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 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: ?

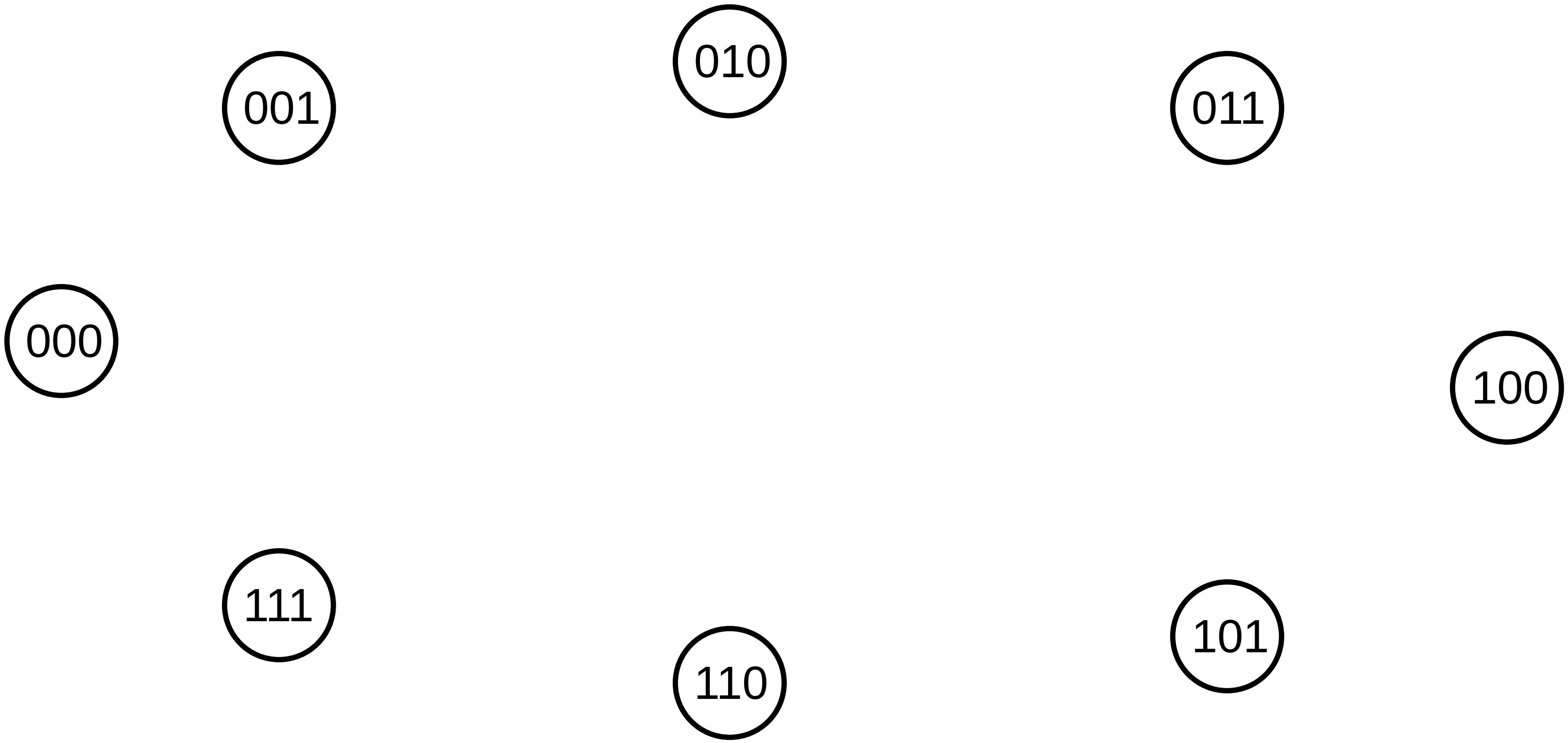
Finite State Machines (FSMs)

An example: a counter

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

FSM Example: Synchronous Counter

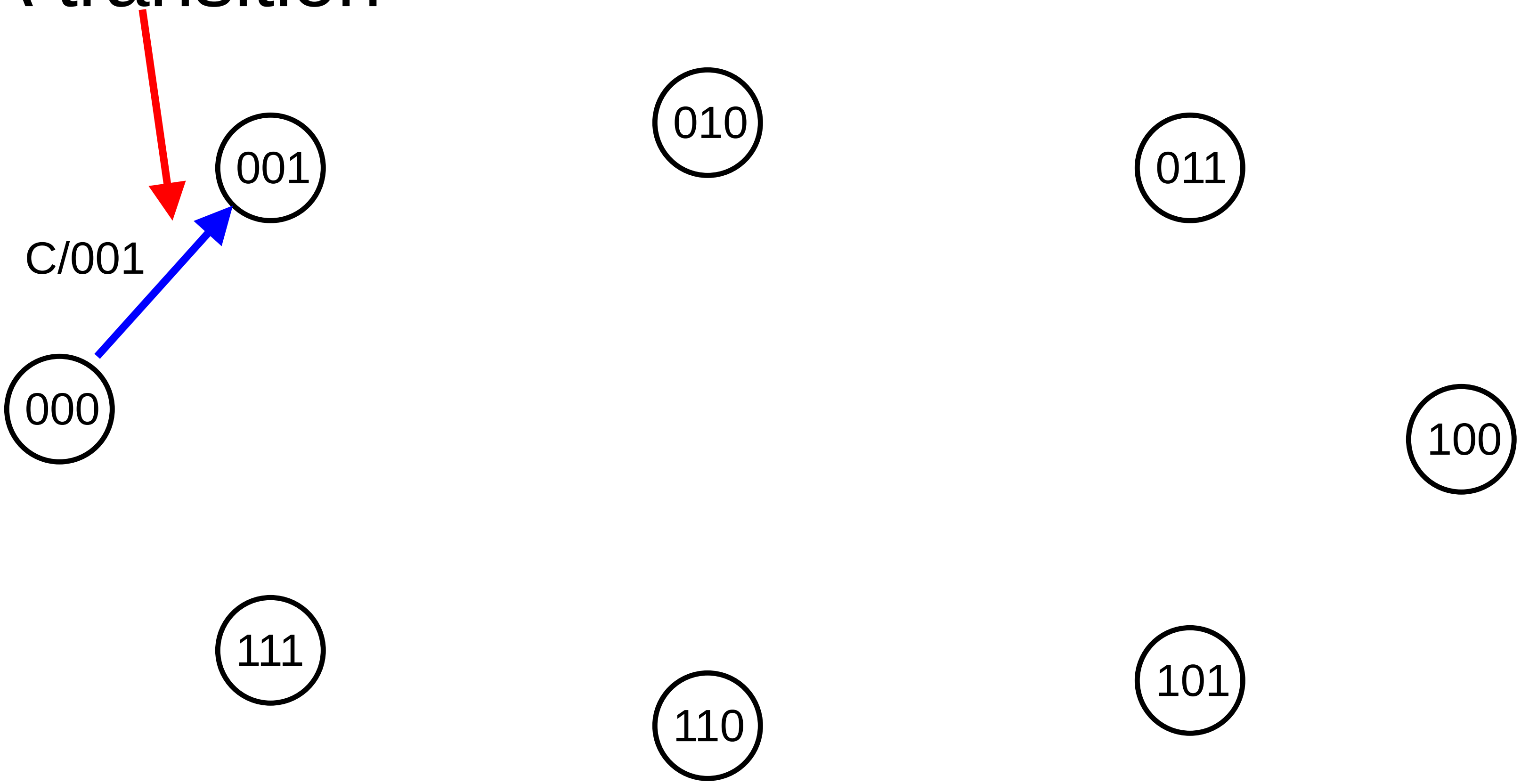
A Graphical Representation:



A set of states

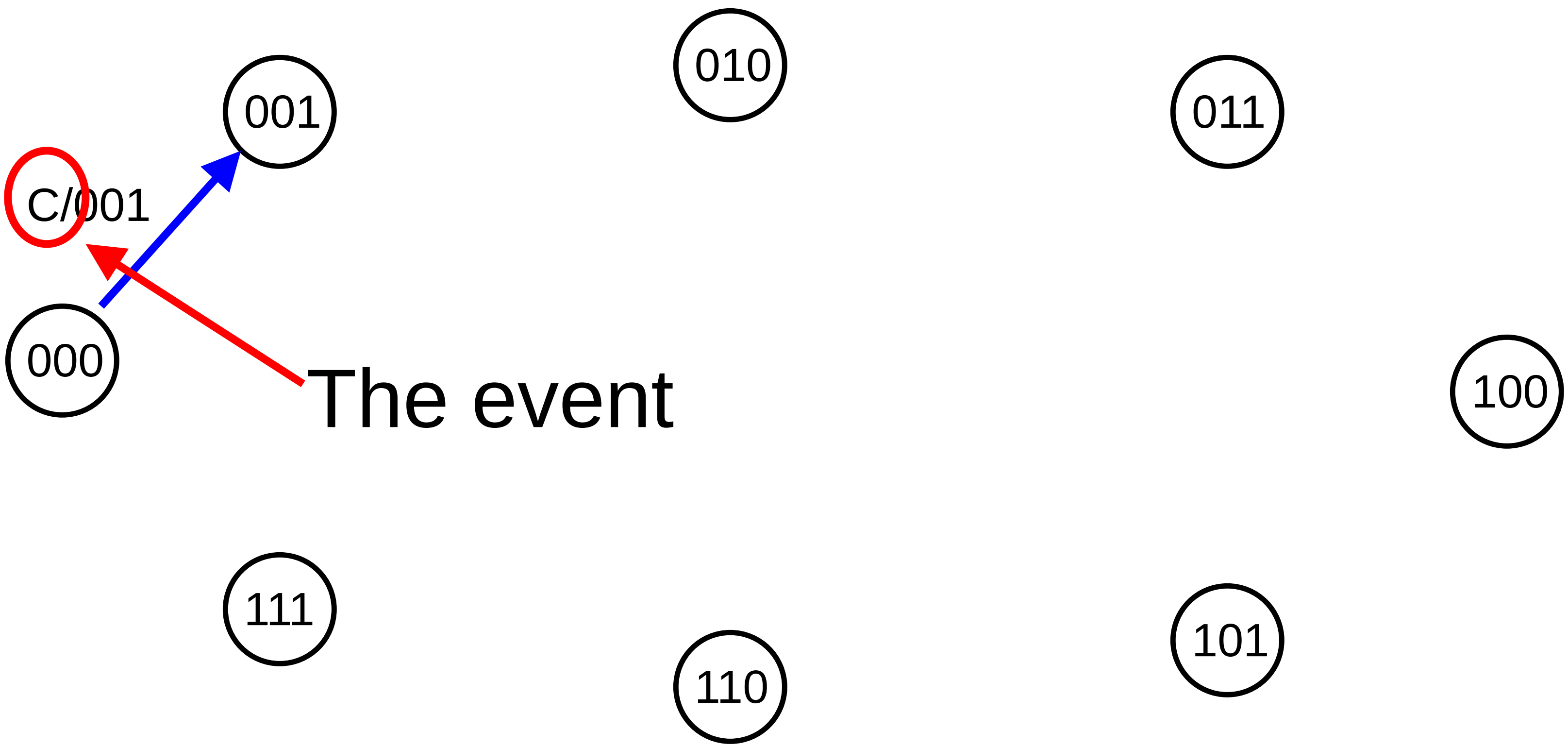
FSM Example: Synchronous Counter

A transition



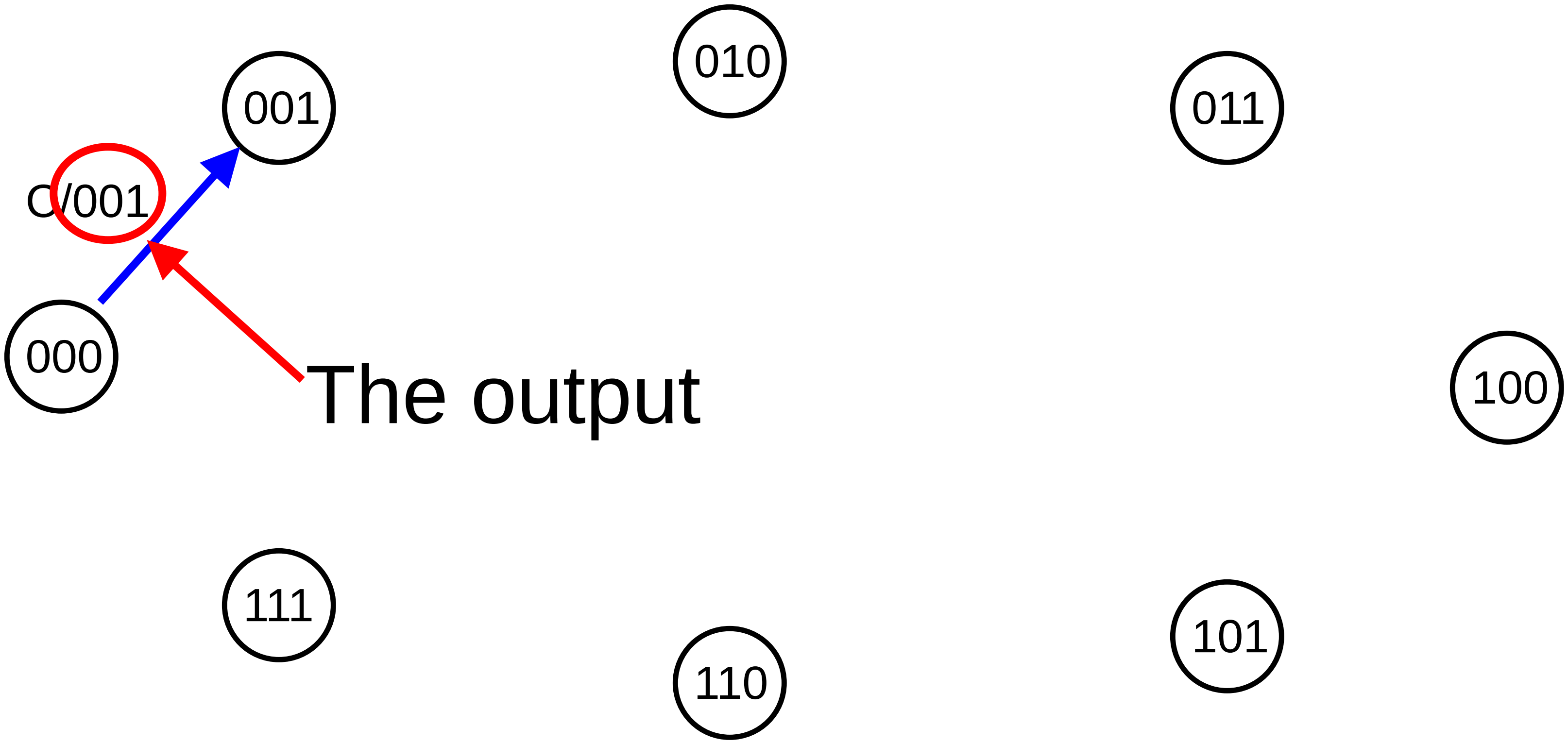
FSM Example: Synchronous Counter

A transition



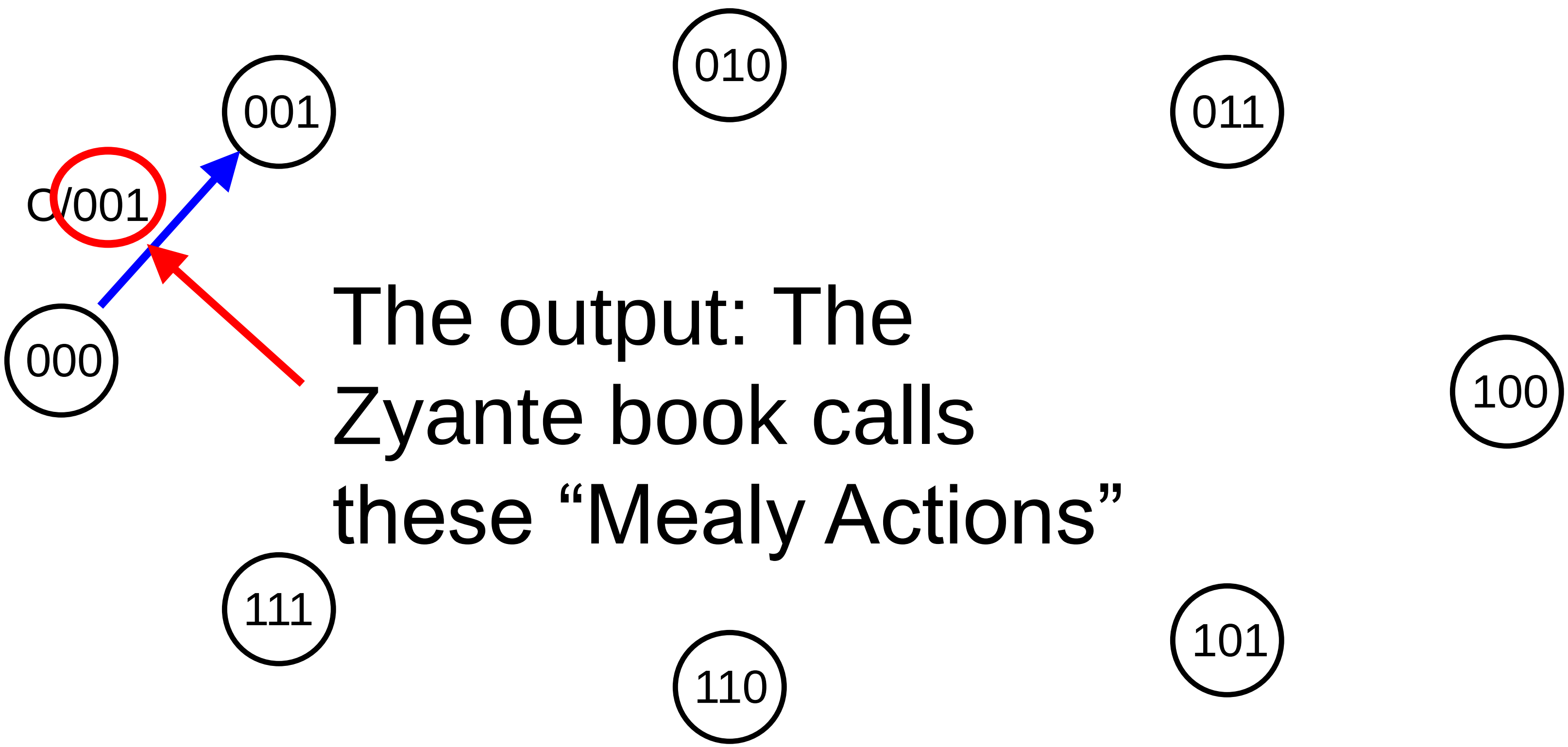
FSM Example: Synchronous Counter

A transition



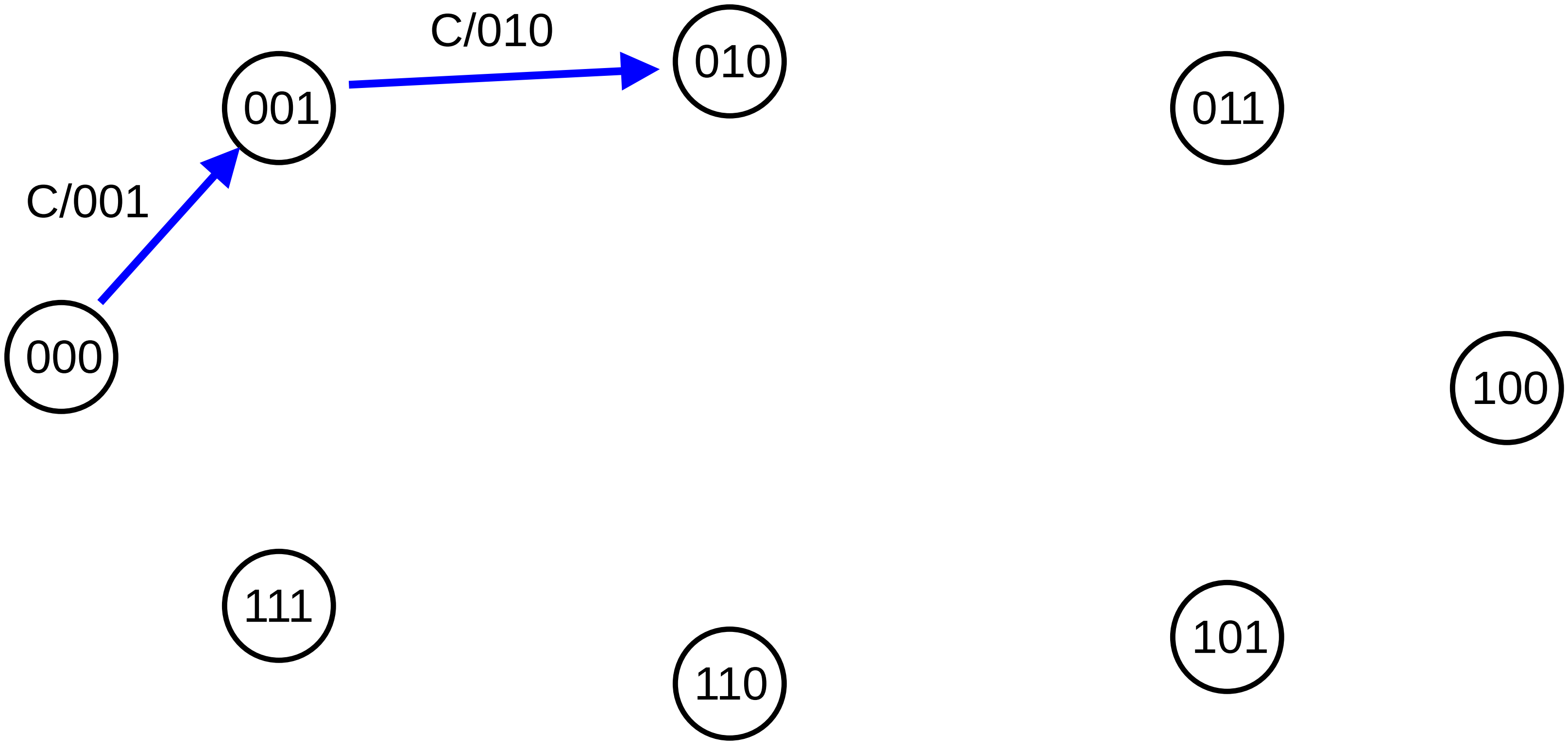
FSM Example: Synchronous Counter

A transition



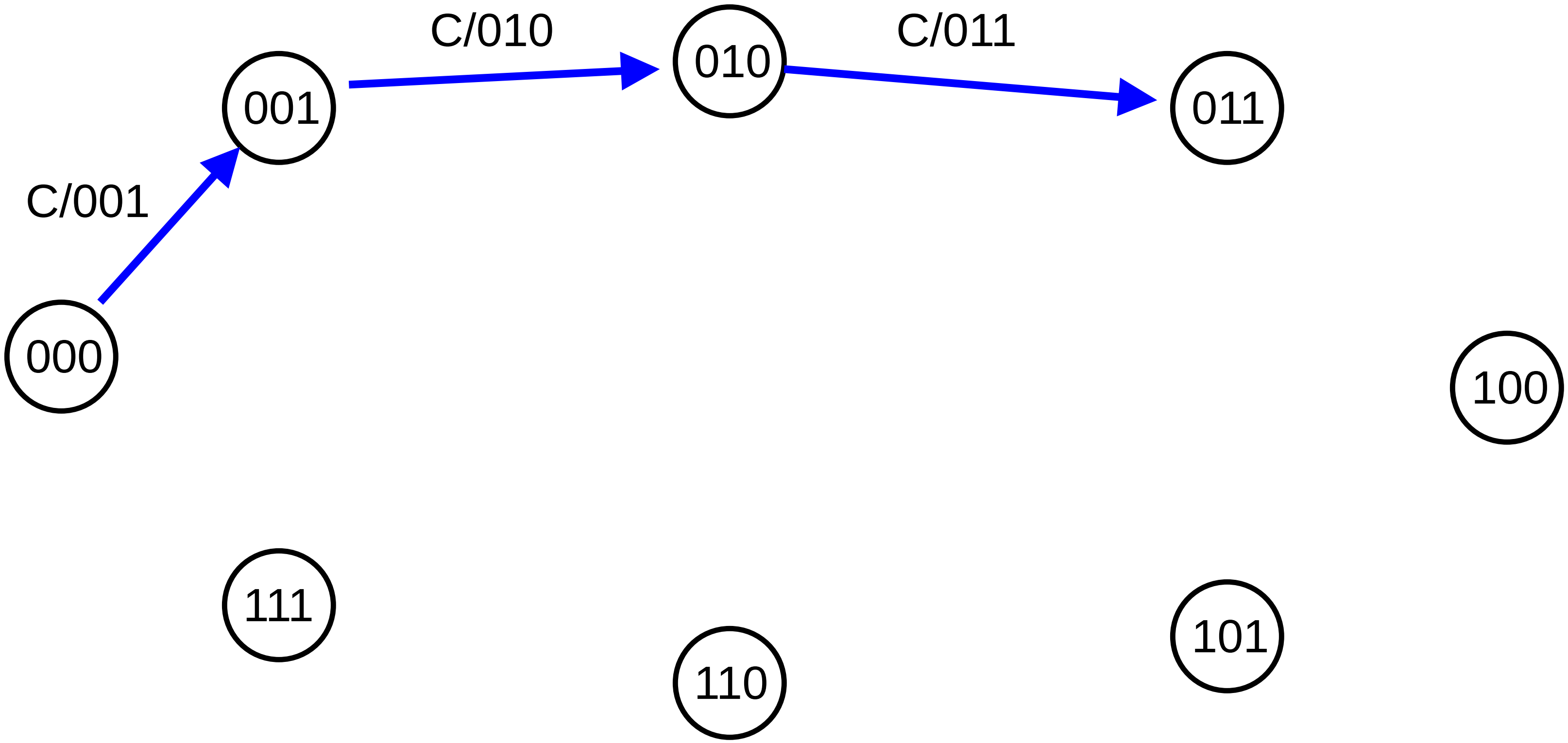
FSM Example: Synchronous Counter

The next transition



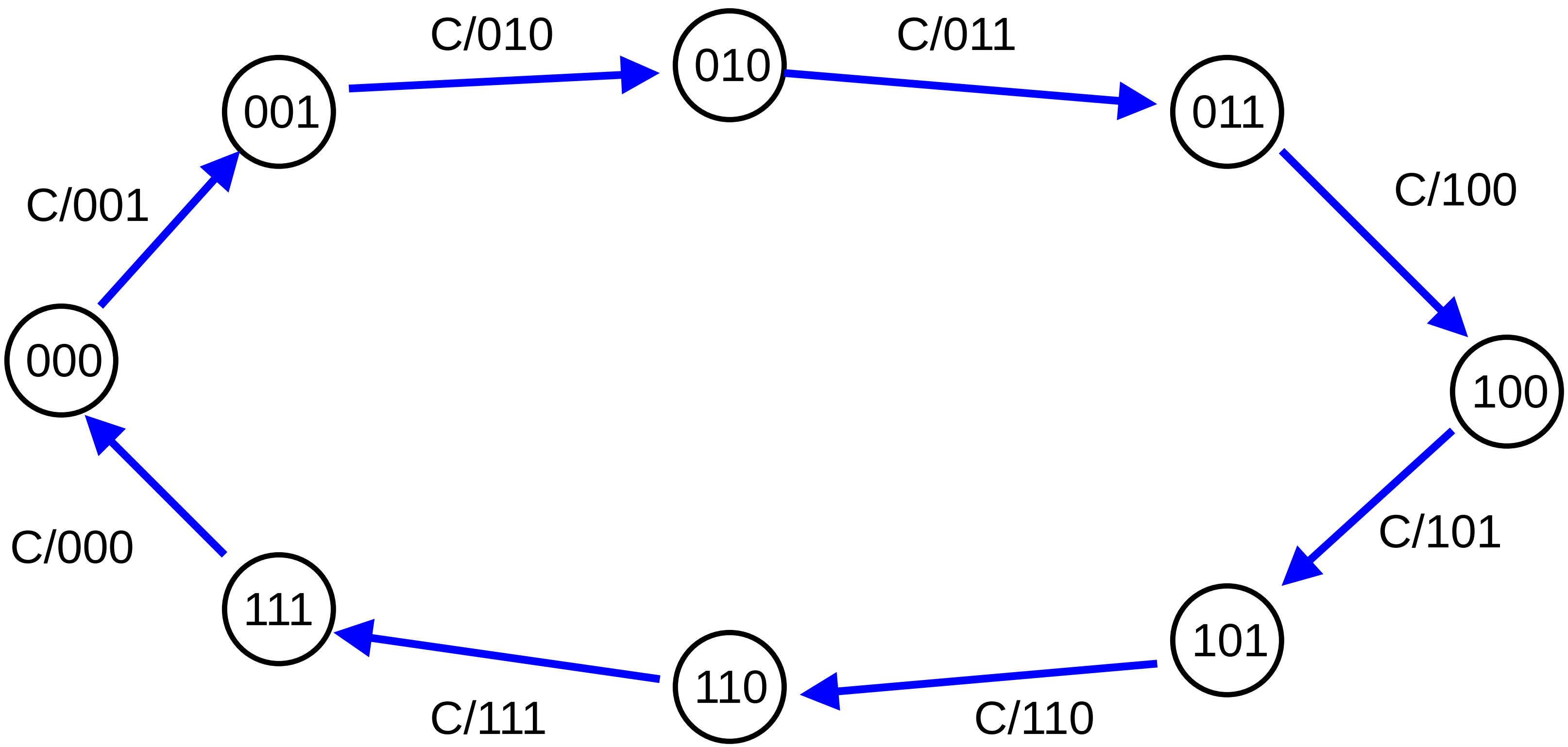
FSM Example: Synchronous Counter

The next transition

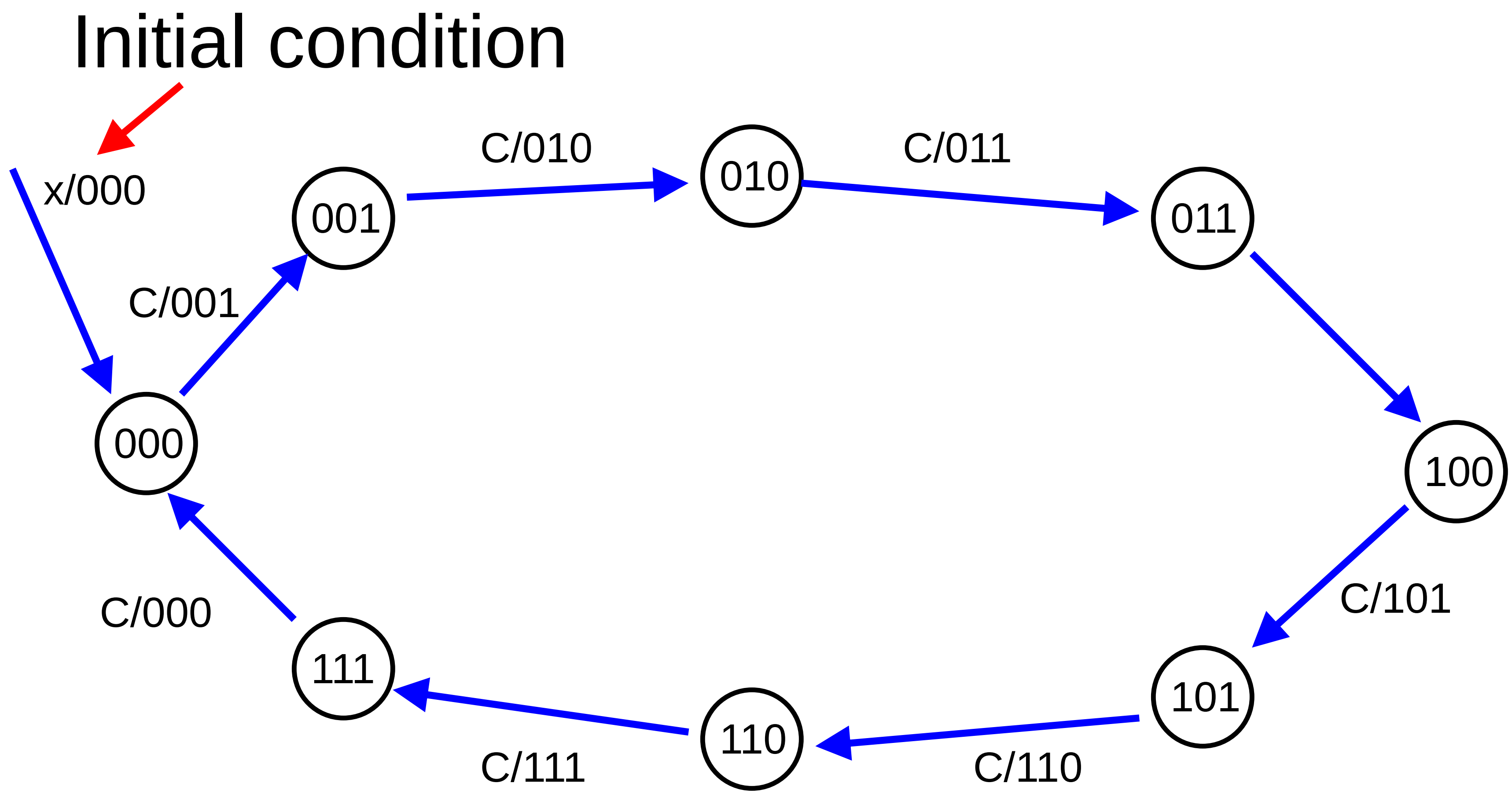


FSM Example: Synchronous Counter

The full transition set



FSM Example: Synchronous Counter



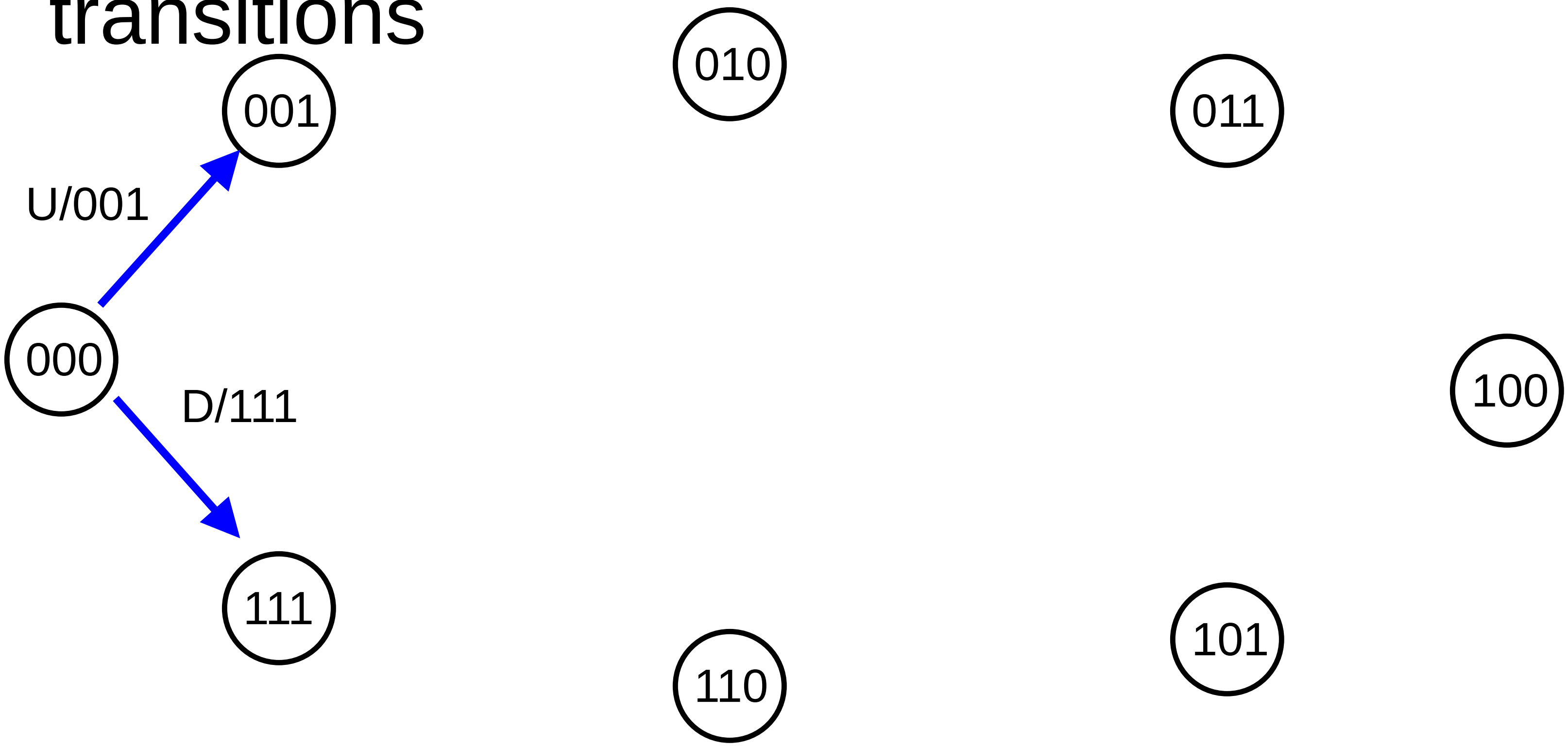
Example II: An Up/Down Counter

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

- How does this change our state transition diagram?

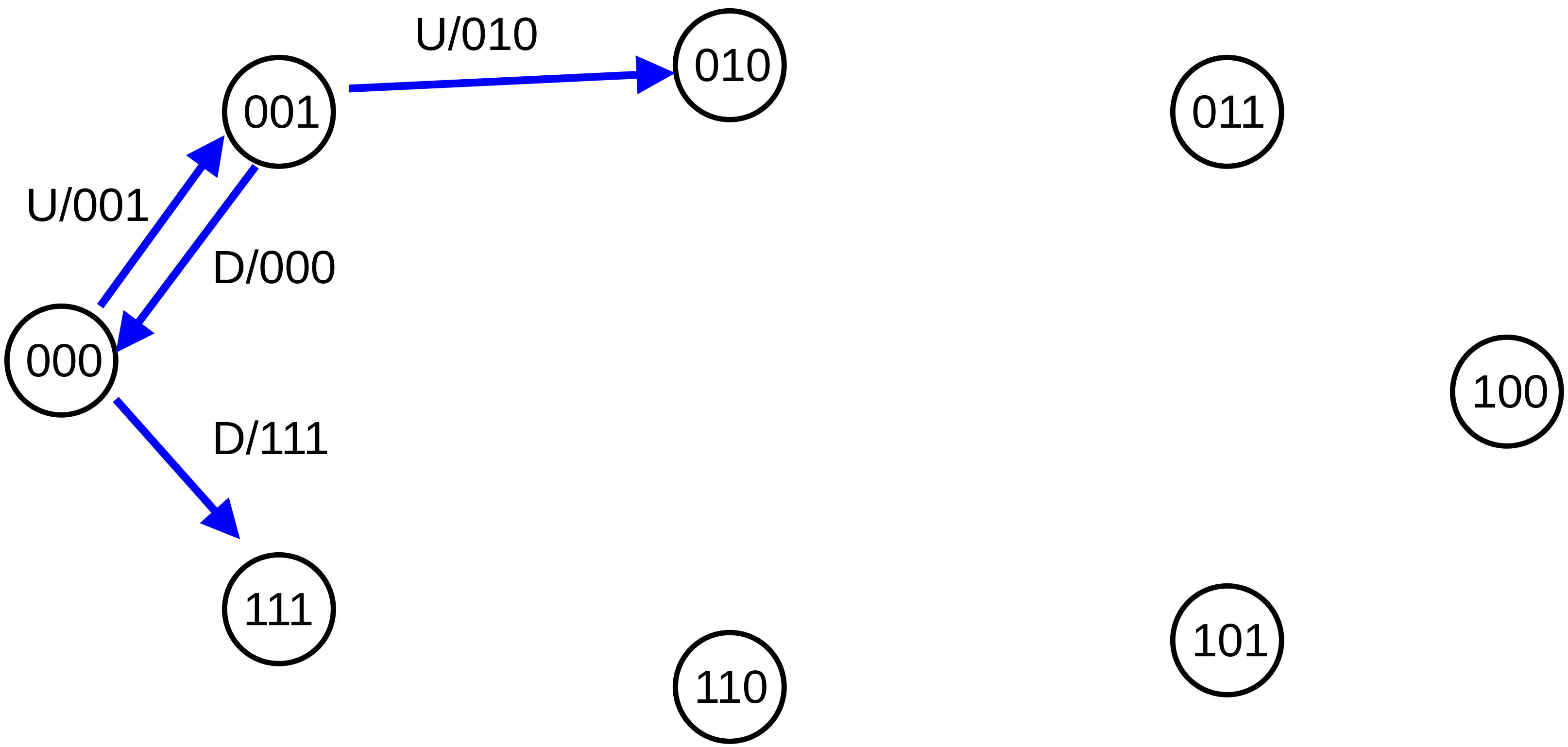
Example II: An Up/Down Counter

From state 000, there are now two possible transitions



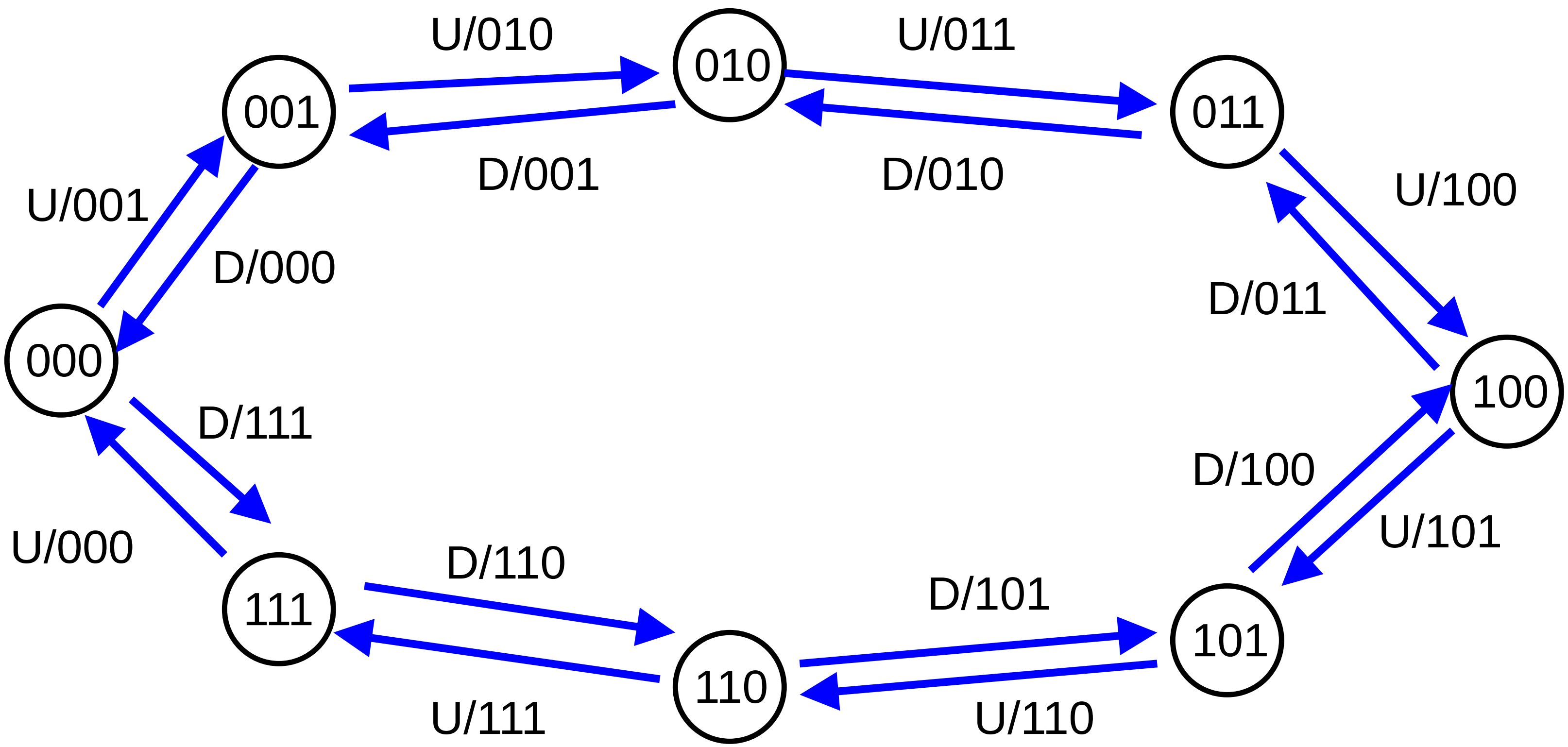
Example II: An Up/Down Counter

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 ?

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
  - 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

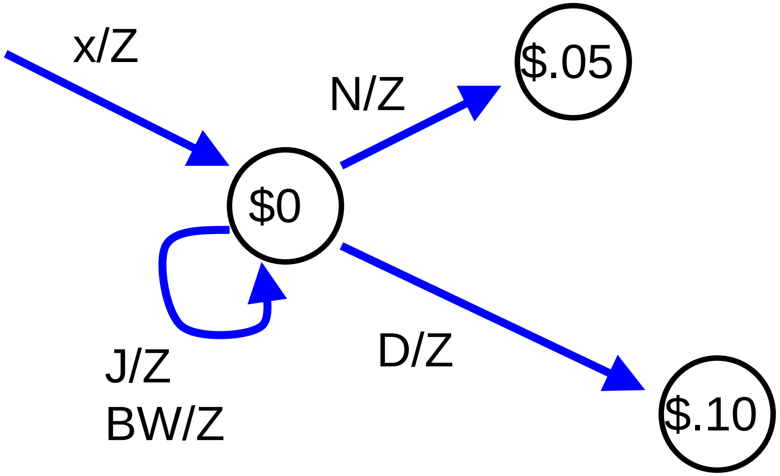
What can happen from S = $0?

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

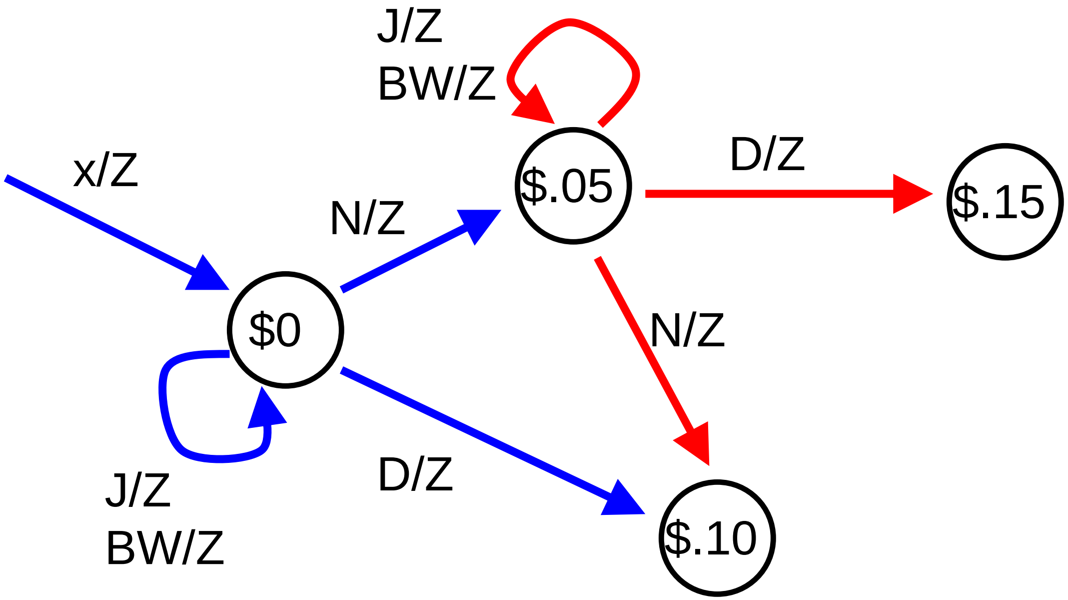
What can happen from S = $0.05?

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

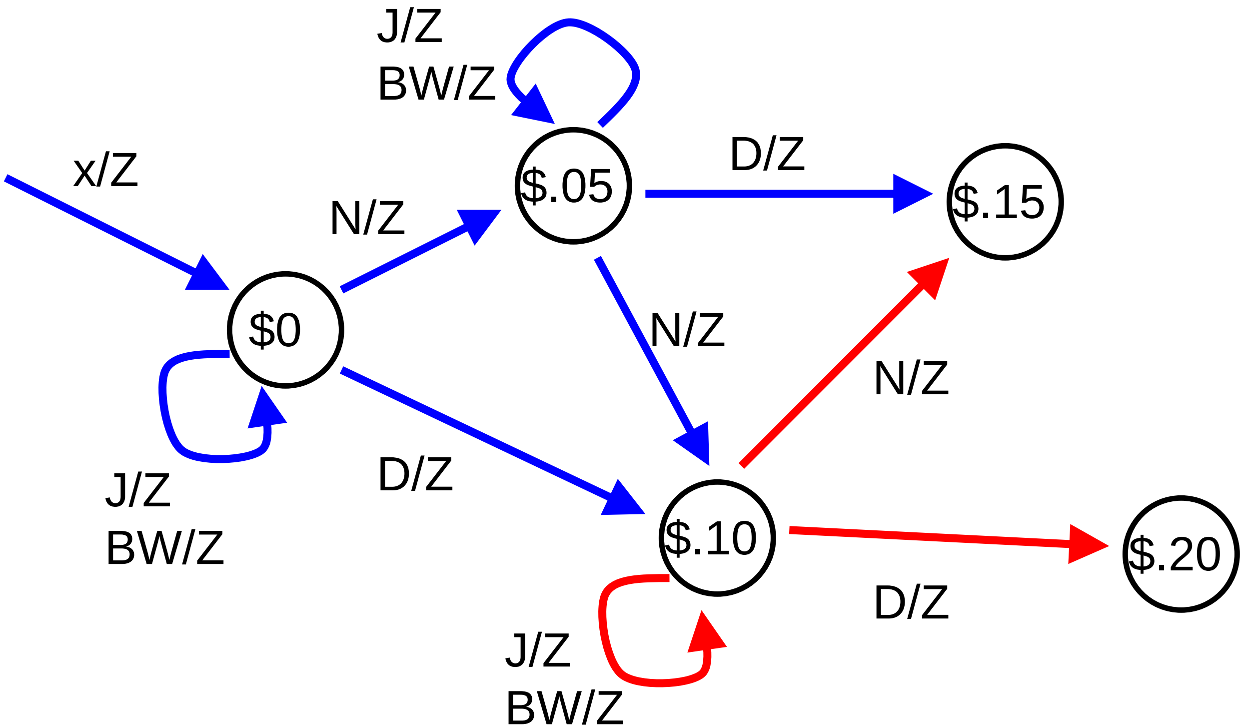
Vending Machine Design

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

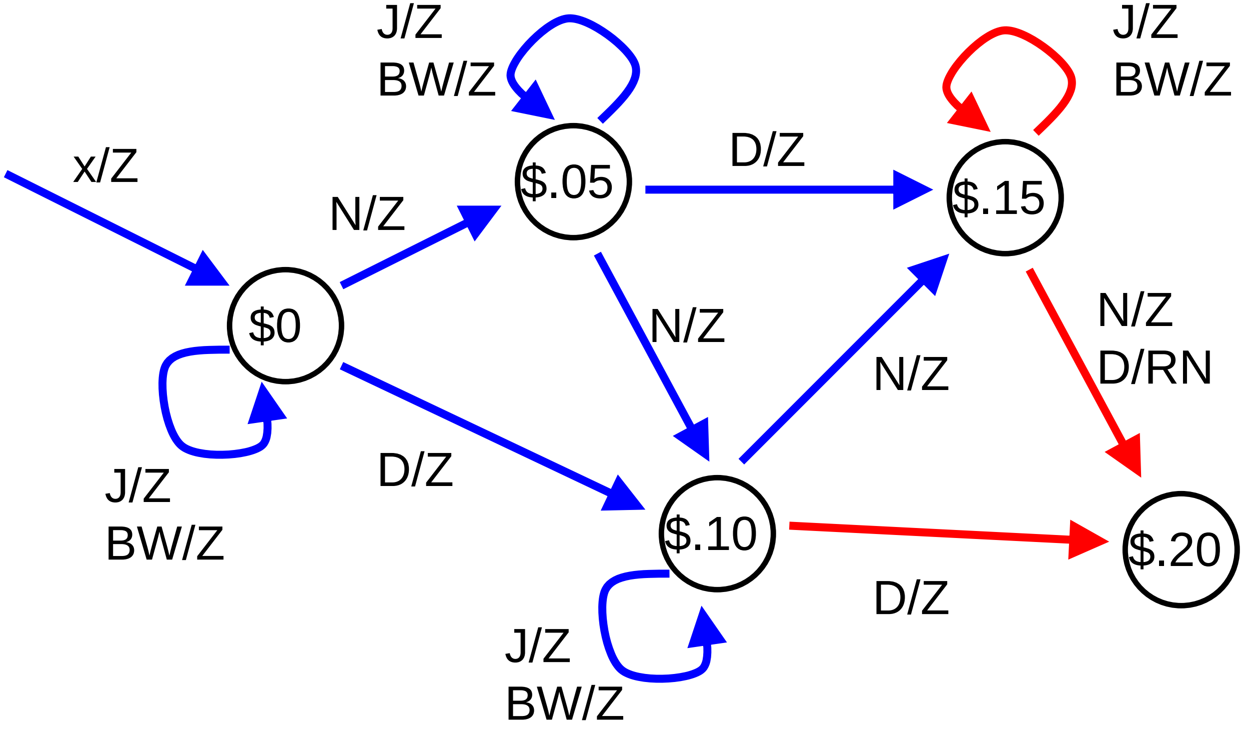
Vending Machine Design

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

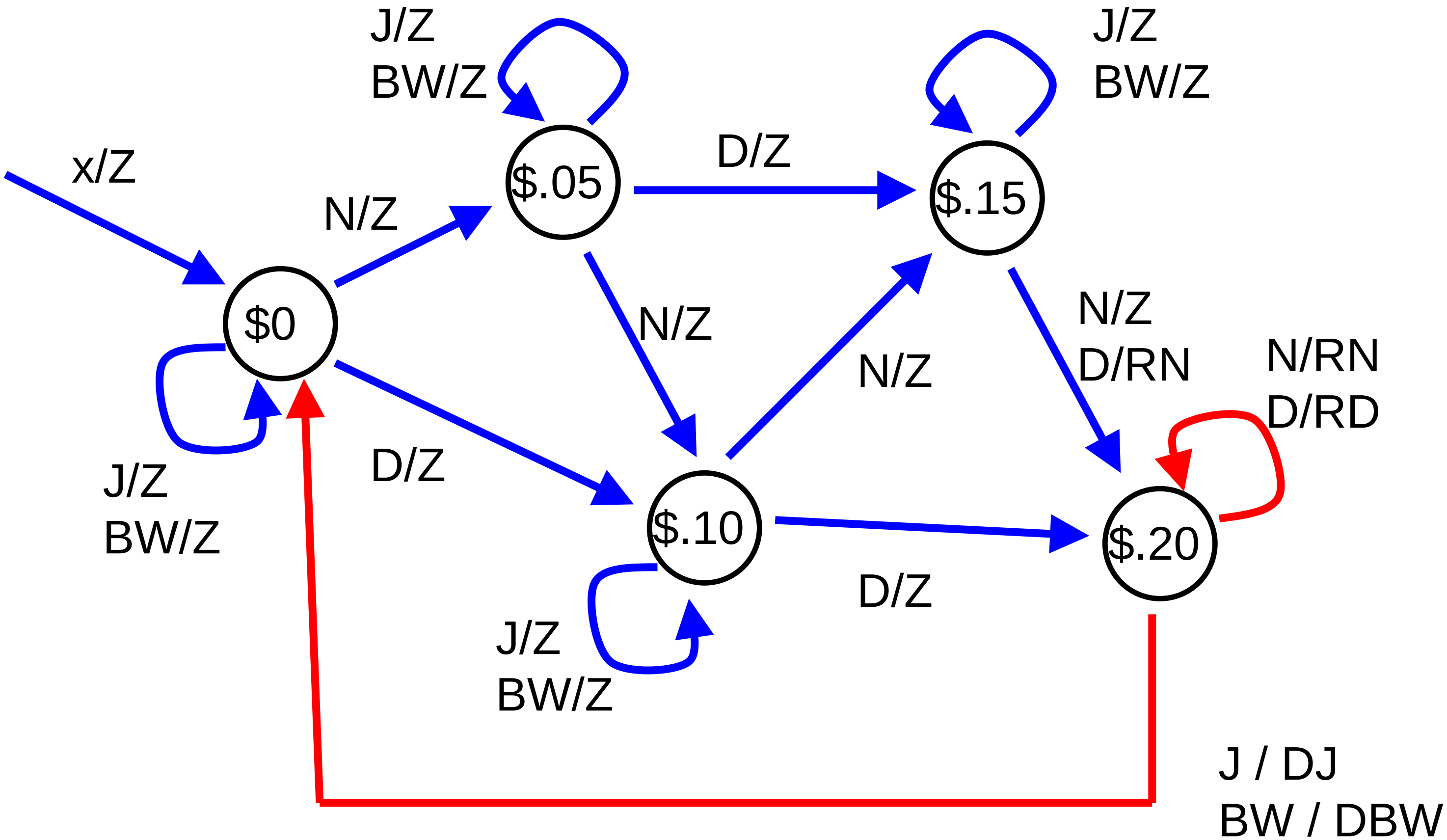
Vending Machine Design

Finally, what can happen from S = $0.20?

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

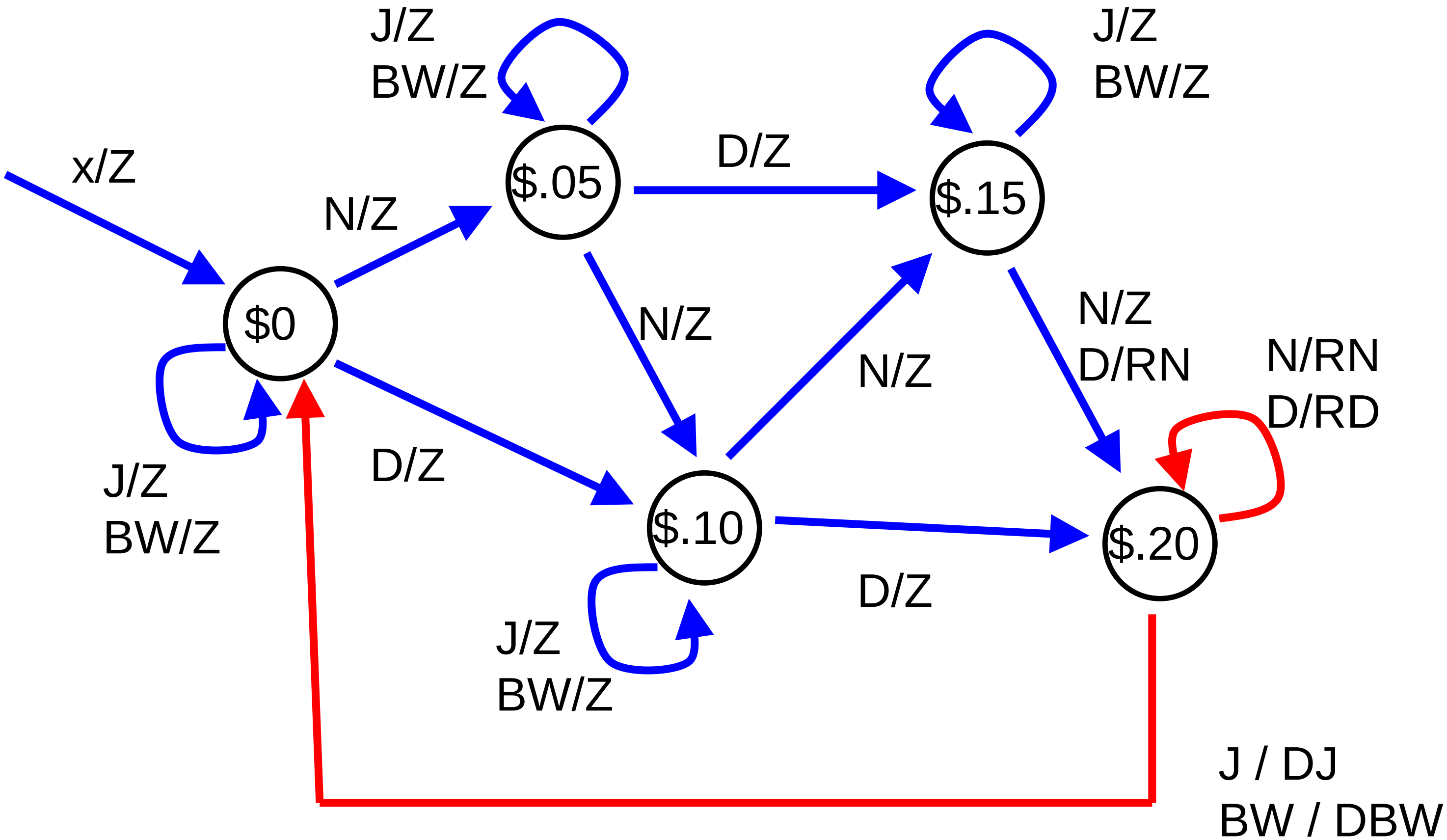
Vending Machine Design

The complete state diagram:



- End for day…

Finite State Machines



FSM Design Pattern

- The system is always in exactly one state
- Think of transitions as happening instantaneously

FSM Design Pattern

Think of transitions as happening instantaneously

- FSM actions are also instantaneous
- For an activity that must take a finite amount of time:
  - The FSM action is to initiate the activity
  - The next state is one in which the system is waiting for activity completion
  - The next event signals completion

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

- Robot 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): initiate a turn of the robot base by 90 degrees to the left
- Turn right (TR): initiate right turn
- Move forward (F): initiate forward movement
- Stop (S)

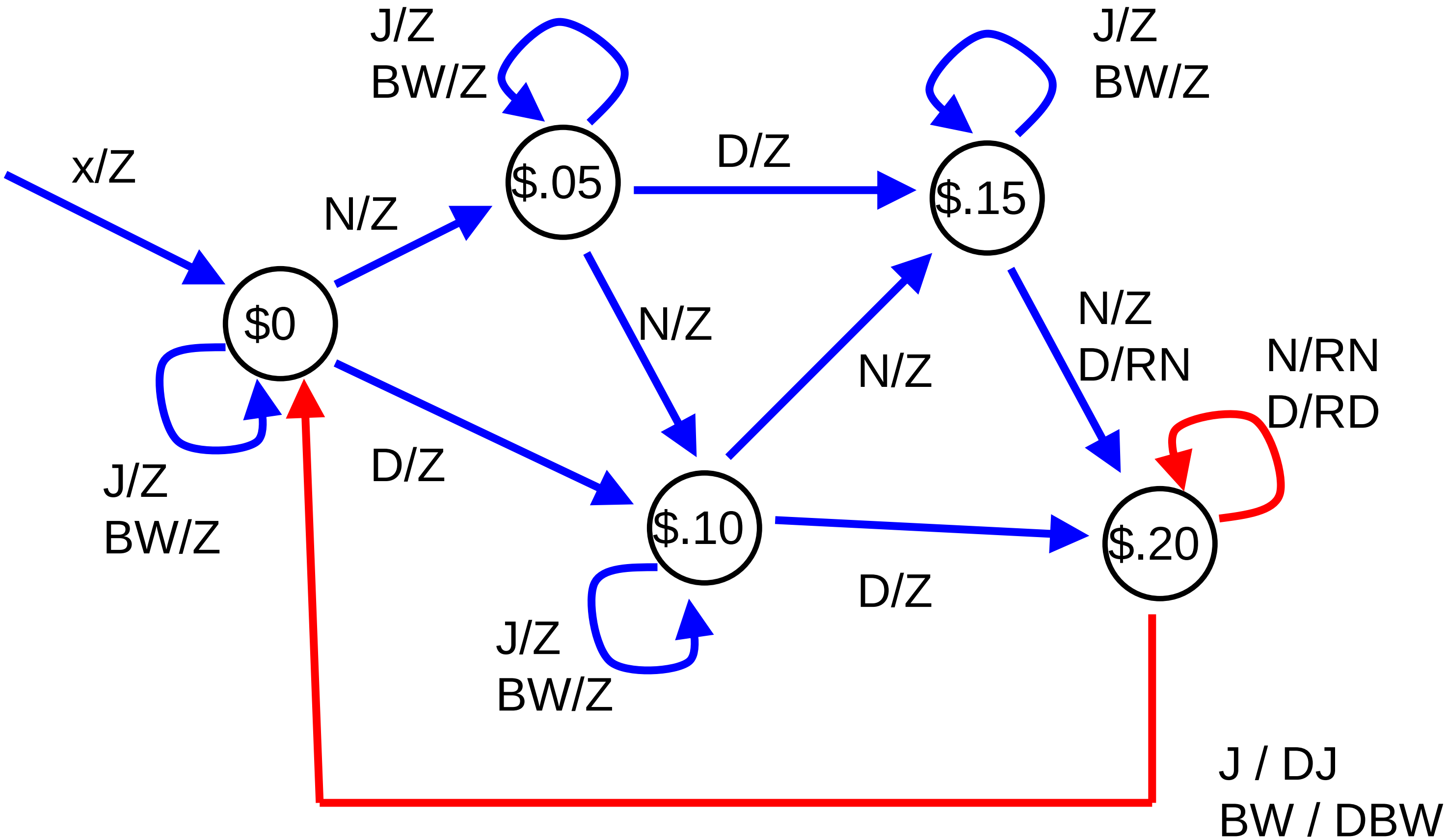
Robot Control Example II

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?

Vending Machine FSM



FSMs and Control

How do we relate FSMs to Control?

- States are our memory of recent inputs
- Inputs/events are some processed representation of what the sensors are observing
- Outputs are the control actions

FSMs in C

Implementation in the Arduino environment

```
void loop()
{
  fsm_step();   // Evaluate the FSM
}
```

FSMs in C

```
fsm_step() {
  static State state = STATE_0;   // Initial state

  <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: …
  }
}
```

Creating an Enumerated Variable Type

- Definition:

```
typedef enum {
   STATE_0, STATE_1, STATE_2
} State;
```

- Use:

```
State s = STATE_1;
```

s can only take on these 3 values

Locally Defined Variables

- Local variables defined inside of a function are allocated to memory only when the function is called
  - Memory region called ***the stack***
- When the function returns, the memory is reclaimed for use by other functions

Static Variables

Declaring a variable inside a function as static:

```
static State state = STATE_0;   // Initial state
```

- The variable acts like a global variable:
  - The memory continues to exist after a return from the function
  - This means that the value from the last call to the function can be used in the next call
  - But: the variable can only be “seen” by this function

Static Variables

Declaring a variable inside a function as static:

```
static State state = STATE_0;   // Initial state
```

- Other key thing to remember: the assignment is executed exactly once (before the main() function is executed)
- We can use this to set the initial value of the static variable

FSMs in C

```
fsm_step() {
  static State state = STATE_0;   // Initial state

  <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 (integrating with other code)

```
fsm_step() {
  static State state = STATE_0;   // Initial state

  <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: …
  }
  <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

Vending Machine

```
typedef enum {
    STATE_0cents, STATE_5cents,
STATE_10cents, STATE_15cents,
STATE_20cents
} State;

typedef enum {
     EVENT_NICKEL, EVENT_DIME,
EVENT_JOLT, EVENT_BUZZ, EVENT_NONE
} Event;
```

FSMs in C

```
fsm_step() {
  static State state = STATE_0cents;   // Initial

  // Translate sensors into event
  Event event = read_sensors();

  // Execute code for the current state
  switch(state) {
     case STATE_0cents:
          <handle state>
          break;
     case STATE_5cents:
          <handle state>
          break;
     case STATE_10cents: …
  }
}
```

FSMs in C: Processing for a Single State

```
:
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

```
fsm_step() {
  static State state = STATE_0;   // Initial state
  static int counter = 0;
  ++counter;

  <do some processing of the sensory inputs>
  switch(state) {
      case STATE_MISSION_PHASE_3:
            <handle phase 3>
            break;
      case STATE_MISSION_PHASE_4 :
            <handle phase 4>
            break;
      case STATE_MISSION_PHASE_5 :
            :
  }
}
```

FSMs in C: Processing for Individual States

```
:
case STATE_MISSION_PHASE_3:
      if(heading_error < 10.0 &&
            heading_error > -10.0)
      {
            // Move forward!
            desired_velocity = .2;    // Action

            // Transition
            state = STATE_MISSION_PHASE_4;
      };
  break;
:
```

FSMs in C: Processing for Individual States

```
:
case STATE_MISSION_PHASE_4:
     if(distance_left < 20.0 ||
          distance_right < 20.0)
     {
          // Brake!
          desired_velocity = 0;
          counter = 0;     // Reset the clock

          // Transition
          state = STATE_MISSION_PHASE_5;
     };
  break;
:
```

FSMs in C

New tweak: fsm_step() is called by loop() once per 50 ms (we will discuss the mechanism in the coming weeks)

```
fsm_step() {
  static State state = STATE_0;   // Initial state
  static int counter = 0;
  counter++;

  switch(state) {
     case STATE_MISSION_PHASE_3:
          <handle phase 3>
          break;
     case STATE_MISSION_PHASE_4 :
          <handle phase 4>
          break;
     case STATE_MISSION_PHASE_5 :
          :
  }
}
```

FSMs in C: Processing for Individual States

```
:
case STATE_MISSION_PHASE_5:
      if(counter > 20)
      {
            // A fixed amount of time has gone by
            heading_goal = heading_goal - 90.0;
            if(heading_goal <= -180.0)
                  heading_goal += 360;

            // Transition
            state = STATE_MISSION_PHASE_6;
      };
  break;
:
```

How much time has gone by?

FSMs in C: Processing for Individual States

```
:
case STATE_MISSION_PHASE_5:
      if(counter > 20)
      {
            // A fixed amount of time has gone by
            heading_goal = heading_goal - 90.0;
            if(heading_goal <= -180.0)
                  heading_goal += 360;

            // Transition
            state = STATE_MISSION_PHASE_6;
      };
  break;
:
```

How much time has gone by?   1 sec

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 print() to indicate current state
  - Do not print too much!
- Implement and test incrementally

FSM Implementation Notes

For your future projects: you will use an enumerated data type to represent your set of states.

- Allows us to be very clear what the possible values are
- Affords type checking by the compiler