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: ?

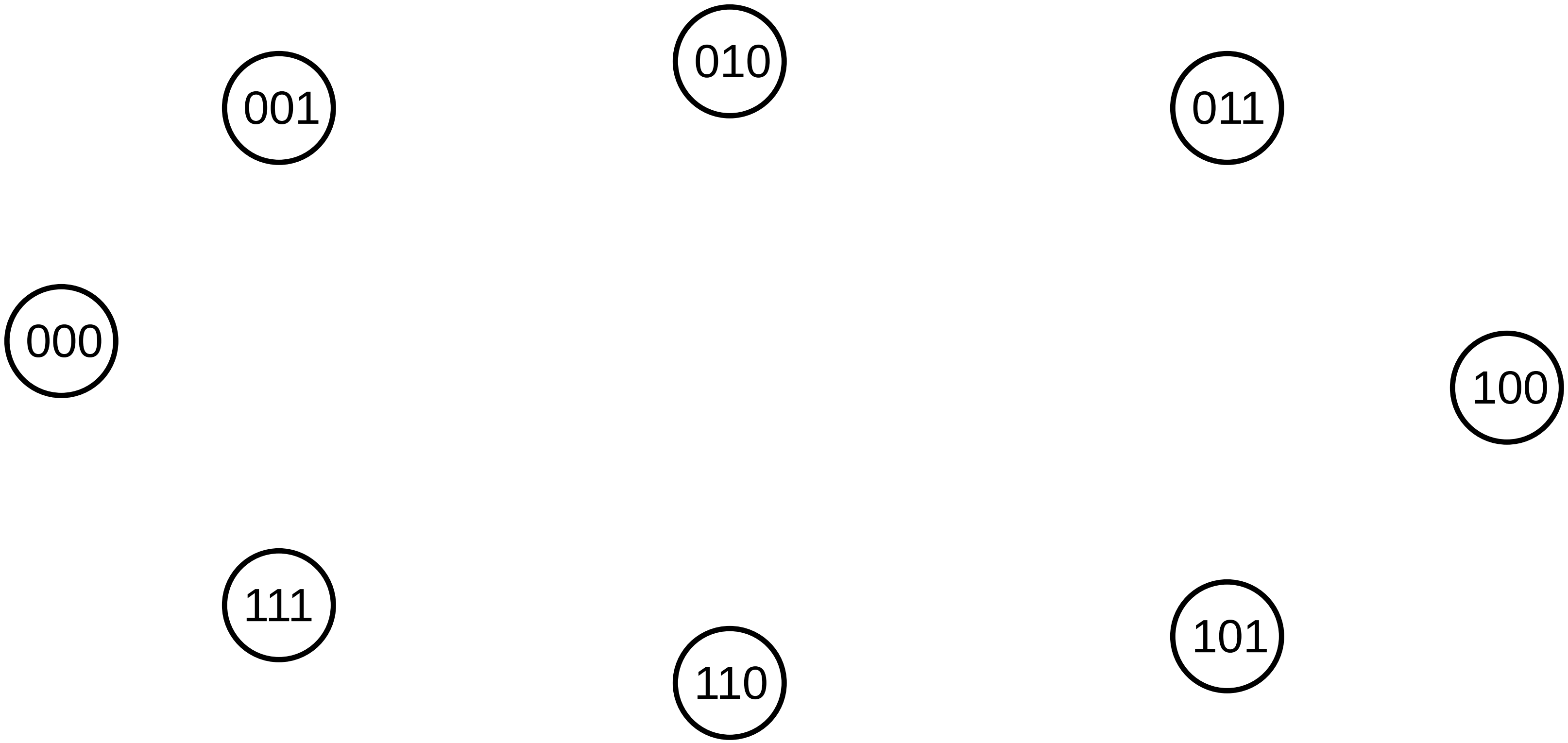
Finite State Machines (FSMs)

An example: a counter

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

FSM Example: Synchronous Counter

A Graphical Representation:

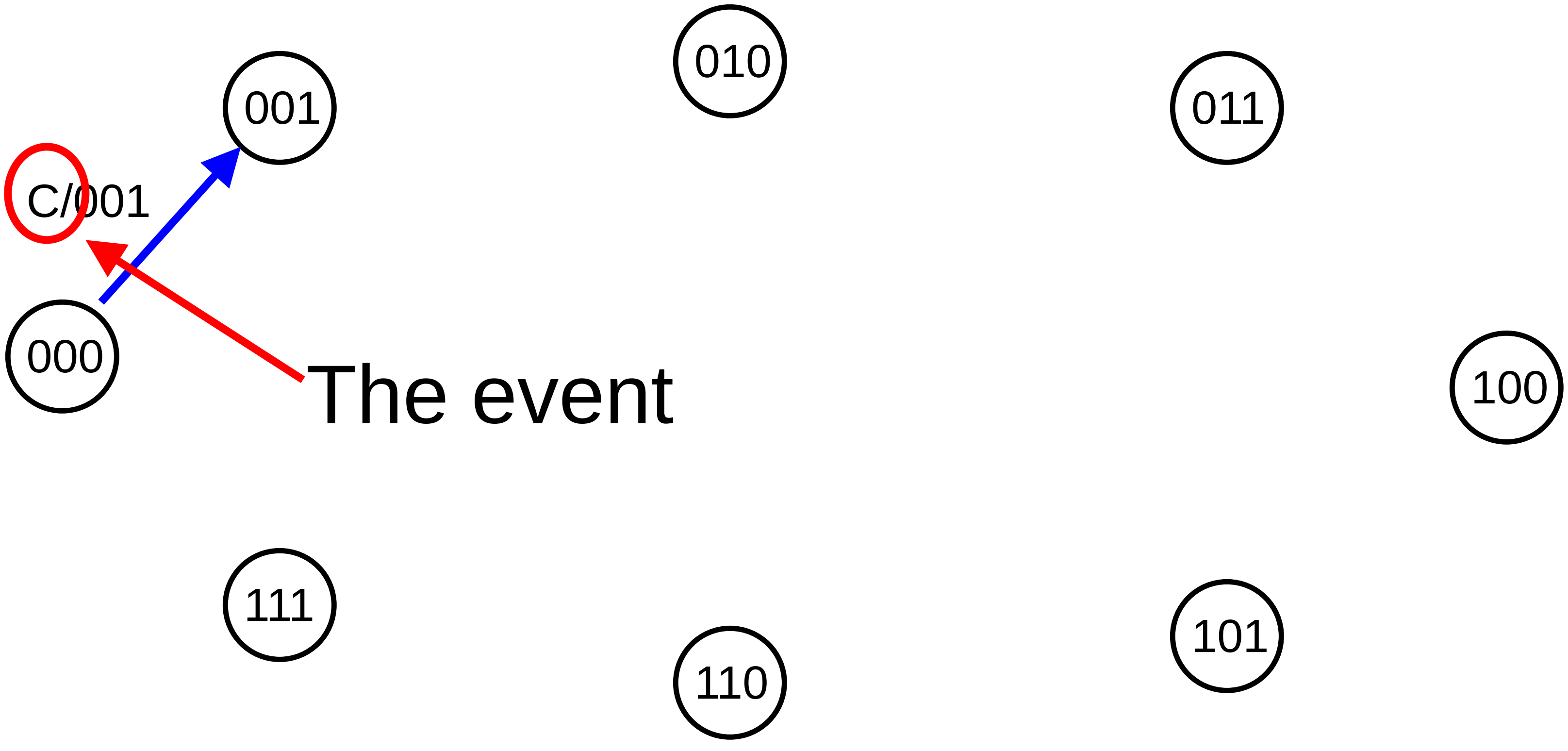


A set of states

FSM Example: Synchronous Counter

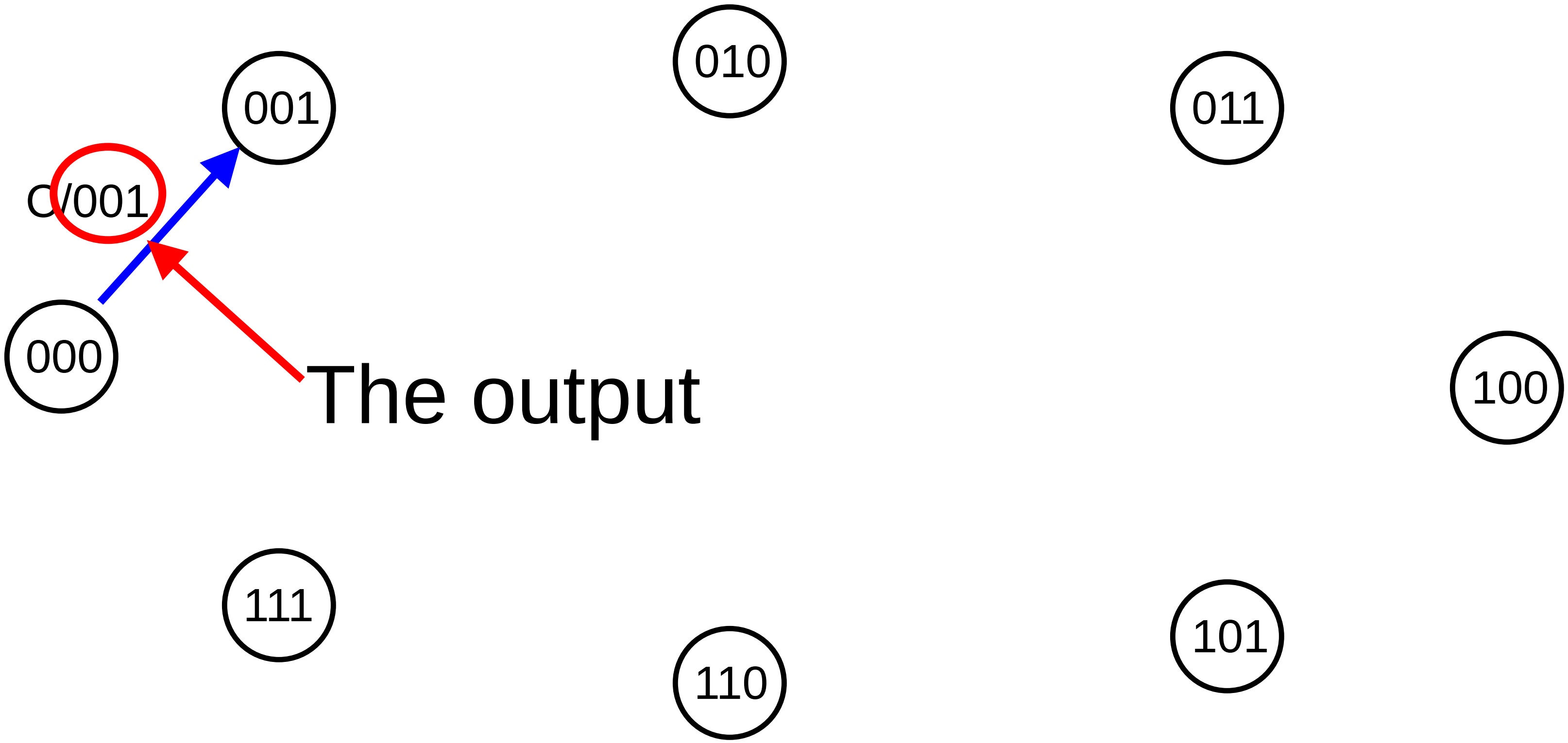
FSM Example: Synchronous Counter

A transition



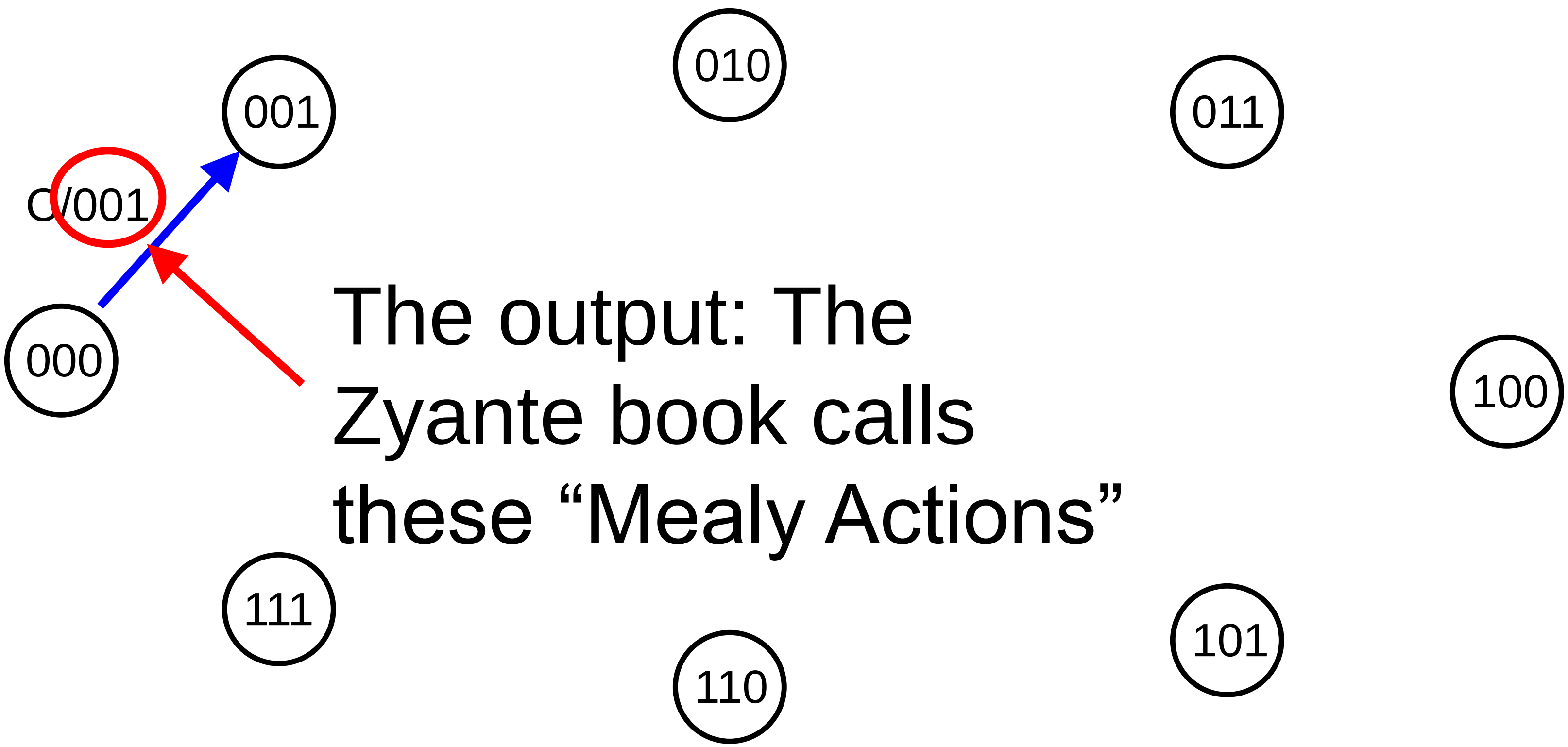
FSM Example: Synchronous Counter

A transition



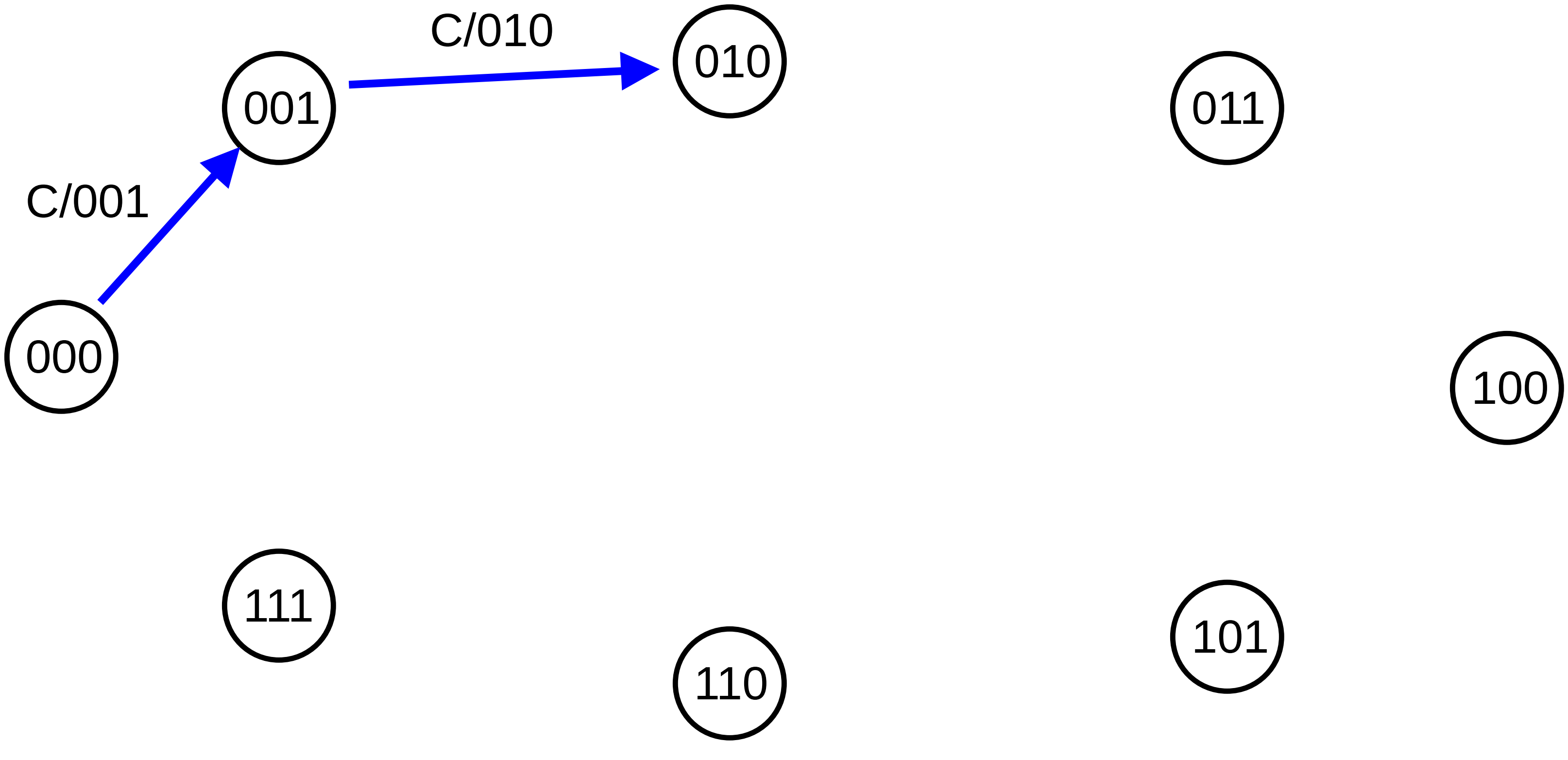
FSM Example: Synchronous Counter

A transition



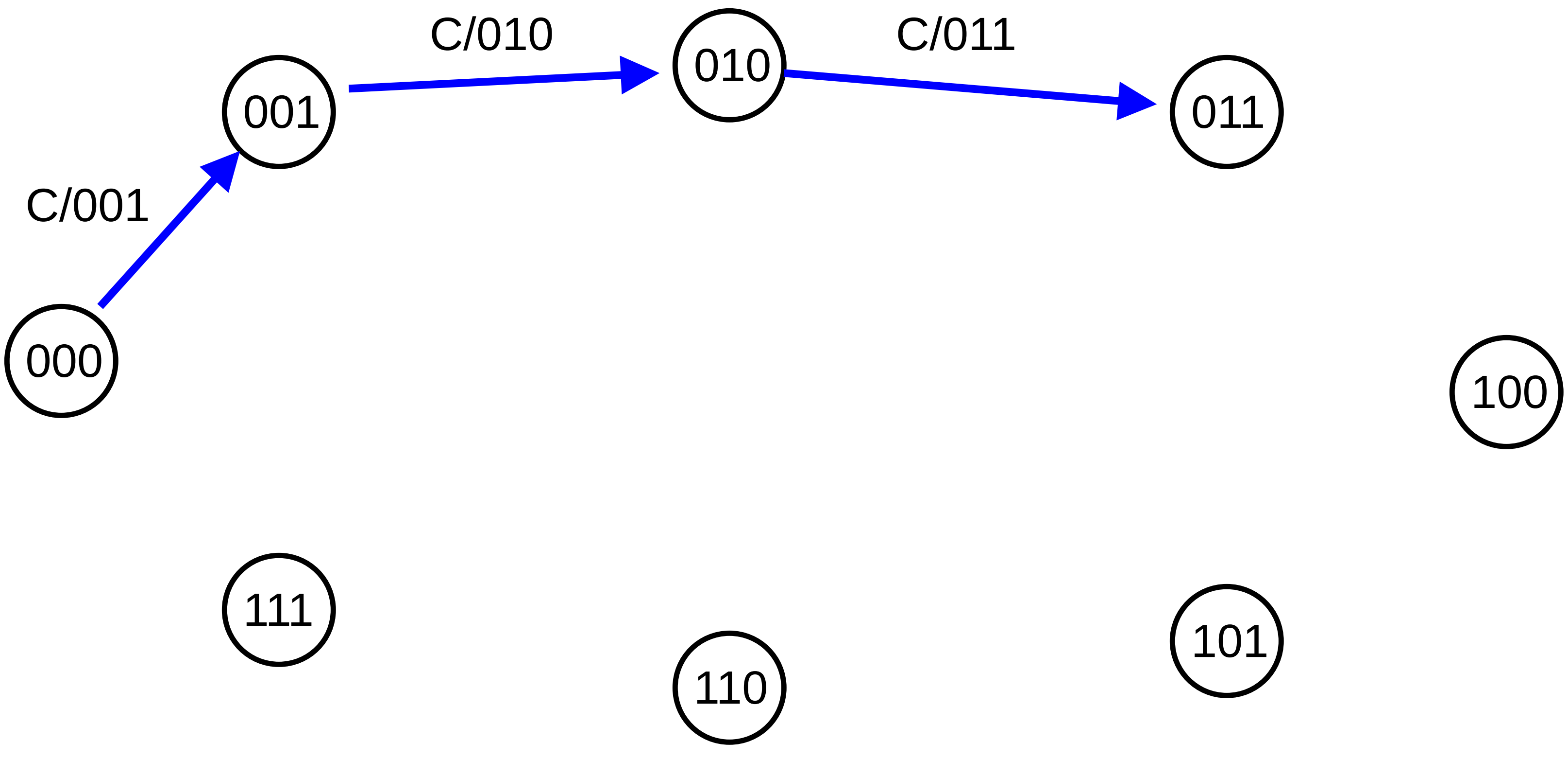
FSM Example: Synchronous Counter

The next transition



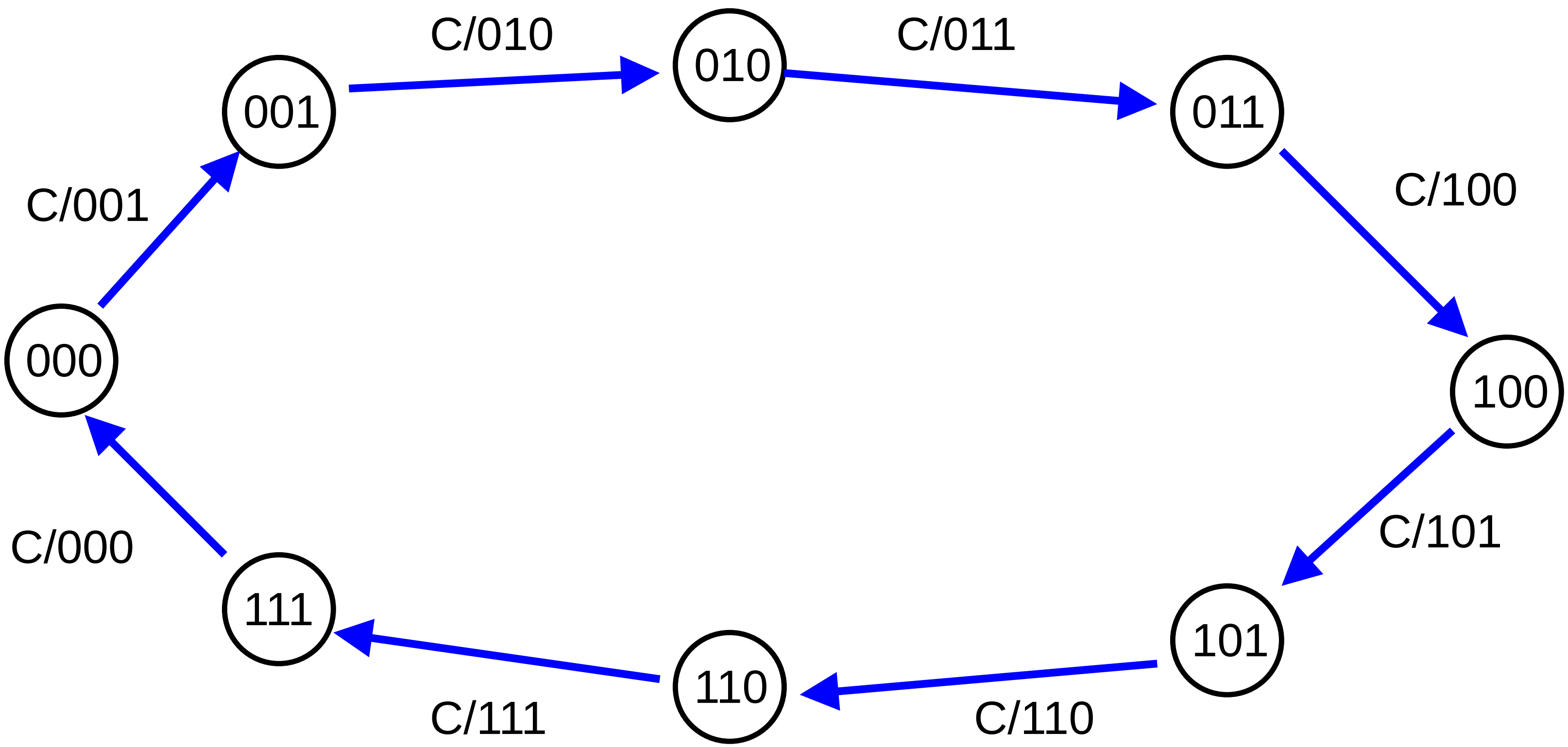
FSM Example: Synchronous Counter

The next transition

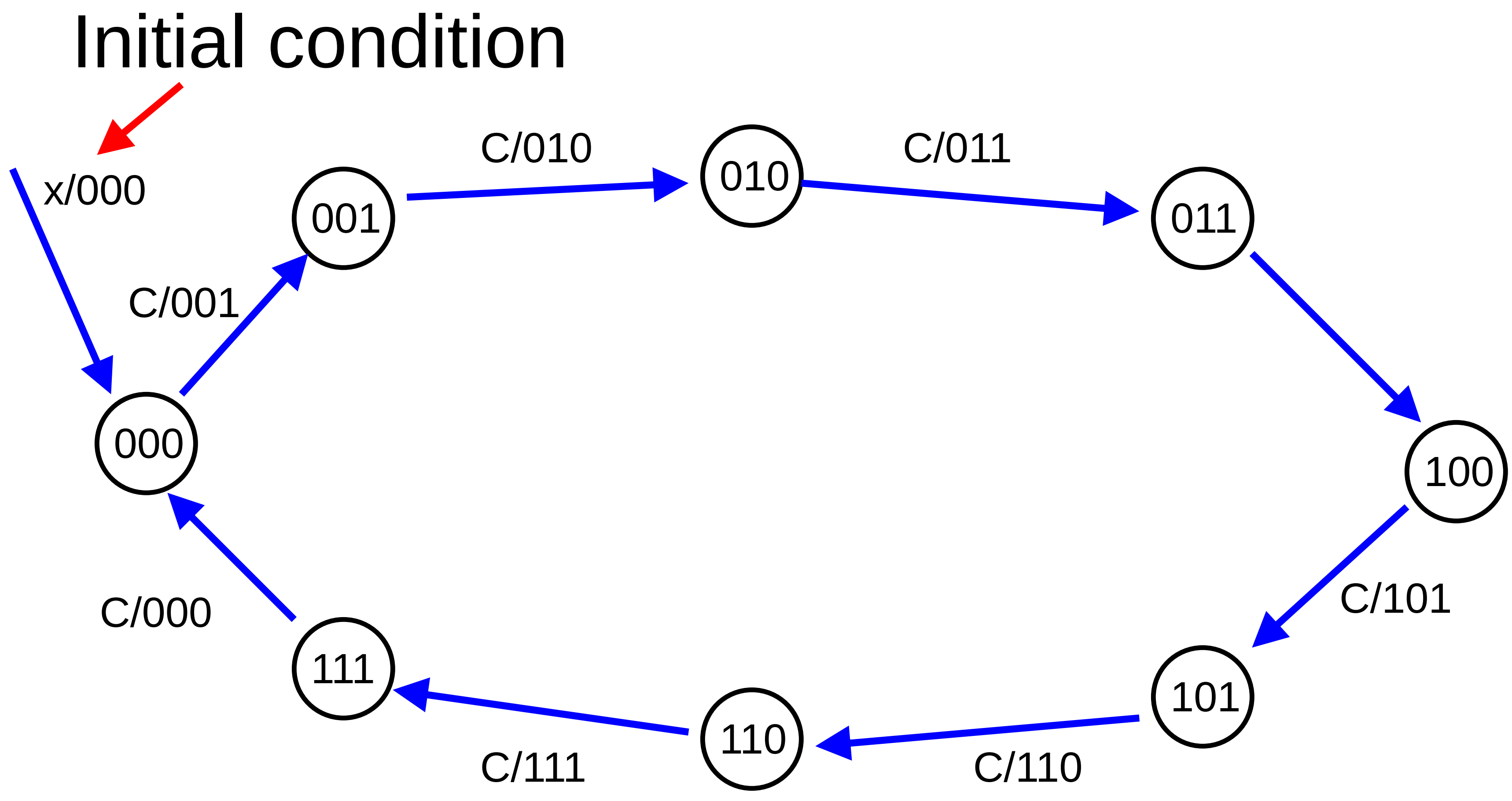


FSM Example: Synchronous Counter

The full transition set



FSM Example: Synchronous Counter



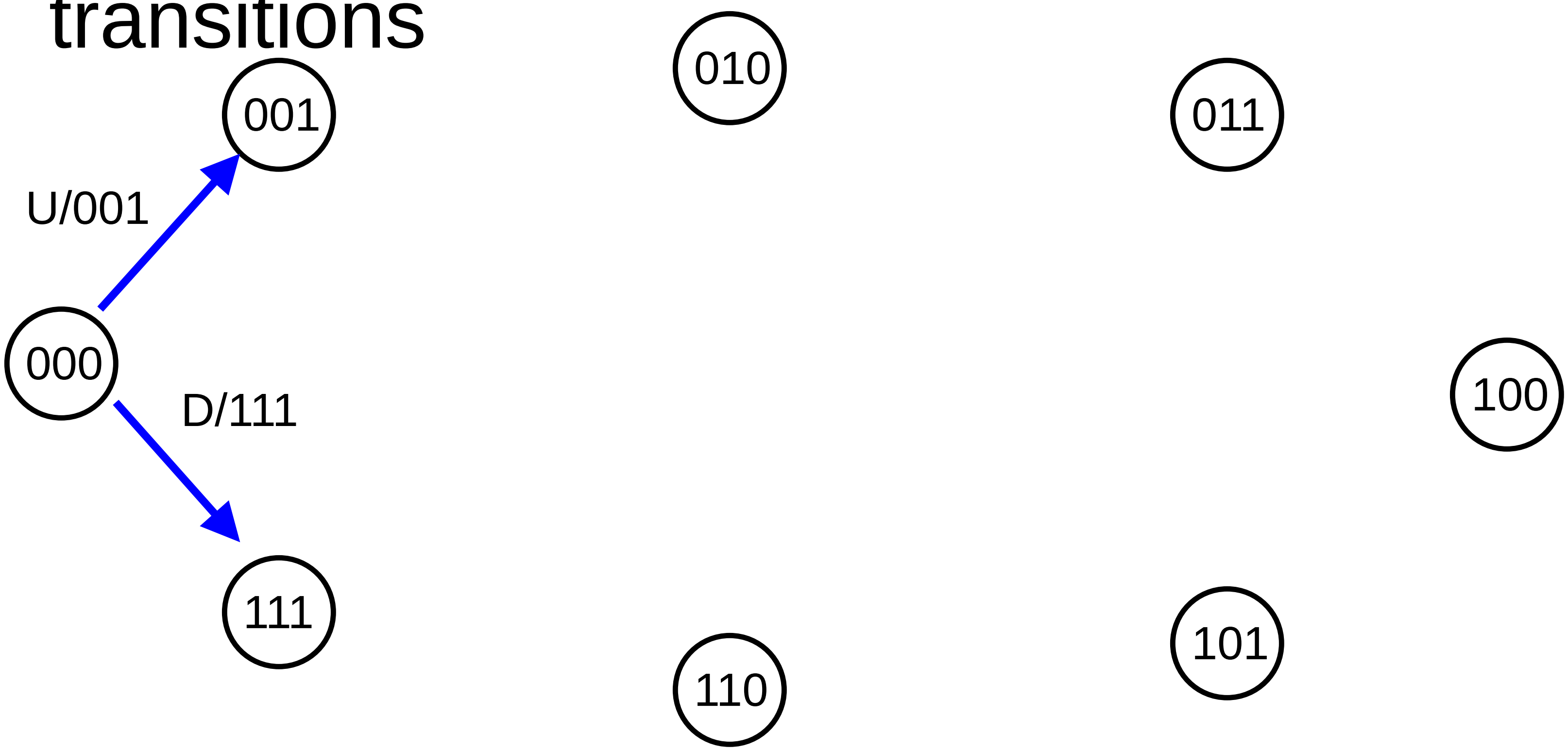
Example II: An Up/Down Counter

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

- How does this change our state transition diagram?

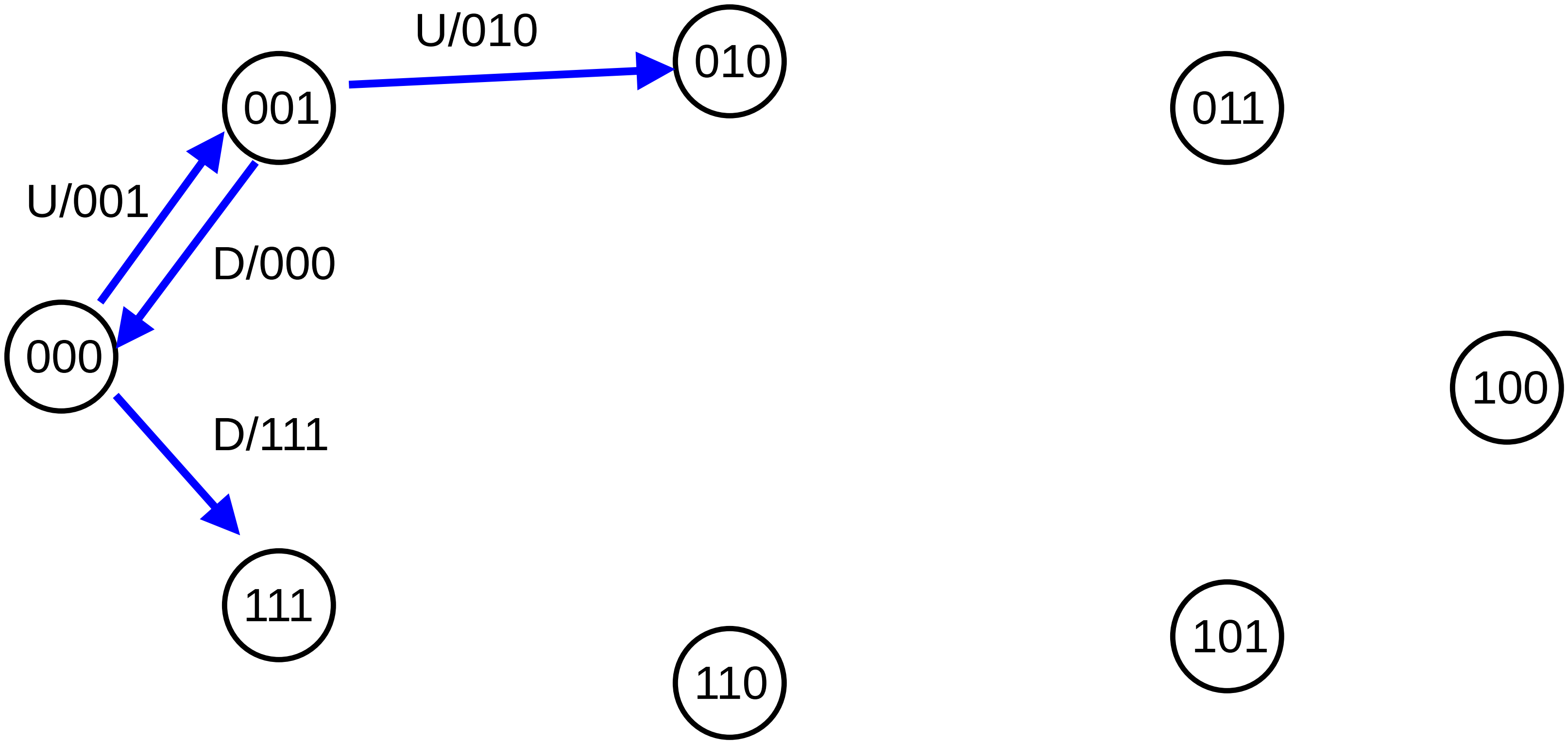
Example II: An Up/Down Counter

From state 000, there are now two possible transitions



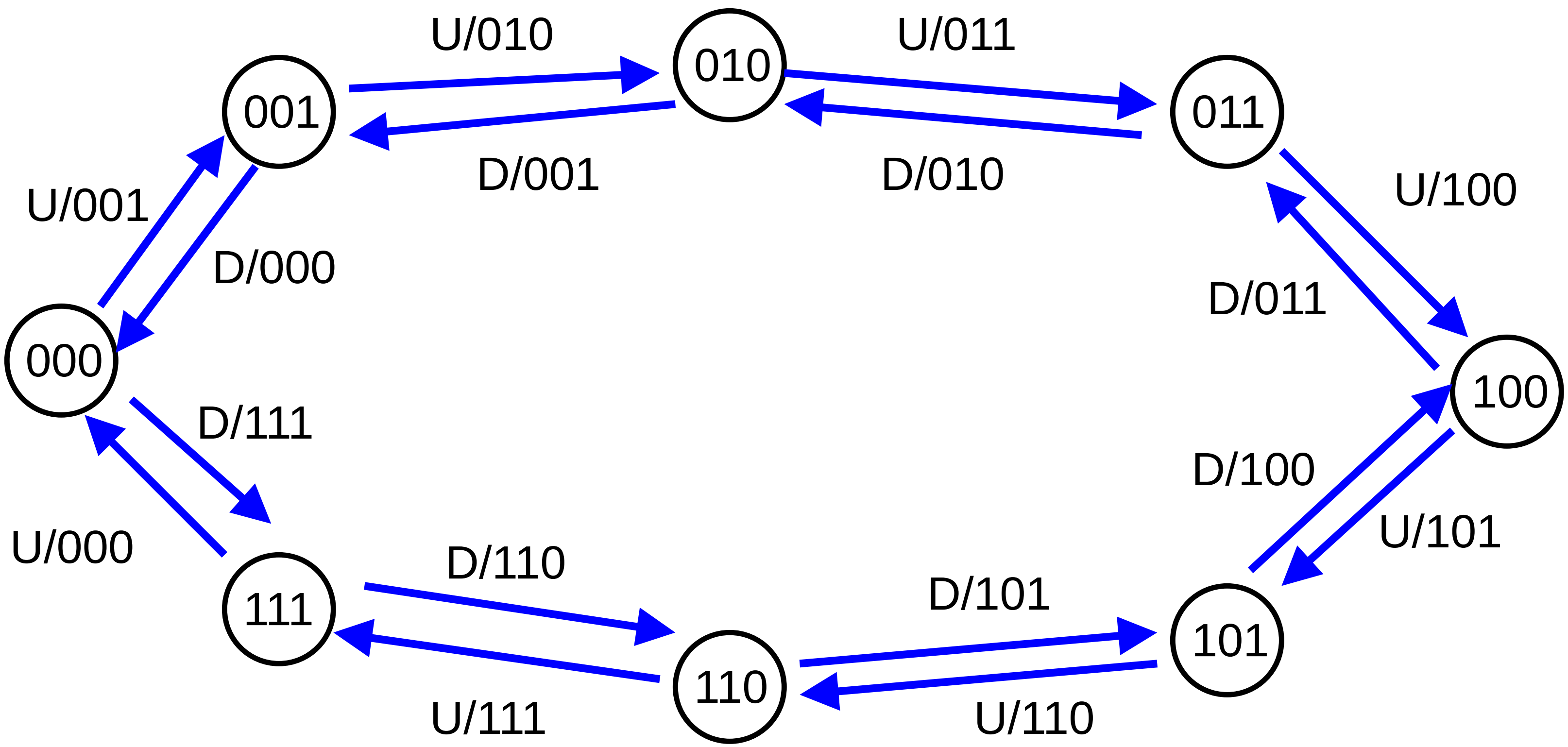
Example II: An Up/Down Counter

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

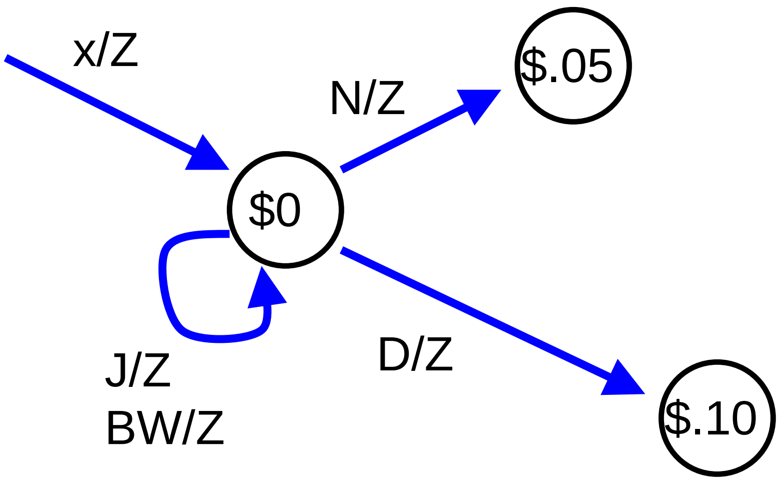
What can happen from S = $0?

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

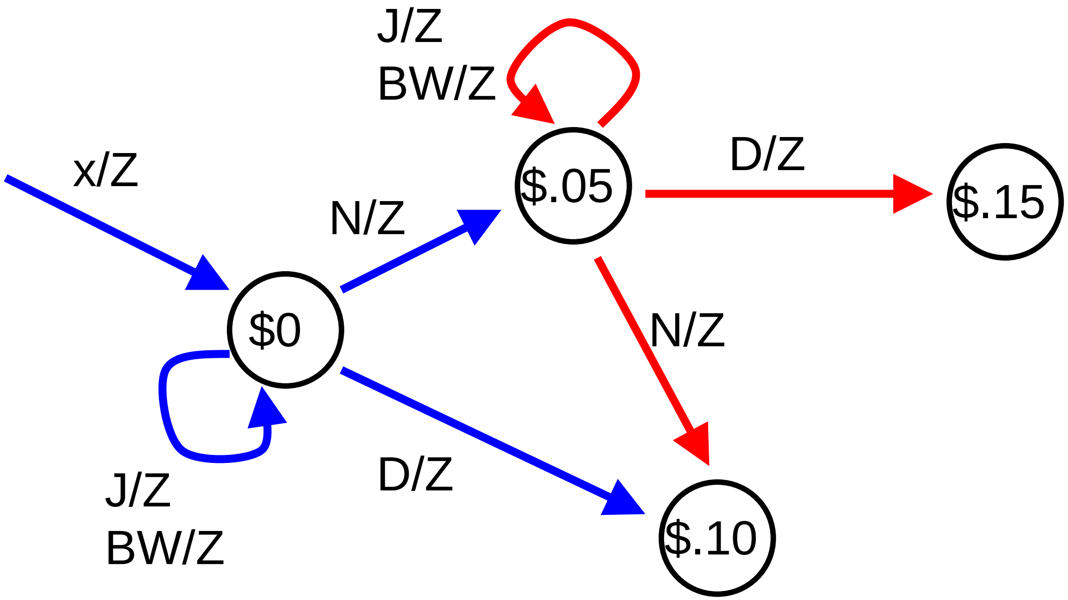
What can happen from S = $0.05?

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

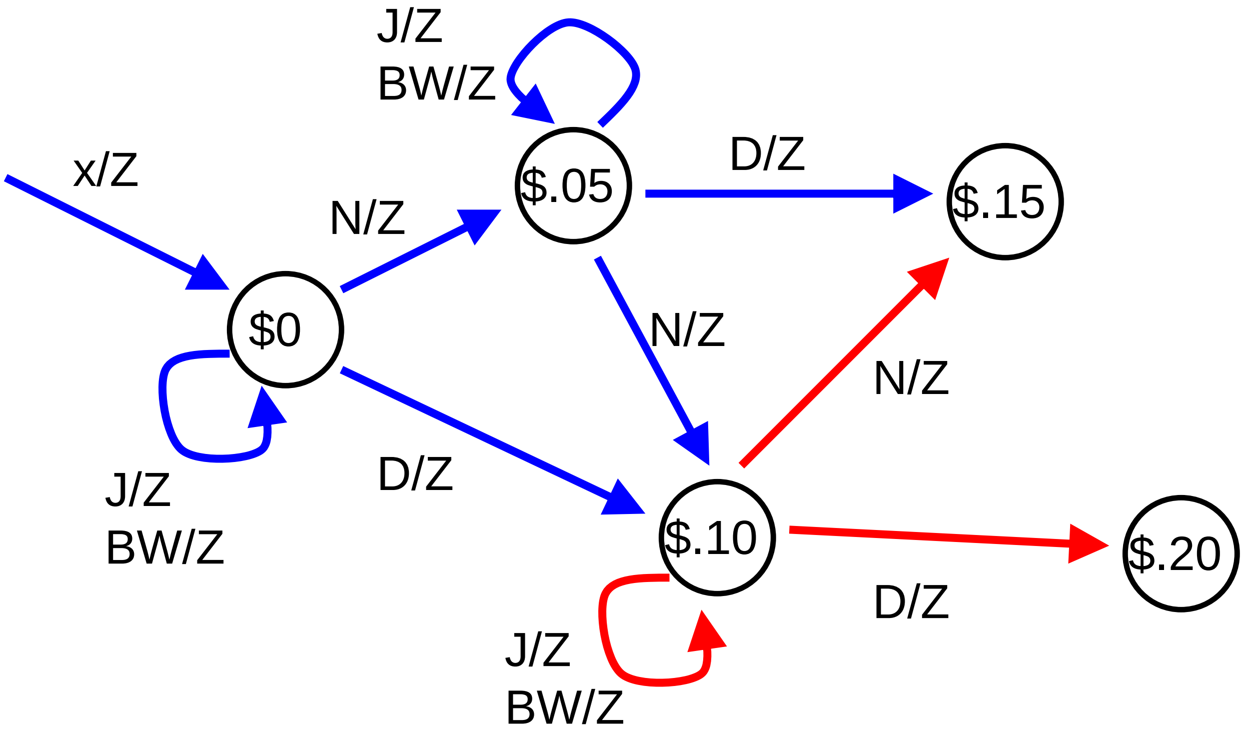
Vending Machine Design

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

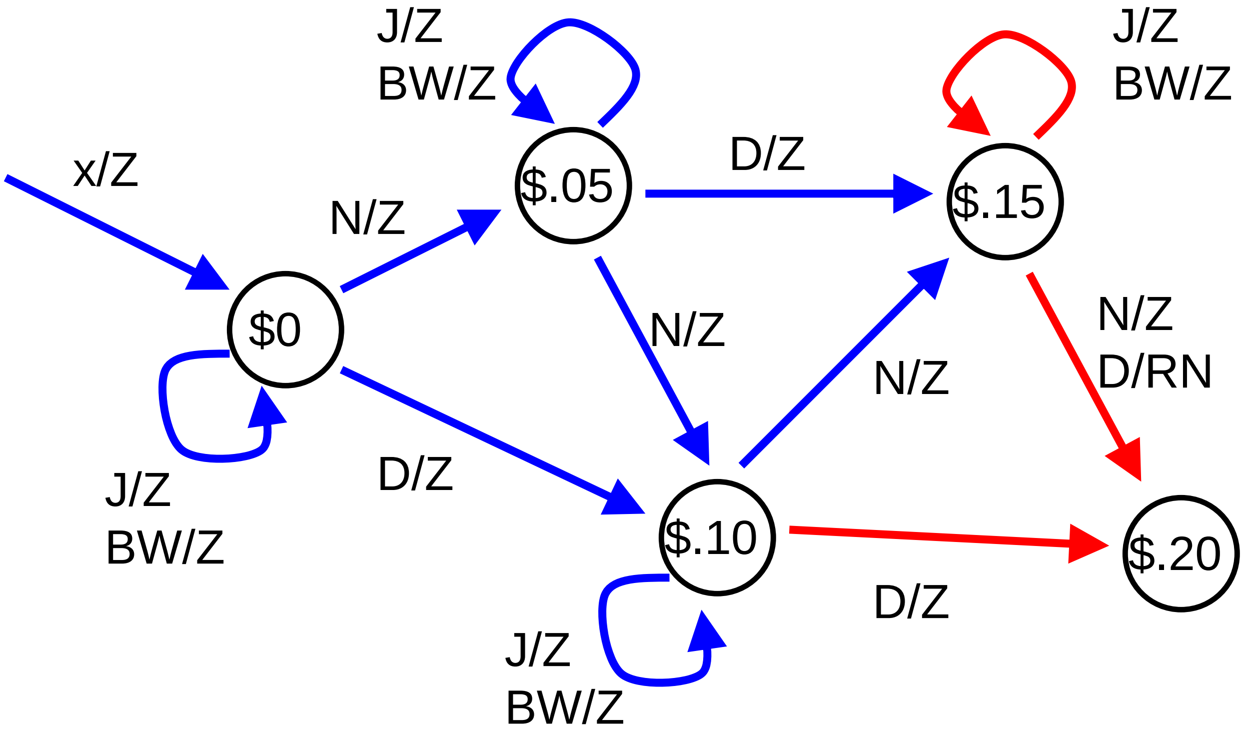
Vending Machine Design

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

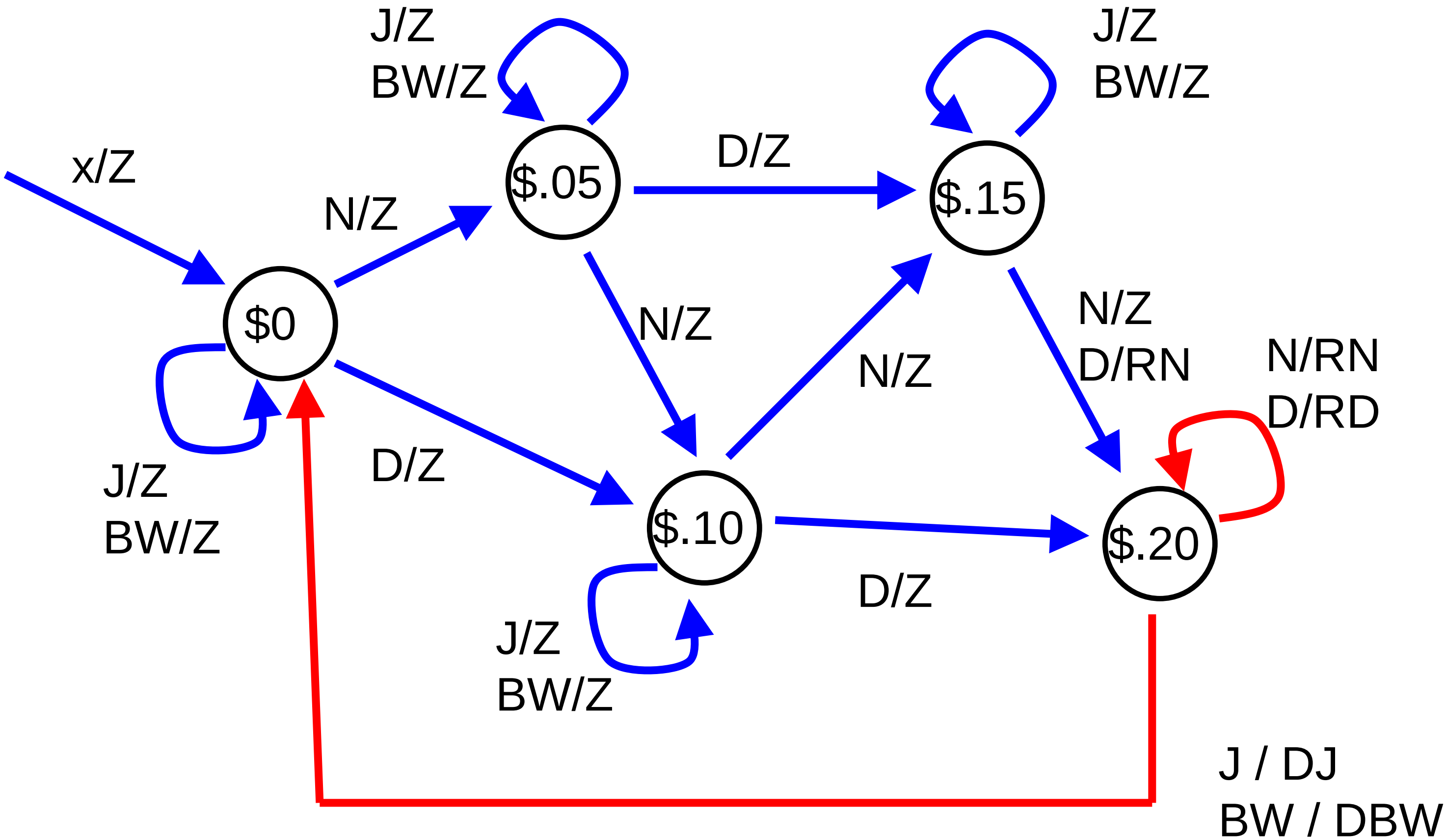
Vending Machine Design

Finally, what can happen from S = $0.20?

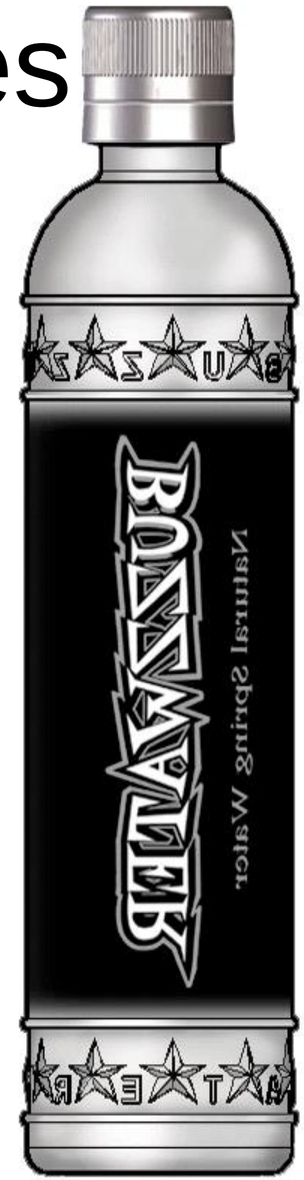
Event	Next State	Output
N	$.20	RN
D	$.20	RD
J	$0	DJ 
BW	$0	DBW 

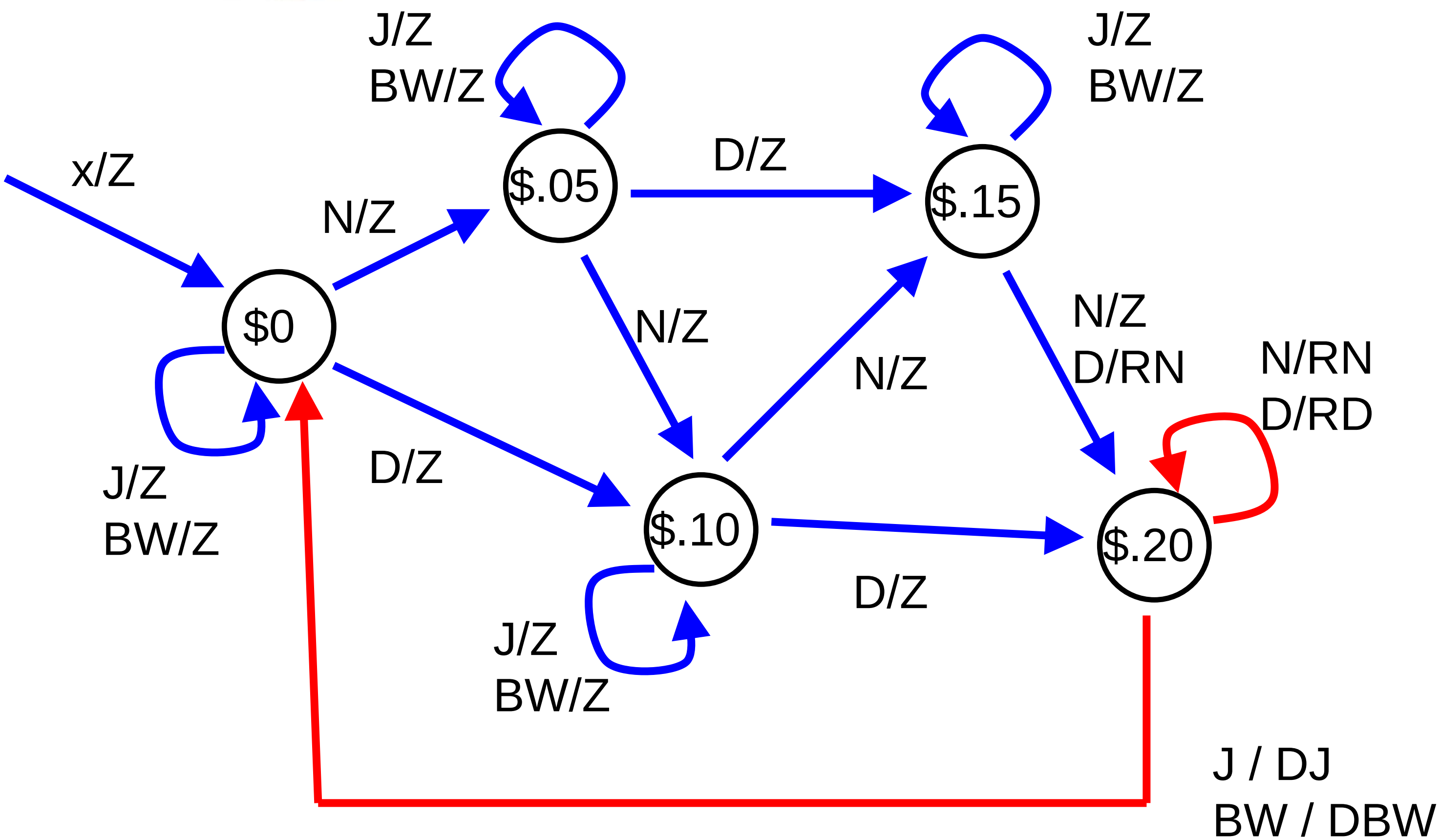
Vending Machine Design

The complete state diagram:



Finite State Machines





FSM Design Pattern

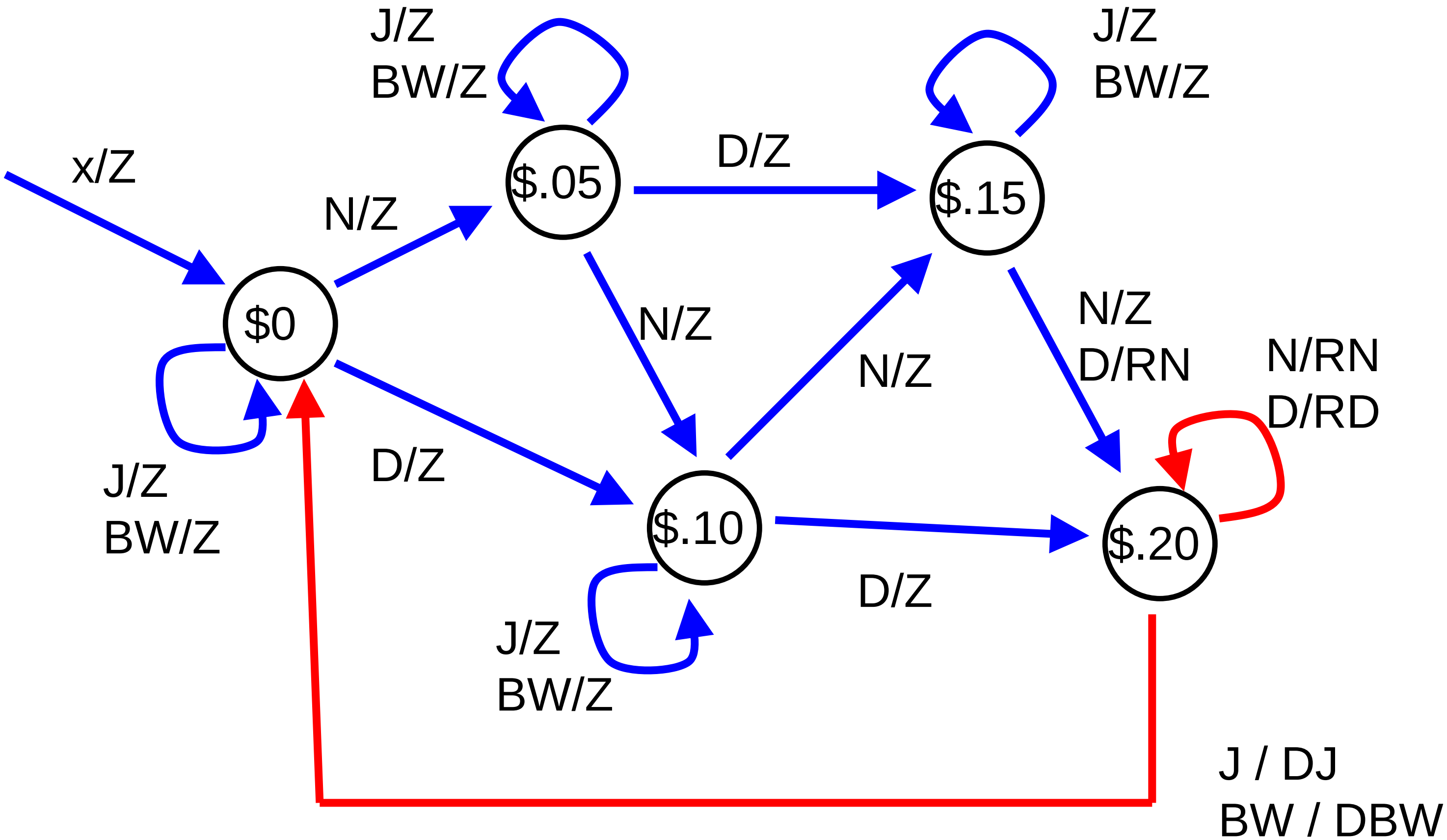
- The system is always in exactly one state
- Think of transitions as happening instantaneously

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

Vending Machine FSM



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?

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()
{
  static PeriodicAction fsm_task(50, fsm_step);

  // Check to see if 50 ms has gone by
  //  If so, then the function
  //  fsm_step() is called
  fsm_task.step();
}
```

FSMs in C

```
void 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)
- We will write an “if()” for each of these cases (or combination of cases)

Vending Machine Definitions

```
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
    if(event == EVENT_NICKEL) {
         state = STATE_15cents;  // Transition to $.15

    } else if(event == EVENT_DIME){
         state = STATE_20cents;  // Transition to $.2

    } else if(event == EVENT_JOLT || event == EVENT_BUZZ) {
         display_NOT_ENOUGH();

    } else {
         // Do nothing
    }
    break;
:
```

Hovercraft Example

Some events do not fall neatly into one of several categories

- So: the “if()” becomes more interesting
- Also: time can be an aspect of an event

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

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