EE178 Lecture
Verilog FSM Examples

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Finite State Machines

- In *Real-time Object-oriented Modeling*, Bran Selic and Garth Gullekson view a state machine as:
  - A set of input events
  - A set of output events
  - A set of states
  - A function that maps states and input to output
  - A function that maps states and inputs to states
  - A description of the initial state
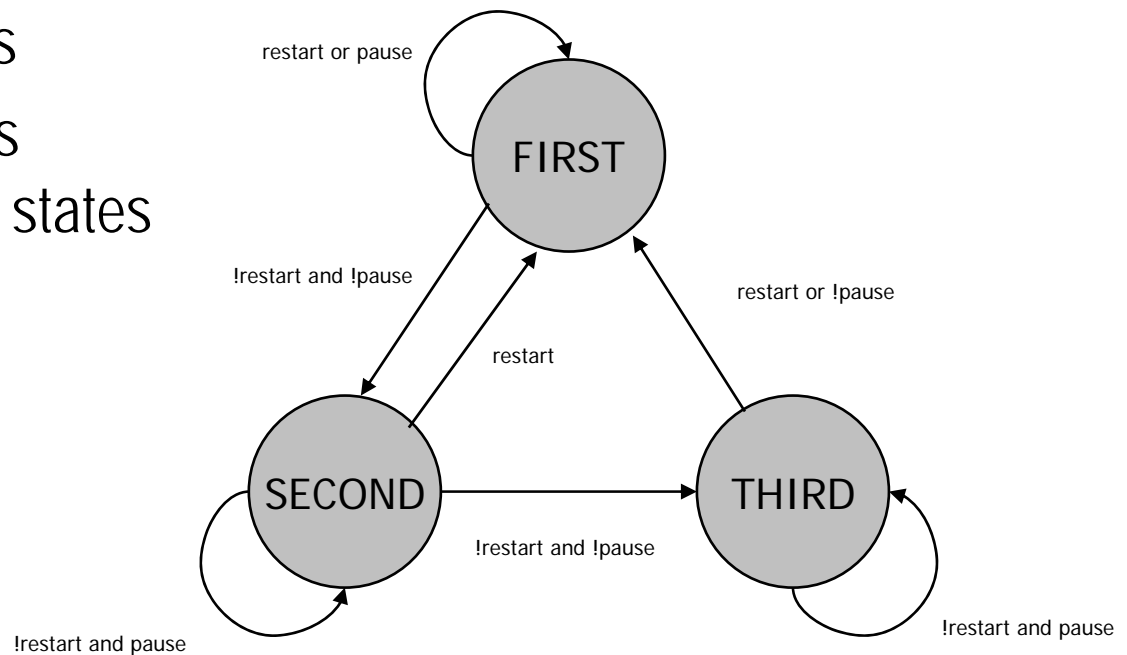
Finite State Machines

- A finite state machine is one that has a limited, or *finite*, number of states.

- The machine state is described by a collection of state variables.

- A finite state machine is an abstract concept, and may be implemented using a variety of techniques, including digital logic.

Finite State Machines

- For an edge-triggered, synchronous FSM implemented in digital logic, consider:
  - A set of input events (input signals, including clock)
  - A set of output events (output signals)
  - A set of states (state variables are flip flops)
  - A function that maps states and input to output (this is the output logic)
  - A function that maps states and inputs to states (this is the next-state logic)
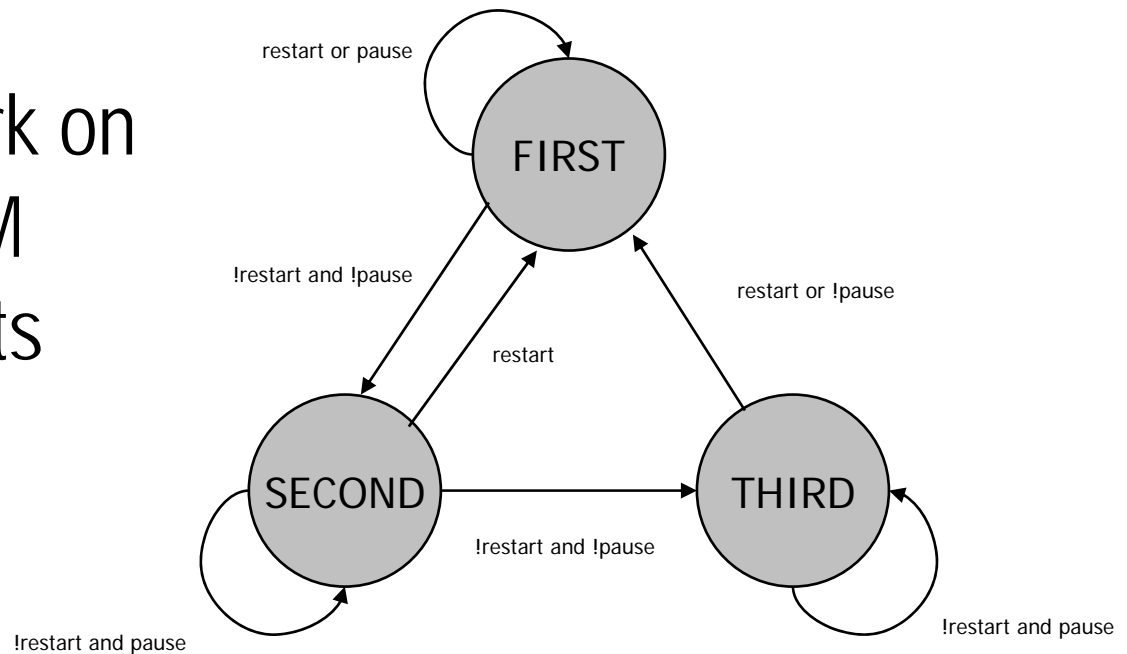 - A description of the initial state (initial flip flop value)

Finite State Machines

- Consider this edge-triggered, synchronous FSM to be implemented in digital logic:
  - A set of states
  - A set of input events
  - A function that maps states and inputs to states
  - A description of the initial state

restart or pause

FIRST

!restart and !pause

restart or !pause

restart

SECOND → THIRD

!restart and !pause

!restart and pause

!restart and pause

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Finite State Machines

- Things that are not shown (yet):
  - A set of output events
  - A function that maps states and input to output

- For now, let's work on modeling the FSM without the outputs and output logic.

restart or pause

FIRST

!restart and !pause

restart or !pause

restart

SECOND

!restart and !pause

THIRD

!restart and pause

!restart and pause

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Finite State Machines

- The state variables must be able to represent at least three unique states for this FSM.
  - A flip flop has two unique states.
  - N flip flops can represent up 2^N unique states.
  - How many flip flops are required for three states?
    - One flip flop is not enough.
    - Two flip flops are minimally sufficient.
    - More flip flops may be used, if desired.

Finite State Machines

- Select a state encoding method:
  - Binary
  - Gray
  - Johnson
  - One Hot
  - Custom

State	Binary	Gray	Johnson	One Hot
0	3'b000	3'b000	4'b0000	8'b00000001
1	3'b001	3'b001	4'b0001	8'b00000010
2	3'b010	3'b011	4'b0011	8'b00000100
3	3'b011	3'b010	4'b0111	8'b00001000
4	3'b100	3'b110	4'b1111	8'b00010000
5	3'b101	3'b111	4'b1110	8'b00100000
6	3'b110	3'b101	4'b1100	8'b01000000
7	3'b111	3'b100	4'b1000	8'b10000000

- Your encoding selection may require more than the minimally sufficient number of flip flops.
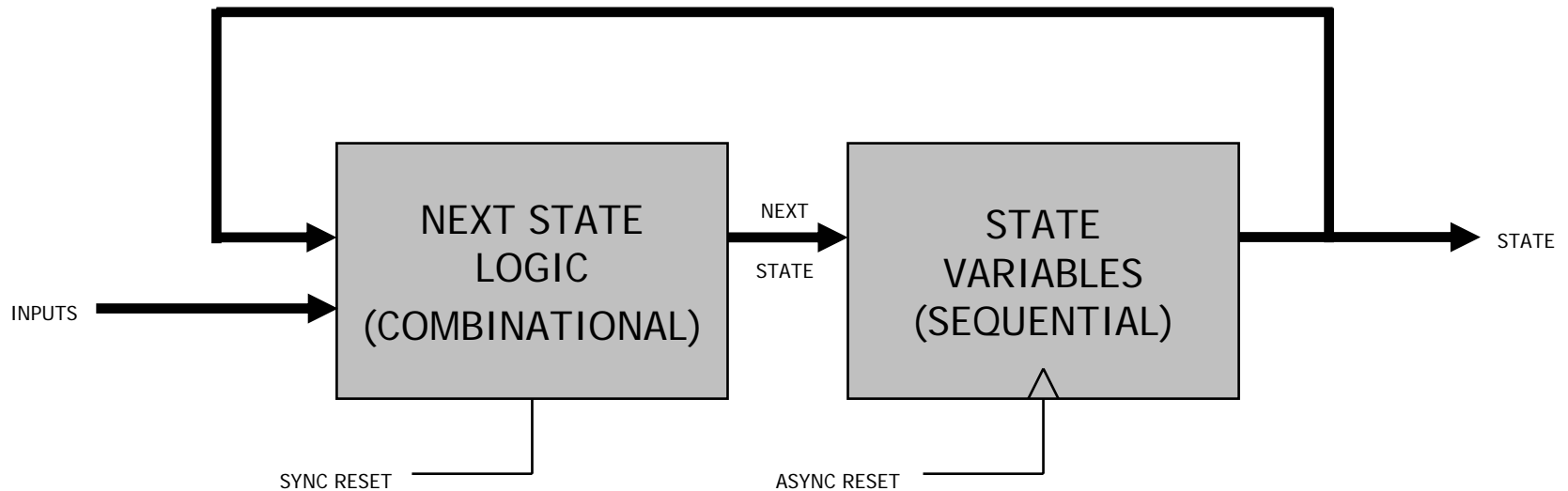
Finite State Machines

- Describe the state variables in Verilog.

- Provide a mechanism to force an initial state.

- Describe a function that maps inputs and current state to a new, or next state.
  - Literal transcription of excitation equations
  - Behavioral description using case, if-else, etc…

- Some additional things to consider:
  - Resets, synchronous or asynchronous?
  - Unused states (error, or no resets) and recovery

Finite State Machines

- Describe it in Verilog just like the block diagram!
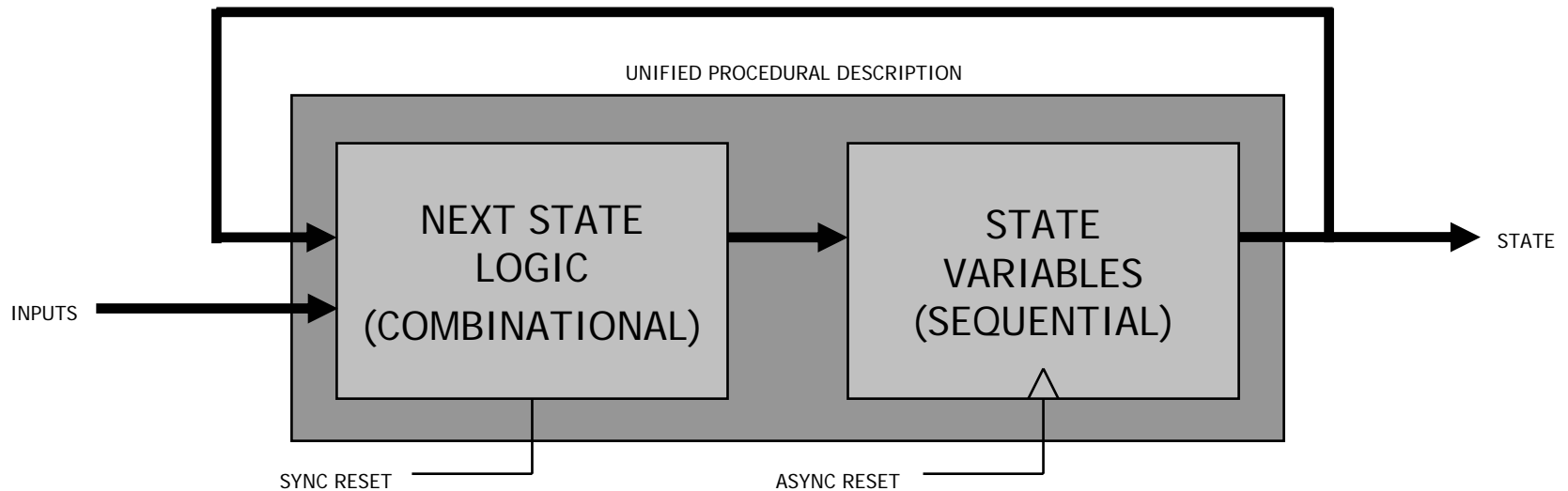- I have selected a custom state encoding.

INPUTS

NEXT STATE LOGIC (COMBINATIONAL)

NEXT STATE

STATE VARIABLES (SEQUENTIAL)

STATE

SYNC RESET

ASYNC RESET

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Finite State Machines

```verilog
module fsm (
  input wire pause,
  input wire restart,
  input wire clk,
  input wire rst,
  output reg [1:0] state
  );

  reg [1:0] next_state;

  parameter [1:0] FIRST  = 2'b11;
  parameter [1:0] SECOND = 2'b01;
  parameter [1:0] THIRD  = 2'b10;

  always @(posedge clk or posedge rst) // sequential
  begin
    if (rst) state <= FIRST;
    else state <= next_state;
  end

  always @* // combinational
  begin
    case(state)
      FIRST:   if (restart | pause) next_state = FIRST;
               else next_state = SECOND;
      SECOND:  if (restart) next_state = FIRST;
               else if (pause) next_state = SECOND;
               else next_state = THIRD;
      THIRD:   if (!restart & pause) next_state = THIRD;
               else next_state = FIRST;
      default: next_state = FIRST;
    endcase
  end

endmodule
```

- Note use of parameters; easy to change encoding
- Asynchronous reset is implemented with state
- Synchronous reset is implemented with logic
- Default clause covers the one unused state
- Explicit next state signal

Finite State Machines

- You can also describe it in one procedural block.
  - No access to "next state" signal (important?)
  - More compact...

UNIFIED PROCEDURAL DESCRIPTION

INPUTS

NEXT STATE
LOGIC
(COMBINATIONAL)

STATE
VARIABLES
(SEQUENTIAL)

STATE

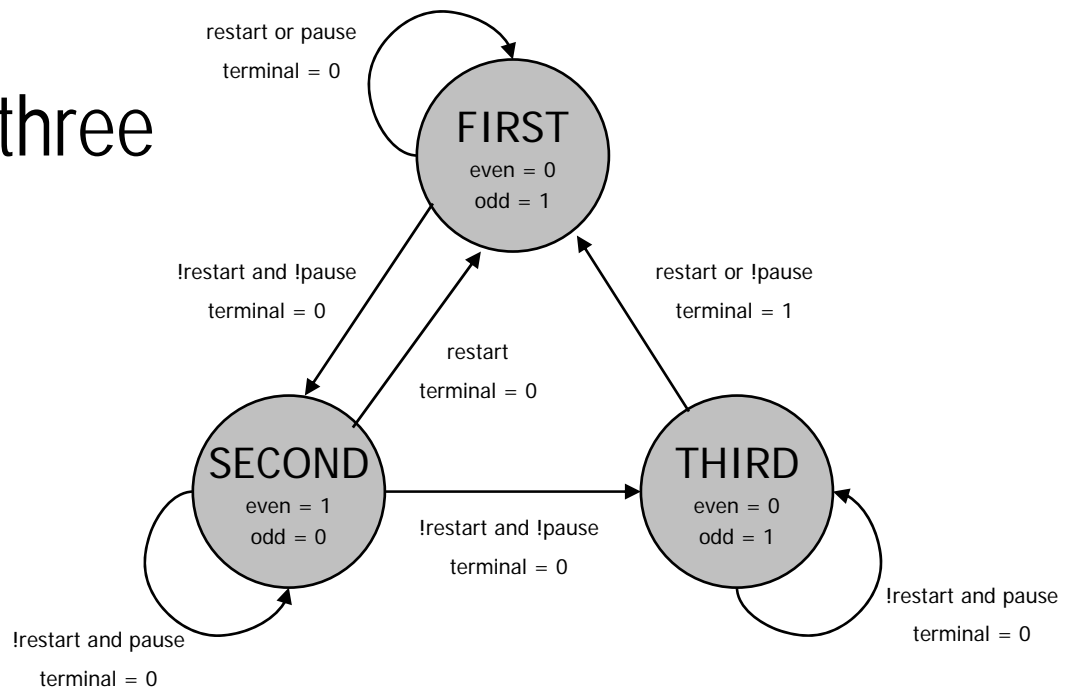SYNC RESET

ASYNC RESET

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Finite State Machines

```
module fsm (
  input wire pause,
  input wire restart,
  input wire clk,
  input wire rst,
  output reg [1:0] state
  );

  parameter [1:0] FIRST  = 2'b11;
  parameter [1:0] SECOND = 2'b01;
  parameter [1:0] THIRD  = 2'b10;

  always @(posedge clk or posedge rst) // sequential
  begin
    if (rst) state <= FIRST;
    else
    begin
      case(state)
        FIRST:   if (restart | pause) state <= FIRST;
                 else state <= SECOND;
        SECOND:  if (restart) state <= FIRST;
                 else if (pause) state <= SECOND;
                 else state <= THIRD;
        THIRD:   if (!restart & pause) state <= THIRD;
                 else state <= FIRST;
        default: state <= FIRST;
      endcase
    end
  end

endmodule
```

- Note use of parameters; easy to change encoding
- Asynchronous reset and synchronous reset both implemented; distinction is made by sensitivity list
- Default clause covers the one unused state
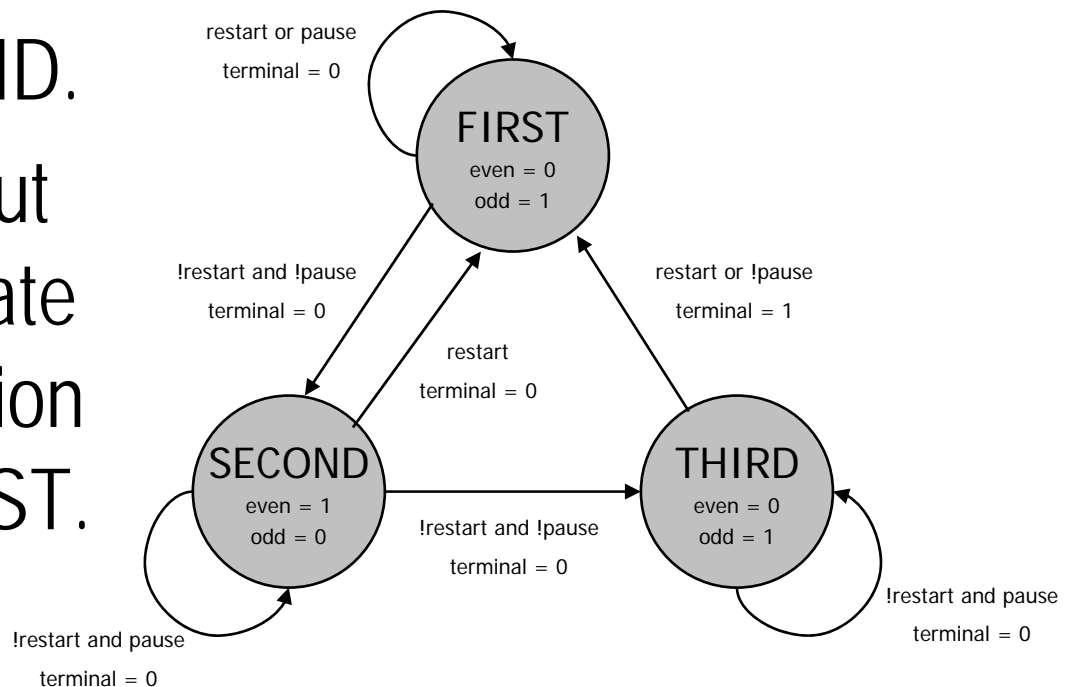- Implicit next state signal

Finite State Machines

- Now, let's consider the following:
  - A set of output events
  - A function that maps states and input to output

- Suppose there are three desired outputs:
  - odd
  - even
  - terminal

restart or pause
terminal = 0

FIRST
even = 0
odd = 1

!restart and !pause
terminal = 0

restart or !pause
terminal = 1

restart
terminal = 0

SECOND
even = 1
odd = 0

!restart and !pause
terminal = 0

THIRD
even = 0
odd = 1

!restart and pause
terminal = 0

!restart and pause
terminal = 0

Finite State Machines

- The "odd" output is asserted in FIRST and THIRD.

- The "even" output is asserted in SECOND.

- The "terminal" output is asserted to indicate the FSM will transition from THIRD to FIRST.

restart or pause
terminal = 0

FIRST
even = 0
odd = 1

!restart and !pause
terminal = 0

restart or !pause
terminal = 1

restart
terminal = 0

SECOND
even = 1
odd = 0

THIRD
even = 0
odd = 1

!restart and !pause
terminal = 0

!restart and pause
terminal = 0

!restart and pause
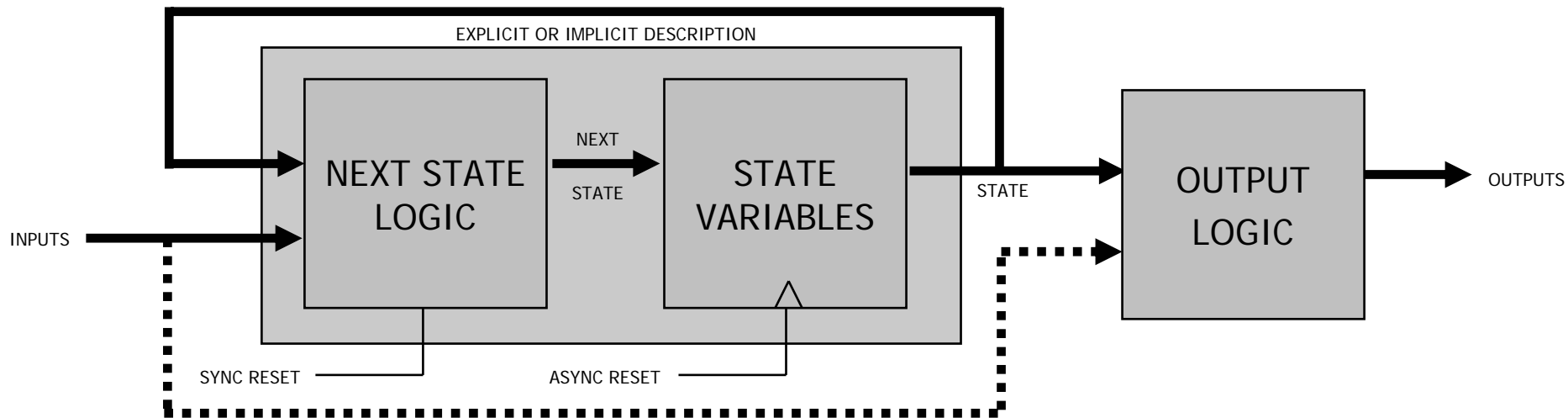terminal = 0

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Finite State Machines

- Outputs that require functions of only the current state are Moore type outputs.

  - This includes using state bits directly.

  - Outputs "odd" and "even" are Moore outputs.

- Outputs that require functions of the current state and the inputs are Mealy type outputs.

  - Output "terminal" is a Mealy output.

- Consider the latency and cycle time tradeoffs.

Finite State Machines

- Describe the output functions in Verilog, just as shown in the block diagram…

Finite State Machines

```verilog
module fsm (
  input wire pause,
  input wire restart,
  input wire clk,
  input wire rst,
  output reg [1:0] state,
  output wire odd,
  output wire even,
  output wire terminal
  );

  reg [1:0] next_state;

  parameter [1:0] FIRST  = 2'b11;
  parameter [1:0] SECOND = 2'b01;
  parameter [1:0] THIRD  = 2'b10;

  always @(posedge clk or posedge rst) // sequential
  begin
    if (rst) state <= FIRST;
    else state <= next_state;
  end

  always @* // combinational
  begin
    case(state)
      FIRST:   if (restart | pause) next_state = FIRST;
               else next_state = SECOND;
      SECOND:  if (restart) next_state = FIRST;
               else if (pause) next_state = SECOND;
               else next_state = THIRD;
      THIRD:   if (!restart & pause) next_state = THIRD;
               else next_state = FIRST;
      default: next_state = FIRST;
    endcase
  end

  // output logic described using continuous assignment
  assign odd = (state == FIRST) | (state == THIRD);
  assign even = (state == SECOND);
  assign terminal = (state == THIRD) & (restart | !pause);

endmodule
```

- Started with the FSM described using explicit next state logic, but could have used the other one.

- Added three assignment statements to create the output functions.

Finite State Machines

```verilog
module fsm (
  input wire pause,
  input wire restart,
  input wire clk,
  input wire rst,
  output reg [1:0] state,
  output reg odd,
  output reg even,
  output reg terminal
  );

  parameter [1:0] FIRST  = 2'b11;
  parameter [1:0] SECOND = 2'b01;
  parameter [1:0] THIRD  = 2'b10;

  always @(posedge clk or posedge rst) // sequential
  begin
    if (rst) state <= FIRST;
    else
    begin
      case(state)
        FIRST:   if (restart | pause) state <= FIRST;
                 else state <= SECOND;
        SECOND:  if (restart) state <= FIRST;
                 else if (pause) state <= SECOND;
                 else state <= THIRD;
        THIRD:   if (!restart & pause) state <= THIRD;
                 else state <= FIRST;
        default: state <= FIRST;
      endcase
    end
  end

  // output logic described using procedural assignment
  always @* // combinational
  begin
    odd = (state == FIRST) | (state == THIRD);
    even = (state == SECOND);
    terminal = (state == THIRD) & (restart | !pause);
  end

endmodule
```

- Started with the FSM described using implicit next state logic, but could have used the other one.

- This describes the same output logic as before, but uses a procedural block to create the outputs.
  - Could have used case…
  - Could have used if-else…

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