Memory

- With combinatorial logic (AND, OR, NOT, etc.), we could only implement “stateless” functions

- By introducing flip-flops, we could remember something about the history of the inputs

Memory

- With combinatorial logic (AND, OR, NOT, etc.), we could only implement “stateless” functions
- By introducing sequential logic (with flip-flops), we could remember something about the history of the inputs

How do we formalize this idea of “history”?

Formalizing Memory

Combinatorial Logic

Boolean Algebra

Formalizing Memory

Combinatorial Logic Boolean Algebra

Sequential Logic

Formalizing Memory

Combinatorial Logic	Boolean Algebra
Sequential Logic	Finite State Machines

Formalizing Memory

Combinatorial Logic	Boolean Algebra
Sequential Logic	Finite State Machines

This will allow us to express controllers that take history into account ….

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: ?

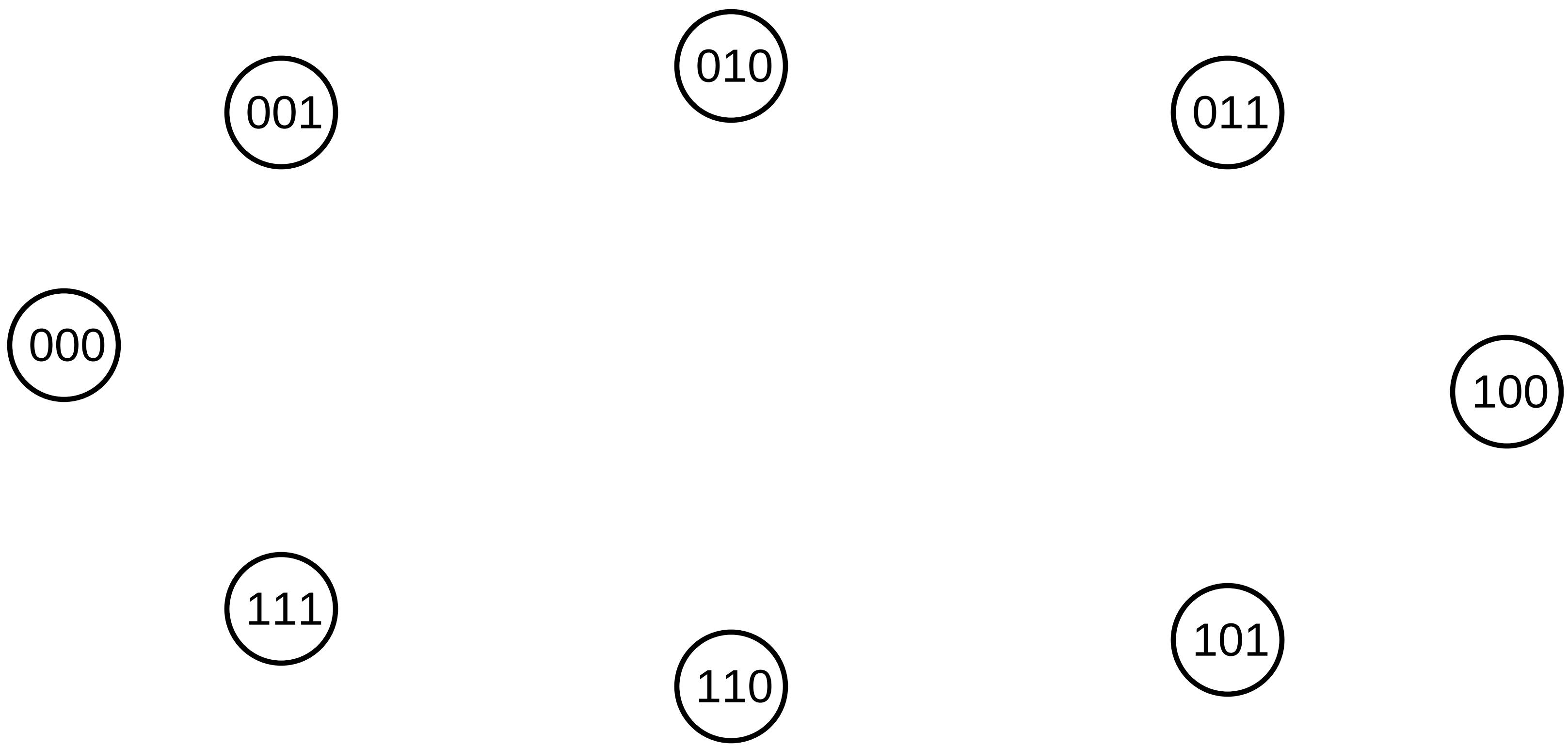
Finite State Machines (FSMs)

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:

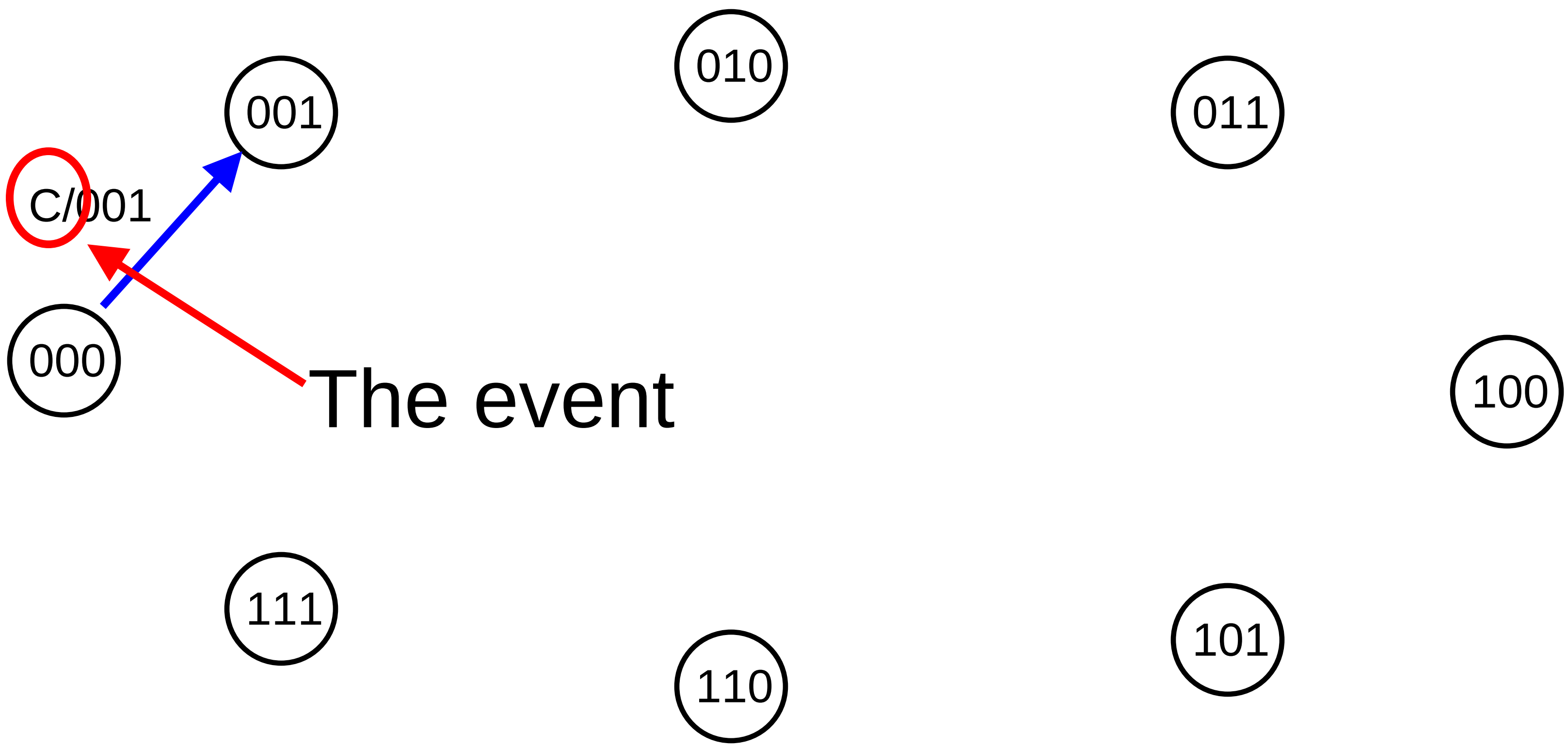


A set of states

FSM Example: Synchronous Counter

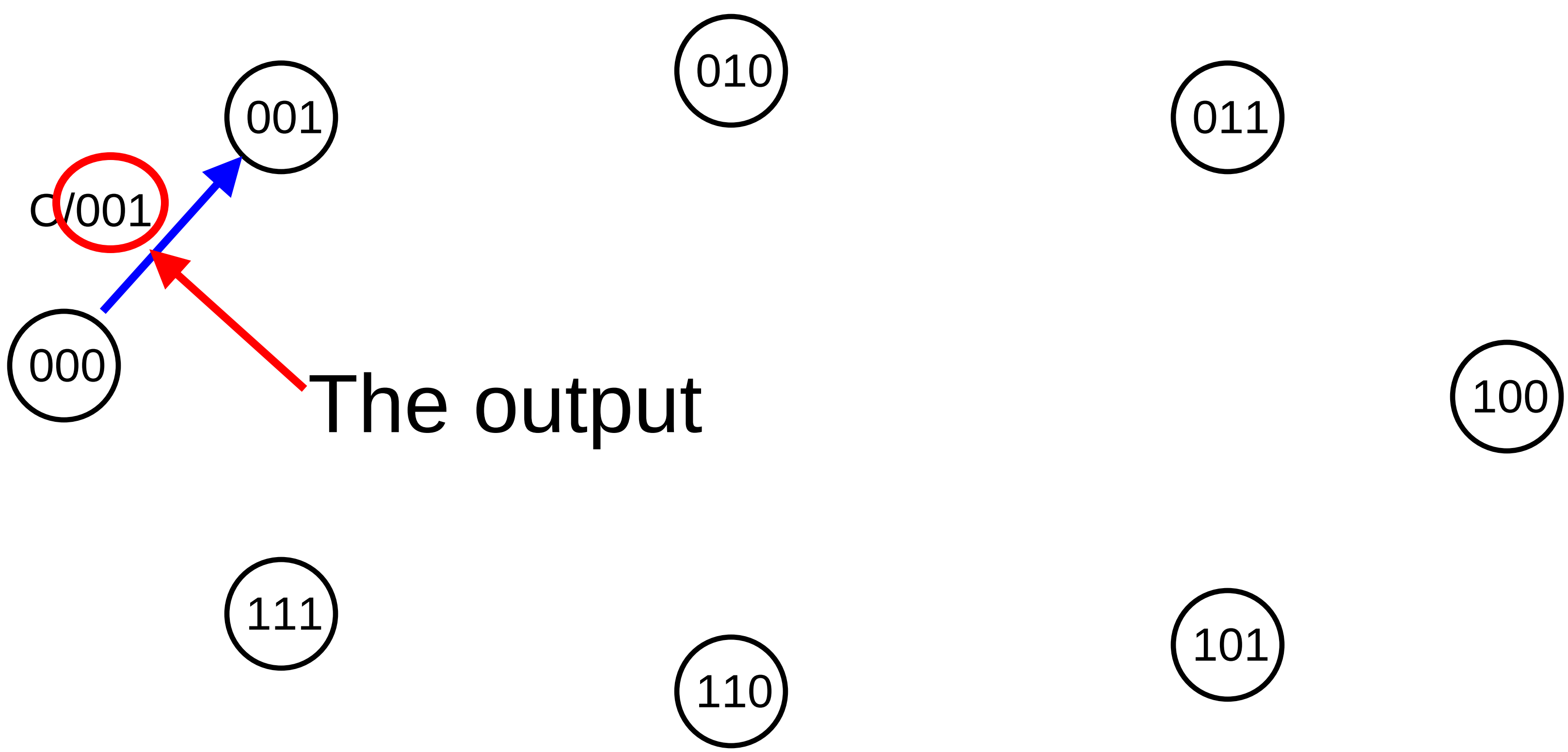
FSM Example: Synchronous Counter

A transition



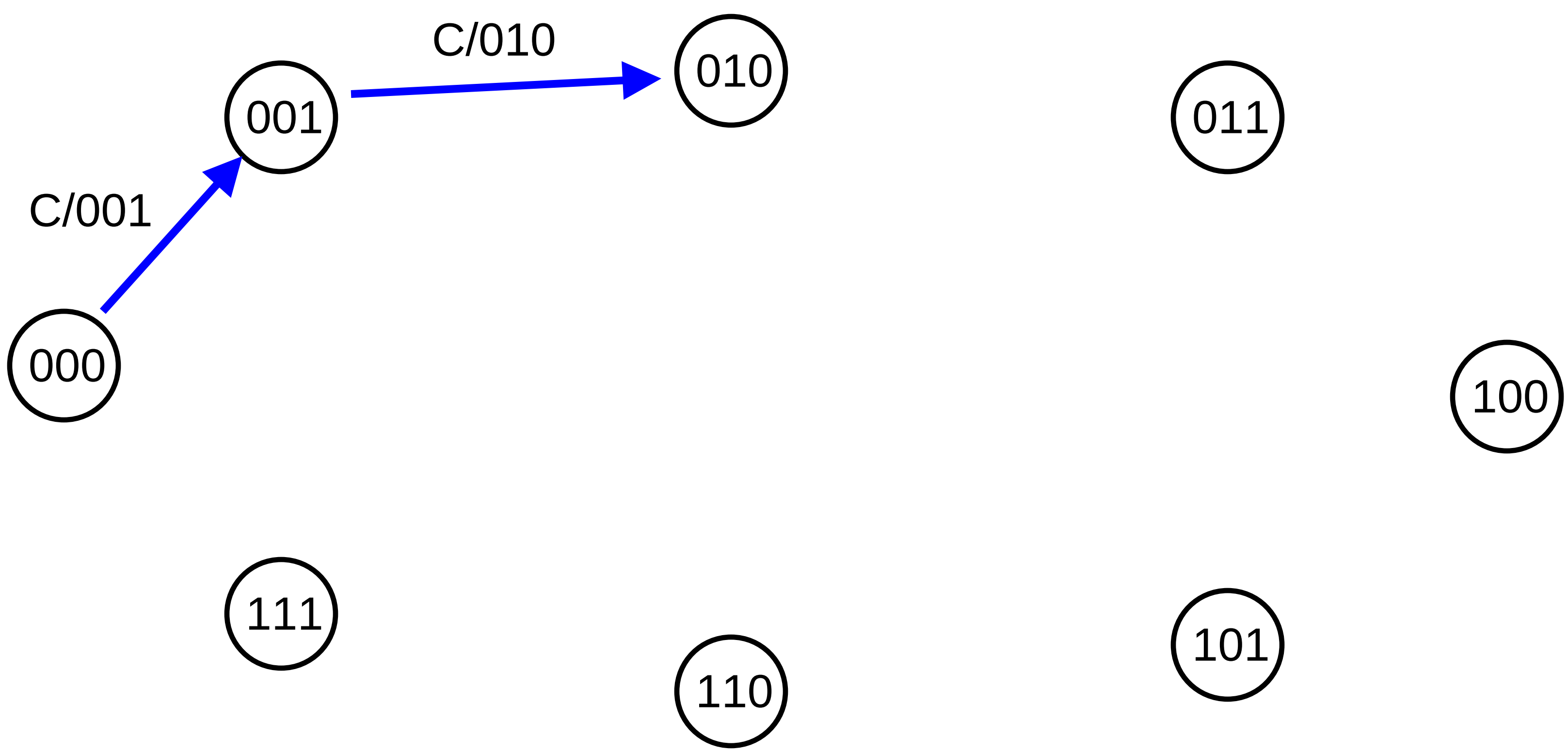
FSM Example: Synchronous Counter

A transition



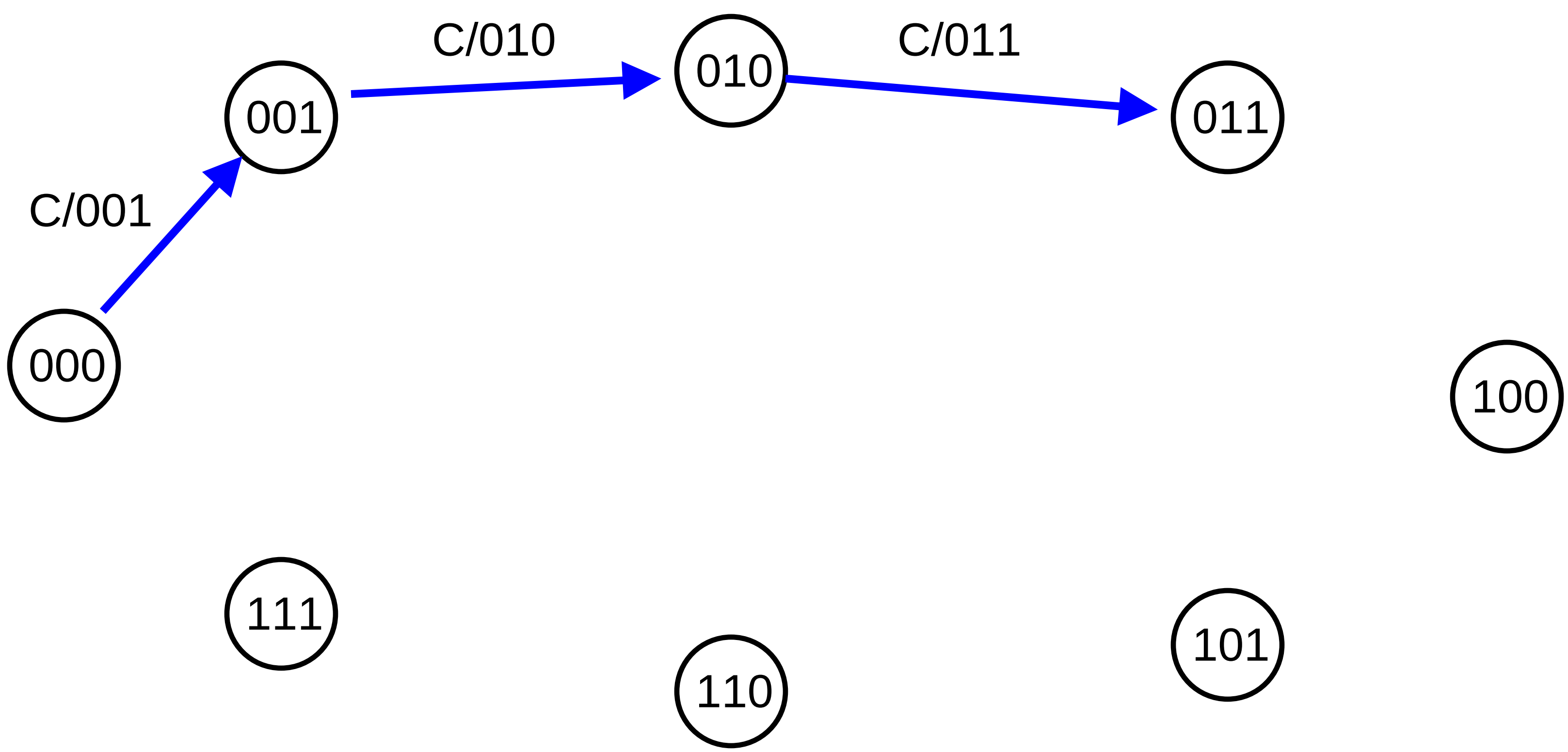
FSM Example: Synchronous Counter

The next transition



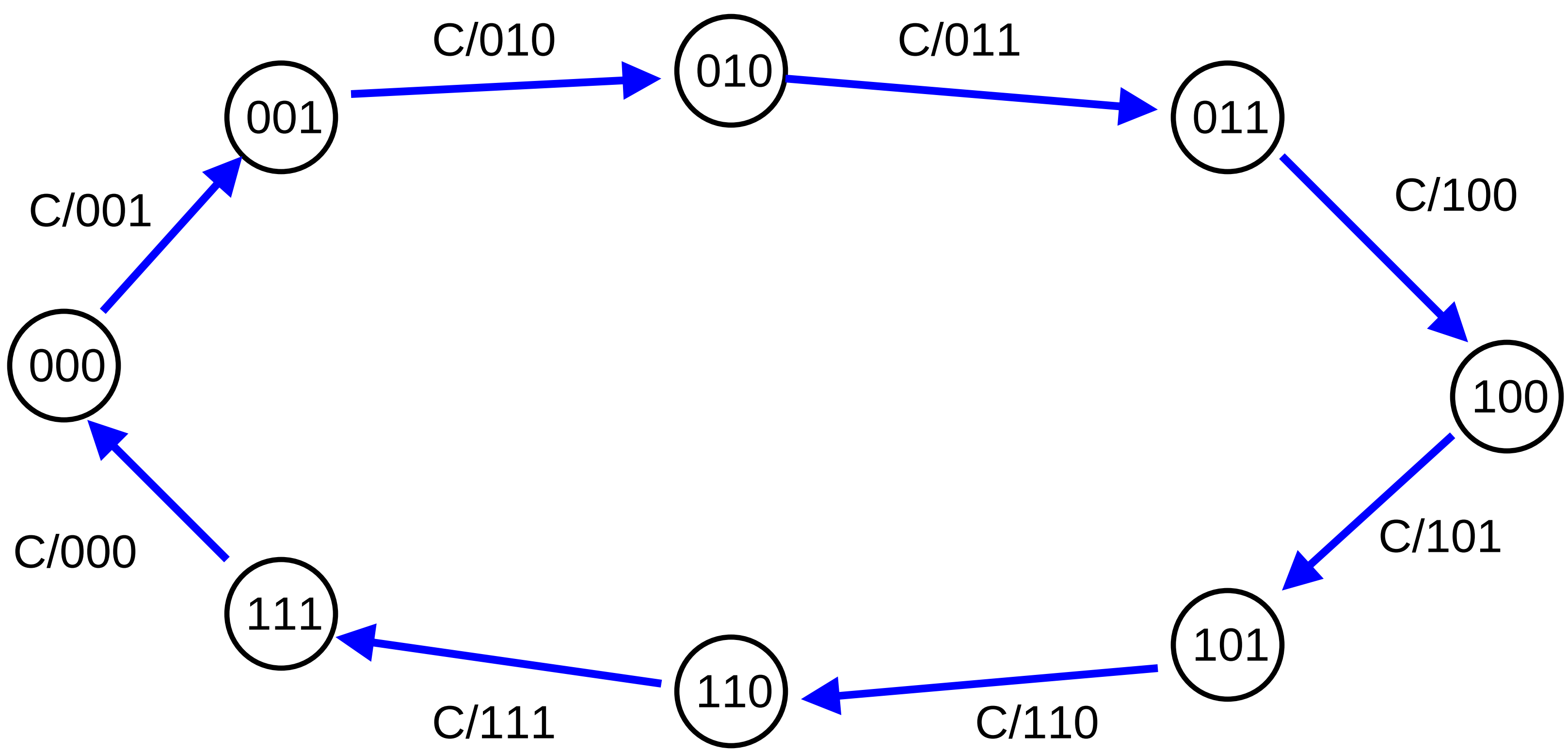
FSM Example: Synchronous Counter

The next transition

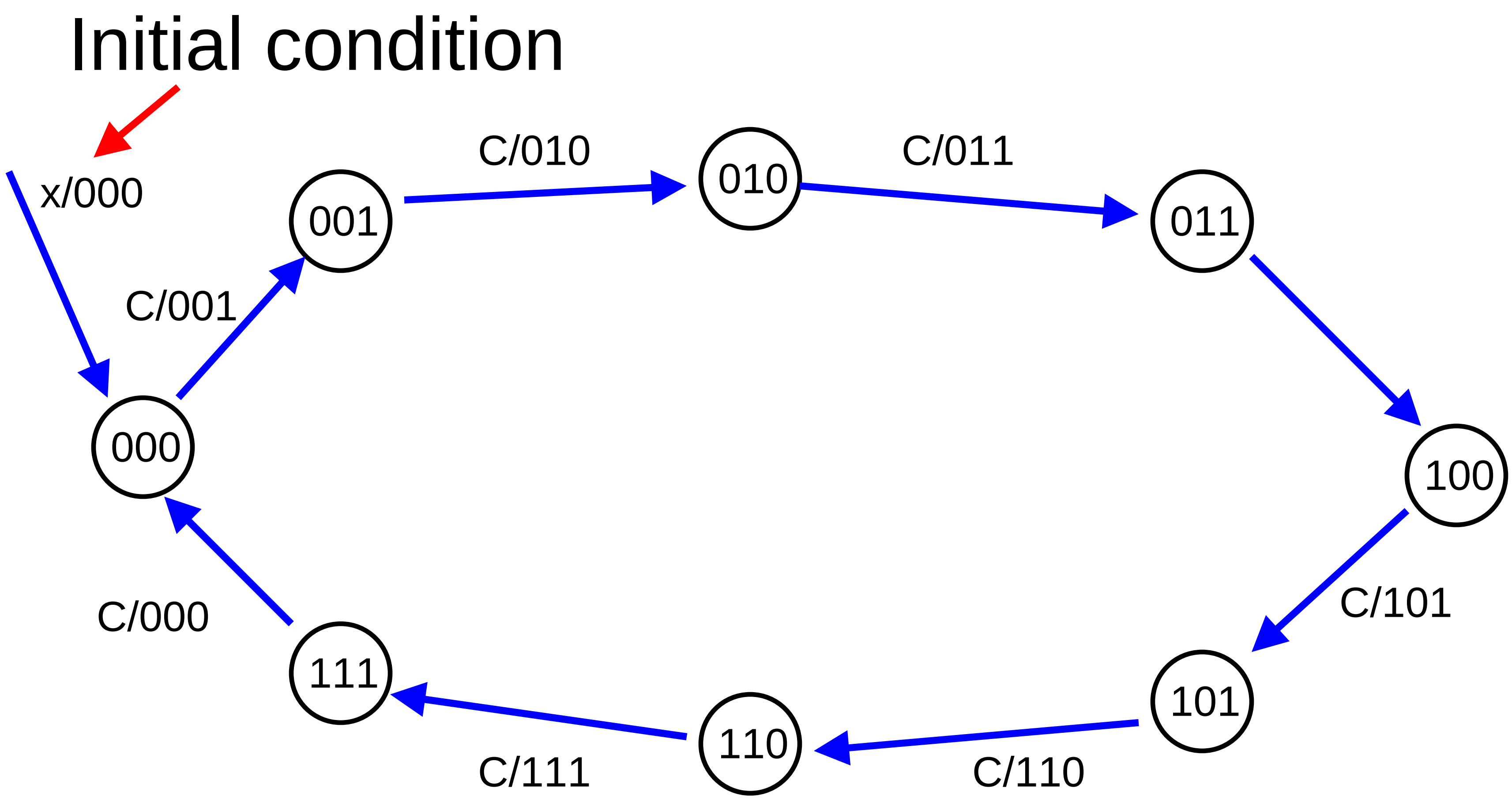


FSM Example: Synchronous Counter

The full transition set



FSM Example: Synchronous Counter



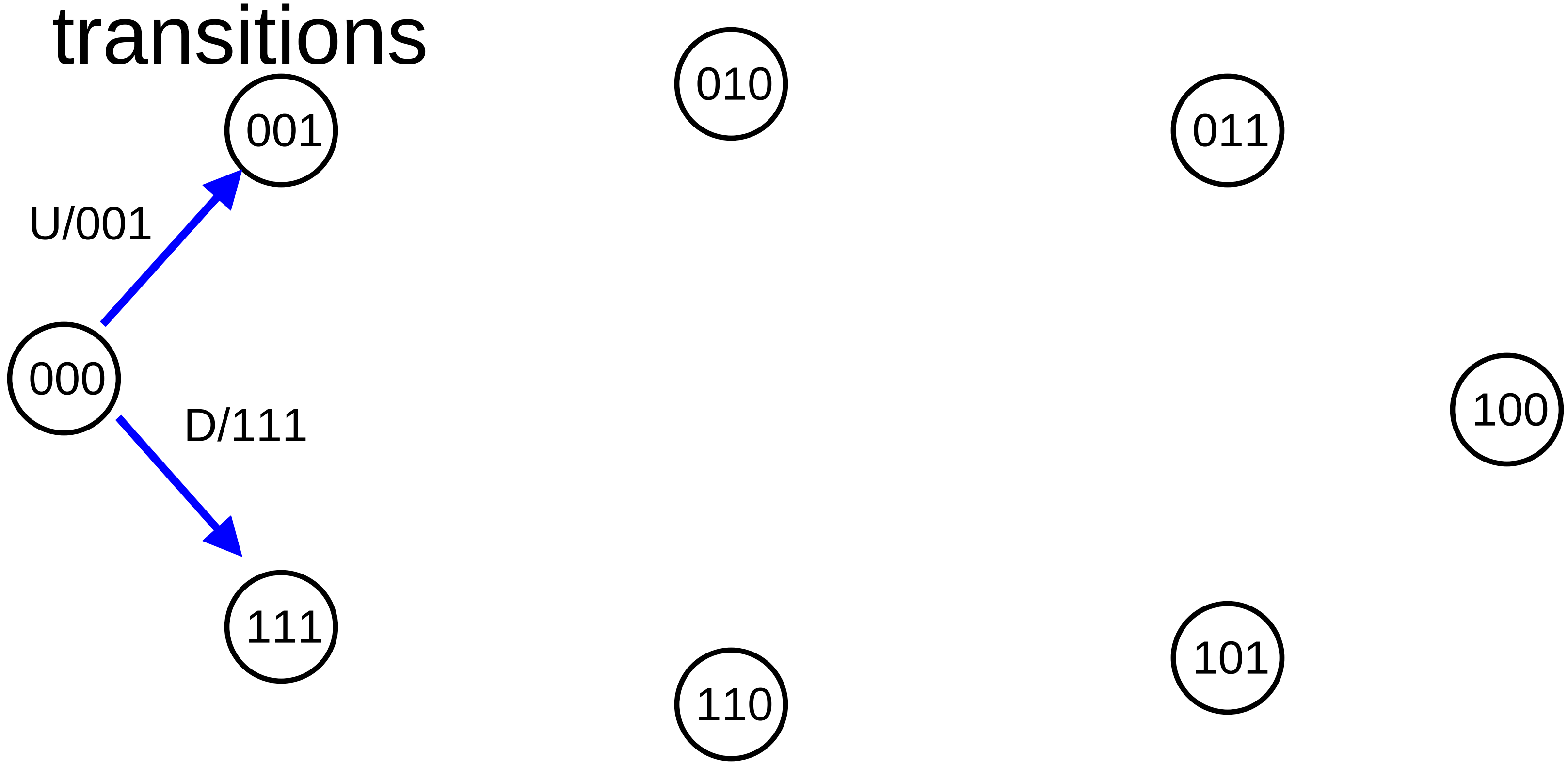
Example II: An Up/Down Counter

Suppose we have two events (instead of one): Up and down

- How does this change our state transition diagram?

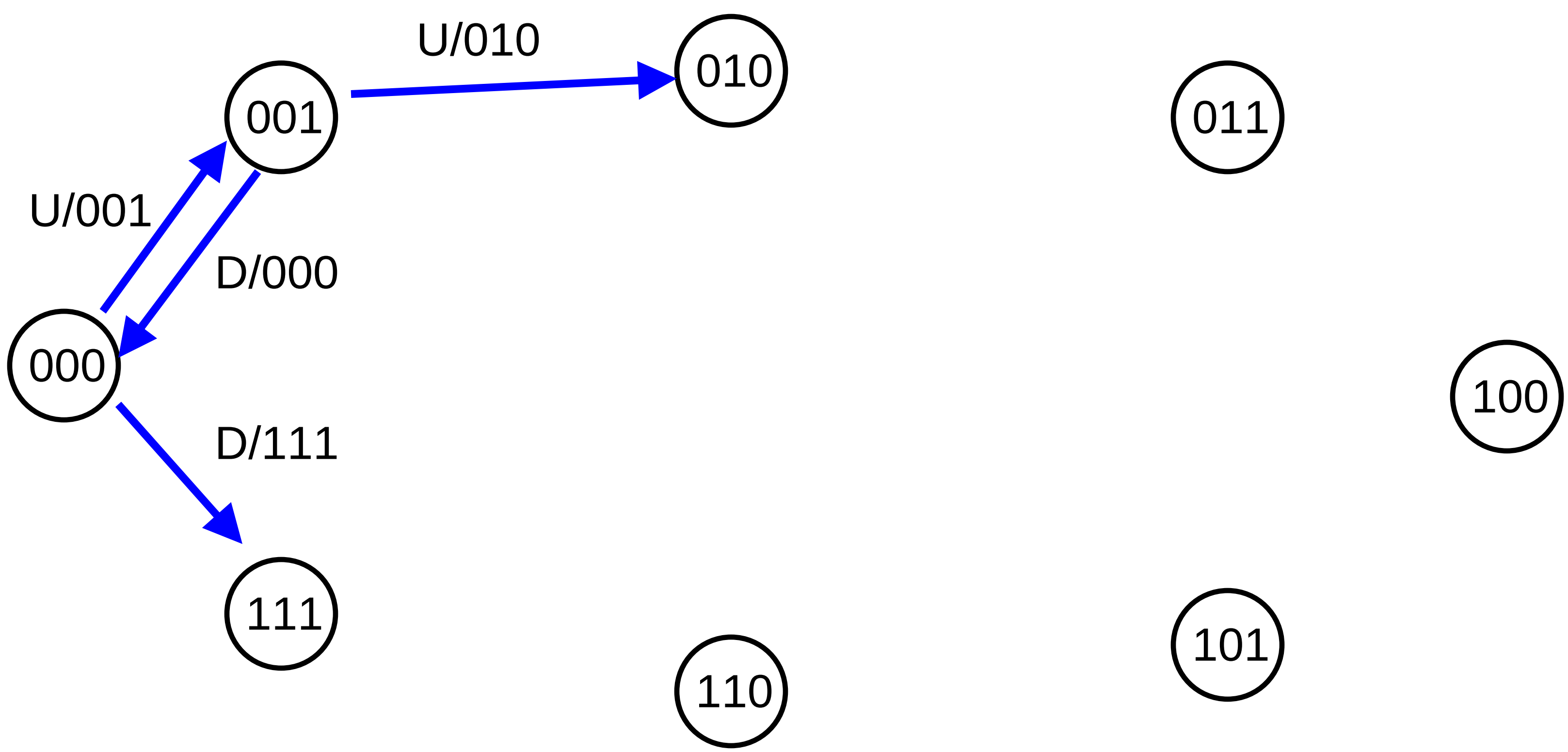
Example II: An Up/Down Counter

From state 000, there are now two possible transitions



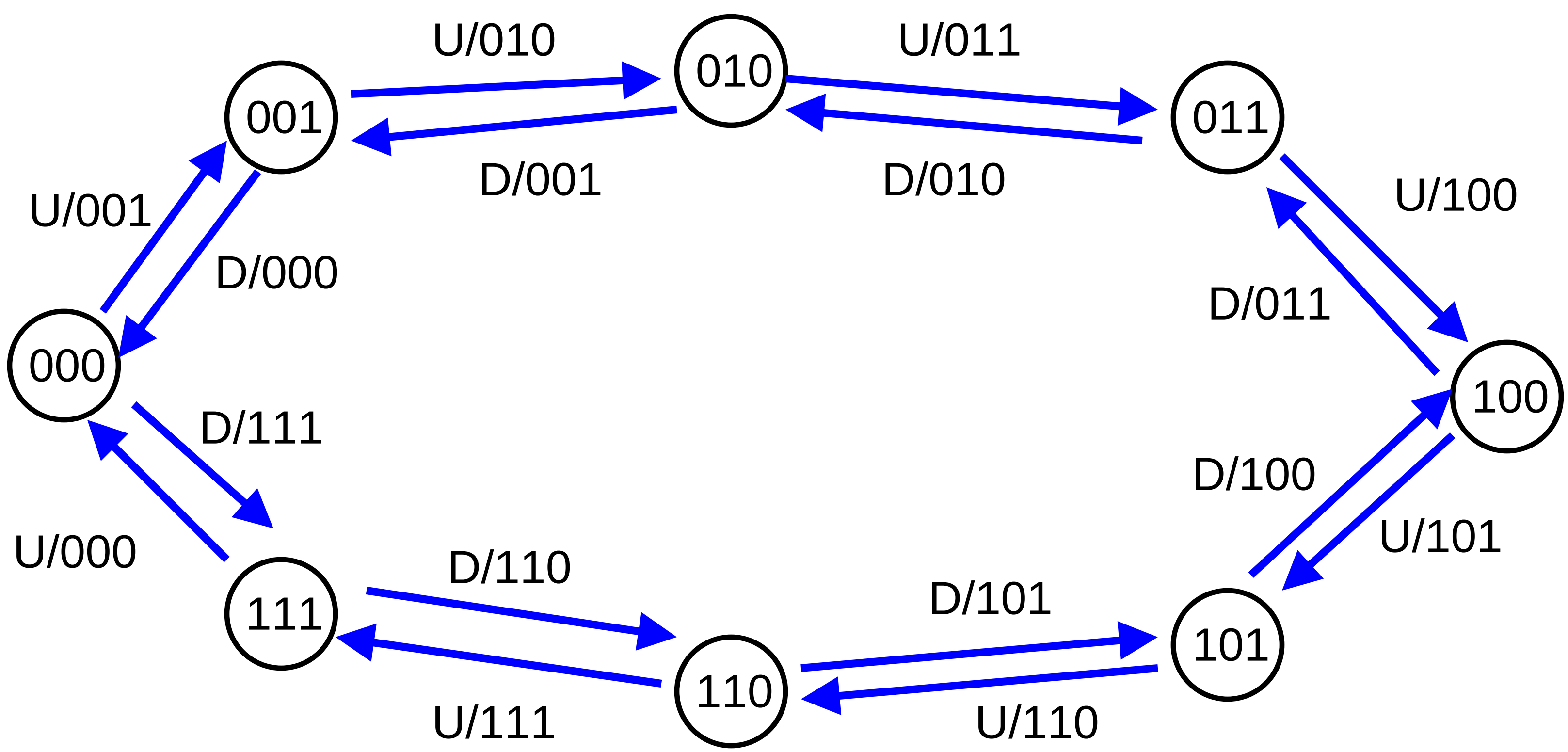
Example II: An Up/Down Counter

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

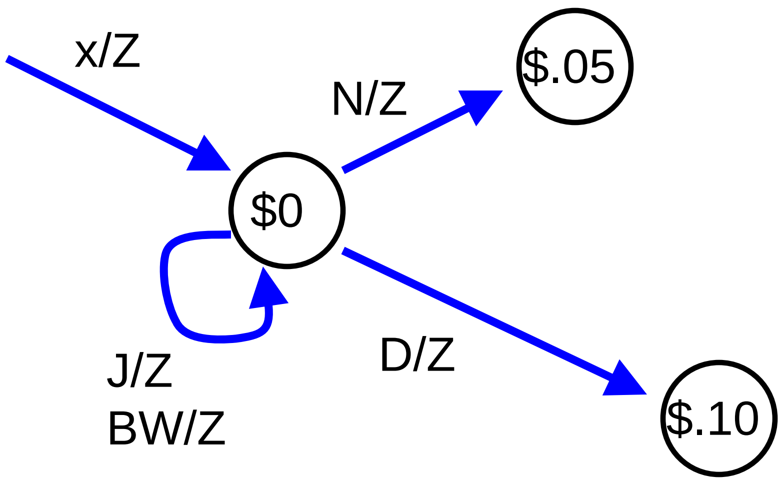
What can happen from S = $0?

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

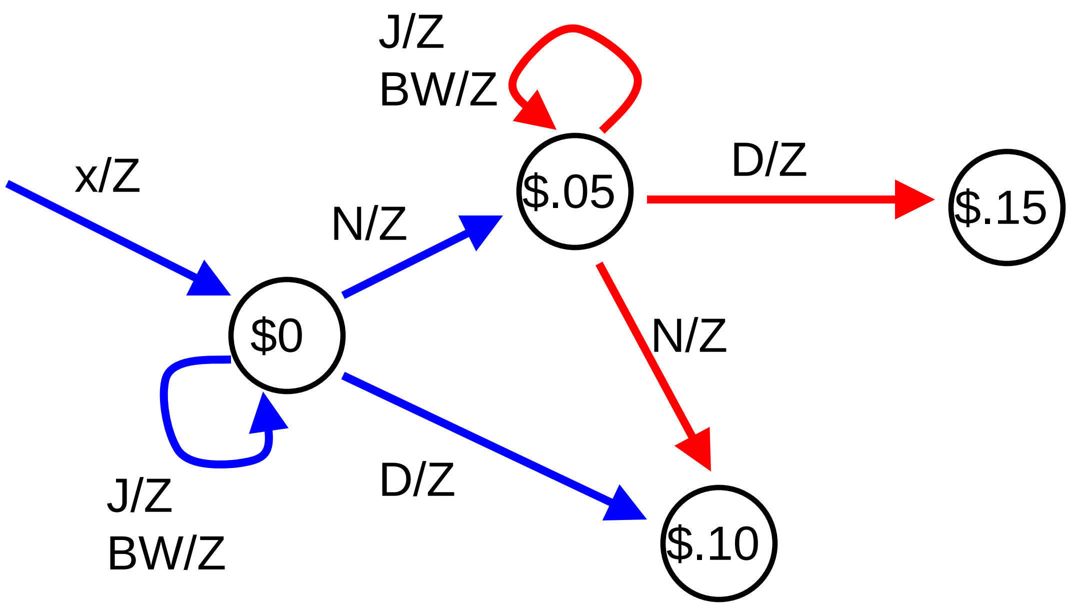
What can happen from S = $0.05?

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

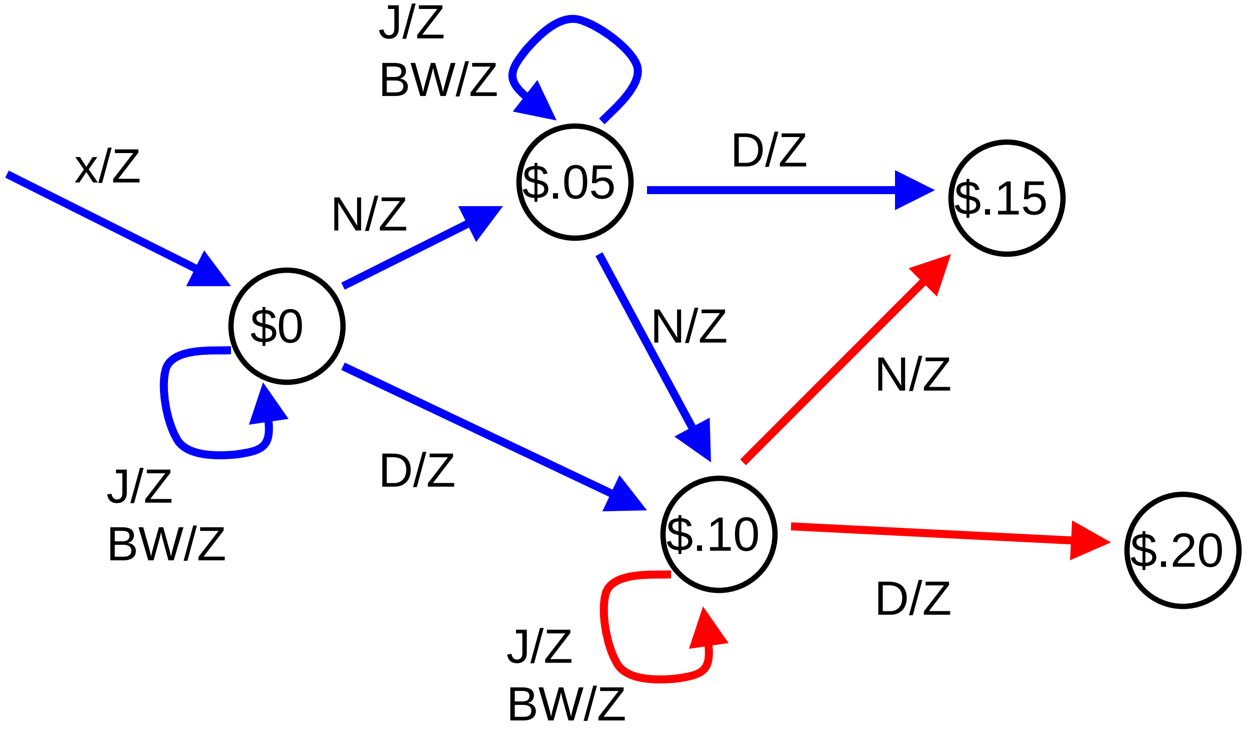
Vending Machine Design

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

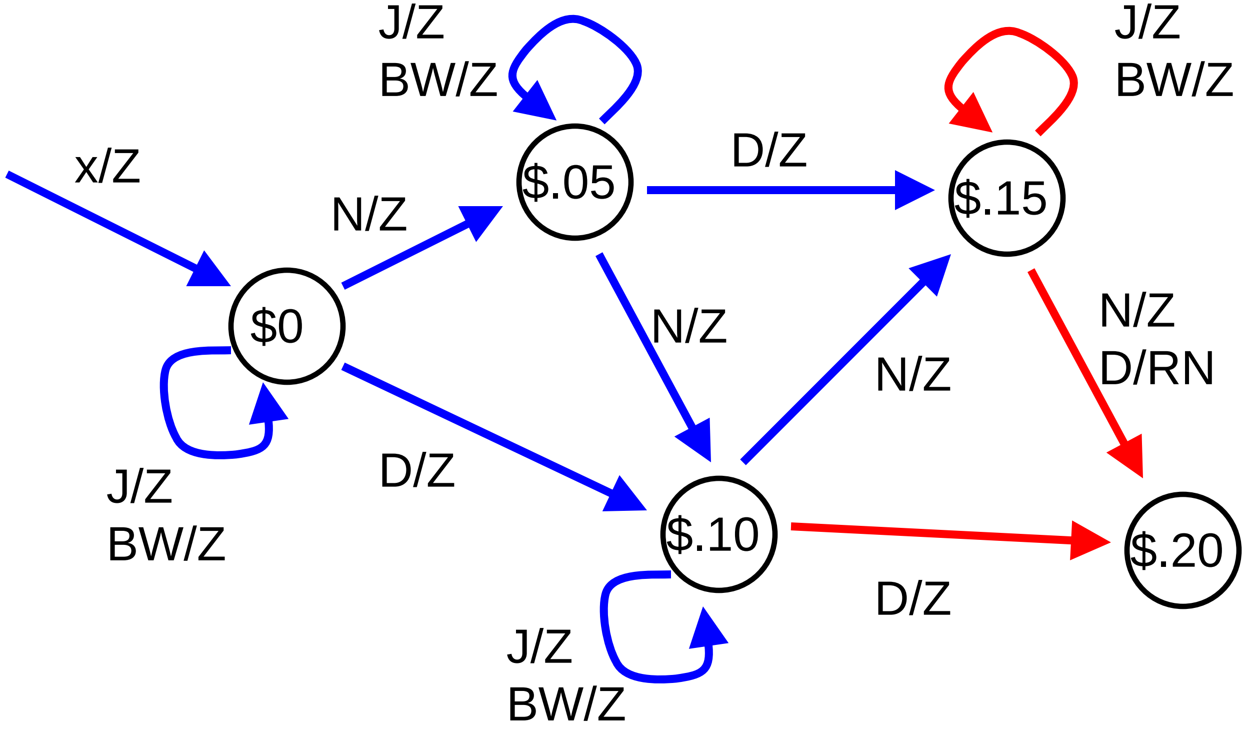
Vending Machine Design

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

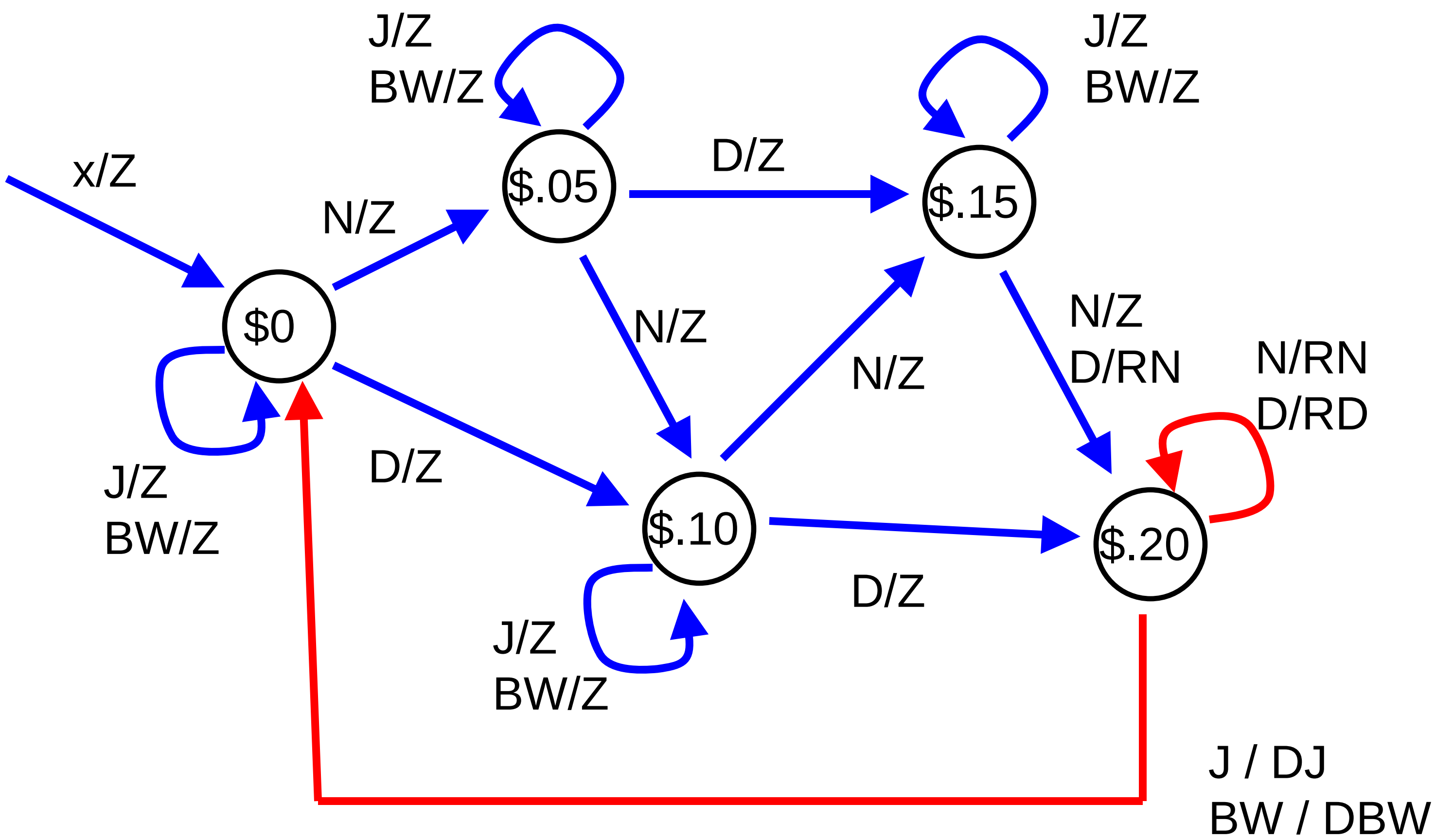
Vending Machine Design

Finally, what can happen from S = $0.20?

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

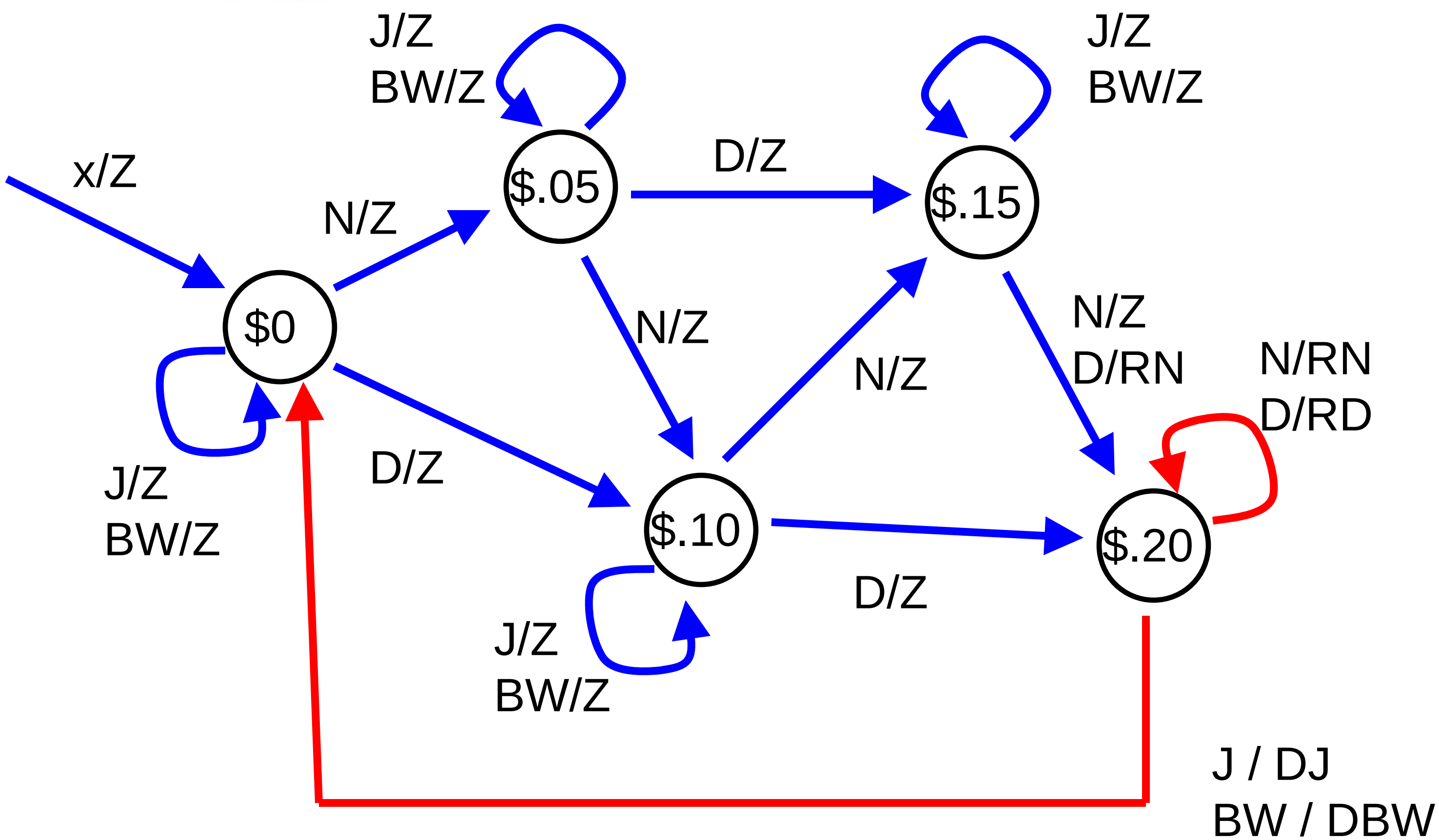
Vending Machine Design

The complete state diagram:




JOLT
SILVER
CHERRY
COLA
BLUE
RED

Last Time


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

Today

- Finite state machines and control
- Implementation of finite state machines in code

Project 3 due Thursday

Homework 4 due Tuesday

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

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?

Control Example III

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

```
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 while 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)

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
```

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 heli reaches a goal orientation or a goal height
- For these continuous situations, we typically use an "if" construct:

```
if(heading_error < 20 && heading_error > -20){…}
```

Next Time

Project 4: come ready to begin work in class