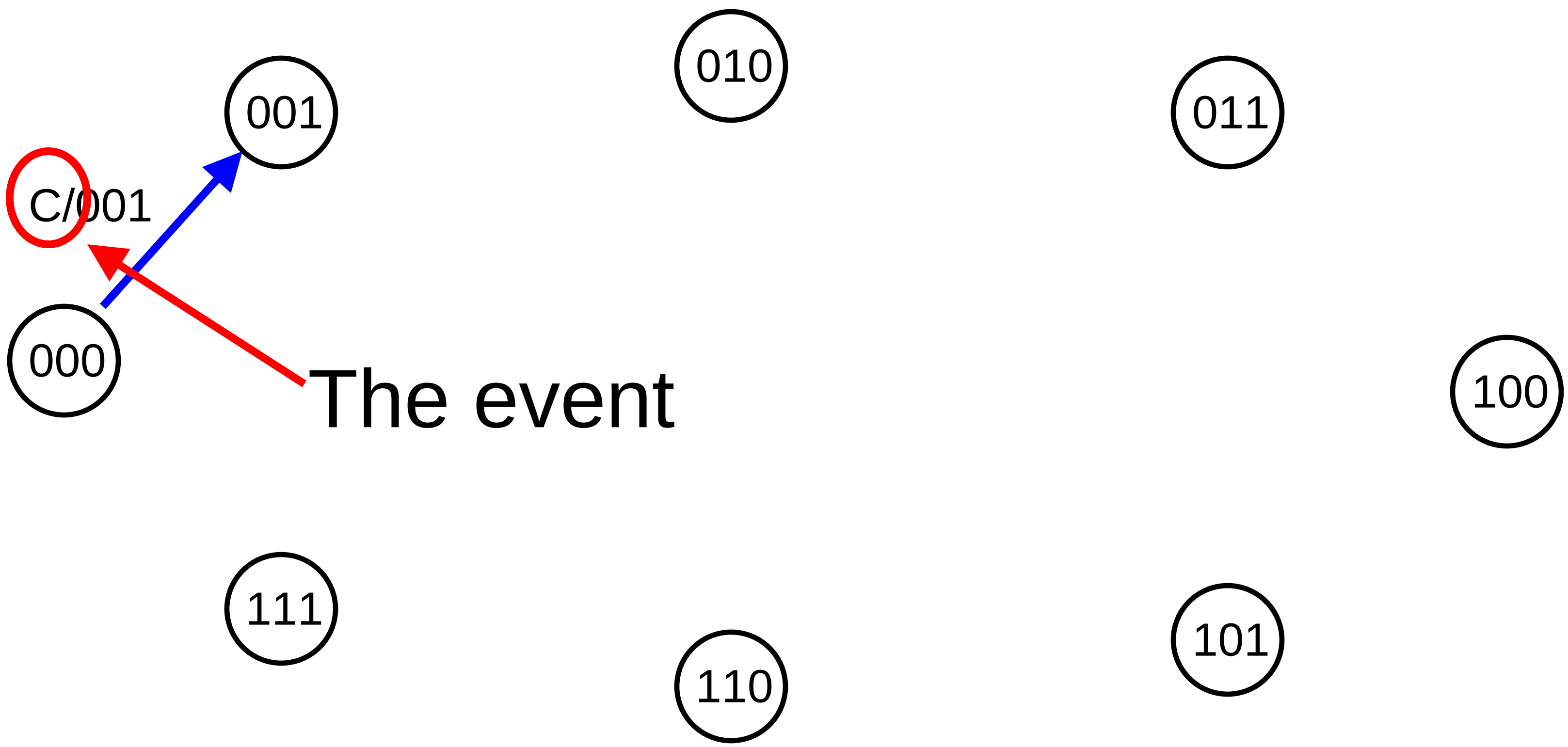


A set of states

FSM Example: Synchronous Counter

FSM Example: Synchronous Counter

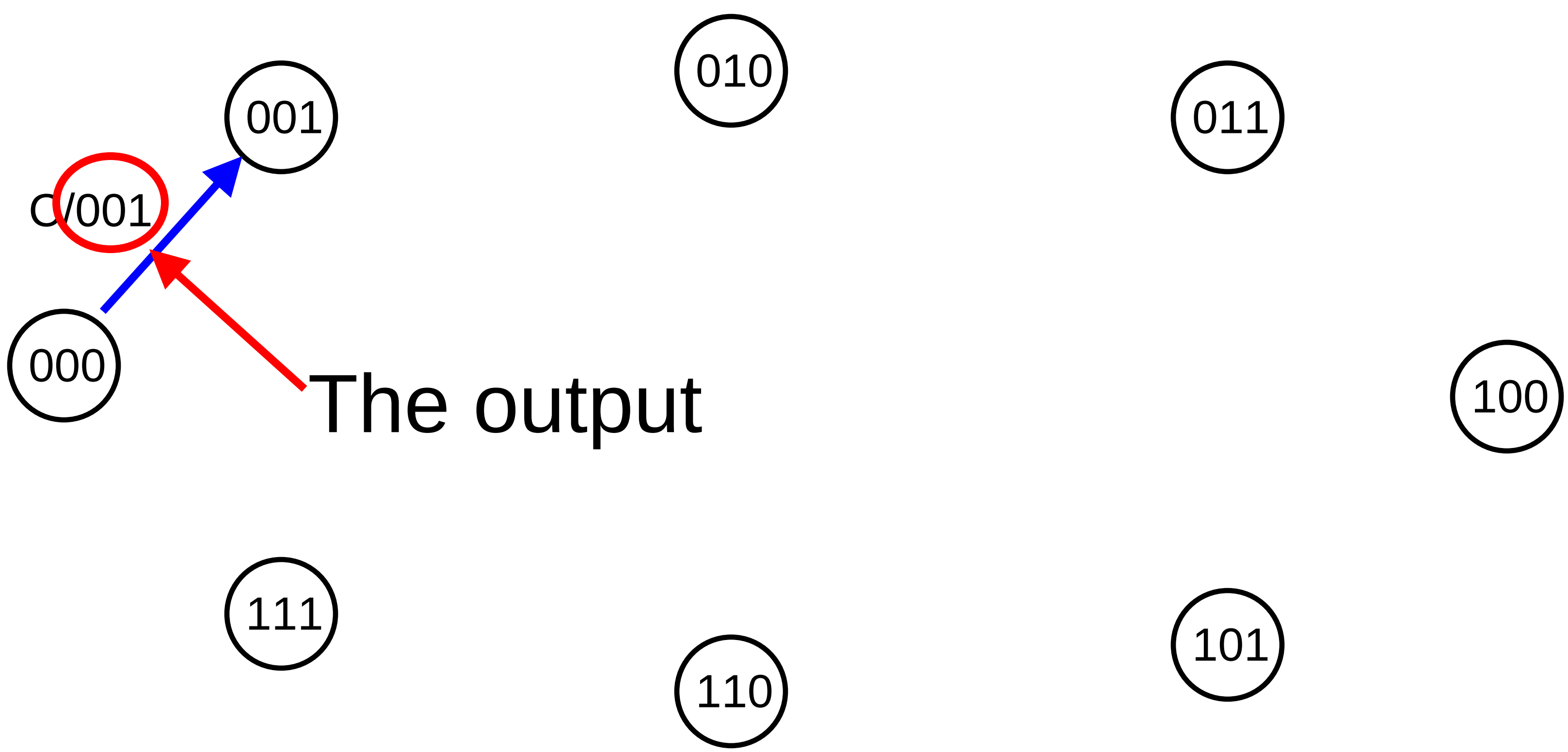
A transition



The event

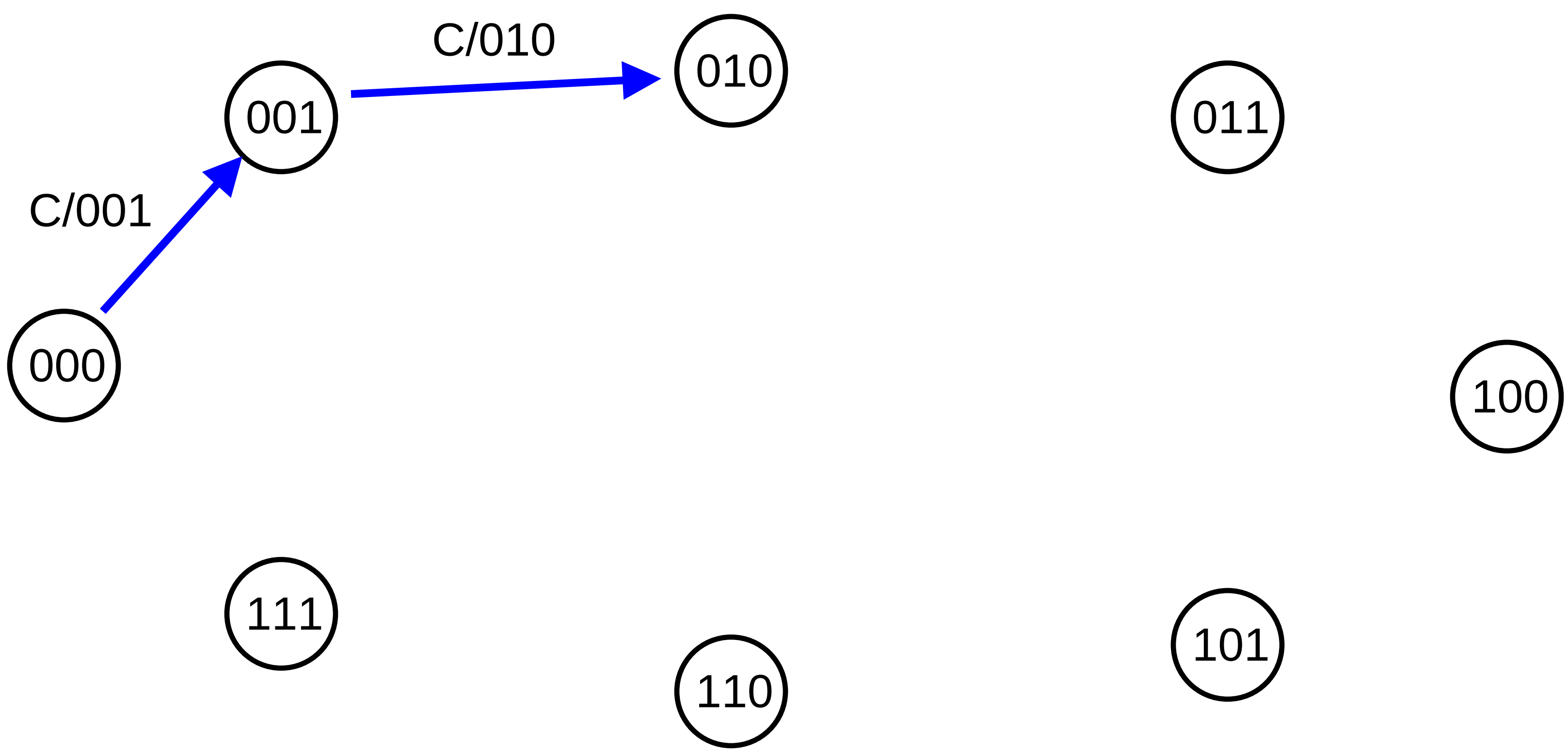
FSM Example: Synchronous Counter

A transition



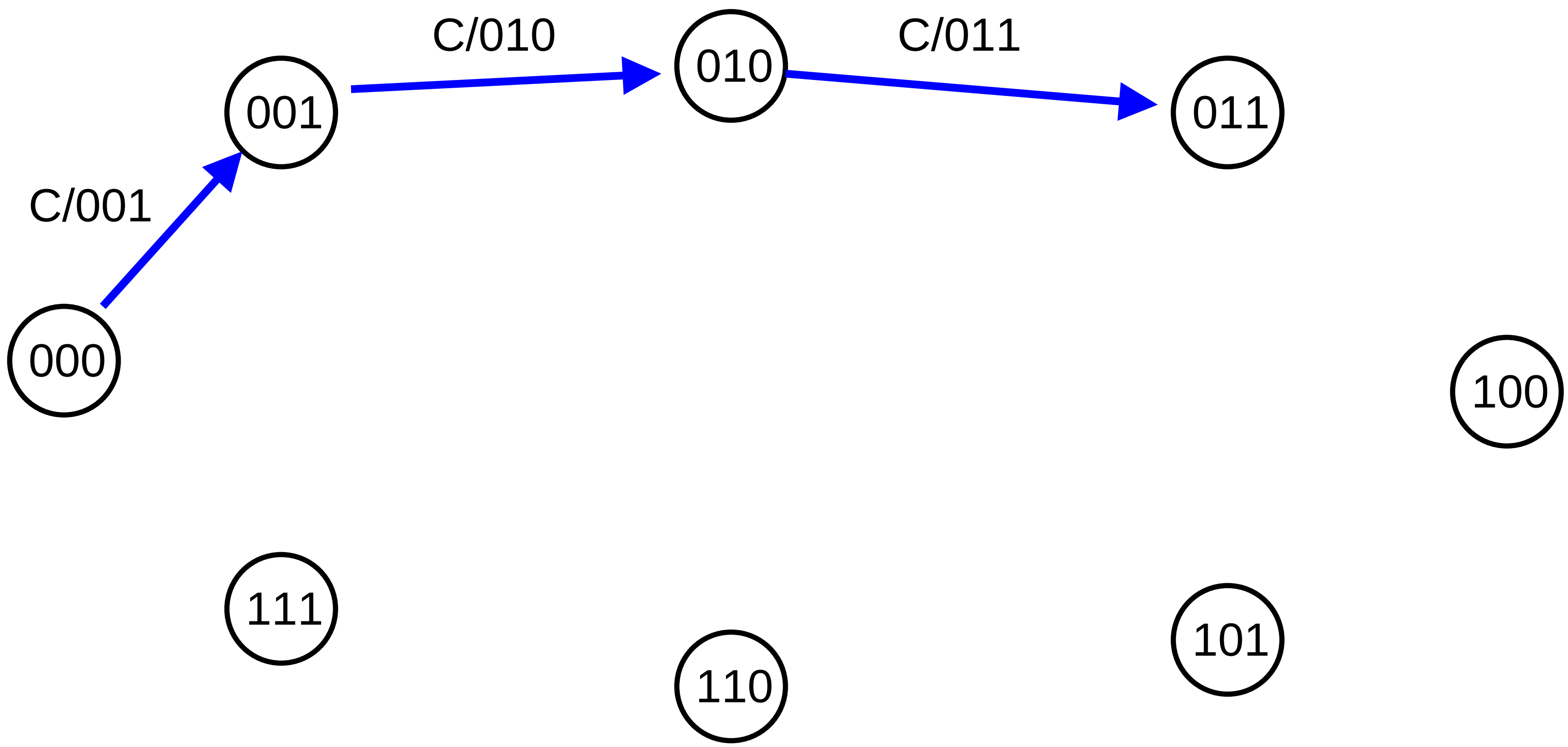
FSM Example: Synchronous Counter

The next transition



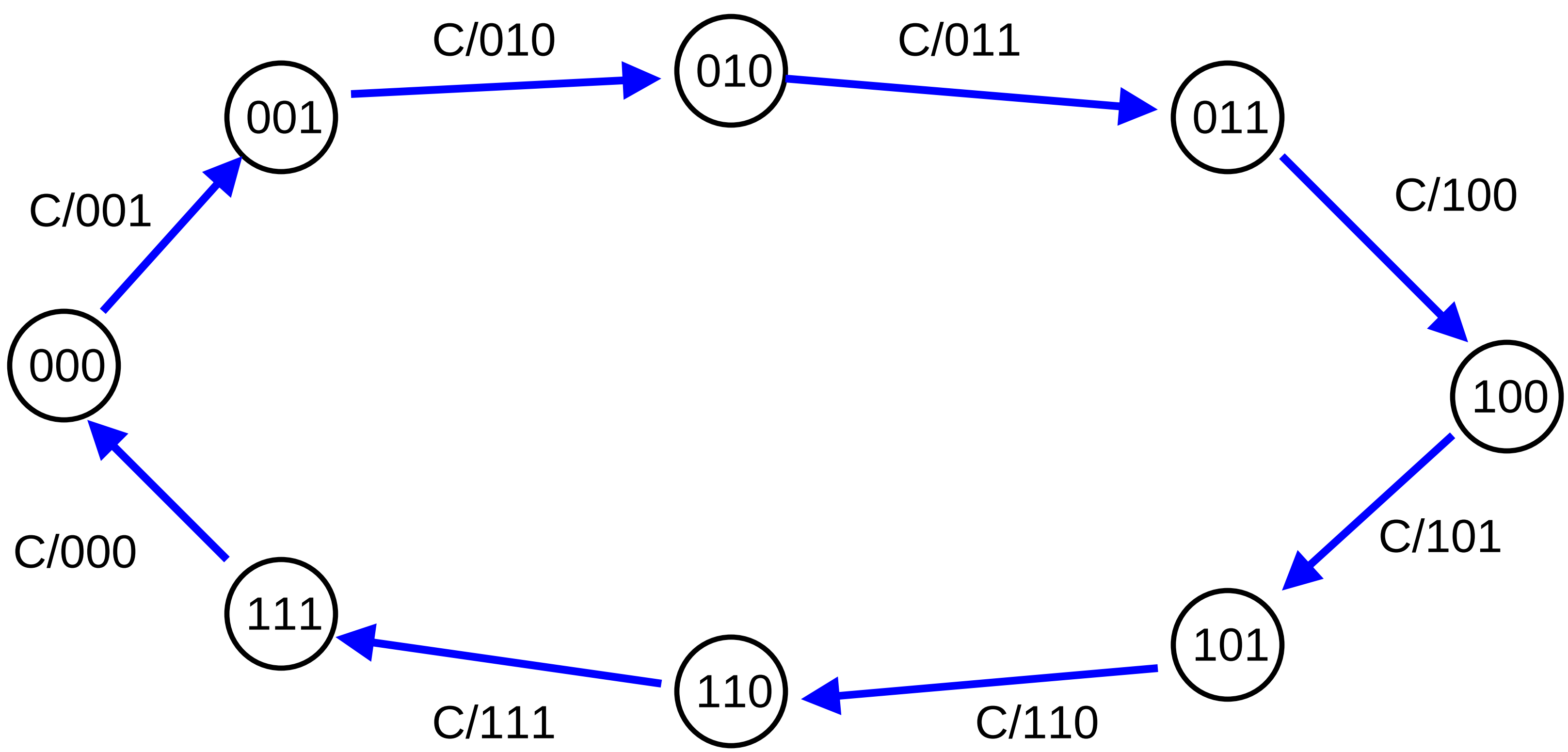
FSM Example: Synchronous Counter

The next transition

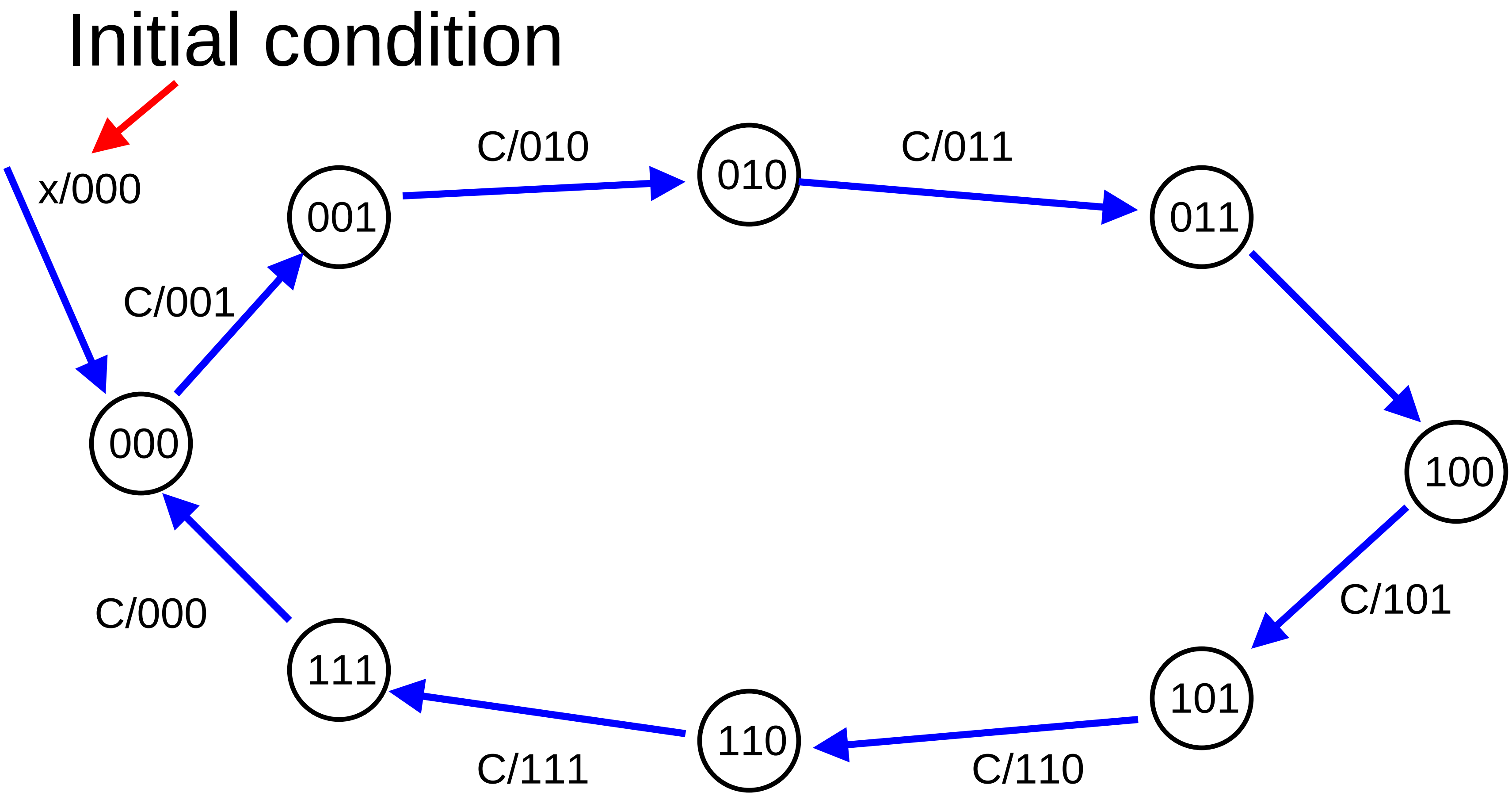


FSM Example: Synchronous Counter

The full transition set



FSM Example: Synchronous Counter



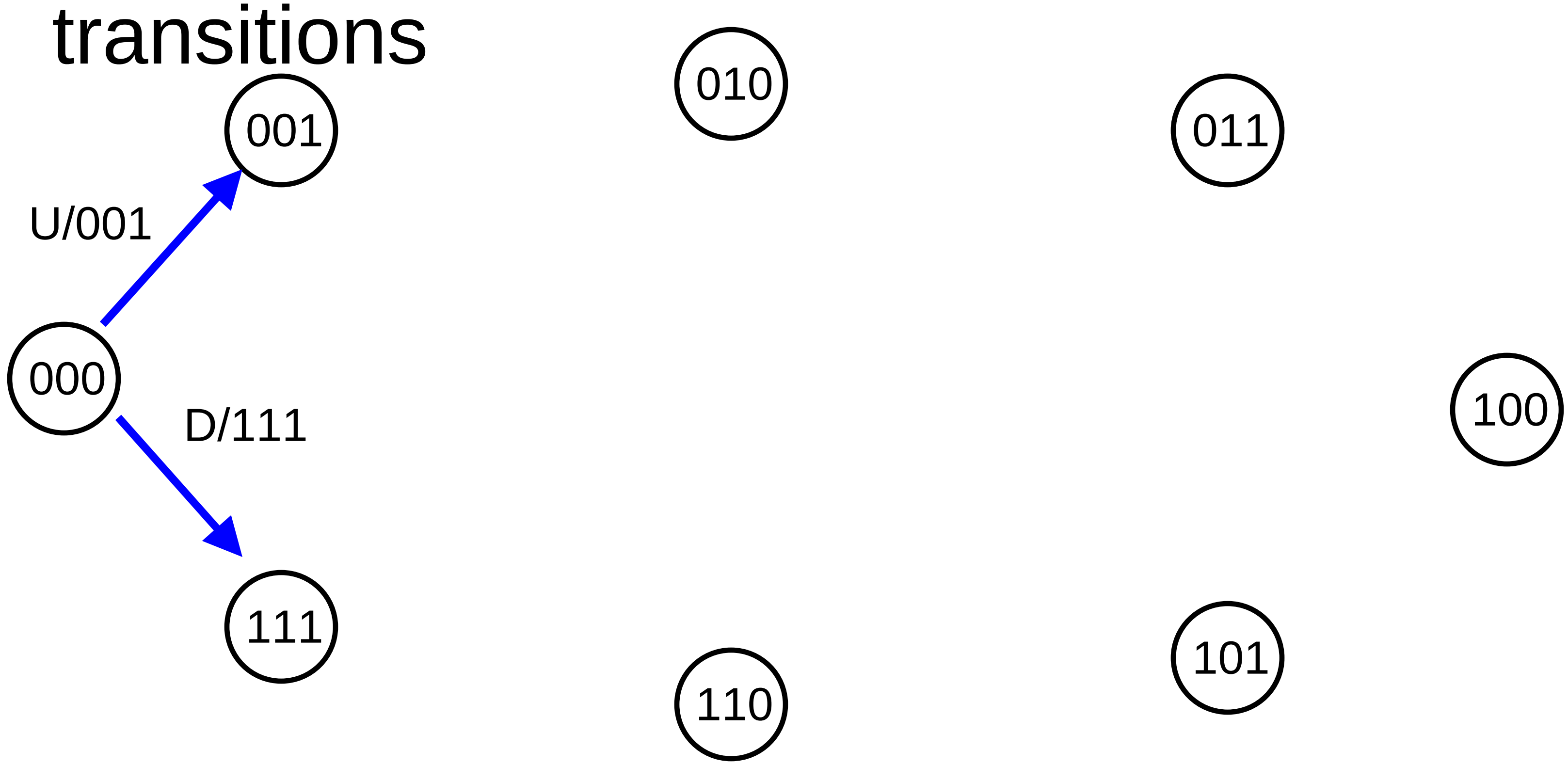
Example II: An Up/Down Counter

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

- How does this change our state transition diagram?

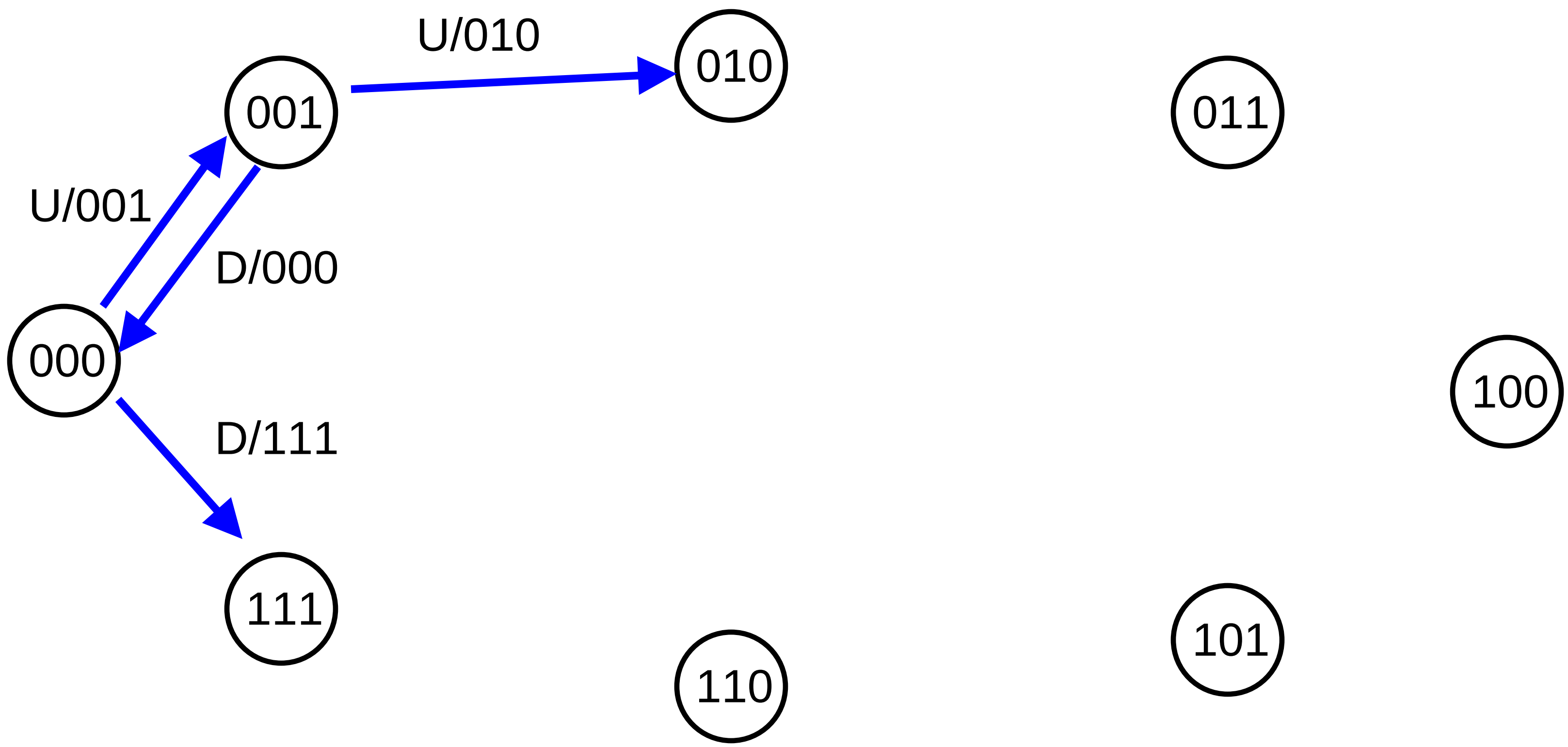
Example II: An Up/Down Counter

From state 000, there are now two possible transitions



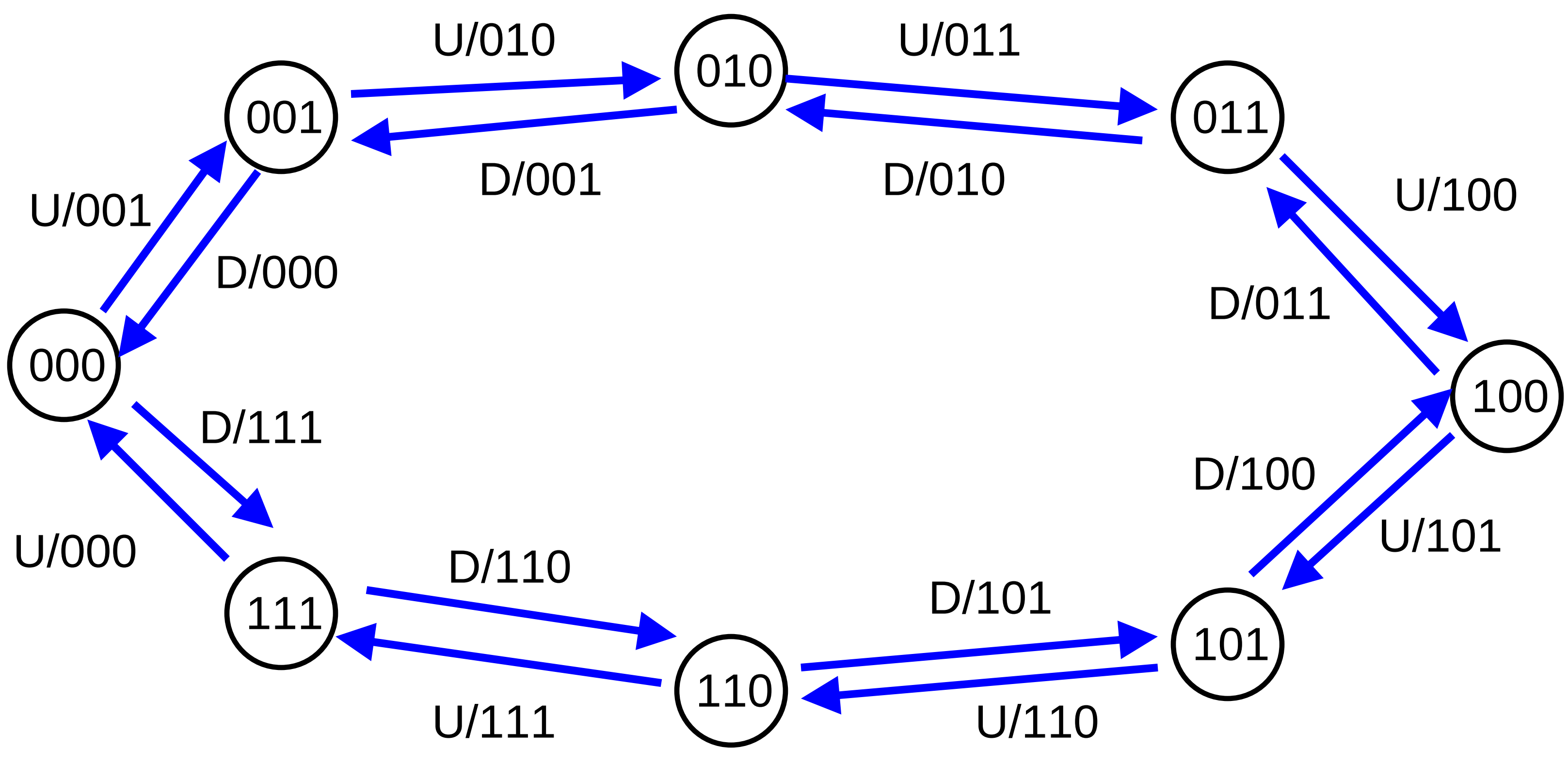
Example II: An Up/Down Counter

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 ?

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 ?

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

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

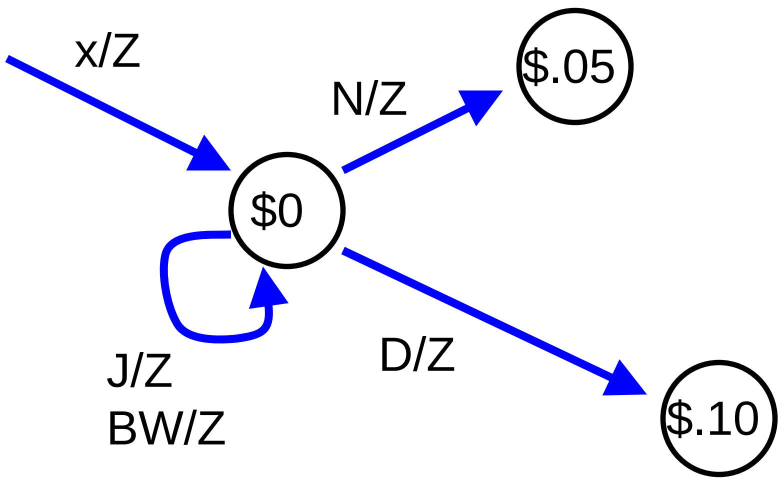
What can happen from S = $0?

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

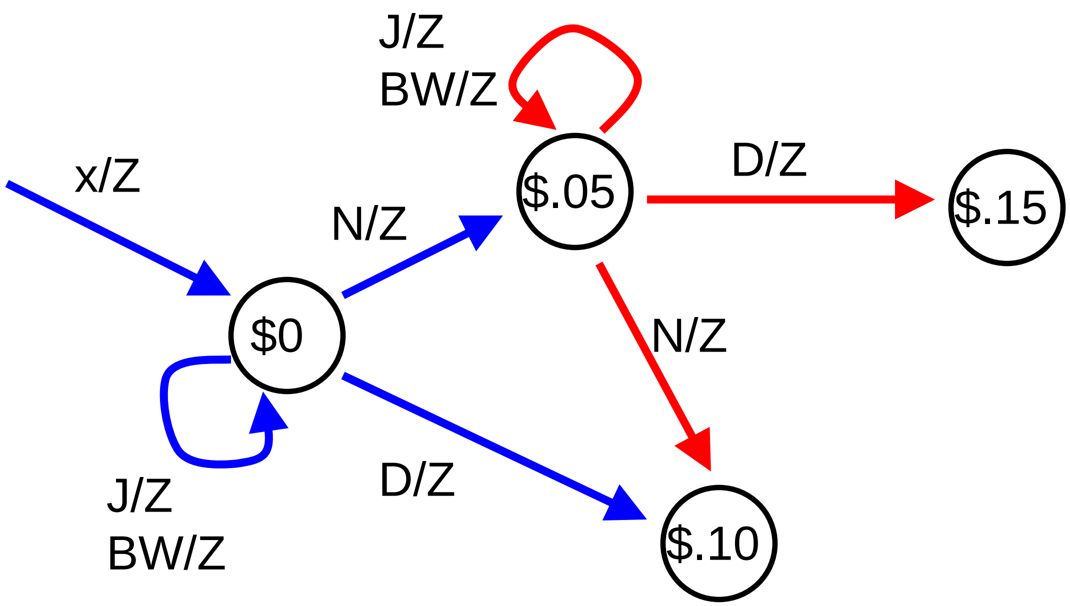
What can happen from S = \$0.05?

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

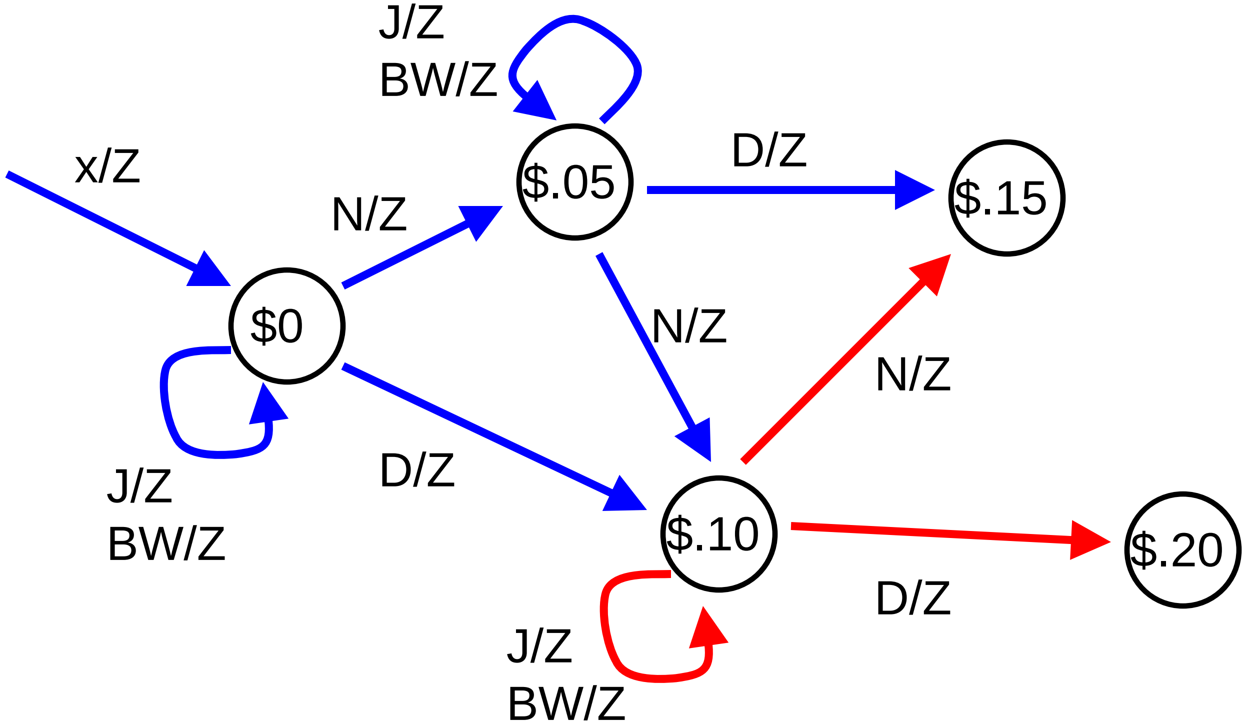
Vending Machine Design

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

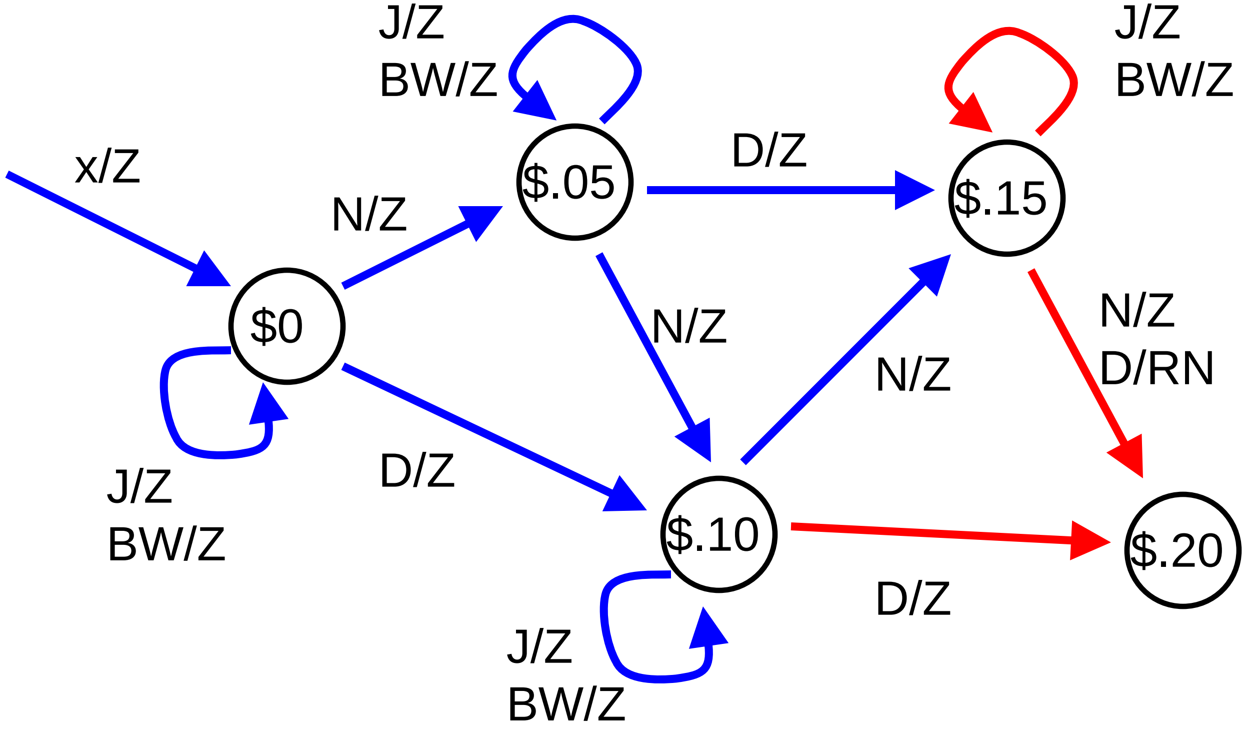
Vending Machine Design

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

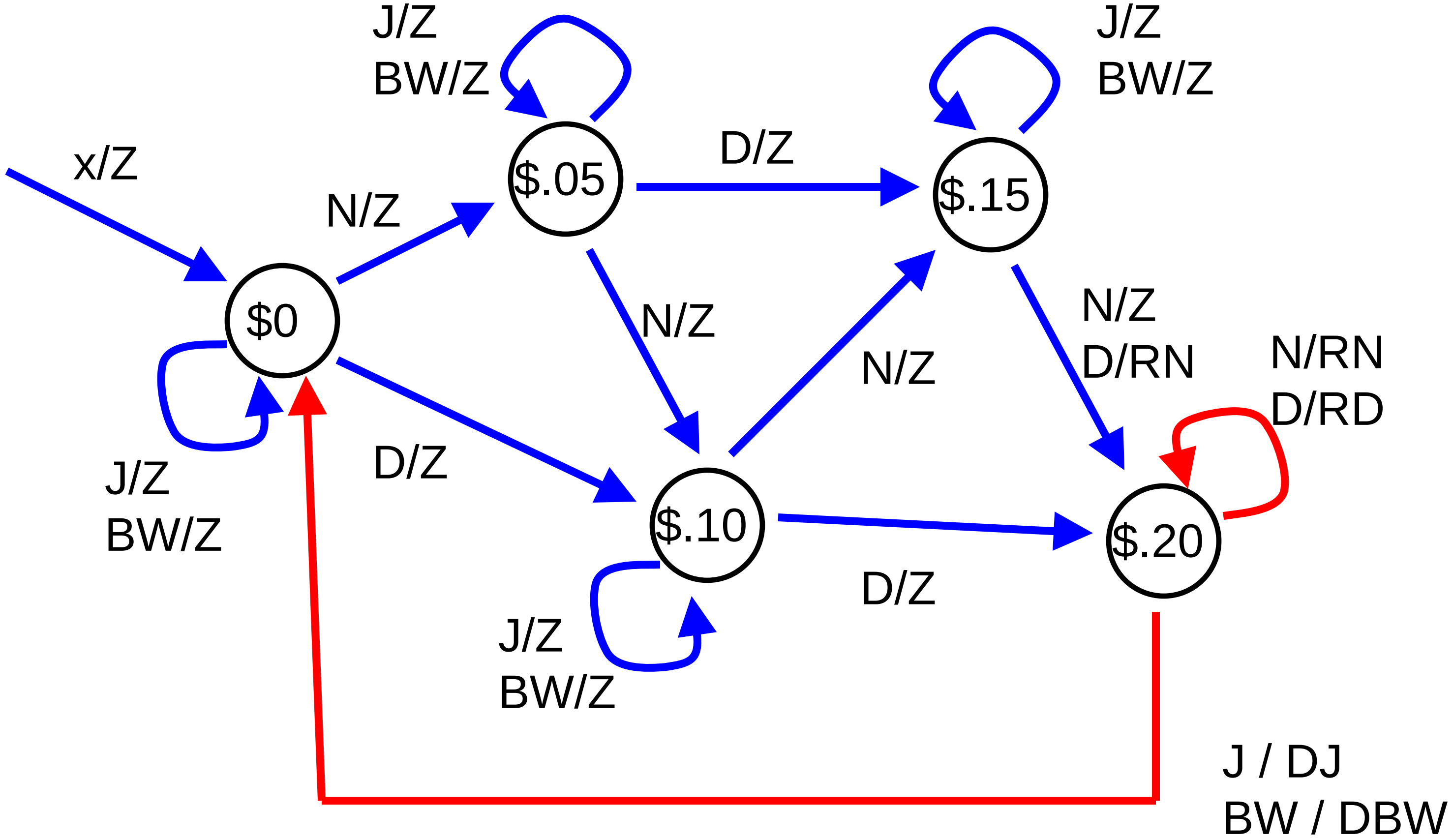
Vending Machine Design

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:



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

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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 ?

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

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

What is the FSM representation?

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

- Need code that translates sensory inputs into FSM events
- An FSM output can require an arbitrary amount of time
  - We will often implement this control action as a separate function call
- Control actions will not necessarily be fixed (but could be a function of sensory input)

FSMs As Controllers (cont)

- We might choose to leave some events out of the implementation
  - Only some events may be relevant to certain states
- When in a state, the FSM may also issue control actions (even when a new event has not arrived)
  - Again, this may be implemented as a function call

FSMs in C

```
int state = 0;   // Initial state
while(1) {
  <do some processing of the sensory inputs>
  switch(state) {
      case 0:
            <handle state 0>
            break;
      case 1:
            <handle state 1>
            break;
      case 2: …
  }
}
```

FSMs in C

```
int state = 0;    // Initial state
while(1) {
   <do some processing of the sensory inputs>
   switch(state) {
        case 0:
              <handle state 0>
              break;
        case 1:
              <handle state 1>
              break;
        case 2: …
   }
}
```

Variable declaration and initialization

FSMs in C

```
int state = 0;   // Initial state
while(1) {
  <do some processing of the sensory inputs>
  switch(state) {
      case 0:
            <handle state 0>
            break;
      case 1:
            <handle state 1>
            break;
      case 2: …
  }
}
```

Loop forever

FSMs in C

```
int state = 0;   // Initial state
while(1) {
  <do some processing of the sensory inputs>
  switch(state) {
      case 0:
            <handle state 0>
            break;
      case 1:
            <handle state 1>
            break;
      case 2: …
  }
}
```

“pseudo code”: not really code, but indicates what is to be done

FSMs in C

```
int state = 0;   // Initial state
while(1) {
  <do some processing of the sensory inputs>
  switch(state) {
      case 0:
            <handle state 0>
            break;
      case 1:
            <handle state 1>
            break;
      case 2: …
  }
}
```

In this case: we will translate the current sensory inputs into a representation of an event (if one has happened)

FSMs in C

```
int state = 0;   // Initial state
while(1) {
  <do some processing of the sensory inputs>
  switch(state) {
     case 0:
           <handle state 0>
           break;
     case 1:
           <handle state 1>
           break;
     case 2: …
  }
}
```

Switch/case syntax allows us to cleanly perform many “if(x==y)” operations

FSMs in C

```
int state = 0;   // Initial state
while(1) {
   <do some processing of the sensory inputs>
   switch(state) {
      case 0:
            <handle state 0>
            break;
      case 1:
            <handle state 1>
            break;
      case 2: …
   }
}
```

If state==0, then execute the following code

FSMs in C

```
int state = 0;   // Initial state
while(1) {
  <do some processing of the sensory inputs>
  switch(state) {
     case 0:
          <handle state 0>
          break;
     case 1:
          <handle state 1>
          break;
     case 2: …
  }
}
```

This code can be as complex as necessary

FSMs in C

```
int state = 0;   // Initial state
while(1) {
  <do some processing of the sensory inputs>
  switch(state) {
     case 0:
          <handle state 0>
          break;
     case 1:
          <handle state 1>
          break;
     case 2: …
  }
}
```

break says to exit the switch (don’t forget it or strange things can happen!)

FSMs in C

```
int state = 0;   // Initial state
while(1) {
  <do some processing of the sensory inputs>
  switch(state) {
      case 0:
            <handle state 0>
            break;
      case 1:
            <handle state 1>
            break;
      case 2: …
  }
}
```

If state==1, then …

FSMs in C

```
int state = 0;   // Initial state
while(1) {
  <do some processing of the sensory inputs>
  switch(state) {
      case 0:
            <handle state 0>
            break;
      case 1:
            <handle state 1>
            break;
      case 2: …
  }
}
```

End of the **switch** block

FSMs in C (some other possibilities)

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

FSMs in C (some other possibilities)

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

Matches any state (if we reach this point)

FSMs in C (some other possibilities)

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

(possibly) alter some control outputs (e.g., steering direction)

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;
```

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;
```

Another integer

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;
```

A nickel has been received

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;
```

Change state for next iteration of the while() loop

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;
```

If any of these match, then execute the following code (which does nothing in this example)

Handling Each State

Some events do not fall neatly into one of several categories

- This precludes the use of the “switch” construct
- 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!
          duty_forward = 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!
          duty_forward = 0;
          duty_middle = 127;
          middle_thrust_dir(0);
          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

            duty_middle = 0;
            state = STATE_MISSION_PHASE_6;
      };
  break;
:

NOTE: clock is being incremented once per control cycle
```

A Note on "Style" in C

- The numbers that we assigned to the different states are arbitrary (and at first glance, hard to interpret)
- Instead, we can define constant strings that have some meaning

- Replace: 0, 1, 2, 3, 4, 5
- With: STATE_00, STATE_05, STATE_10, STATE_15, STATE_20

A Note on “Style” in C

In C, this is done by adding some definitions to the beginning of your program (either in the .c file or the .h file):

```
#define STATE_00cents   0
#define STATE_05cents   1
#define STATE_10cents   2
#define STATE_15cents   3
#define STATE_20cents   4
```