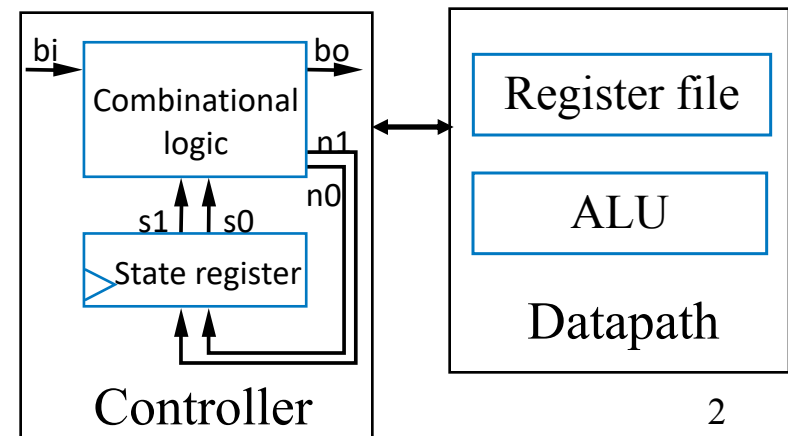
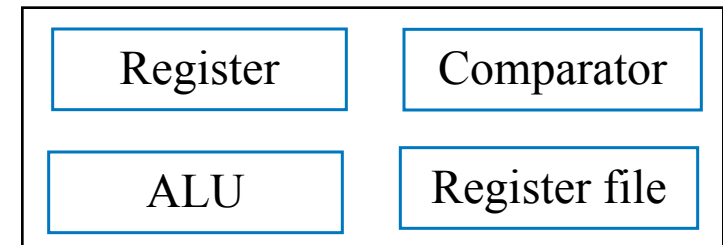
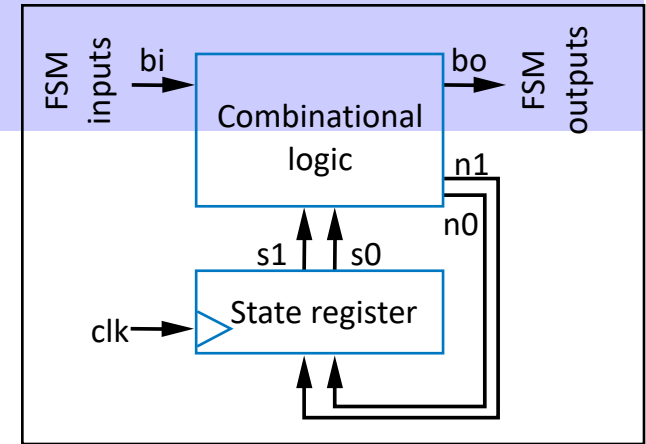


Topic 12

RTL Design

Introduction

- **Controllers (FSM)**
 - Describes behavior of circuits
 - Takes inputs, generates outputs
 - Implemented with state register and combinational logic
- **Datapath components**
 - Operations on data
 - Path that data flows through
 - Places data is stored
- **Digital Device**
 - Controller and datapath components working together
 - To implement an algorithm
 - Design on Register Transfer Level

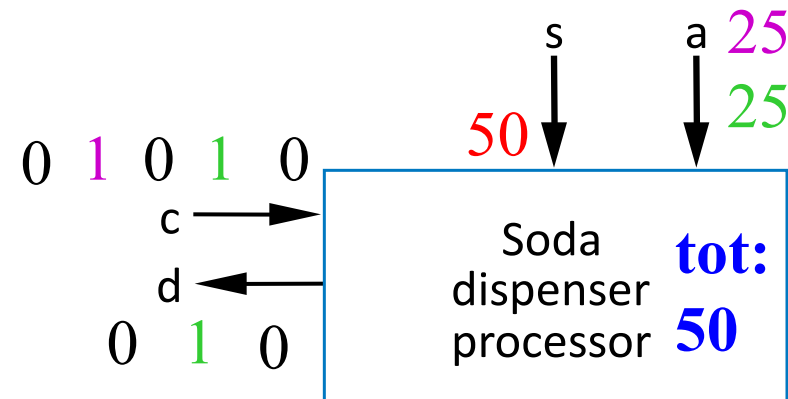
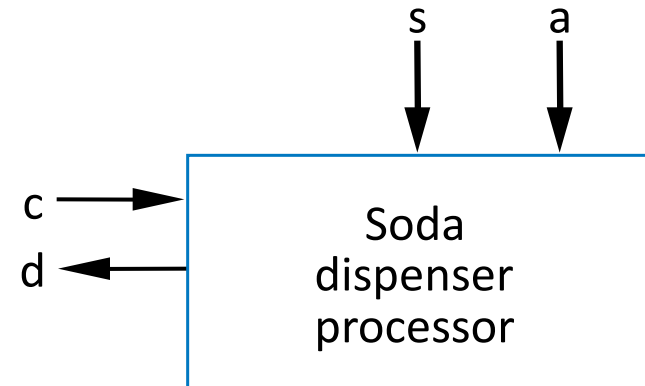


RTL Design Method

Step	Description
Step 1 <i>Capture a high-level state machine</i>	Describe the system's desired behavior as a high-level state machine. The state machine consists of states and transitions. The state machine is "high-level" because the transition conditions and the state actions are more than just Boolean operations on bit inputs and outputs.
Step 2 <i>Create a datapath</i>	Create a datapath to carry out the data operations of the high-level state machine.
Step 3 <i>Connect the datapath to a controller</i>	Connect the datapath to a controller block. Connect external Boolean inputs and outputs to the controller block.
Step 4 <i>Derive the controller's FSM</i>	Convert the high-level state machine to a finite-state machine (FSM) for the controller, by replacing data operations with setting and reading of control signals to and from the datapath.

Example: Vending Machine (Selling Soda)

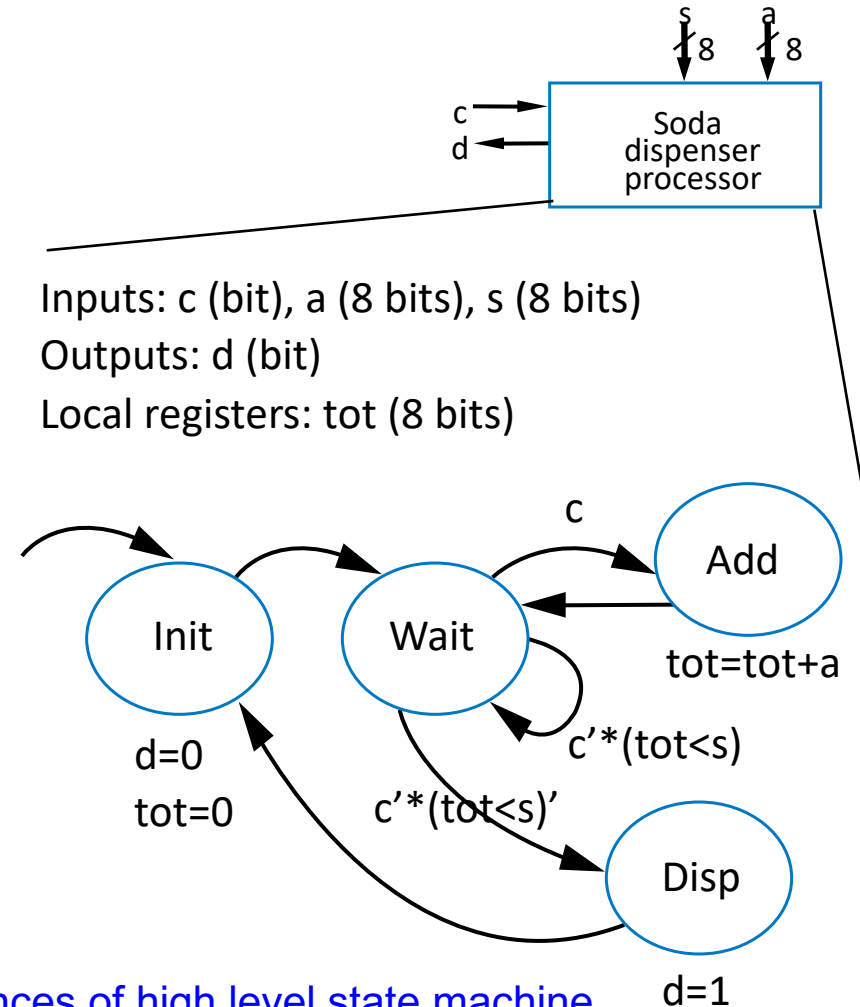
- Soda dispenser
 - c : 1-bit input, 1 when coin deposited
 - a : 8-bit input having value of deposited coin
 - s : 8-bit input having cost of a soda
 - d : 1-bit output, processor sets to 1 when total value of deposited coins equals or exceeds cost of a soda



How can we precisely describe this processor's behavior?

Example: Step 1 – Capture High-Level State Machine

- Declare local register *tot*
- **Init** state: Set $d=0$, $tot=0$
- **Wait** state: wait for coin
 - If see coin, go to **Add** state
- **Add** state: Update total value:
 $tot = tot + a$
 - Remember, *a* is present coin's value
 - Go back to **Wait** state
- In **Wait** state, if $tot \geq s$, go to **Disp** state
- **Disp** state: Set $d=1$ (dispense soda)
 - Return to **Init** state



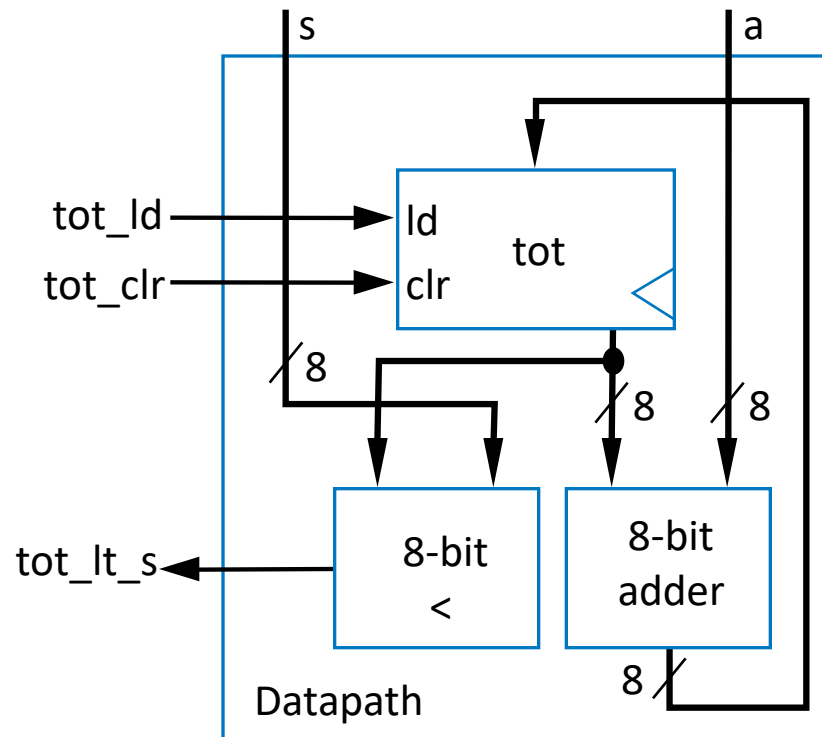
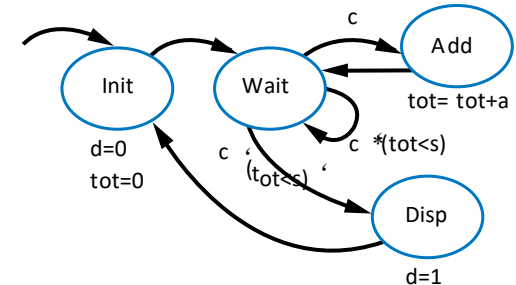
Differences of high level state machine

- Data types beyond just bits
- Arithmetic operations in states

Example: Step 2 – Create Datapath

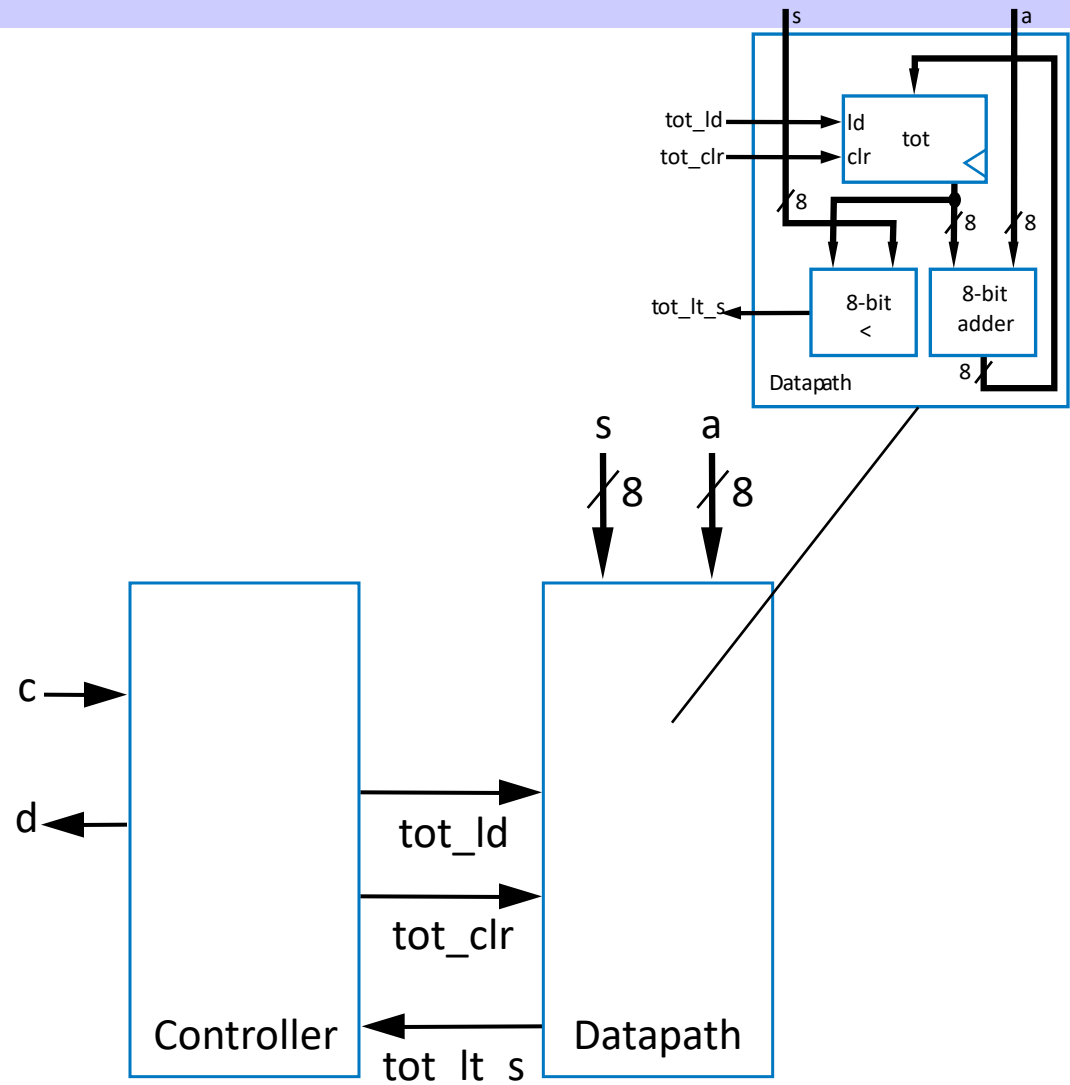
Inputs : c (bit), a(8 bits) , s (8 bits)
 Outputs : d (bit)
 Local registers : tot (8 bits)

- Need *tot* register
 - To hold value between states
- Need 8-bit comparator
 - To compare *s* and *tot*
- Need 8-bit adder
 - To perform $tot = tot + a$
- Create control input/outputs for datapath components
 - Give them names



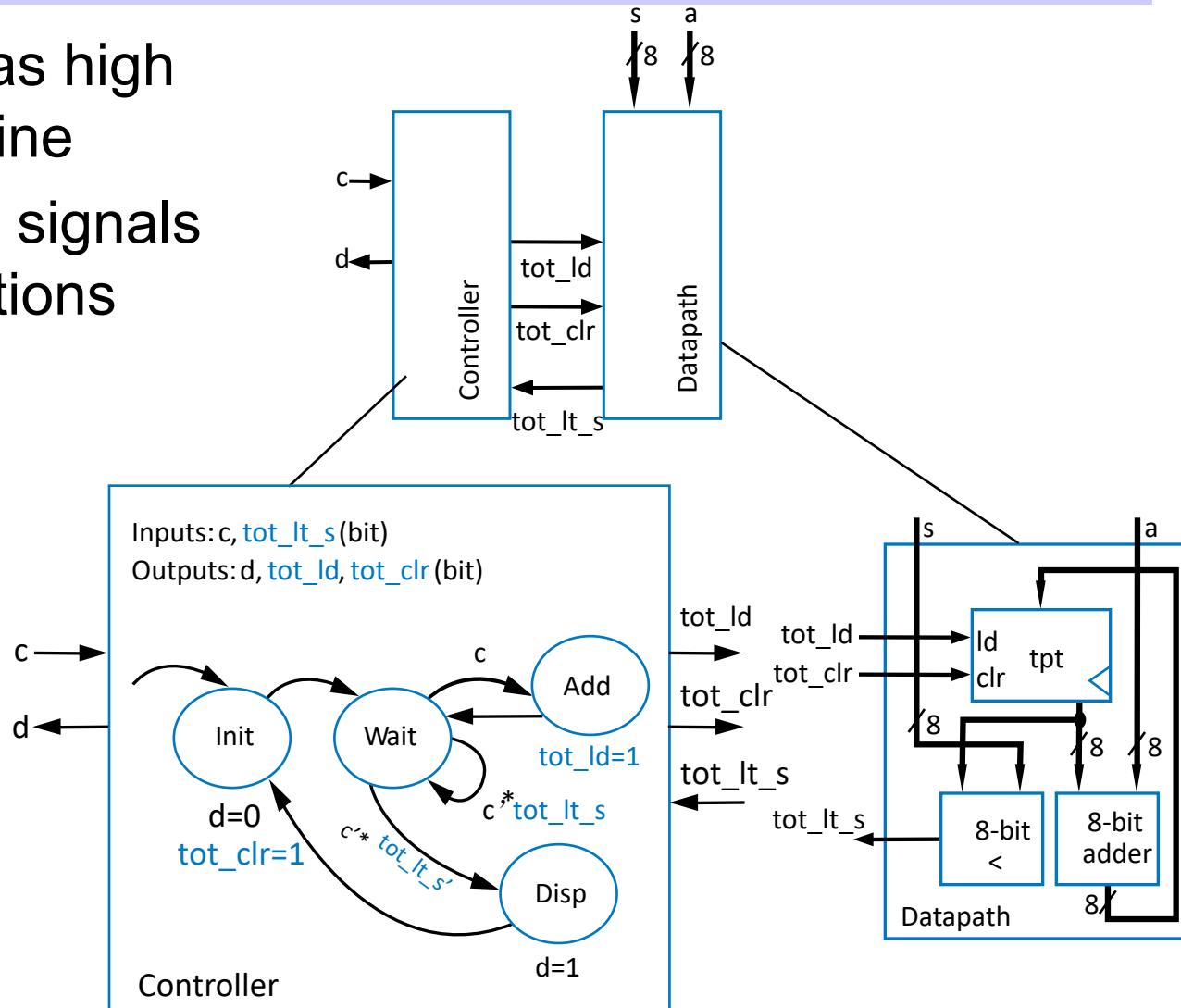
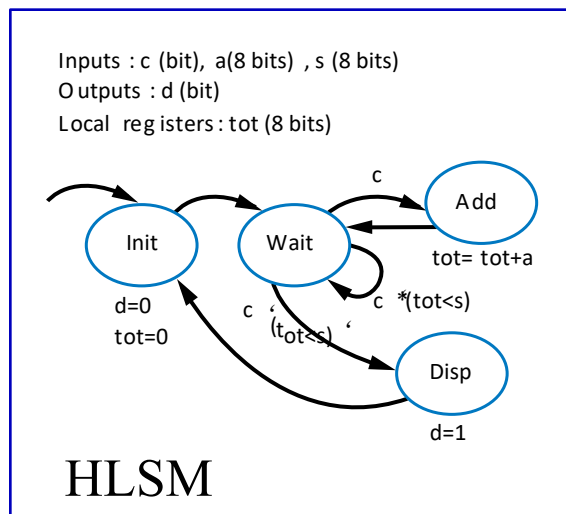
Example: Step 3 – Connect Datapath to a Controller

- Identify controller's inputs
 - c (coin detected)
 - comparator's output, which we named tot_lt_s
- Identify controller's outputs
 - d (dispense soda)
 - Signals to control datapath: tot_ld and tot_clr



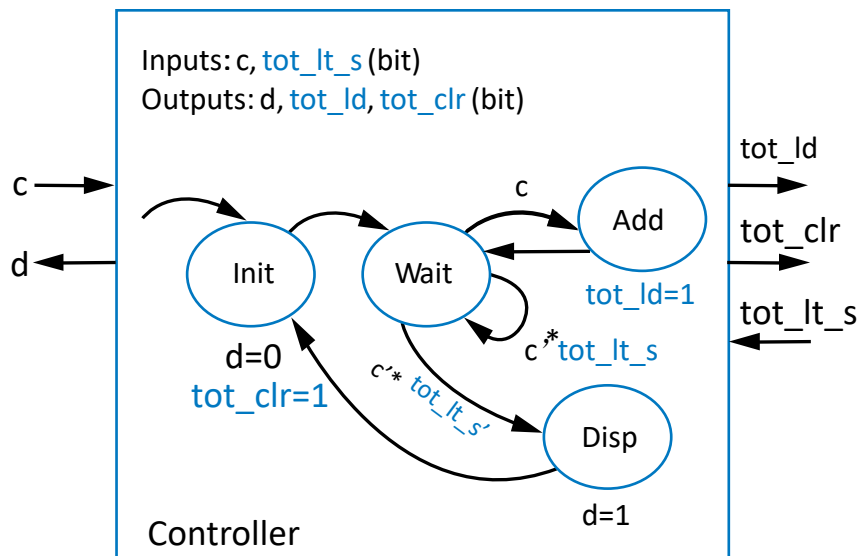
Example: Step 4 – Derive the Controller's FSM

- Same structure as high level state machine
- But deal with I/O signals instead of operations



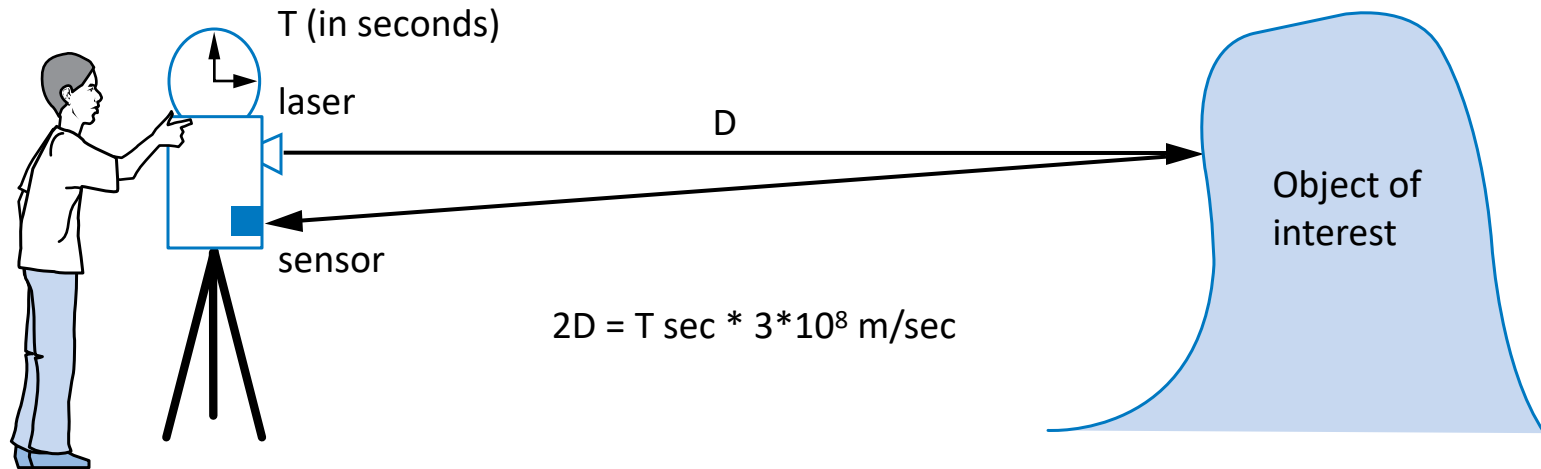
Example: Completing the Design

- Implement the FSM as a state register and logic



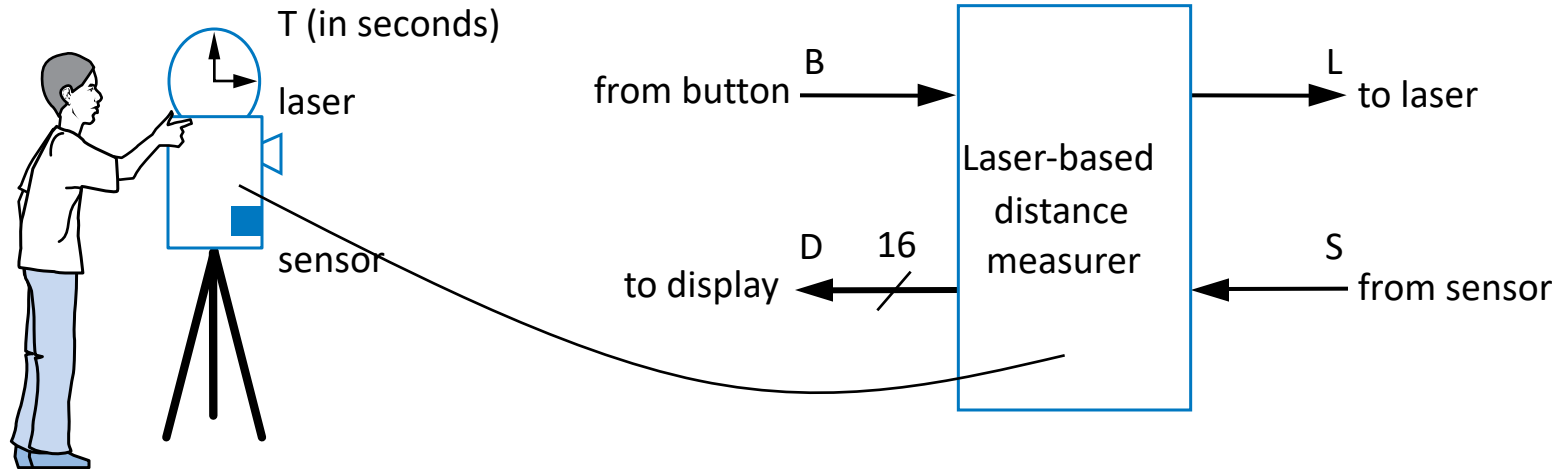
	s1	s0	c	tot_lt_s	n1	n0	d	tot_ld	tot_clr
Init	0	0	0	0	0	1	0	0	1
	0	0	0	1	0	1	0	0	1
	0	0	1	0	0	1	0	0	1
	0	0	1	1	0	1	0	0	1
Wait	0	1	0	0	1	1	0	0	0
	0	1	0	1	0	1	0	0	0
	0	1	1	0	1	0	0	0	0
	0	1	1	1	1	0	0	0	0
Add	1	0	0	0	0	1	0	1	0
					
Disp	1	1	0	0	0	0	1	0	0
					

Example: Laser-Based Distance Measurer



- Laser-based distance measurement – pulse laser, measure time T to sense reflection
 - Laser light travels at speed of light, $3 * 10^8 \text{ m/sec}$
 - Distance is thus $D = T \text{ sec} * 3 * 10^8 \text{ m/sec} / 2$

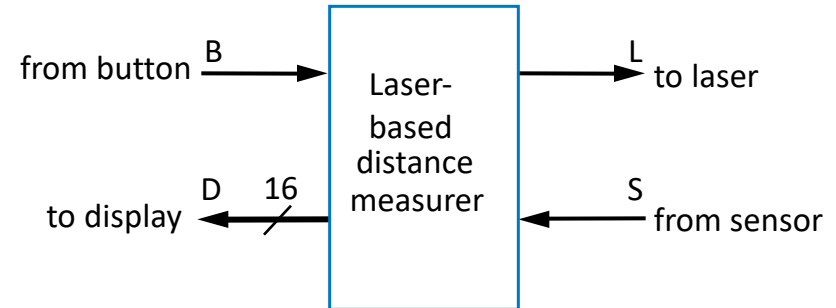
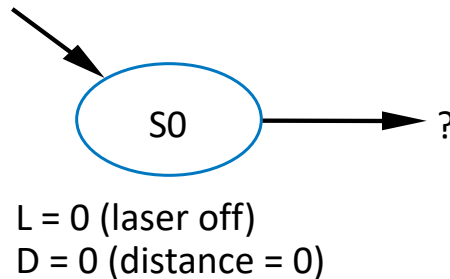
Example: Laser-Based Distance Measurer



- Inputs/outputs
 - B : 1-bit input, from button to begin measurement
 - L : 1-bit output, activates laser
 - S : 1-bit input, senses laser reflection
 - D : 16-bit output, displays computed distance

Step 1: Capture High-Level State Machine

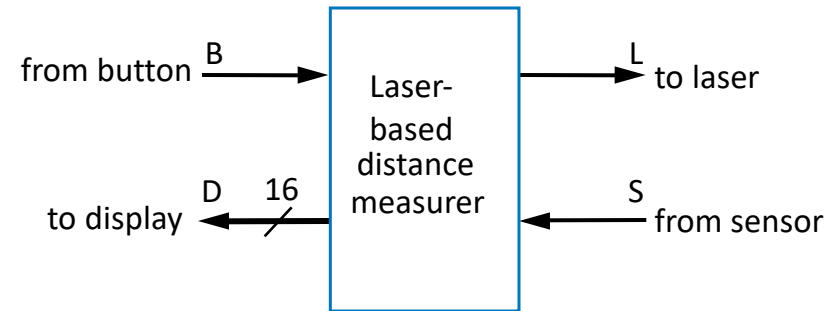
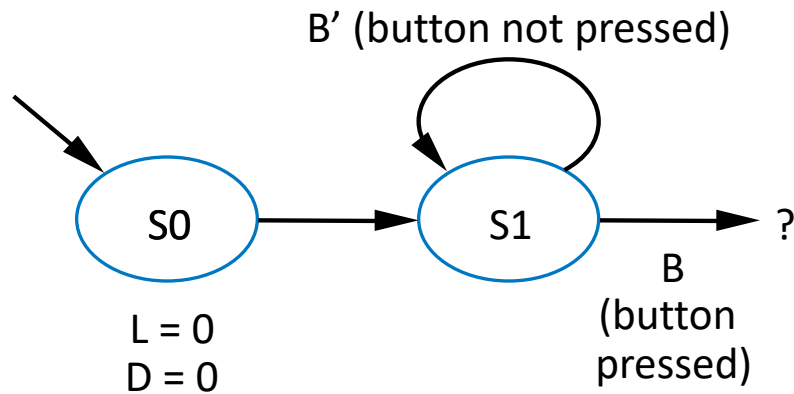
Inputs: B, S (1 bit each)
Outputs: L (bit), D (16 bits)



- Step 1: Create high-level state machine
 - Begin by declaring inputs and outputs
 - Create initial state, name it **S0**
 - Initialize laser to off (L=0)
 - Initialize displayed distance to 0 (D=0)

Step 1: Capture High-Level State Machine

Inputs: B, S (1 bit each)
Outputs: L (bit), D (16 bits)

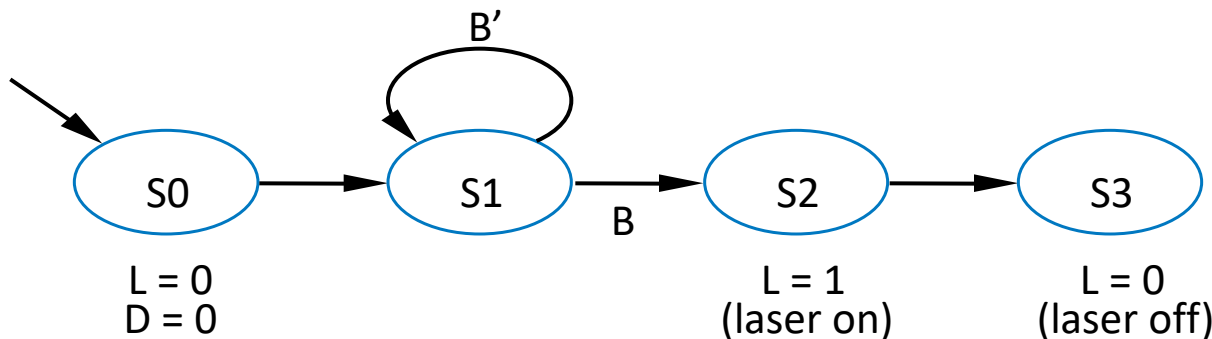
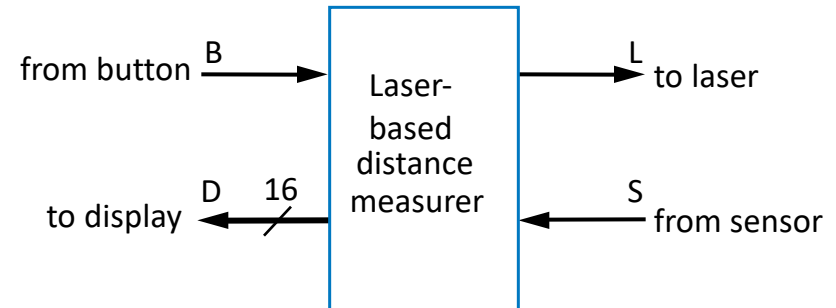


- Add another state, call **S1**, that waits for a button press
 - B' – stay in **S1**, keep waiting
 - B – go to a new state **S2**

Q: What should S2 do? A: Turn on the laser

Step 1: Capture High-Level State Machine

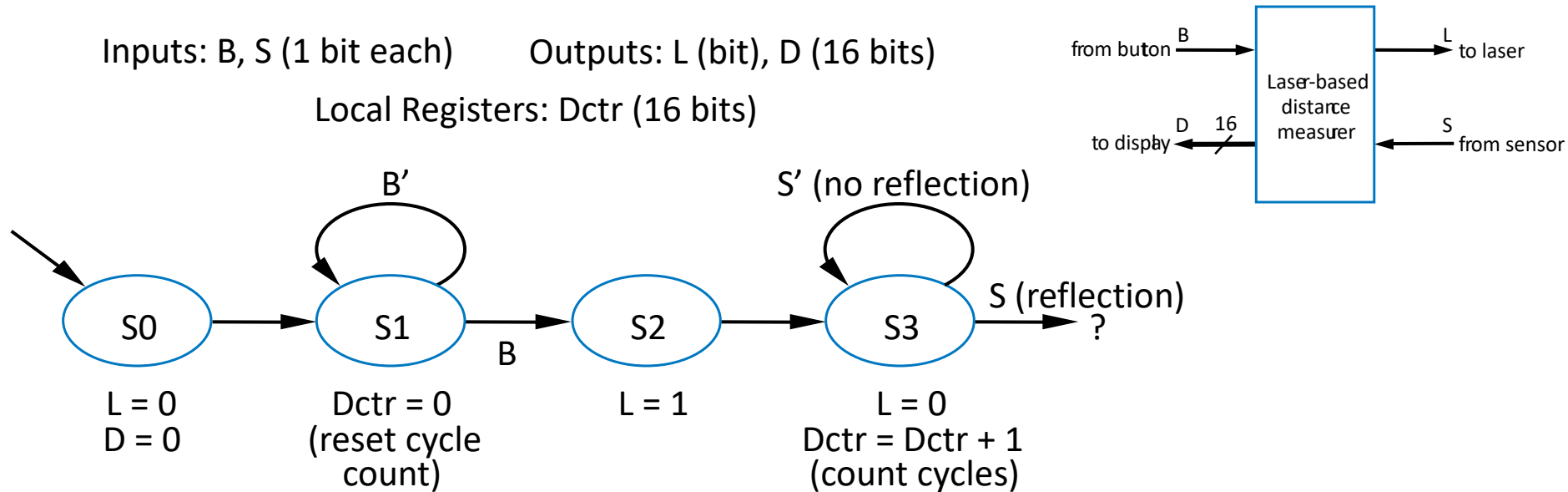
Inputs: B, S (1 bit each)
Outputs: L (bit), D (16 bits)



- Add a state **S2** that turns on the laser (L=1)
- Then turn off laser (L=0) in a state **S3**

Q: What do next? A: Start timer, wait to sense reflection

Step 1: Capture High-Level State Machine

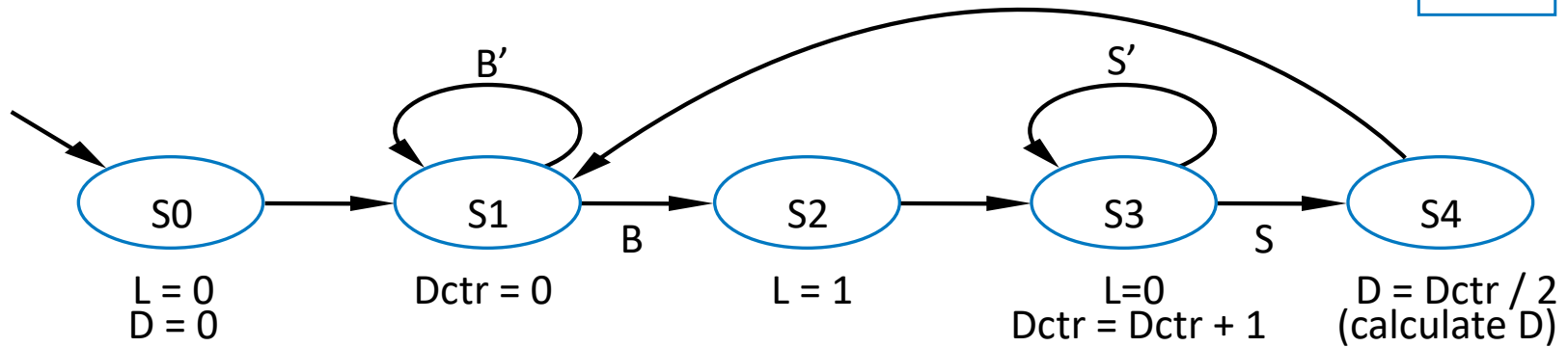
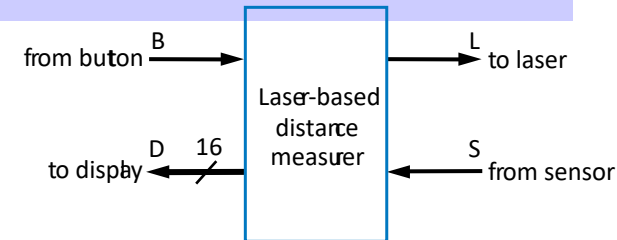


- Stay in **S3** until sense reflection (S)
- To measure time, count cycles for which we are in **S3**
 - To count, declare local register *Dctr*
 - Increment *Dctr* each cycle in **S3**
 - Initialize *Dctr* to 0 in **S1**. **S2** would have been O.K. too

Q: What do next? A: Stop timer, calculate distance

Step 1: Capture High-Level State Machine

Inputs: B, S (1 bit each) Outputs: L (bit), D (16 bits)
Local Registers: Dctr (16 bits)

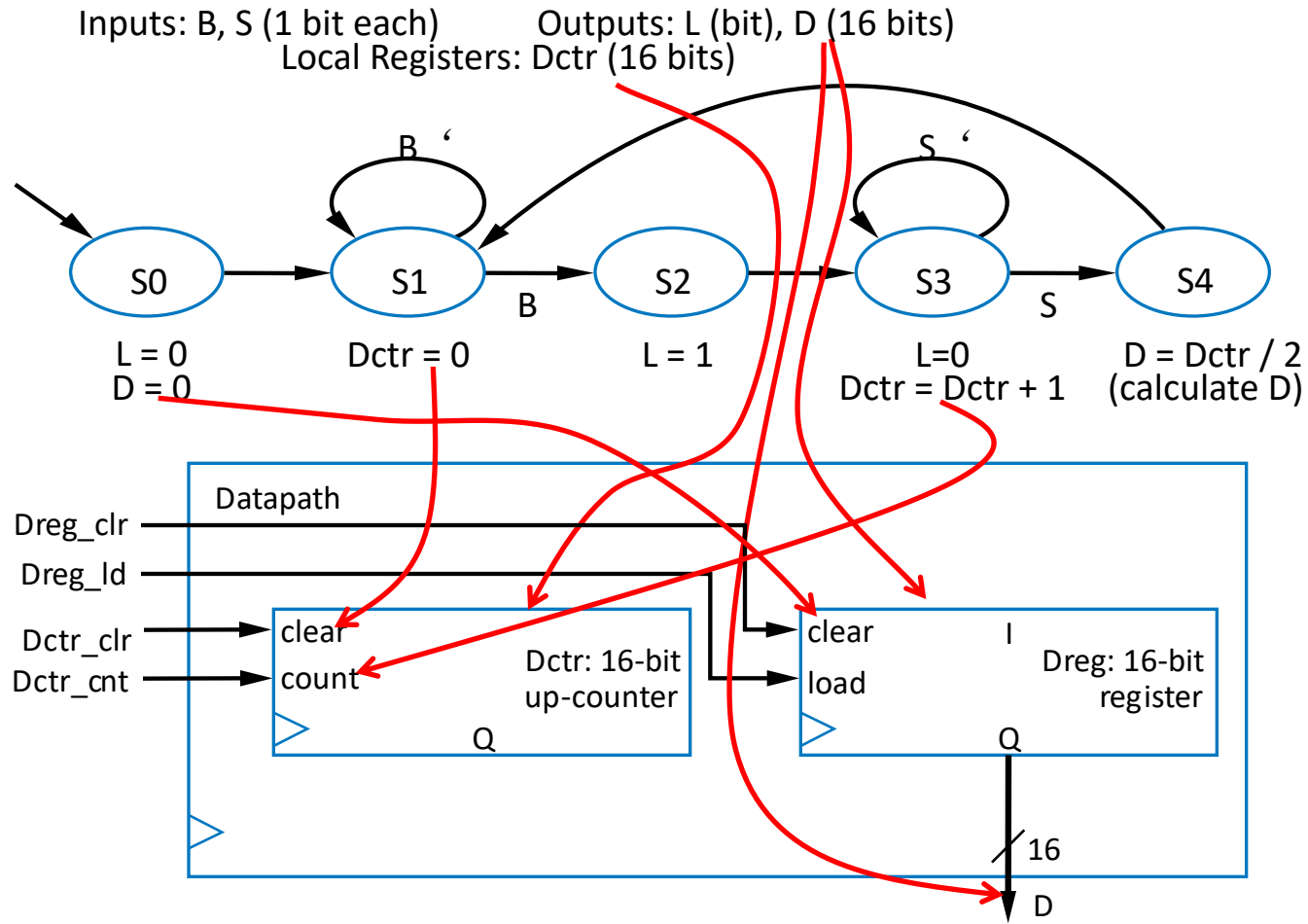


- Once reflection detected (S), go to new state **S4**
 - Calculate distance
 - Assuming clock frequency is 3×10^8 , *Dctr* holds number of meters, so $D = Dctr / 2$
- After **S4**, go back to **S1** to wait for button again

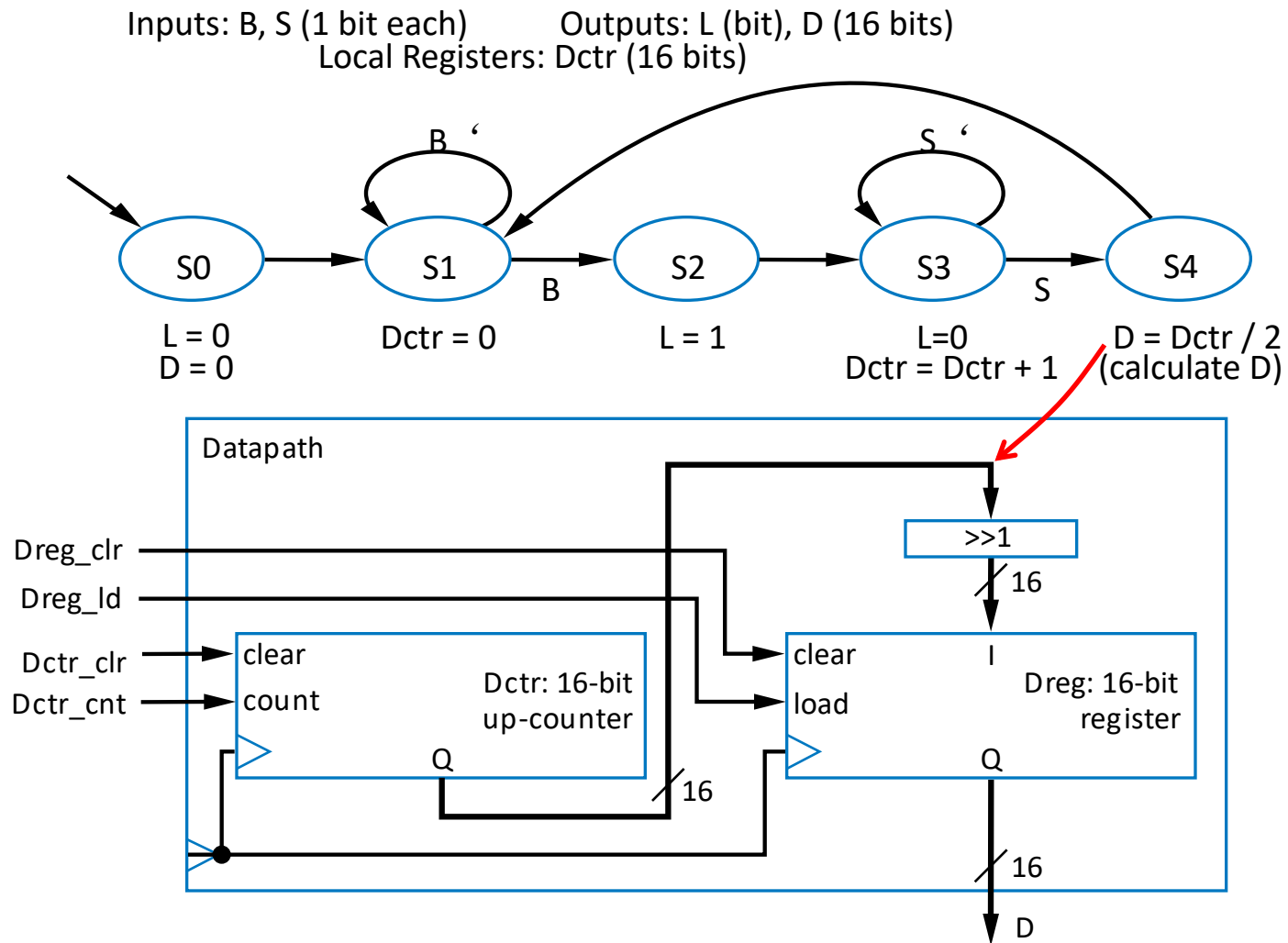
Step 2: Create a Datapath

- Datapath must
 - Implement data storage
 - Implement data computations
- Look at high-level state machine, instantiate required components

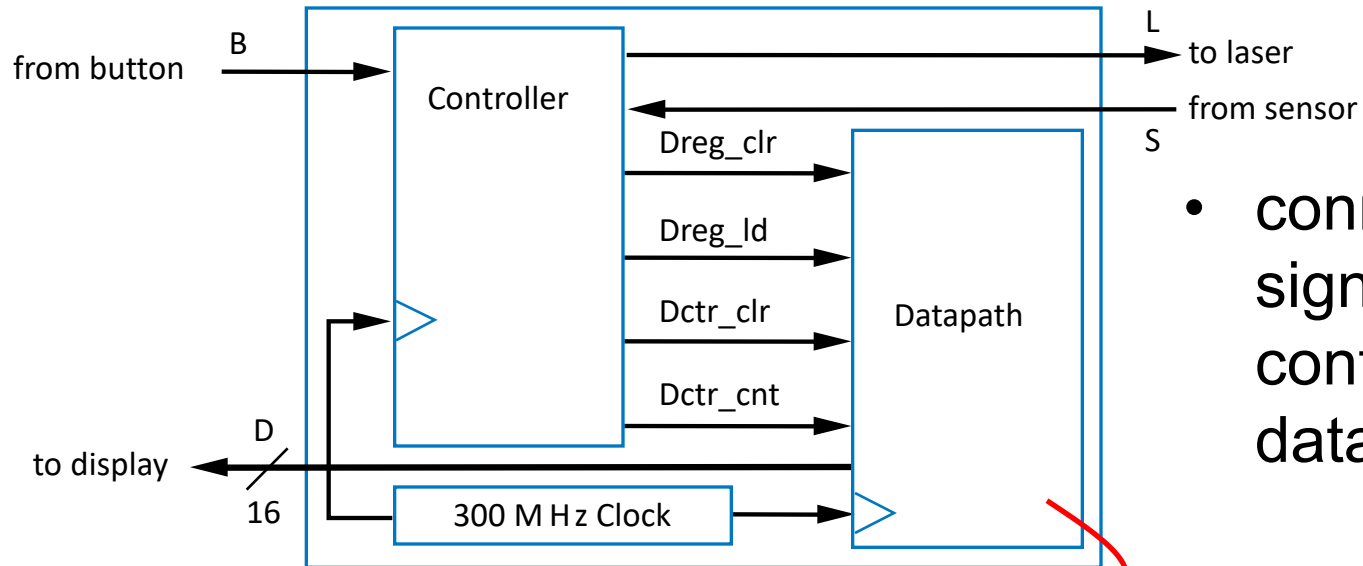
Step 2: Create a Datapath



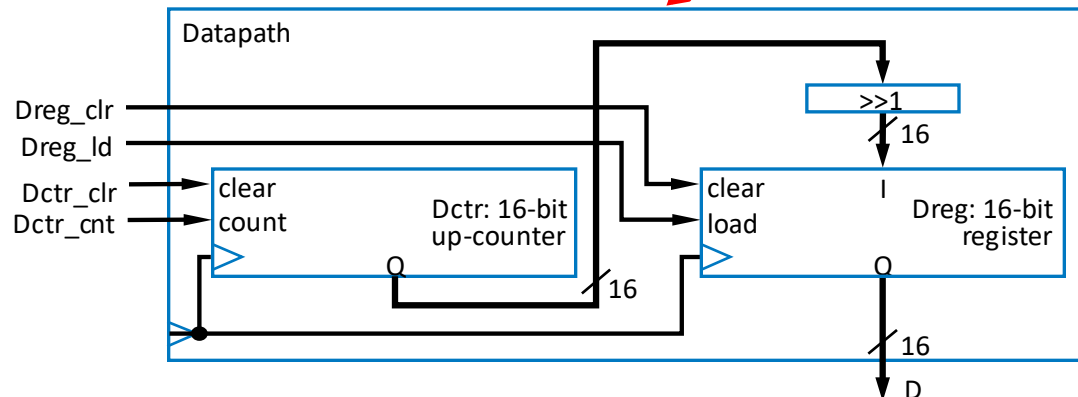
Step 2: Create a Datapath



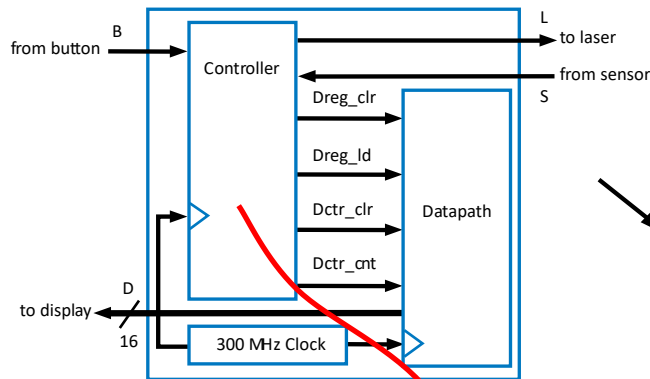
Step 3: Connecting the Datapath to a Controller



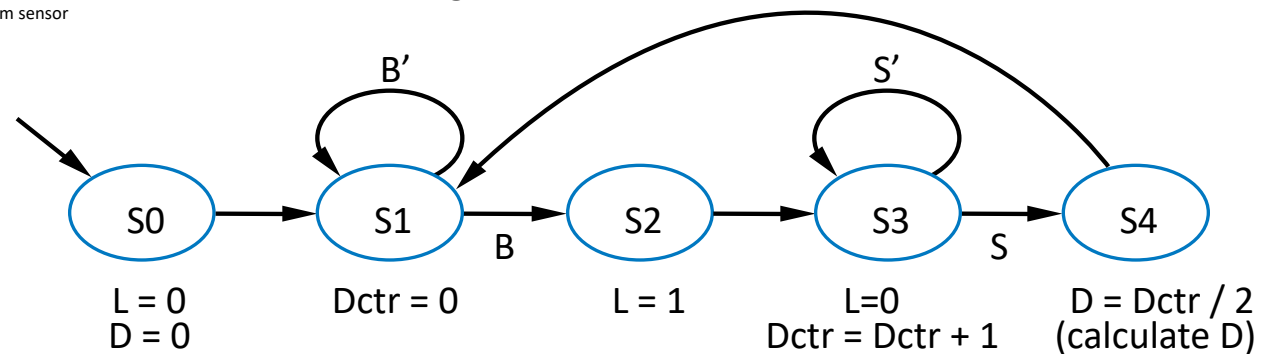
- connect all control signals between controller and datapath



Step 4: Deriving the Controller's FSM

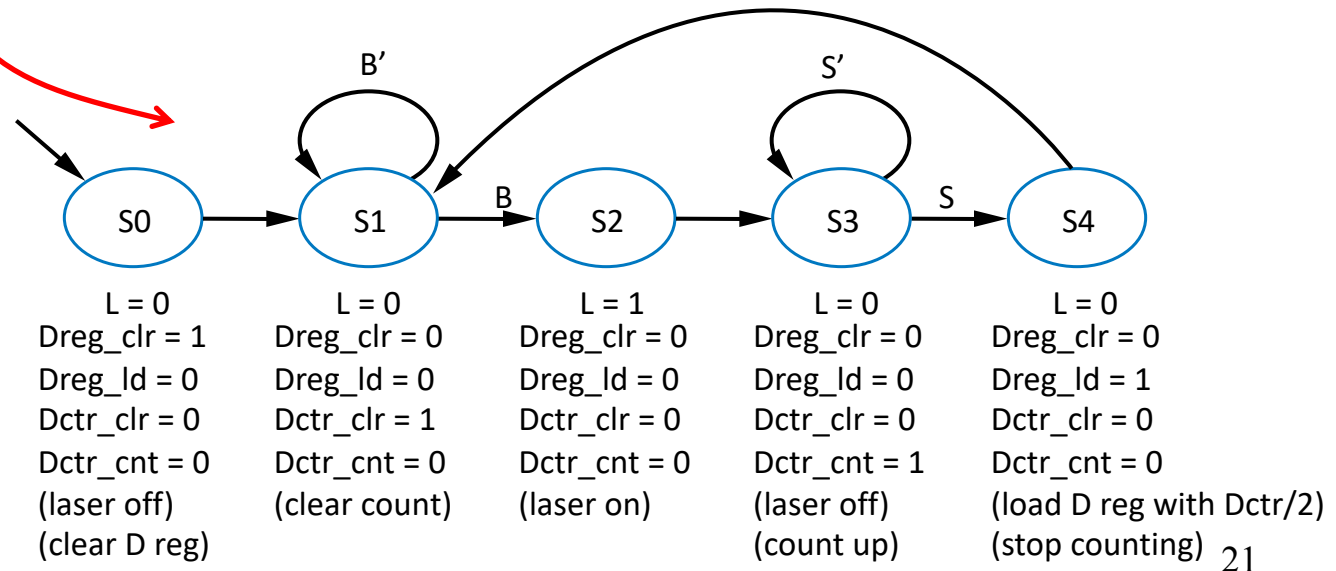


Inputs: B, S (1 bit each) Outputs: L (bit), D (16 bits)
Local Registers: Dctr (16 bits)

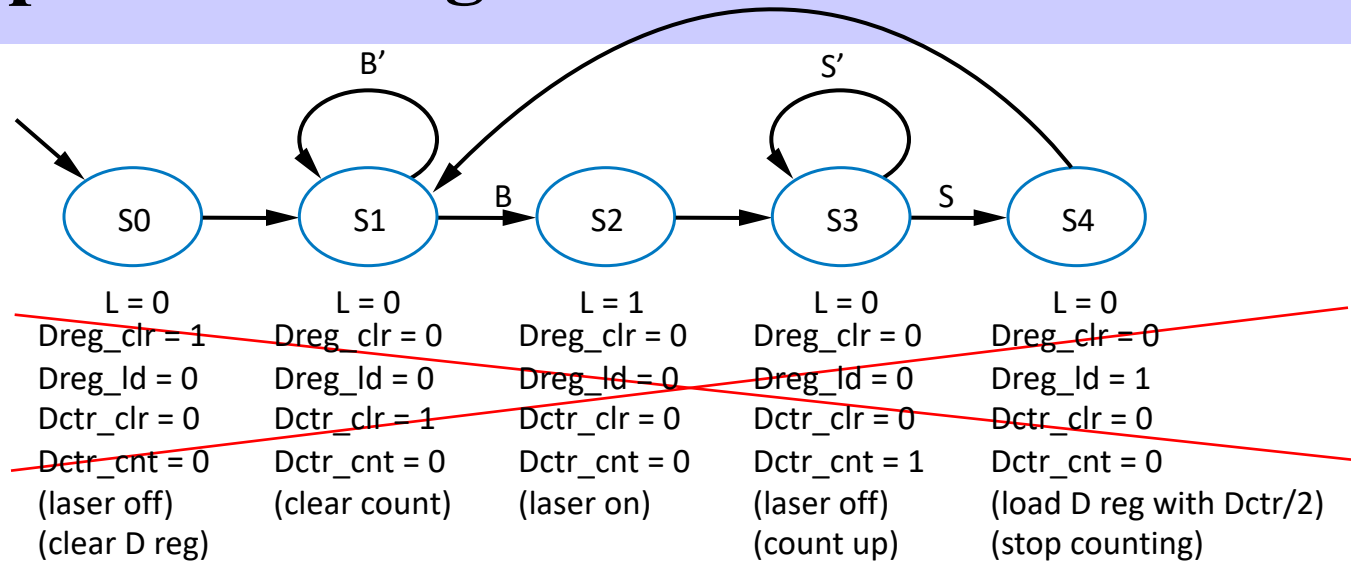


- Replace data operations by bit operations using datapath

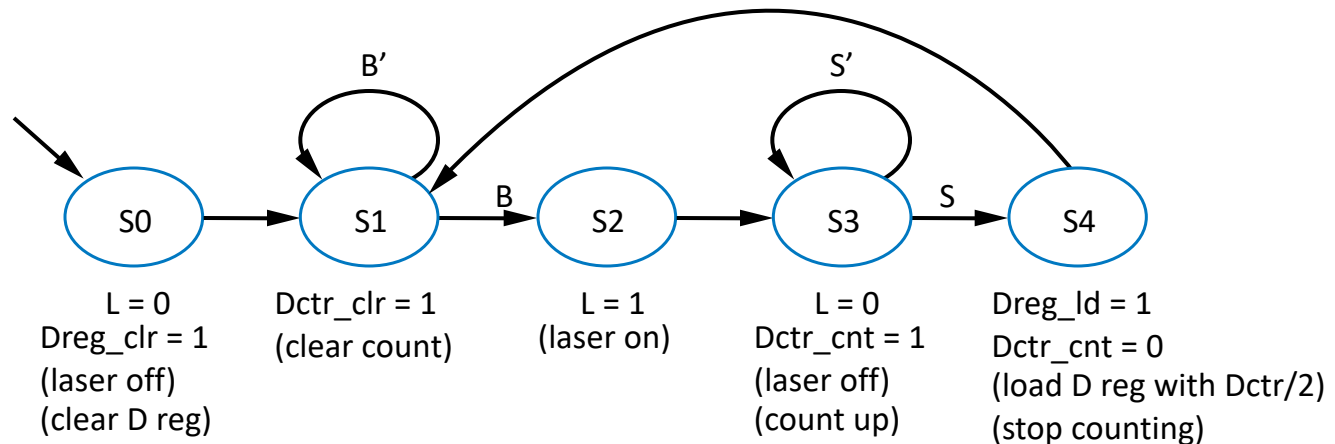
Inputs: B, S
Outputs: L, Dreg_clr, Dreg_ld, Dctr_clr, Dctr_cnt



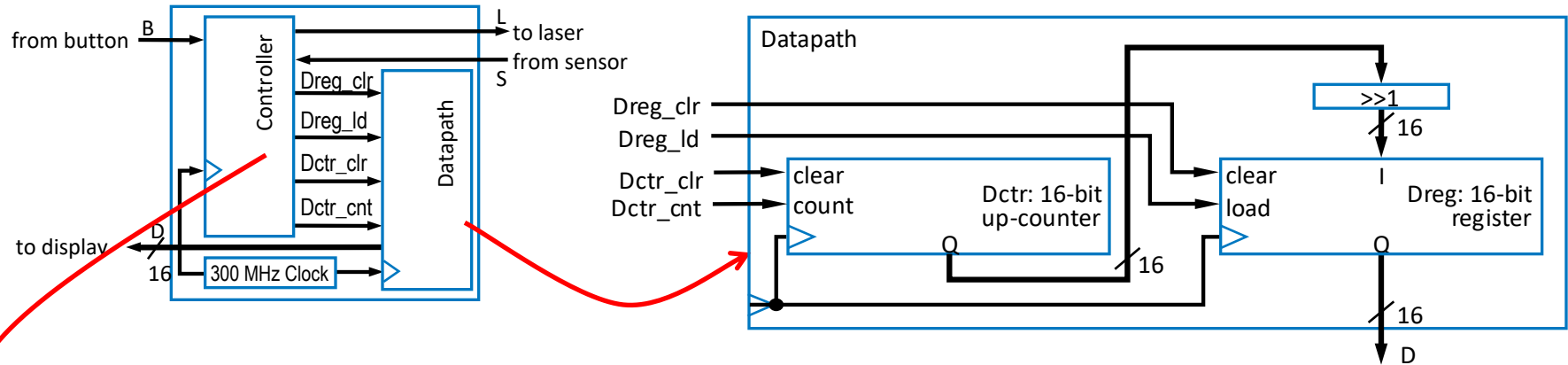
Step 4: Deriving the Controller's FSM



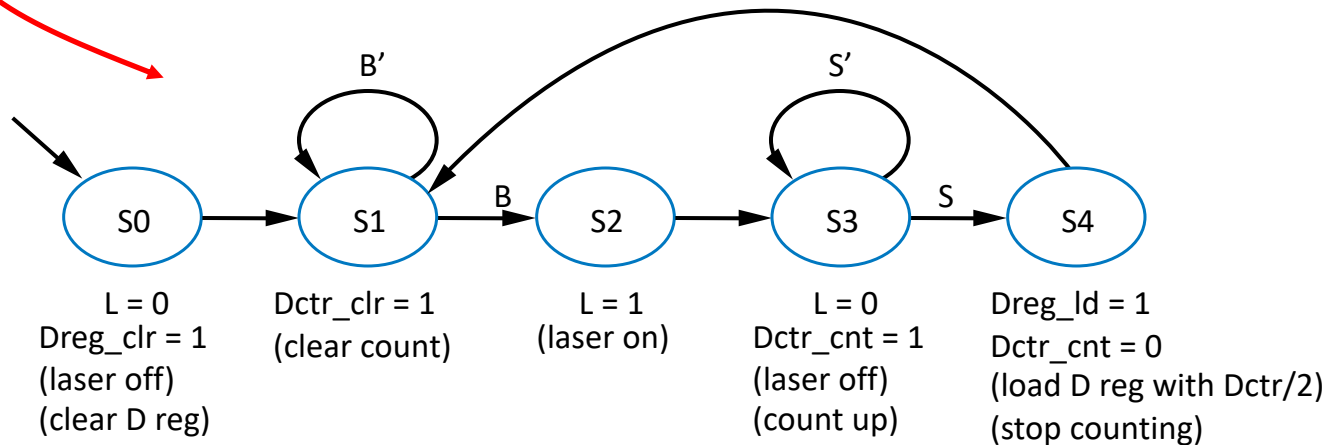
Inputs: B, S Outputs: L, Dreg_clr, Dreg_ld, Dctr_clr, Dctr_cnt



Step 4: Deriving the Controller's FSM

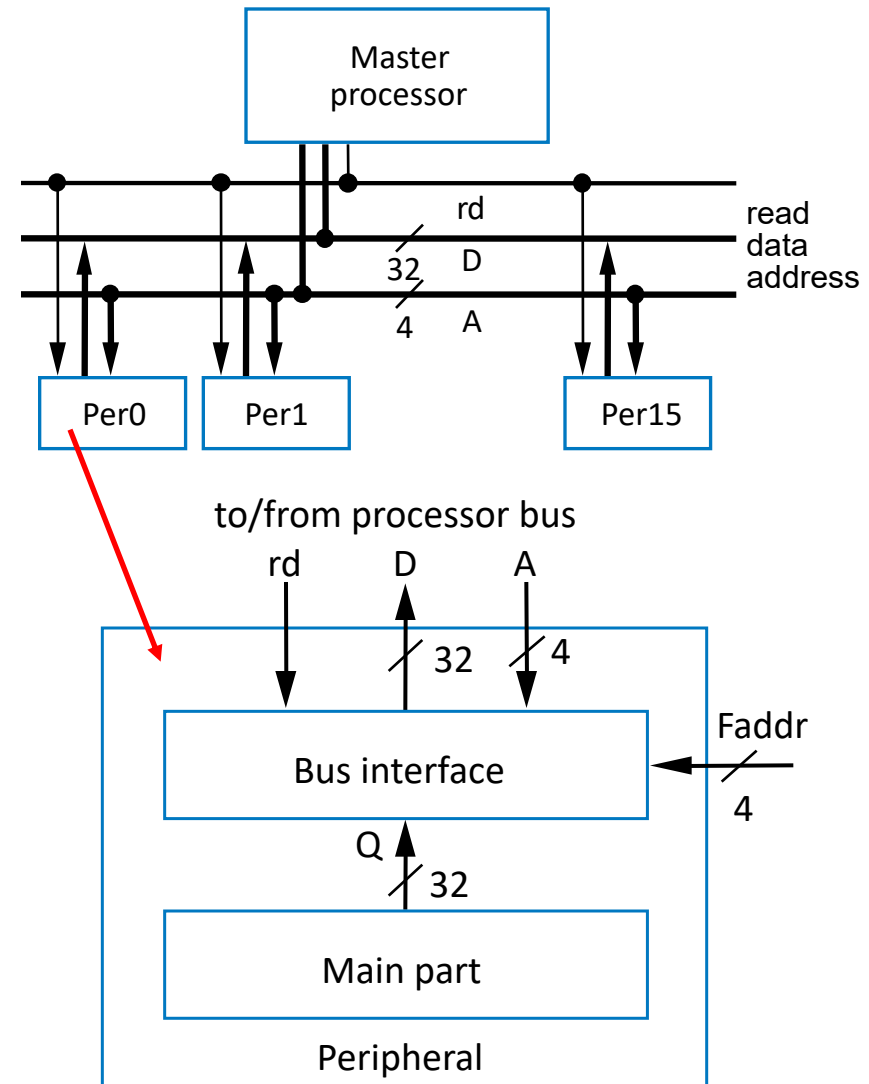


Inputs: B, S Outputs: L, Dreg_clr, Dreg_ld, Dctr_clr, Dctr_cnt

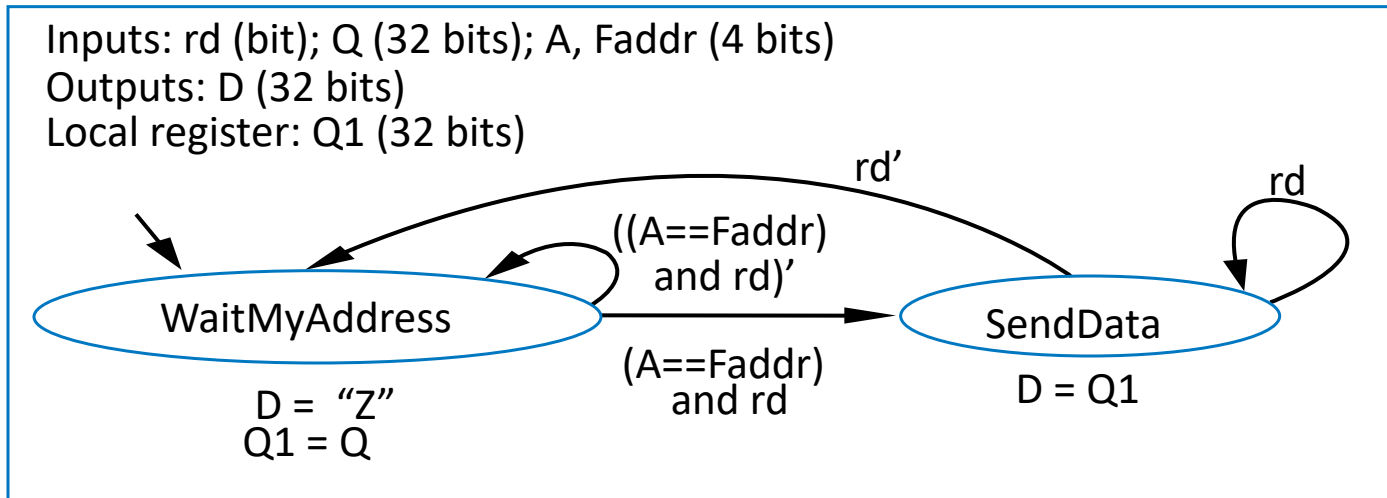


RTL Example: Bus Interface

- Example: **Bus interface**
 - Master processor can read register from any peripheral
 - Each register has unique 4-bit address
 - Assume 1 register/peripheral
 - Sets $rd=1$, $A=address$
 - Appropriate peripheral places register data on 32-bit D lines
 - Peripheral's address provided on $Faddr$ inputs (maybe from DIP switches, or another register)

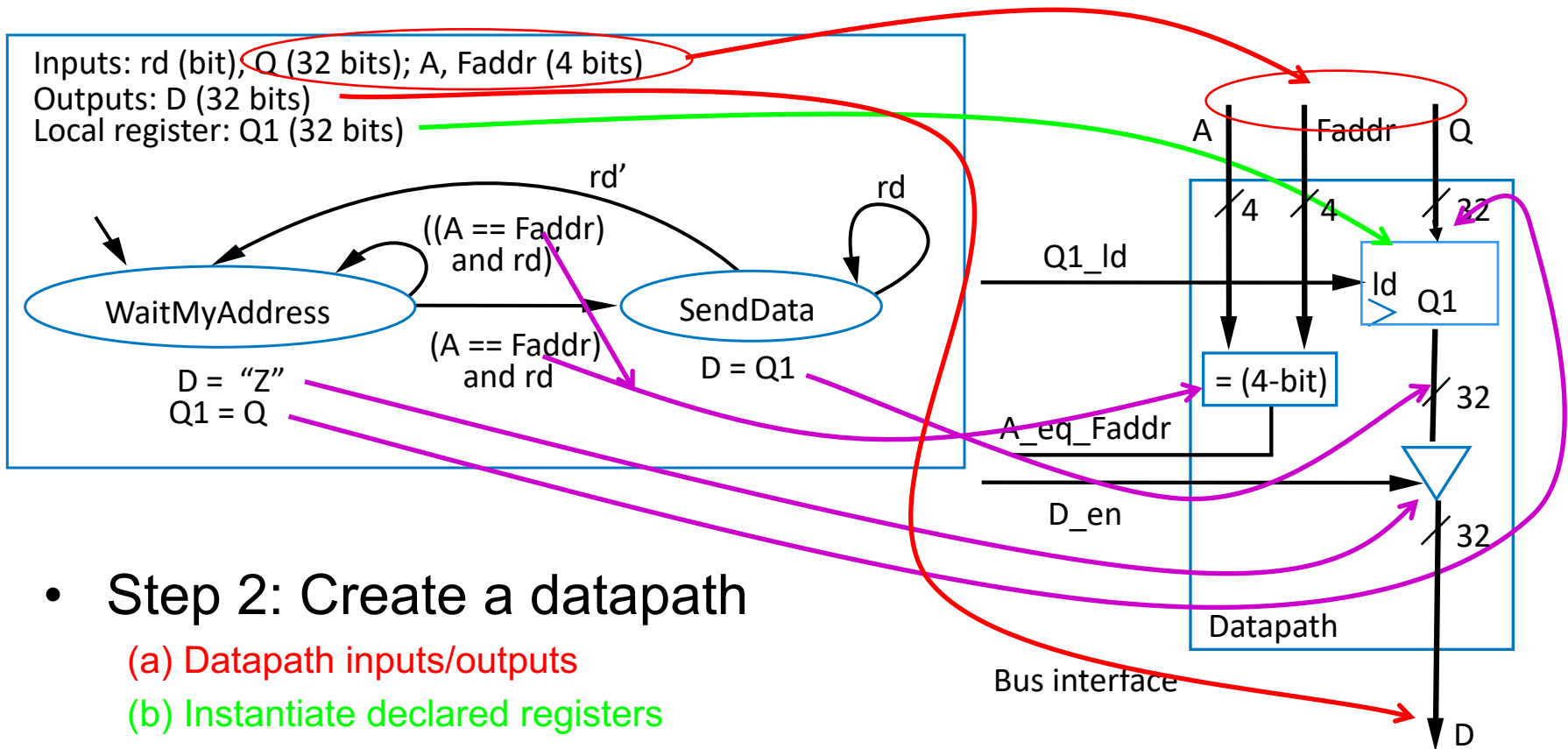


RTL Example: Bus Interface



- Step 1: Create high-level state machine
 - State **WaitMyAddress**
 - Output “nothing” (“Z”) on D , store peripheral’s register value Q into local register $Q1$
 - Wait until this peripheral’s address is seen ($A == Faddr$) and $rd = 1$
 - State **SendData**
 - Output $Q1$ onto D , wait for $rd = 0$ (meaning main processor is done reading the D lines)

RTL Example: Bus Interface



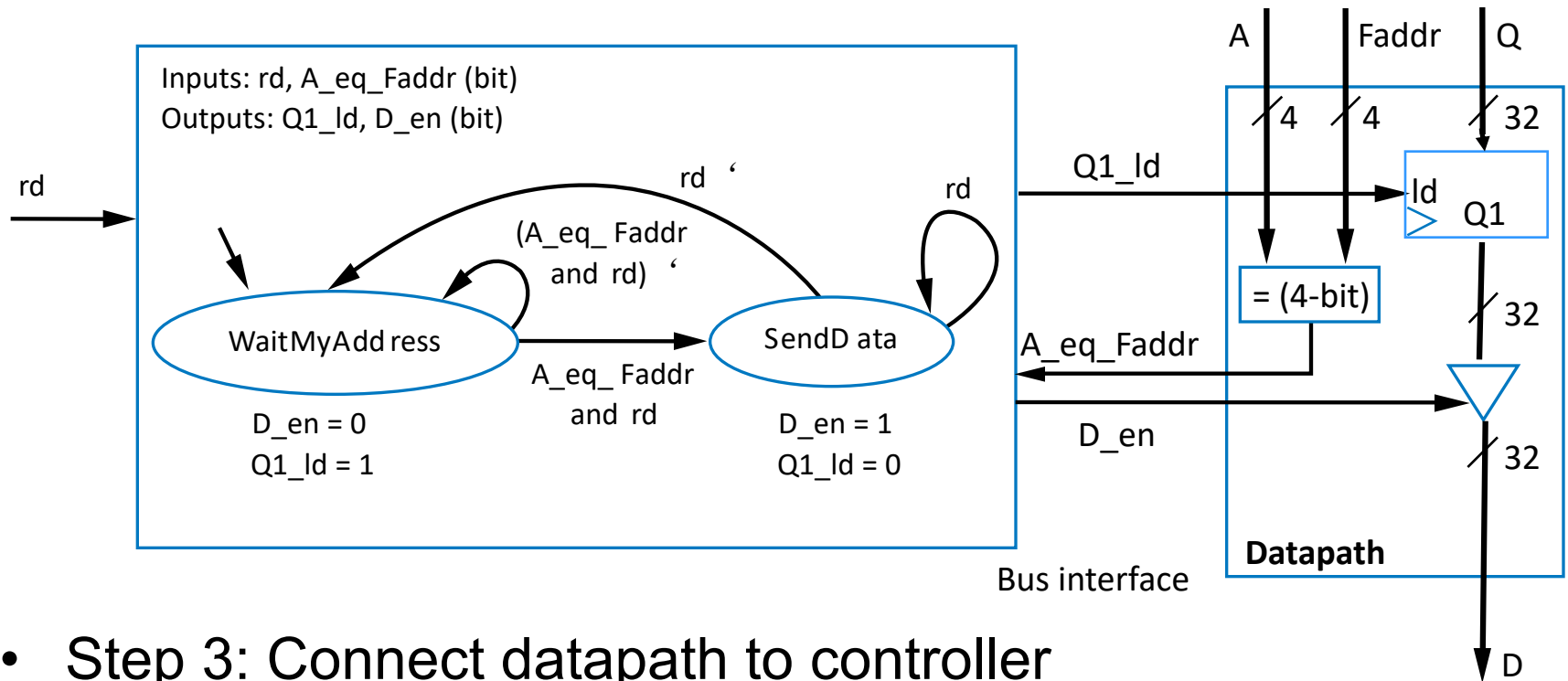
- Step 2: Create a datapath

- (a) Datapath inputs/outputs

- (b) Instantiate declared registers

- (c) Instantiate datapath components and connections

RTL Example: Bus Interface

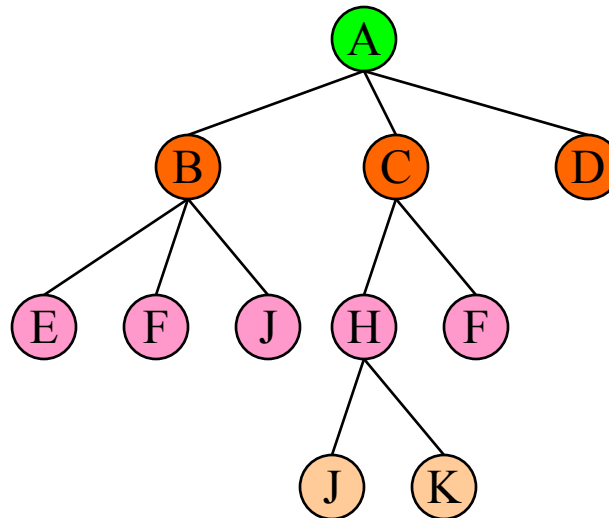


- Step 3: Connect datapath to controller
- Step 4: Derive controller's FSM

Handle the Complexity with Hierarchical Design

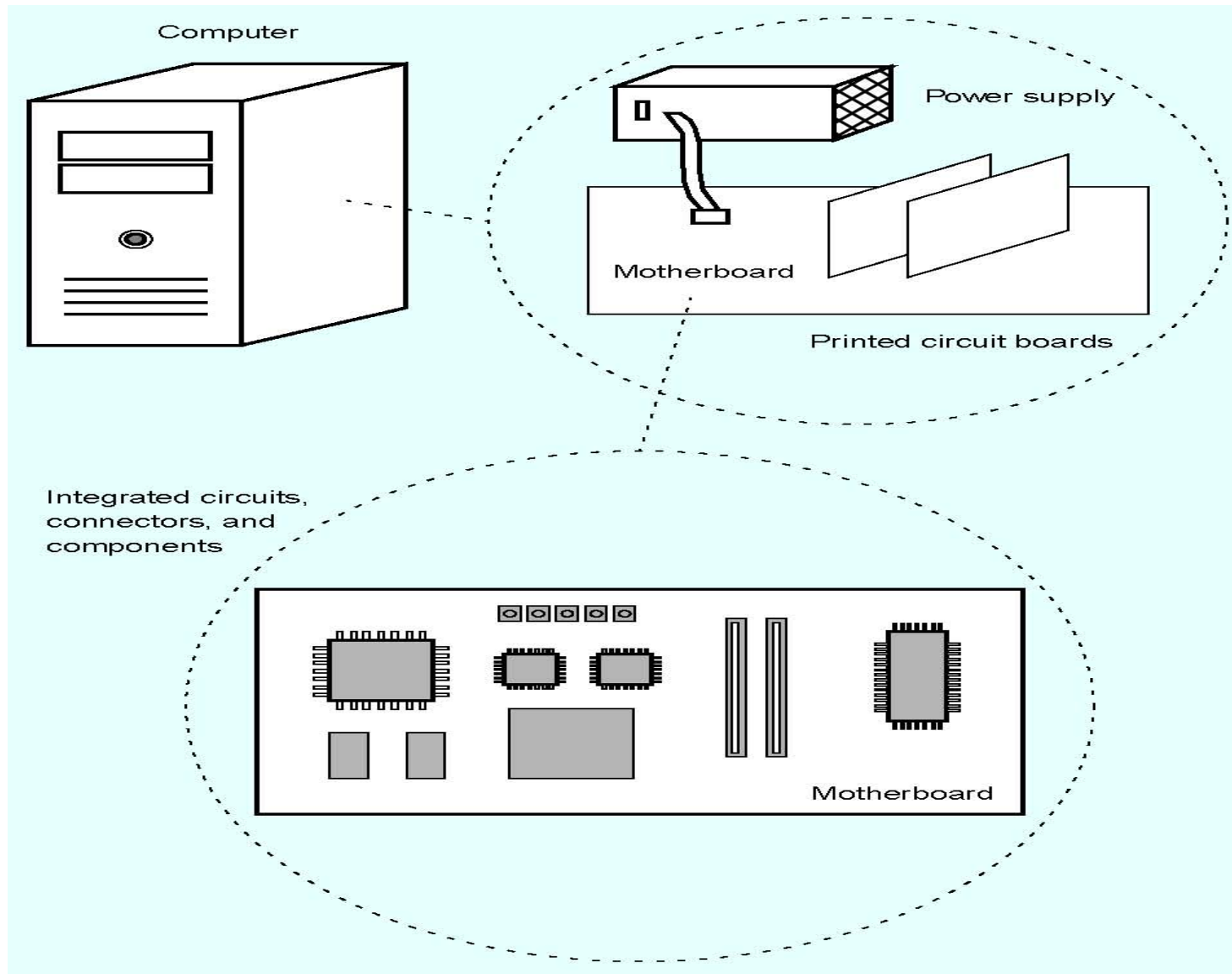
- Hierarchical design structure at different levels of abstraction
- Levels of abstraction: hiding the details in lower levels

- Hide details
- Reuse subsystems

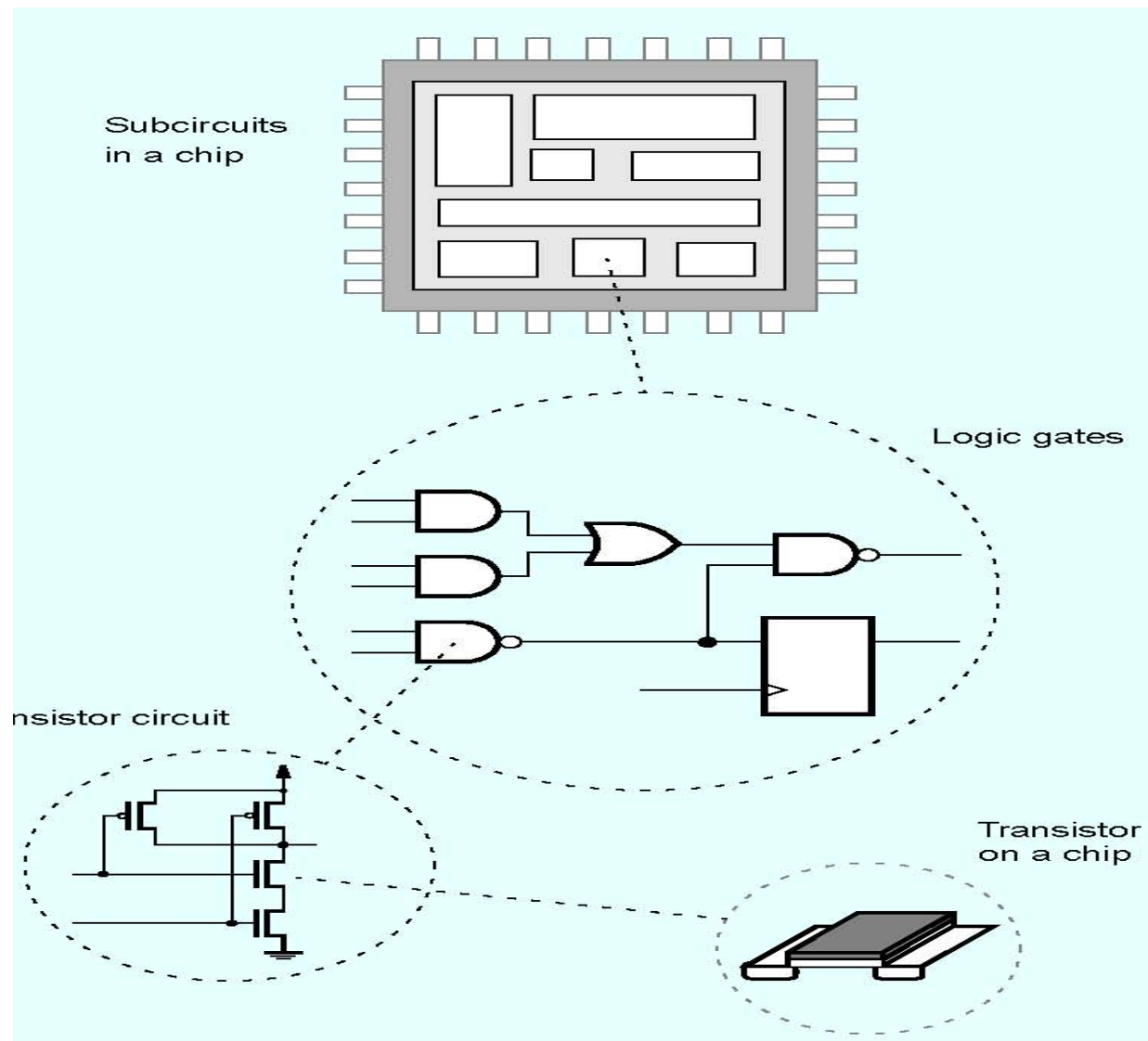


Hierarchical Structure of a Design

Hierarchical Digital System



Hierarchical Digital System



Pacemaker

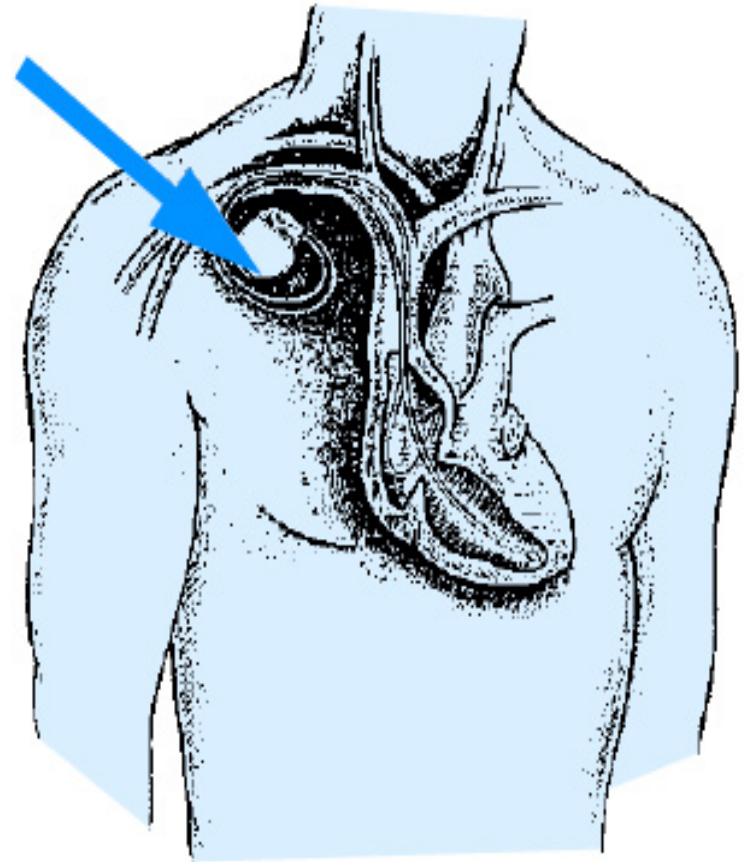
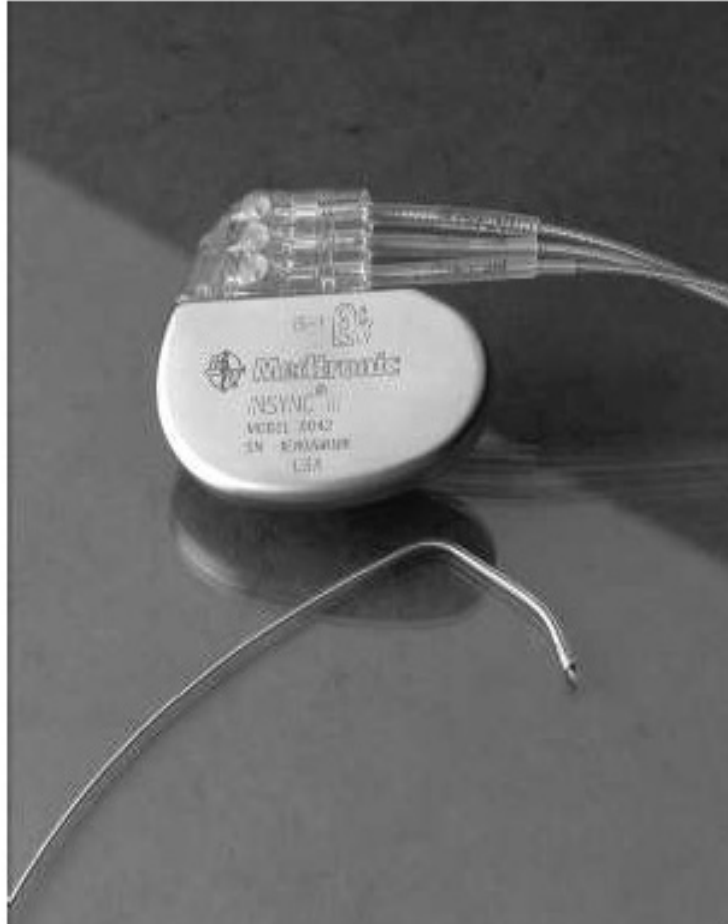
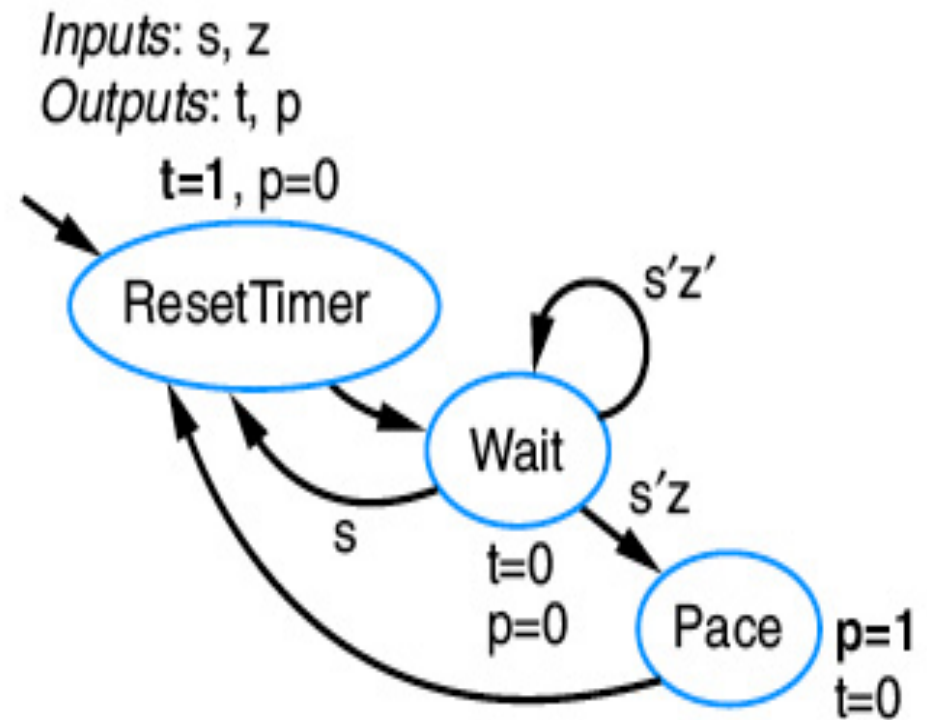
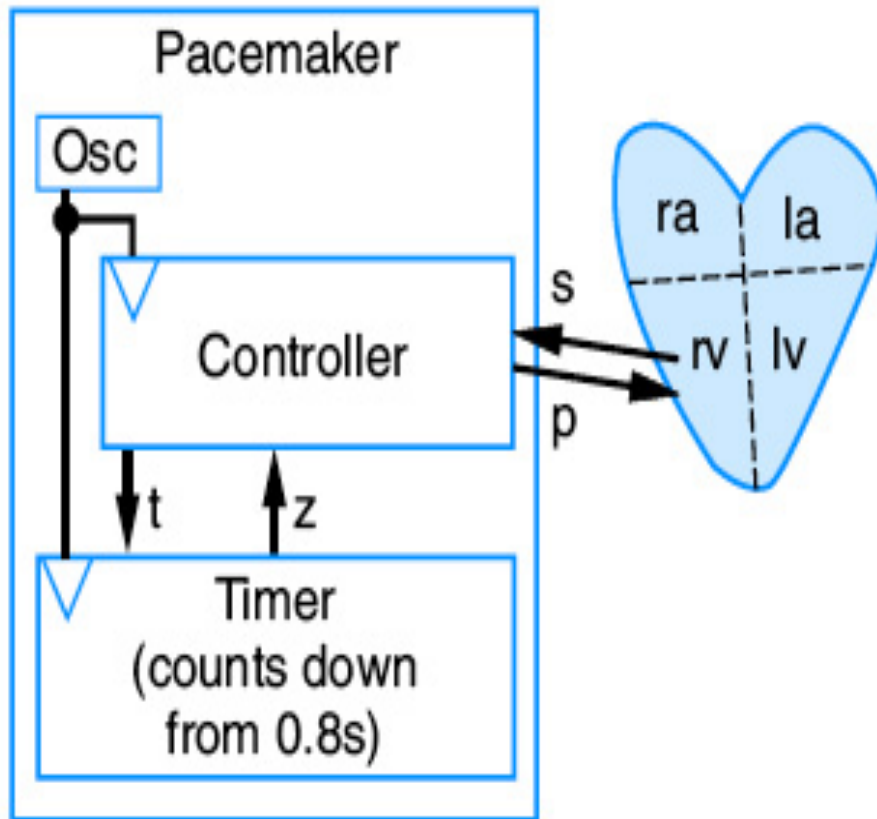


Figure 3.68 Pacemaker with leads (left), and pacemaker's location under the skin (right). Courtesy of Medtronic, Inc.



- **a: atrium** (心房)
- **v: ventricle** (心室)

