

Sequential logic examples

- Basic design approach: a 4-step design process
- Hardware description languages and finite state machines
- Implementation examples and case studies
 - finite-string pattern recognizer
 - complex counter
 - traffic light controller
 - door combination lock

General FSM design procedure

- (1) Determine inputs and outputs
- (2) Determine possible states of machine
 - – state minimization
- (3) Encode states and outputs into a binary code
 - – state assignment or state encoding
 - – output encoding
 - – possibly input encoding (if under our control)
- (4) Realize logic to implement functions for states and outputs
 - – combinational logic implementation and optimization
 - – choices made in steps 2 and 3 can have large effect on resulting logic

Finite string pattern recognizer (step 1)

■ Finite string pattern recognizer

- one input (X) and one output (Z)
- output is asserted whenever the input sequence ...010... has been observed, as long as the sequence 100 has never been seen

■ Step 1: understanding the problem statement

- sample input/output behavior:

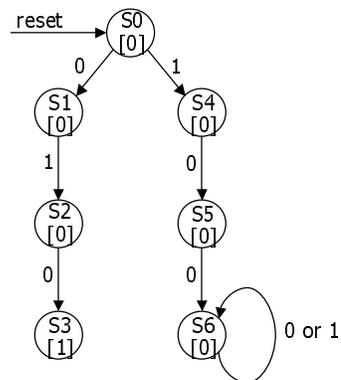
X: 0 0 1 0 1 0 1 0 0 1 0 ...
Z: 0 0 0 1 0 1 0 1 0 0 0 ...

X: 1 1 0 1 1 0 1 0 0 1 0 ...
Z: 0 0 0 0 0 0 0 1 0 0 0 ...

Finite string pattern recognizer (step 2)

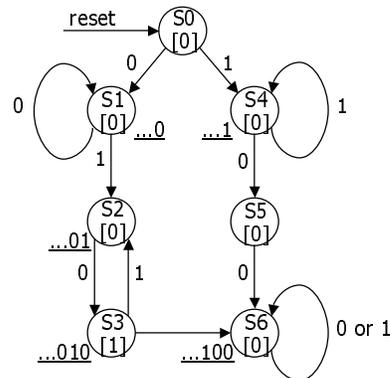
■ Step 2: draw state diagram

- for the strings that must be recognized, i.e., 010 and 100
- a Moore implementation



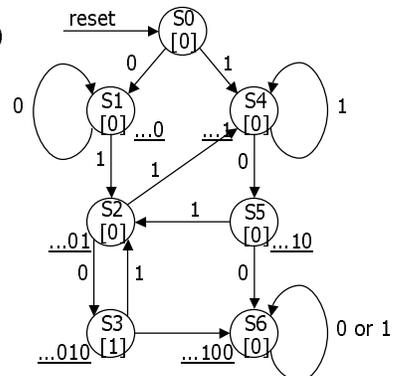
Finite string pattern recognizer (step 2, cont'd)

- Exit conditions from state S3: have recognized ...010
 - ▮ if next input is 0 then have ...0100 = ...100 (state S6)
 - ▮ if next input is 1 then have ...0101 = ...01 (state S2)
- Exit conditions from S1: recognizes strings of form ...0 (no 1 seen)
 - ▮ loop back to S1 if input is 0
- Exit conditions from S4: recognizes strings of form ...1 (no 0 seen)
 - ▮ loop back to S4 if input is 1



Finite string pattern recognizer (step 2, cont'd)

- S2 and S5 still have incomplete transitions
 - ▮ S2 = ...01; If next input is 1, then string could be prefix of (01)1(00) S4 handles just this case
 - ▮ S5 = ...10; If next input is 1, then string could be prefix of (10)1(0) S2 handles just this case
- Reuse states as much as possible
 - ▮ look for same meaning
 - ▮ state minimization leads to smaller number of bits to represent states
- Once all states have a complete set of transitions we have a final state diagram



Finite string pattern recognizer (step 3)

■ Verilog description including state assignment (or state encoding)

```
module string (clk, X, rst, Q0, Q1, Q2, Z);
input clk, X, rst;
output Q0, Q1, Q2, Z;

reg state[0:2];
`define S0 [0,0,0] //reset state
`define S1 [0,0,1] //strings ending in ...0
`define S2 [0,1,0] //strings ending in ...01
`define S3 [0,1,1] //strings ending in ...010
`define S4 [1,0,0] //strings ending in ...1
`define S5 [1,0,1] //strings ending in ...10
`define S6 [1,1,0] //strings ending in ...100

assign Q0 = state[0];
assign Q1 = state[1];
assign Q2 = state[2];
assign Z = (state == `S3);

always @(posedge clk) begin
    if rst state = `S0;
    else
        case (state)
            `S0: if (X) state = `S4 else state = `S1;
            `S1: if (X) state = `S2 else state = `S1;
            `S2: if (X) state = `S4 else state = `S3;
            `S3: if (X) state = `S2 else state = `S6;
            `S4: if (X) state = `S4 else state = `S5;
            `S5: if (X) state = `S2 else state = `S6;
            `S6: state = `S6;
        default: begin
            $display ("invalid state reached");
            state = 3'bxxx;
        endcase
    end
end

endmodule
```

Finite string pattern recognizer

■ Review of process

- understanding problem
 - | write down sample inputs and outputs to understand specification
- derive a state diagram
 - | write down sequences of states and transitions for sequences to be recognized
- minimize number of states
 - | add missing transitions; reuse states as much as possible
- state assignment or encoding
 - | encode states with unique patterns
- simulate realization
 - | verify I/O behavior of your state diagram to ensure it matches specification

Complex counter

- A synchronous 3-bit counter has a mode control M
 - when $M = 0$, the counter counts up in the binary sequence
 - when $M = 1$, the counter advances through the Gray code sequence

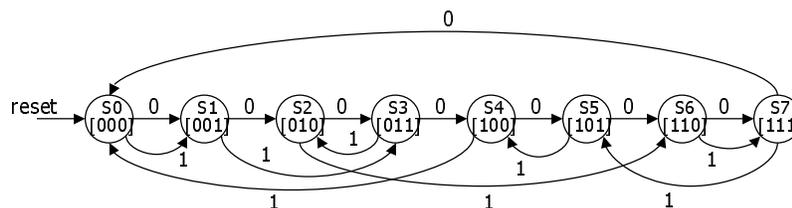
binary: 000, 001, 010, 011, 100, 101, 110, 111
 Gray: 000, 001, 011, 010, 110, 111, 101, 100

- Valid I/O behavior (partial)

Mode Input M	Current State	Next State
0	000	001
0	001	010
1	010	110
1	110	111
1	111	101
0	101	110
0	110	111

Complex counter (state diagram)

- Deriving state diagram
 - one state for each output combination
 - add appropriate arcs for the mode control



Complex counter (state encoding)

Verilog description including state encoding

```

module string (clk, M, rst, Z0, Z1, Z2);
input clk, X, rst;
output Z0, Z1, Z2;

reg state[0:2];
`define S0 = [0,0,0];
`define S1 = [0,0,1];
`define S2 = [0,1,0];
`define S3 = [0,1,1];
`define S4 = [1,0,0];
`define S5 = [1,0,1];
`define S6 = [1,1,0];
`define S7 = [1,1,1];

assign Z0 = state[0];
assign Z1 = state[1];
assign Z2 = state[2];

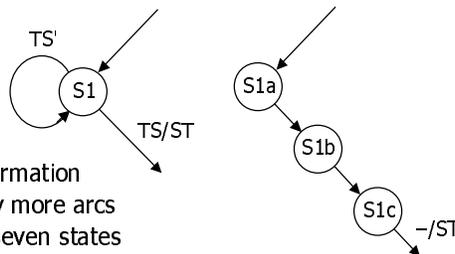
always @(posedge clk) begin
if rst state = `S0;
else
case (state)
`S0: state = `S1;
`S1: if (M) state = `S3 else state = `S2;
`S2: if (M) state = `S6 else state = `S3;
`S3: if (M) state = `S2 else state = `S4;
`S4: if (M) state = `S0 else state = `S5;
`S5: if (M) state = `S4 else state = `S6;
`S6: if (M) state = `S7 else state = `S7;
`S7: if (M) state = `S5 else state = `S0;
endcase
end
endmodule

```

Traffic light controller as two communicating FSMs

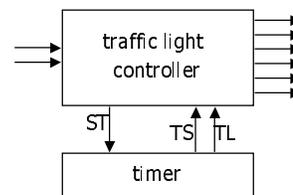
Without separate timer

- | S0 would require 7 states
- | S1 would require 3 states
- | S2 would require 7 states
- | S3 would require 3 states
- | S1 and S3 have simple transformation
- | S0 and S2 would require many more arcs
 - | C could change in any of seven states



By factoring out timer

- | greatly reduce number of states
 - | 4 instead of 20
- | counter only requires seven or eight states
 - | 12 total instead of 20



Traffic light controller FSM

■ Specification of inputs, outputs, and state elements

```
module FSM(HR, HY, HG, FR, FY, FG, ST, TS, TL, C, reset, Clk);
  output HR;
  output HY;
  output HG;
  output FR;
  output FY;
  output FG;
  output ST;
  input TS;
  input TL;
  input C;
  input reset;
  input Clk;

  reg [6:1] state;
  reg ST;

  `define highwaygreen 6'b001100
  `define highwayyellow 6'b010100
  `define farmroadgreen 6'b100001
  `define farmroadyellow 6'b100010

  assign HR = state[6];
  assign HY = state[5];
  assign HG = state[4];
  assign FR = state[3];
  assign FY = state[2];
  assign FG = state[1];
endmodule
```

specify state bits and codes
for each state as well as
connections to outputs

Traffic light controller FSM (cont'd)

```
initial begin state = `highwaygreen; ST = 0; end

always @(posedge Clk)
  begin
    if (reset)
      begin state = `highwaygreen; ST = 1; end
    else
      begin
        ST = 0;
        case (state)
          `highwaygreen:
            if (TL & C) begin state = `highwayyellow; ST = 1; end
          `highwayyellow:
            if (TS) begin state = `farmroadgreen; ST = 1; end
          `farmroadgreen:
            if (TL | !C) begin state = `farmroadyellow; ST = 1; end
          `farmroadyellow:
            if (TS) begin state = `highwaygreen; ST = 1; end
        endcase
      end
    end
  end
endmodule
```

case statement
triggered by
clock edge

Timer for traffic light controller

■ Another FSM

```
module Timer(TS, TL, ST, Clk);
    output TS;
    output TL;
    input  ST;
    input  Clk;
    integer value;

    assign TS = (value >= 4); // 5 cycles after reset
    assign TL = (value >= 14); // 15 cycles after reset

    always @(posedge ST) value = 0; // async reset

    always @(posedge Clk) value = value + 1;
endmodule
```

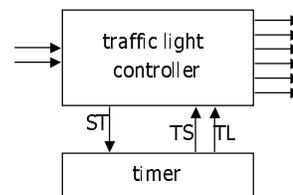
Complete traffic light controller

■ Tying it all together (FSM + timer)

- structural Verilog not supported by DesignWorks (which uses schematic)

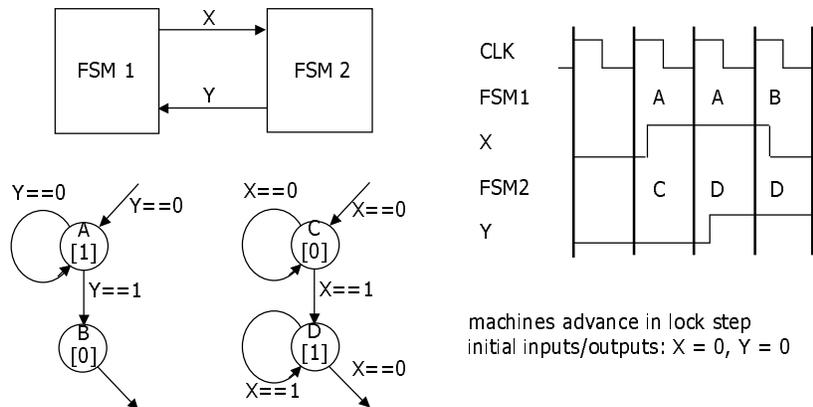
```
module main(HR, HY, HG, FR, FY, FG, reset, C, Clk);
    output HR, HY, HG, FR, FY, FG;
    input  reset, C, Clk;

    Timer part1(TS, TL, ST, Clk);
    FSM part2(HR, HY, HG, FR, FY, FG, ST, TS, TL, C, reset, Clk);
endmodule
```



Communicating finite state machines

- One machine's output is another machine's input



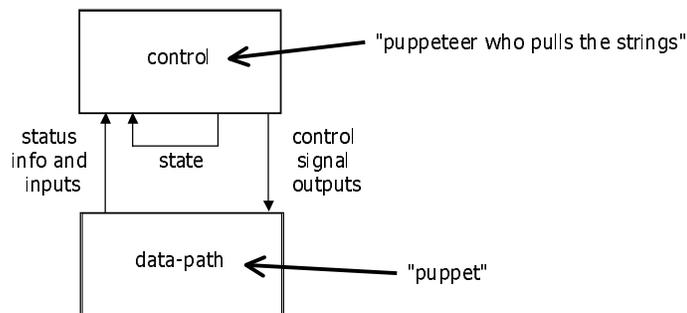
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Data-path and control

- Digital hardware systems = data-path + control
 - datapath: registers, counters, combinational functional units (e.g., ALU), communication (e.g., busses)
 - control: FSM generating sequences of control signals that instructs datapath what to do next



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Digital combinational lock

■ Door combination lock:

- punch in 3 values in sequence and the door opens; if there is an error the lock must be reset; once the door opens the lock must be reset

- inputs: sequence of input values, reset
- outputs: door open/close
- memory: must remember combination or always have it available

- open questions: how do you set the internal combination?
 - ┆ stored in registers (how loaded?)
 - ┆ hardwired via switches set by user

Implementation in software

```
integer combination_lock ( ) {
    integer v1, v2, v3;
    integer error = 0;
    static integer c[3] = 3, 4, 2;

    while (!new_value( ));
    v1 = read_value( );
    if (v1 != c[1]) then error = 1;

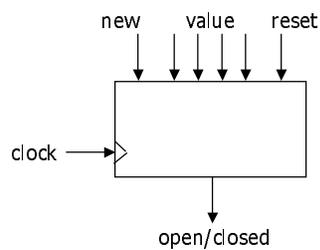
    while (!new_value( ));
    v2 = read_value( );
    if (v2 != c[2]) then error = 1;

    while (!new_value( ));
    v3 = read_value( );
    if (v3 != c[3]) then error = 1;

    if (error == 1) then return(0); else return (1);
}
```

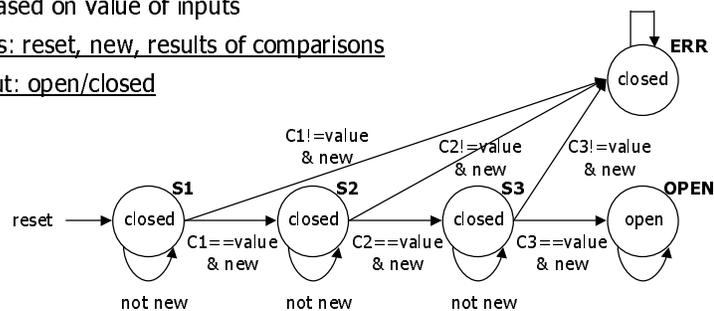
Determining details of the specification

- How many bits per input value?
- How many values in sequence?
- How do we know a new input value is entered?
- What are the states and state transitions of the system?



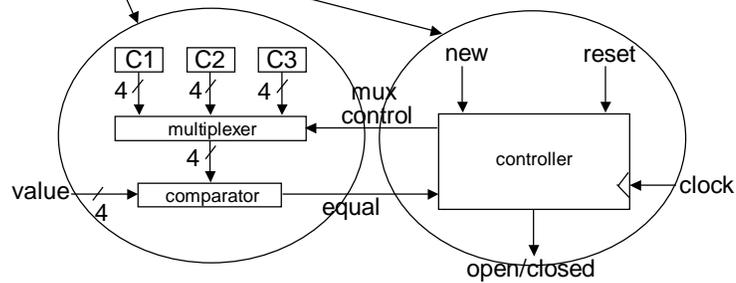
Digital combination lock state diagram

- States: 5 states
 - represent point in execution of machine
 - each state has outputs
- Transitions: 6 from state to state, 5 self transitions, 1 global
 - changes of state occur when clock says its ok
 - based on value of inputs
- Inputs: reset, new, results of comparisons
- Output: open/closed



Data-path and control structure

- Data-path
 - ┆ storage registers for combination values
 - ┆ multiplexer
 - ┆ comparator
- Control
 - ┆ finite-state machine controller
 - ┆ control for data-path (which value to compare)



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State table for combination lock

- Finite-state machine
 - ┆ refine state diagram to take internal structure into account
 - ┆ state table ready for encoding

reset	new	equal	state	next state	mux	open/closed
1	–	–	–	S1	C1	closed
0	0	–	S1	S1	C1	closed
0	1	0	S1	ERR	–	closed
0	1	1	S1	S2	C2	closed
...						
0	1	1	S3	OPEN	–	open
...						

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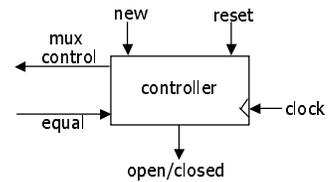
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Encodings for combination lock

Encode state table

- state can be: S1, S2, S3, OPEN, or ERR
 - needs at least 3 bits to encode: 000, 001, 010, 011, 100
 - and as many as 5: 00001, 00010, 00100, 01000, 10000
 - choose 4 bits: 0001, 0010, 0100, 1000, 0000
- output mux can be: C1, C2, or C3
 - needs 2 to 3 bits to encode
 - choose 3 bits: 001, 010, 100
- output open/closed can be: open or closed
 - needs 1 or 2 bits to encode
 - choose 1 bit: 1, 0



reset	new	equal	state	next state	mux	open/closed
1	-	-	-	0001	001	0
0	0	-	0001	0001	001	0
0	1	0	0001	0000	-	0
0	1	1	0001	0010	010	0
...						
0	1	1	0100	1000	-	1

mux is identical to last 3 bits of state
open/closed is identical to first bit of state
therefore, we do not even need to implement FFs to hold state, just use outputs

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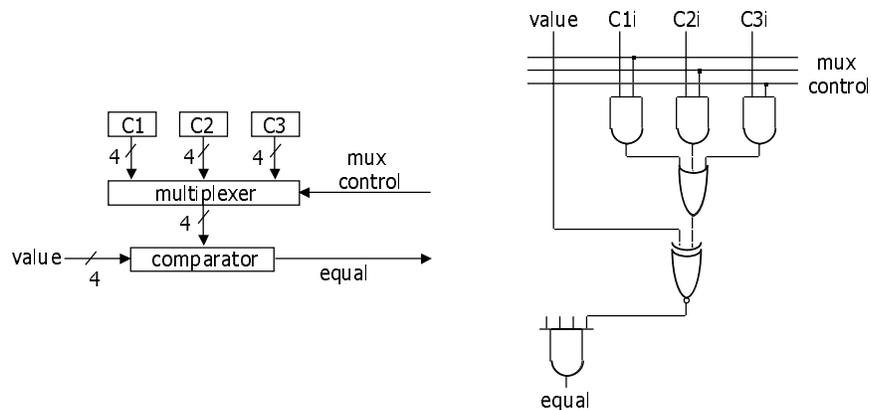
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Data-path implementation for combination lock

Multiplexer

- easy to implement as combinational logic when few inputs
- logic can easily get too big for most PLDs



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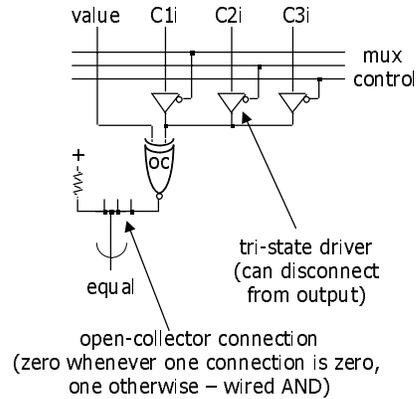
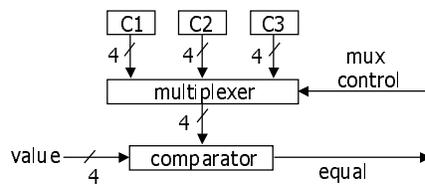
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Data-path implementation (cont'd)

Tri-state logic

- ┆ utilize a third output state: "no connection" or "float"
- ┆ connect outputs together as long as only one is "enabled"
- ┆ open-collector gates can only output 0, not 1
 - ┆ can be used to implement logical AND with only wires



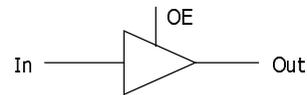
Tri-state gates

The third value

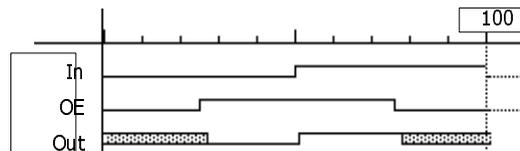
- ┆ logic values: "0", "1"
- ┆ don't care: "X" (must be 0 or 1 in real circuit!)
- ┆ third value or state: "Z" — high impedance, infinite R, no connection

Tri-state gates

- ┆ additional input – output enable (OE)
- ┆ output values are 0, 1, and Z
- ┆ when OE is high, the gate functions normally
- ┆ when OE is low, the gate is disconnected from wire at output
- ┆ allows more than one gate to be connected to the same output wire
 - ┆ as long as only one has its output enabled at any one time (otherwise, sparks could fly)

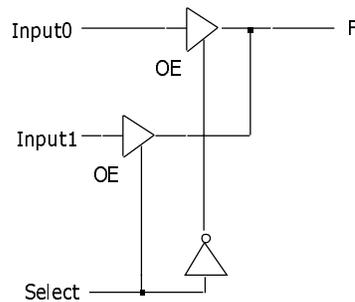


	In	OE	Out
non-inverting	X	0	Z
tri-state	0	1	0
buffer	1	1	1



Tri-state and multiplexing

- When using tri-state logic
 - (1) make sure never more than one "driver" for a wire at any one time (pulling high and low at the same time can severely damage circuits)
 - (2) make sure to only use value on wire when its being driven (using a floating value may cause failures)
- Using tri-state gates to implement an economical multiplexer



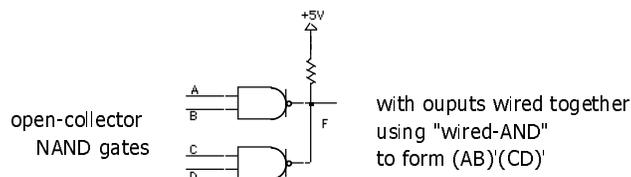
when Select is high
Input1 is connected to F

when Select is low
Input0 is connected to F

this is essentially a 2:1 mux

Open-collector gates and wired-AND

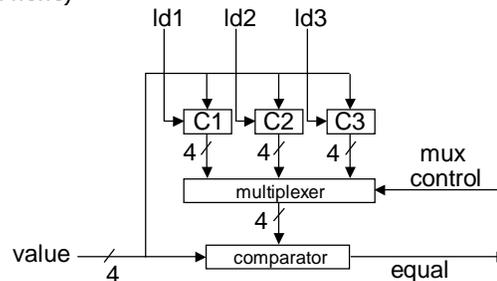
- Open collector: another way to connect gate outputs to the same wire
 - gate only has the ability to pull its output low
 - it cannot actively drive the wire high (default – pulled high through resistor)
- Wired-AND can be implemented with open collector logic
 - if A and B are "1", output is actively pulled low
 - if C and D are "1", output is actively pulled low
 - if one gate output is low and the other high, then low wins
 - if both gate outputs are "1", the wire value "floats", pulled high by resistor
 - low to high transition usually slower than it would have been with a gate pulling high
 - hence, the two NAND functions are ANDed together



with outputs wired together
using "wired-AND"
to form $(AB)(CD)$

Digital combination lock (new data-path)

- Decrease number of inputs
- Remove 3 code digits as inputs
 - use code registers
 - make them loadable from value
 - need 3 load signal inputs (net gain in input $(4*3)-3=9$)
 - could be done with 2 signals and decoder (ld1, ld2, ld3, load none)



Section summary

- FSM design
 - understanding the problem
 - generating state diagram
 - communicating state machines
- Four case studies
 - understand I/O behavior
 - draw diagrams
 - enumerate states for the "goal"
 - expand with error conditions
 - reuse states whenever possible