

COMPUTER HARDWARE

Registers, Register Transfers and Counters



Overview

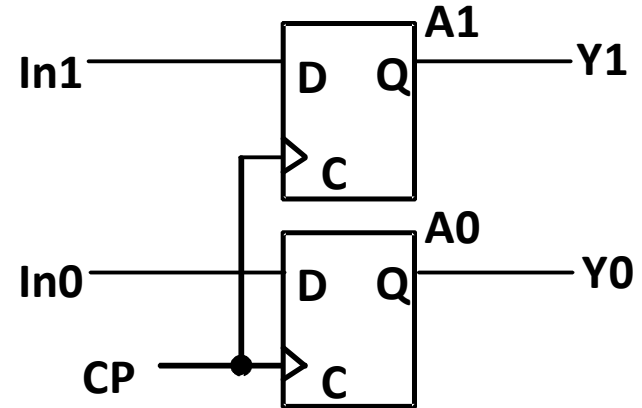
- Registers, Microoperations and Implementations
 - ▣ Registers and load enable
 - ▣ Register transfer operations
 - ▣ Microoperations - arithmetic, logic, and shift
 - ▣ Microoperations on a single register
 - Multiplexer-based transfers
 - Shift registers
- Register Cells, Buses, & Serial Operations
- Control of Register Transfers
- Counters

Registers

- Register – a collection of binary storage elements
- In theory, a register is sequential logic which can be defined by a state table
- More often, think of a register as storing a vector of binary values
- Frequently used to perform simple data storage and data movement and processing operations

Example: 2-bit Register

- How many states are there?
- How many input combinations?
Output combinations?
- What is the output function?
- What is the next state function?
- Moore or Mealy?

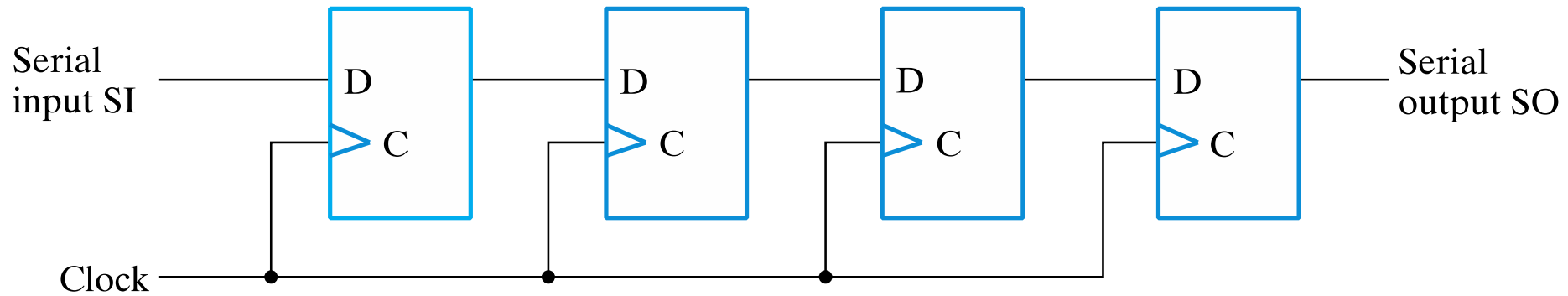


State Table:

Current State	Next State A1(t+1) A0(t+1) For In1 In0 =	Output (=A1 A0)
A1 A0	00 01 10 11	Y1 Y0
0 0	00 01 10 11	0 0
0 1	00 01 10 11	0 1
1 0	00 01 10 11	1 0
1 1	00 01 10 11	1 1

- What are the quantities above for an n -bit register?

Simple Shift Register



(a) Logic diagram



(b) Symbol

Register Design Models

- Due to the large numbers of states and input combinations as n becomes large, the state diagram/state table model is not feasible!
- What are methods we can use to design registers?
 - ▣ Add predefined combinational circuits to registers
 - Example: To count up, connect the register flip-flops to an incrementer
 - ▣ Design individual cells using the state diagram/state table model and combine them into a register
 - A 1-bit cell has just two states
 - Output is usually the state variable

Register Storage

□ Expectations:

- ▣ A register can store information for multiple clock cycles
- ▣ To “store” or “load” information should be controlled by a signal

□ Reality:

- ▣ A D flip-flop register loads information on every clock cycle

□ Realizing expectations:

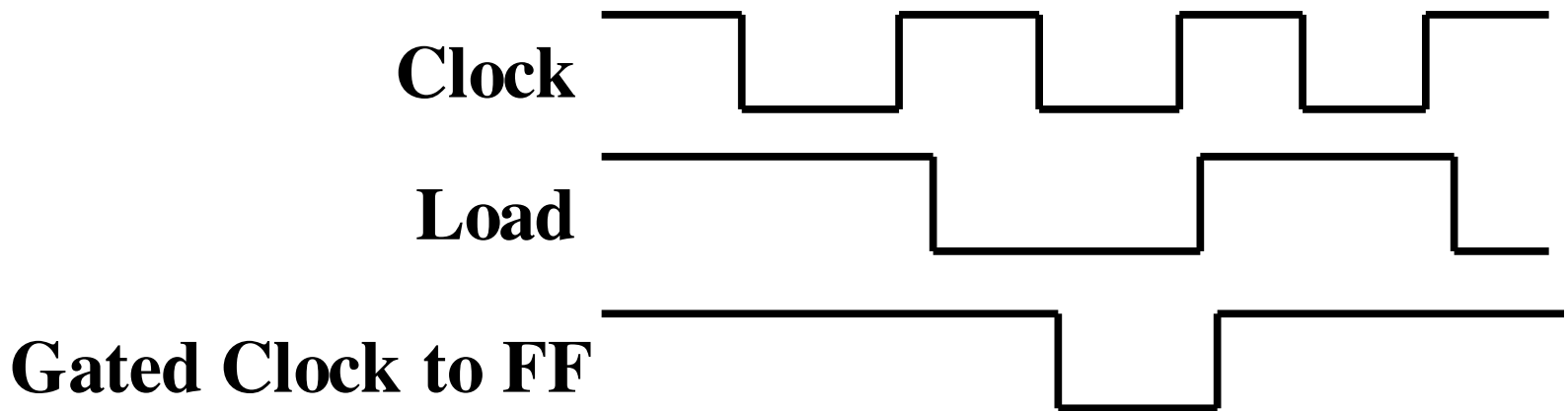
- ▣ Use a signal to block the clock to the register,
- ▣ Use a signal to control feedback of the output of the register back to its inputs, or
- ▣ Use other SR or JK flip-flops, that for (0,0) applied, store their state

□ Load is a frequent name for the signal that controls register storage and loading

- ▣ Load = 1: Load the values on the data inputs
- ▣ Load = 0: Store the values in the register

Registers with Clock Gating

- The $\overline{\text{Load}}$ signal enables the clock signal to pass through if 1 and prevents the clock signal from passing through if 0.
- Example: For Positive Edge-Triggered or Negative Pulse Master-Slave Flip-flop:

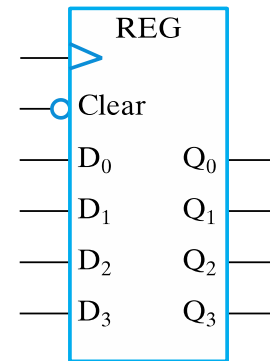
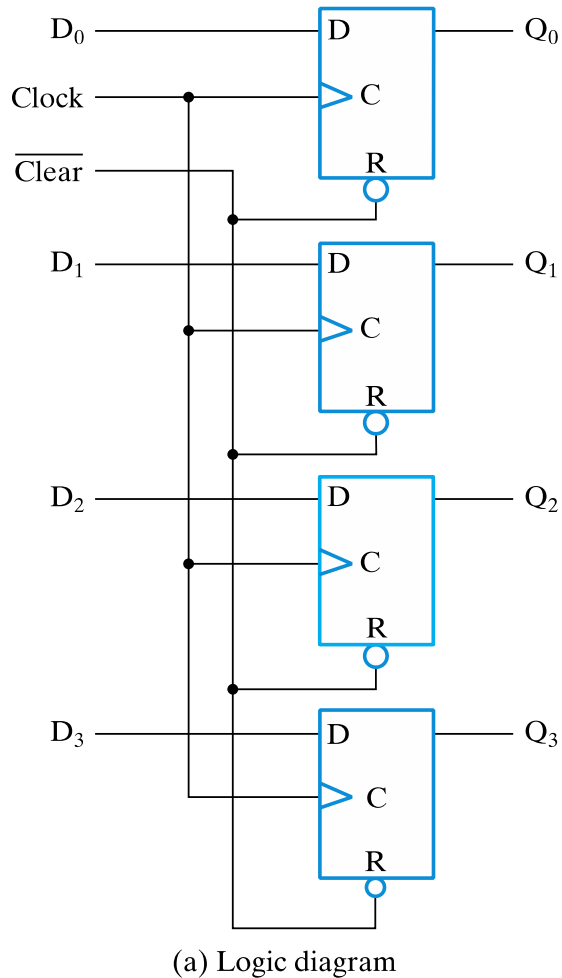


- What logic is needed for gating?
- What is the problem?

$$\text{Gated Clock} = \text{Clock} + \overline{\text{Load}}$$

Clock Skew of gated clocks with respect to clock or each other

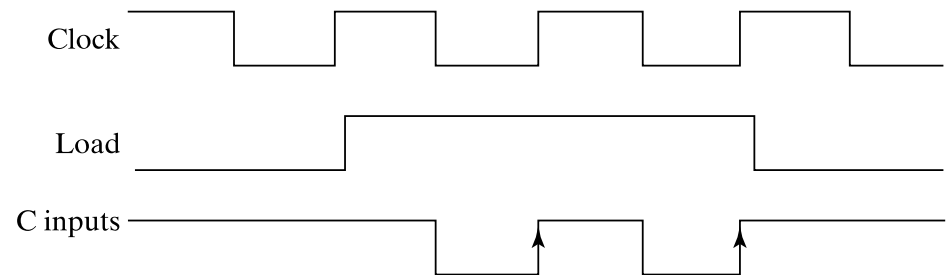
Registers with Clock Gating



(b) Symbol



(c) Load control input



(d) Timing diagram

Registers with Load-Controlled Feedback

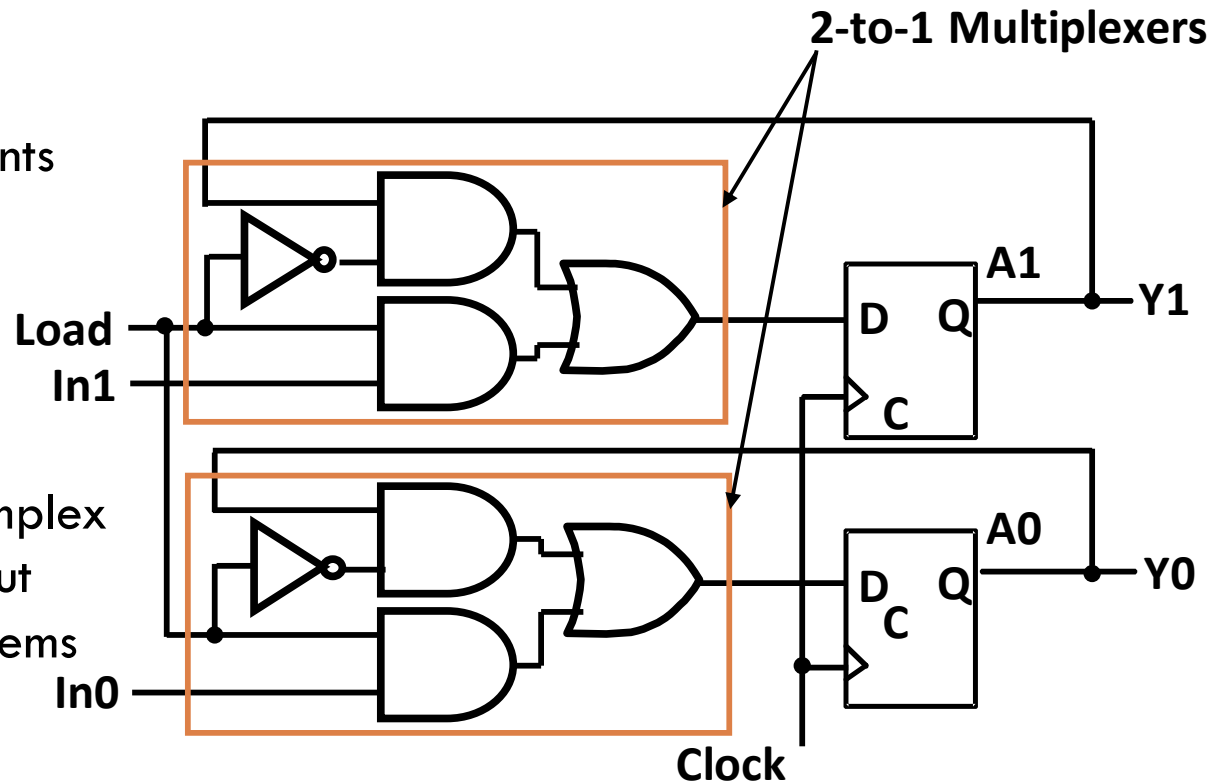
- A more reliable way to selectively load a register:
 - ▣ Run the clock continuously, and
 - ▣ Selectively use a load control to change the register contents.

- Example: 2-bit register with Load Control:

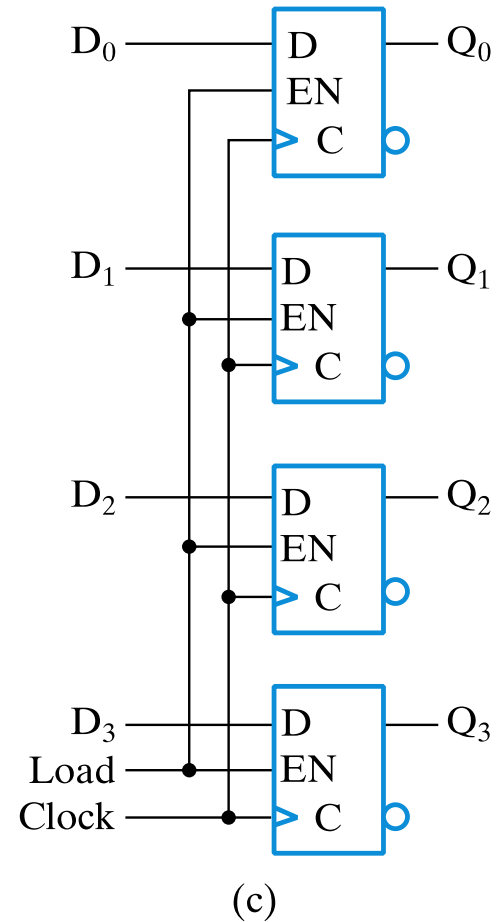
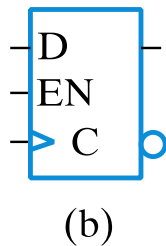
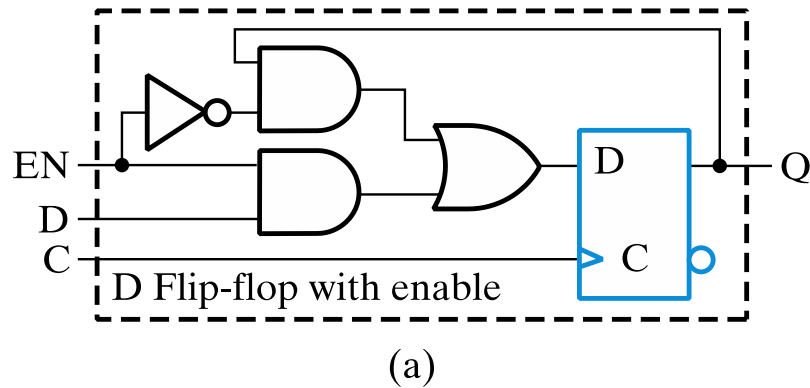
- For Load = 0, loads register contents (hold current values)

- For Load = 1, loads input values (load new values)

- Hardware more complex than clock gating, but free of timing problems



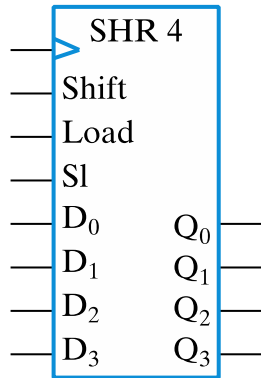
Registers with Load-Controlled Feedback



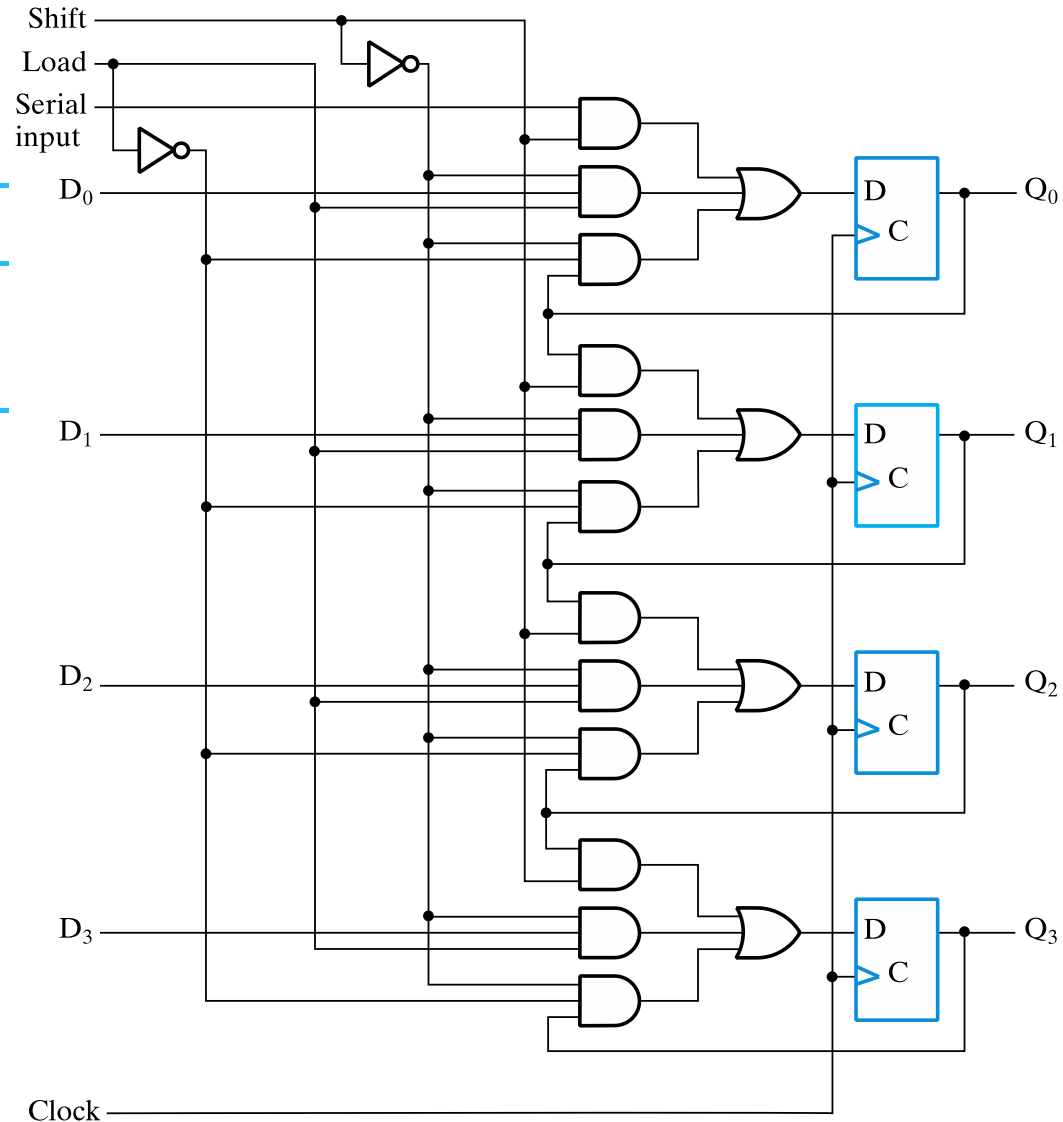
Registers

Function Table

Shift	Load	Operation
0	0	No change
0	1	Load parallel data
1	X	Shift down from Q_0 to Q_3



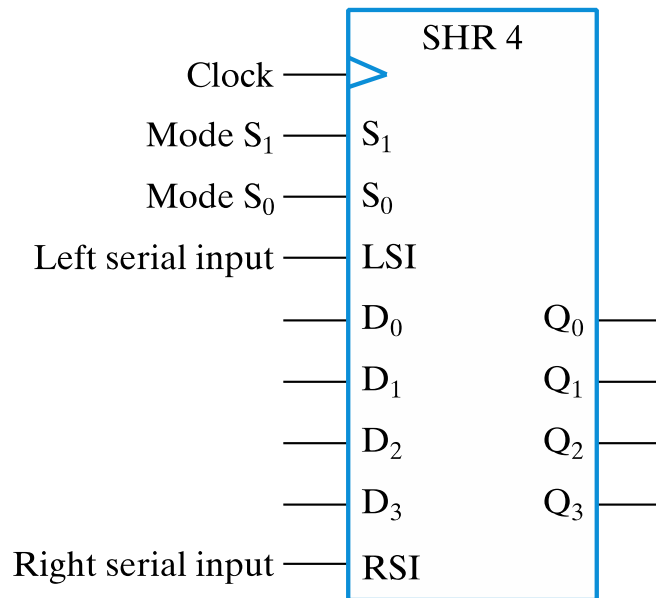
(b) Symbol



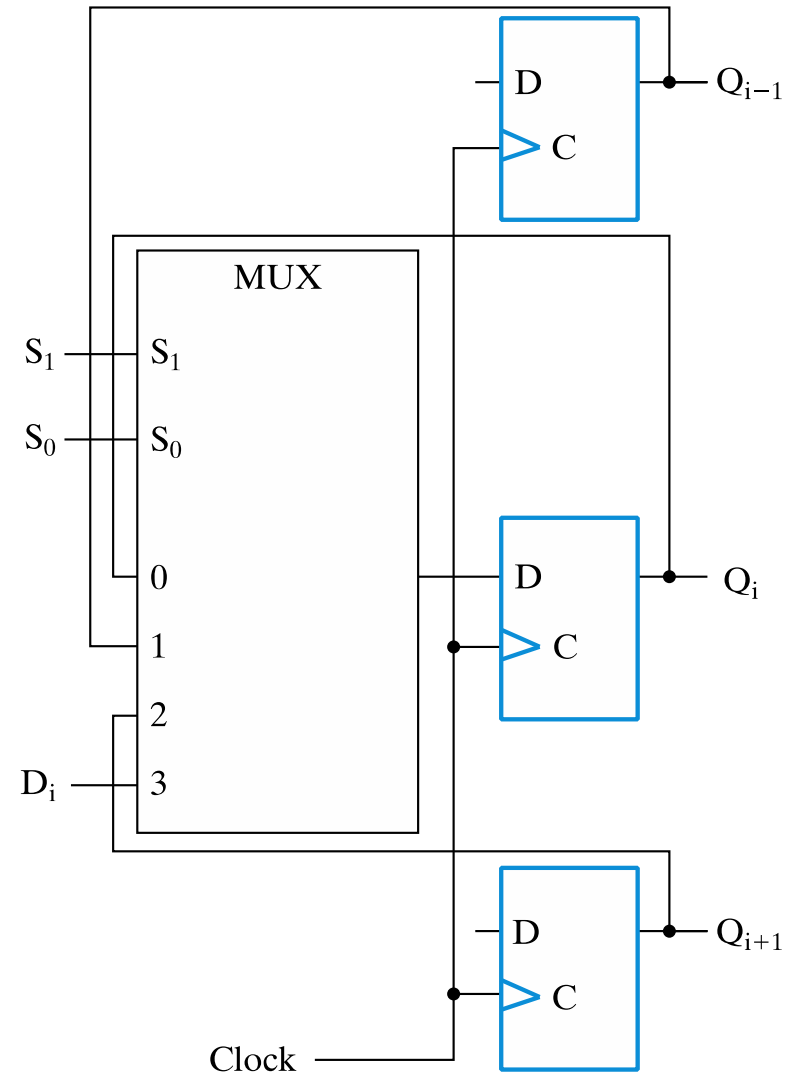
Registers

Function Table

Mode control		Register Operation
S_1	S_0	
0	0	No change
0	1	Shift down
1	0	Shift up
1	1	Parallel load



(b) Symbol



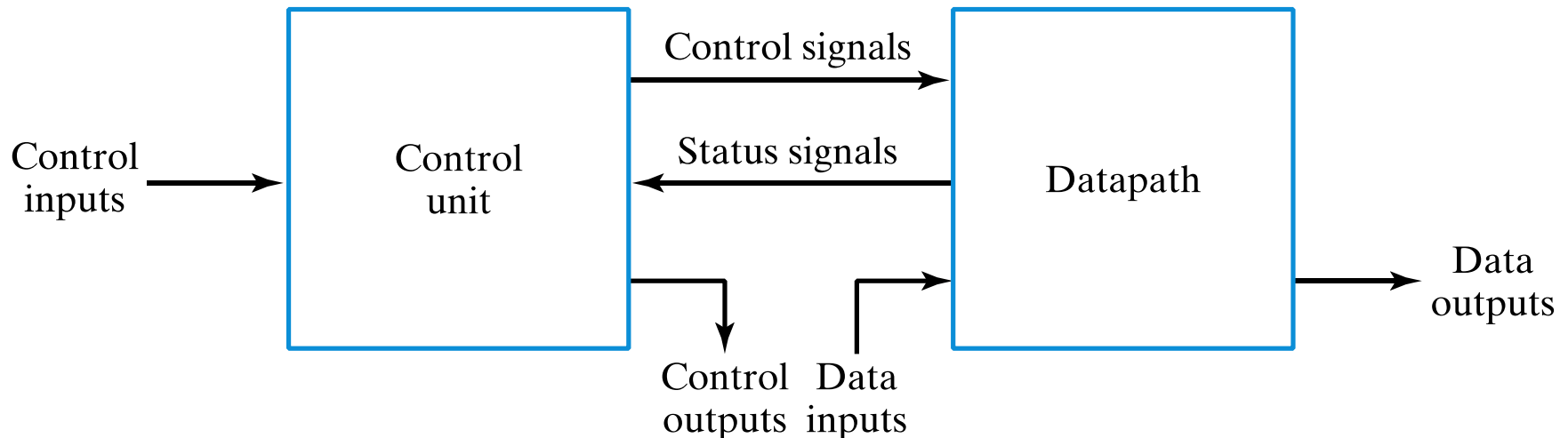
(a) Logic diagram of one typical stage

Register Transfer Operations

- Register Transfer Operations – The movement and processing of data stored in registers
- Three basic components:
 - ▣ set of registers
 - ▣ operations
 - ▣ control of operations
- Elementary Operations -- load, count, shift, add, bitwise "OR", etc.
 - ▣ Elementary operations called *microoperations*

Register Transfer Operations

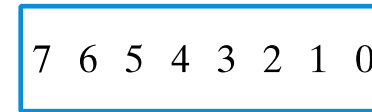
- The system is partitioned into 2 types of modules:
 - ▣ Datapath: performs data processing operations.
 - ▣ Control unit: determines the sequence of those operations.
- Datapaths are defined by their registers and the operations performed on binary data stored in the registers



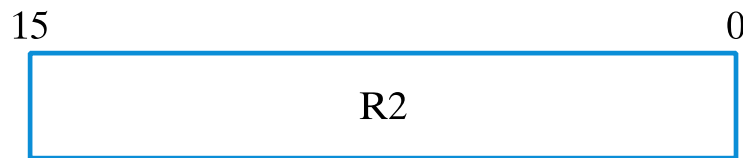
Register Notation



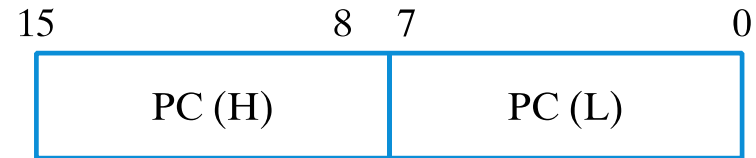
(a) Register R



(b) Individual bits of 8-bit register



(c) Numbering of 16-bit register



(d) Two-part 16-bit register

Basic Symbols for Register Transfers

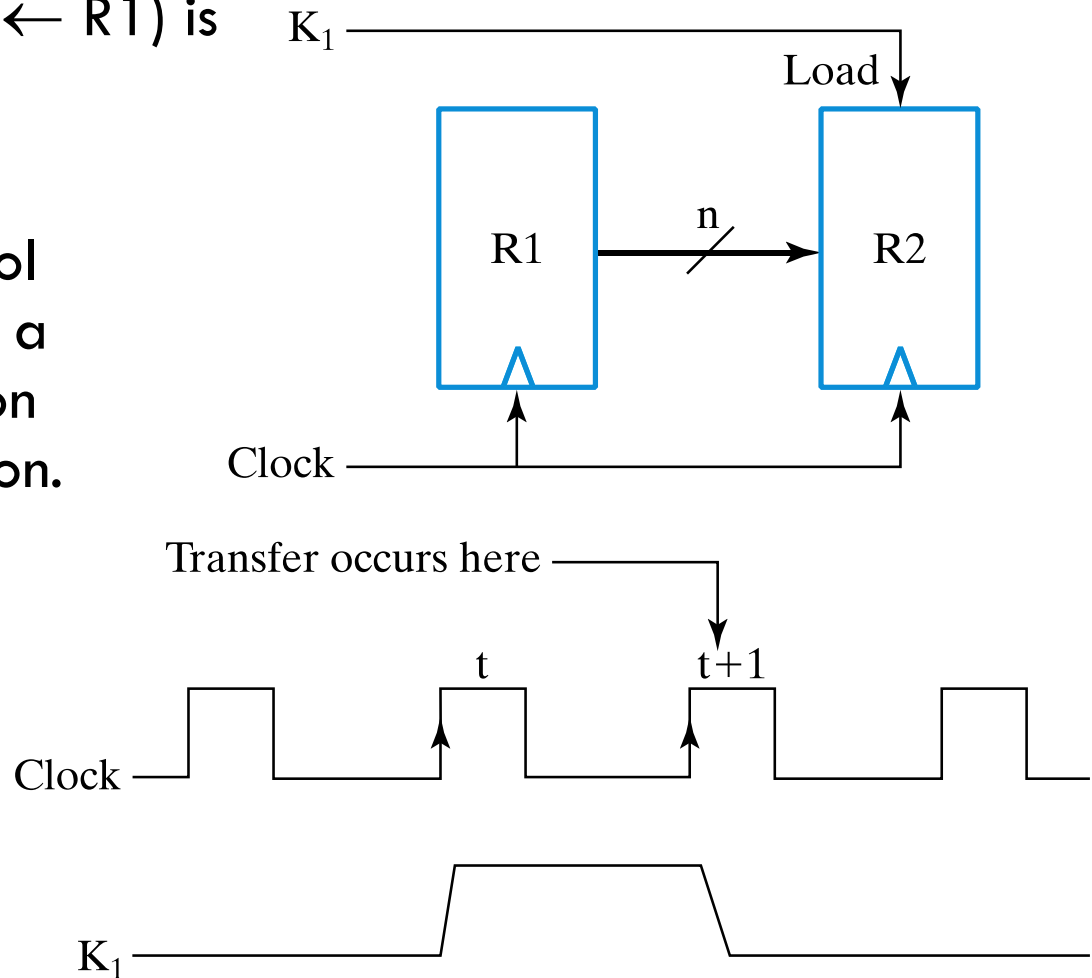
Symbol	Description	Examples
Letters (and numerals)	Denotes a register	$AR, R2, DR, IR$
Parentheses	Denotes a part of a register	$R2(1), R2(7:0), AR(L)$
Arrow	Denotes transfer of data	$R1 \leftarrow R2$
Comma	Separates simultaneous transfers	$R1 \leftarrow R2, R2 \leftarrow R1$
Square brackets	Specifies an address for memory	$DR \leftarrow M[AR]$

Conditional Transfer

- If $(K1 = 1)$ then $(R2 \leftarrow R1)$ is shortened to

$K1: (R2 \leftarrow R1)$

where $K1$ is a control variable specifying a conditional execution of the microoperation.



Microoperations

- A microoperation is an elementary operation performed on data stored in register or in memory.
- Types of microoprations:
 - ▣ Transfer - move data from one register to another
 - ▣ Arithmetic - perform arithmetic on data in registers
 - ▣ Logic - manipulate data or use bitwise logical operations
 - ▣ Shift - shift data in registers

Arithmetic operations

+ Addition
- Subtraction
* Multiplication
/ Division

Logical operations

∨ Logical OR
∧ Logical AND
⊕ Logical Exclusive OR
- Not

Register Trasfers

Textbook RTL, VHDL, and Verilog Symbols for Register Transfers

Operation	Text RTL	VHDL	Verilog
Combinational assignment	=	<= (concurrent)	assign = (nonblocking)
Register transfer	←	<= (concurrent)	<= (nonblocking)
Addition	+	+	+
Subtraction	−	−	−
Bitwise AND	^	and	&
Bitwise OR	∨	or	
Bitwise XOR	⊕	xor	^
Bitwise NOT	− (overline)	not	~
Shift left (logical)	sl	sll	<<
Shift right (logical)	sr	srl	>>
Vectors/registers	A(3:0)	A(3 down to 0)	A[3:0]
Concatenation		&	{ , }

Example Microoperations

- Add the content of R1 to the content of R2 and place the result in R1.

$$R1 \leftarrow R1 + R2$$

- Subtract the content of R6 from R1 and place the result in R1

$$R1 \leftarrow R1 + R6' + 1$$

- Exclusive OR the content of R1 with the content of R2 and place the result in R1.

$$R1 \leftarrow R1 \oplus R2$$

Example Microoperations (Continued)

- Take the 1's Complement of the contents of R2 and place it in the PC.

$$PC \leftarrow \overline{R2}$$

- On condition K1 OR K2, the content of R1 is Logic bitwise Ored with the content of R3 and the result placed in R1.

$$(K1 + K2): R1 \leftarrow R1 \vee R3$$

- NOTE: "+" (as in $K_1 + K_2$) and means "OR."

In $R1 \leftarrow R1 + R3$, + means "plus."

Control Expressions

- The control expression for an operation appears to the left of the operation and is separated from it by a colon
- Control expressions specify the logical condition for the operation to occur
- Control expression values of:
 - ▣ Logic "1" -- the operation occurs.
 - ▣ Logic "0" -- the operation is does not occur.

- **Example:**

$$\overline{X} \text{ K1} : R1 \leftarrow R1 + R2$$

$$X \text{ K1} : R1 \leftarrow R1 + \overline{R2} + 1$$

- Variable K1 enables the add or subtract operation.
- If $X = 0$, then $\overline{X} = 1$ so $\overline{X} \text{ K1} = 1$, activating the addition of R1 and R2.
- If $X = 1$, then $X \text{ K1} = 1$, activating the addition of R1 and the two's complement of R2 (subtract).

Arithmetic Microoperations

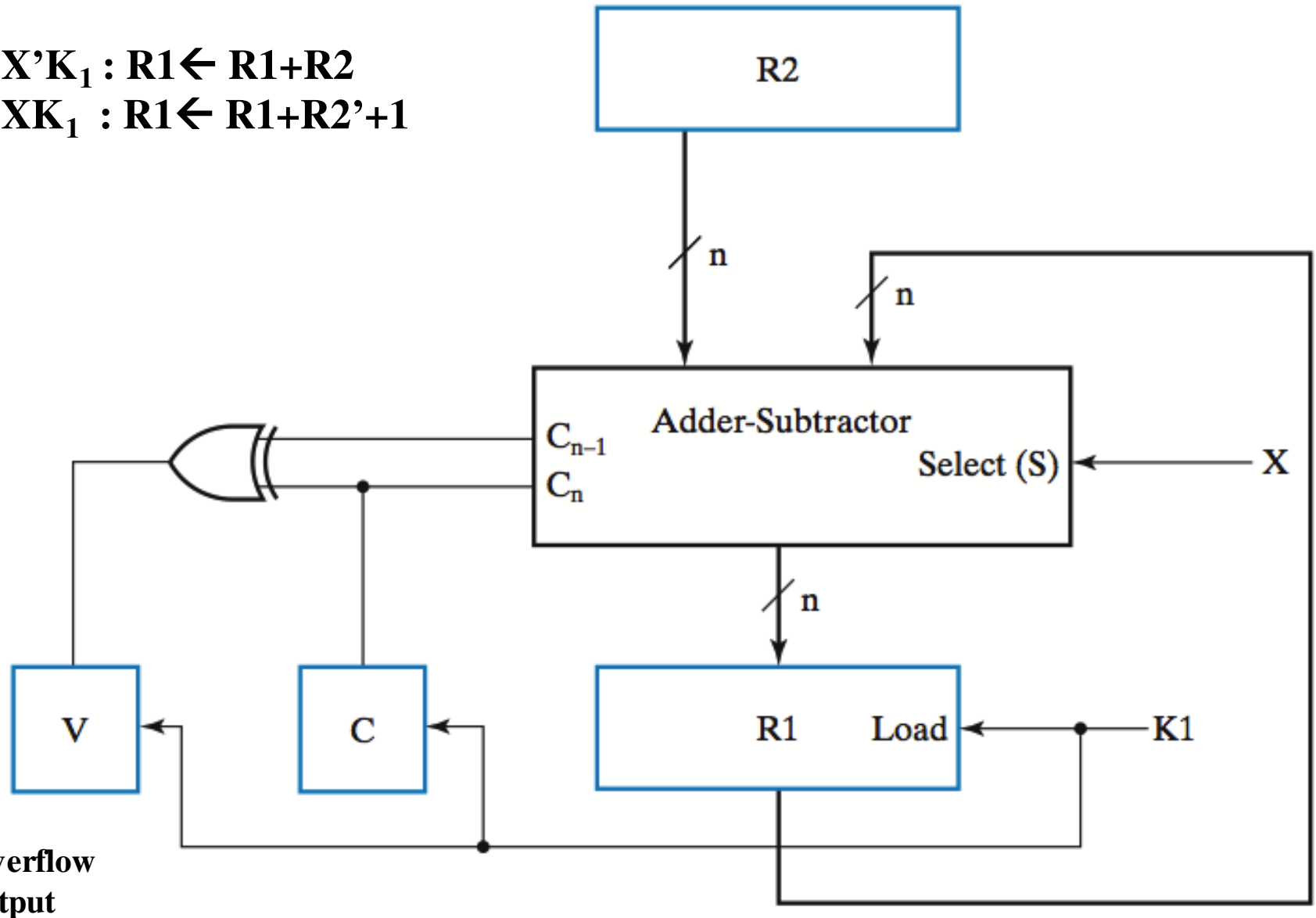
Arithmetic Microoperations

Symbolic designation	Description
$R0 \leftarrow R1 + R2$	Contents of $R1$ plus $R2$ transferred to $R0$
$R2 \leftarrow \overline{R2}$	Complement of the contents of $R2$ (1's complement)
$R2 \leftarrow \overline{R2} + 1$	2's complement of the contents of $R2$
$R0 \leftarrow R1 + \overline{R2} + 1$	$R1$ plus 2's complement of $R2$ transferred to $R0$ (subtraction)
$R1 \leftarrow R1 + 1$	Increment the contents of $R1$ (count up)
$R1 \leftarrow R1 - 1$	Decrement the contents of $R1$ (count down)

- Note that any register may be specified for source 1, source 2, or destination.
- These simple microoperations operate on the whole word

Adder/ Subtractor Unit

$X'K_1 : R1 \leftarrow R1 + R2$
 $XK_1 : R1 \leftarrow R1 + R2' + 1$



Logical Microoperations

Logic Microoperations

Symbolic designation

Description

$R0 \leftarrow \overline{R1}$	Logical bitwise NOT (1's complement)
$R0 \leftarrow R1 \wedge R2$	Logical bitwise AND (clears bits)
$R0 \leftarrow R1 \vee R2$	Logical bitwise OR (sets bits)
$R0 \leftarrow R1 \oplus R2$	Logical bitwise XOR (complements bits)

- Let $R1 = 10101010$, and $R2 = 11110000$
- Then after the operation, $R0$ becomes:

R0	Operation
01010101	$R0 \leftarrow R1$
11111010	$R0 \leftarrow R1 \vee R2$
10100000	$R0 \leftarrow R1 \wedge R2$
01011010	$R0 \leftarrow R1 \oplus R2$

Shift Microoperations

Examples of Shifts

Type	Symbolic designation	Eight-bit examples	
		Source <i>R2</i>	After shift: Destination <i>R1</i>
shift left	$R1 \leftarrow sl\ R2$	10011110	00111100
shift right	$R1 \leftarrow sr\ R2$	11100101	01110010

- Note: These shifts "zero fill". Sometimes a separate flip-flop is used to provide the data shifted in, or to "catch" the data shifted out.
- Other shifts are possible (rotates, arithmetic).

Register Cell Design

- Assume that a register consists of identical cells
- Then register design can be approached as follows:
 - ▣ Design representative cell for the register
 - ▣ Connect copies of the cell together to form the register
 - ▣ Applying appropriate “boundary conditions” to cells that need to be different and contract if appropriate
- Register cell design is the first step of the above process

Register Cell Specifications

- A register
- Data inputs to the register
- Control input combinations to the register
 - ▣ Example 1: Not encoded
 - Control inputs: Load, Shift, Add
 - At most, one of Load, Shift, Add is 1 for any clock cycle
(0,0,0), (1,0,0), (0,1,0), (0,0,1)
 - ▣ Example 2: Encoded
 - Control inputs: S1, S0
 - All possible binary combinations on S1, S0
(0,0), (0,1), (1,0), (1,1)

Register Cell Specifications

- A set of register functions (typically specified as register transfers)

- Example:

Load: $A \leftarrow B$

Shift: $A \leftarrow \text{sr } B$

Add: $A \leftarrow A + B$

- A hold state specification

- Example:

- Control inputs: Load, Shift, Add

- If all control inputs are 0, hold the current register state

Example 1: Register Cell Design

- Register A (m-bits) Specification:
 - Data input: B
 - Control inputs (CX, CY)
 - Control input combinations (0,0), (0,1) (1,0)
 - Register transfers:
 - CX : $A \leftarrow B \vee A$
 - CY : $A \leftarrow B \oplus A$
 - Hold state: (0,0)

Example 1: Register Cell Design (continued)

- Load Control

$$\text{Load} = \text{CX} + \text{CY}$$

- Since all control combinations appear as if encoded (0,0), (0,1), (1,0) can use multiplexer without encoder:

$$S1 = \text{CX}$$

$$S0 = \text{CY}$$

$$D0 = A_i$$

Hold A

$$D1 = A_i \leftarrow B_i \oplus A_i$$

$$\text{CY} = 1$$

$$D2 = A_i \leftarrow B_i \vee A_i$$

$$\text{CX} = 1$$

- Note that the decoder part of the 3-input multiplexer can be shared between bits if desired

Sequential Circuit Design Approach

- Find a state diagram or state table
 - ▣ Note that there are only two states with the state assignment equal to the register cell output value
- Use the design procedure in Chapter 5 to complete the cell design
- For optimization:
 - ▣ Use K-maps for up to 4 to 6 variables
 - ▣ Otherwise, use computer-aided or manual optimization

Example 1 Again

□ State Table:

	Hold	$A_i \vee B_i$		$A_i + B_i$	
A_i	$CX = 0$ $CY = 0$	$CX = 1$ $B_i = 0$	$CX = 1$ $B_i = 1$	$CY = 1$ $B_i = 0$	$CY = 1$ $B_i = 1$
0	0	0	1	0	1
1	1	1	1	1	0

▣ Four variables give a total of 16 state table entries

▣ By using:

- ▣ Combinations of variable names and values
- ▣ Don't care conditions (for $CX = CY = 1$)

only 8 entries are required to represent the 16 entries

Example 1 Again (continued)

- K-map - Use variable ordering CX, CY, A_i B_i and assume a D flip-flop

Di		Ai		
	0	0	1	1
	0	1	0	1
CX	X	X	X	X
	0	1	1	1
	Bi			CY

Example 1 Again (continued)

- The resulting SOP equation:

$$D_i = CX B_i + CY \bar{A}_i B_i + A_i \bar{B}_i + \bar{C}Y A_i$$

- Using factoring and DeMorgan's law:

$$D_i = CX B_i + \bar{A}_i (CY B_i) + A_i (\overline{CY B_i})$$

$$D_i = CX B_i + A_i \oplus (CY B_i)$$

The gate input cost per cell = $2 + 8 + 2 + 2 = 14$

- The gate input cost per cell for the previous version is:

Per cell: 19

Shared decoder logic: 8

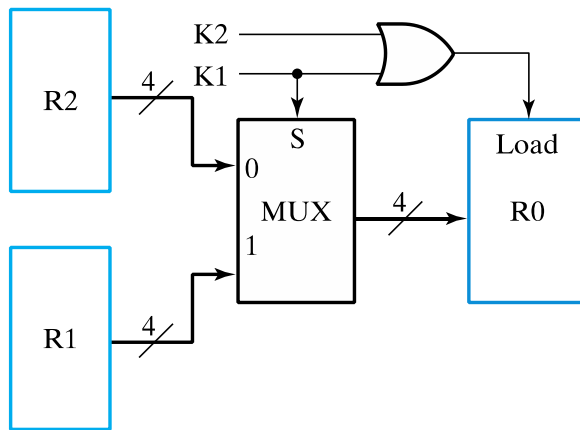
- Cost gain by sequential design > 5 per cell
- Also, no Enable on the flip-flop makes it cost less

Register Transfer Structures

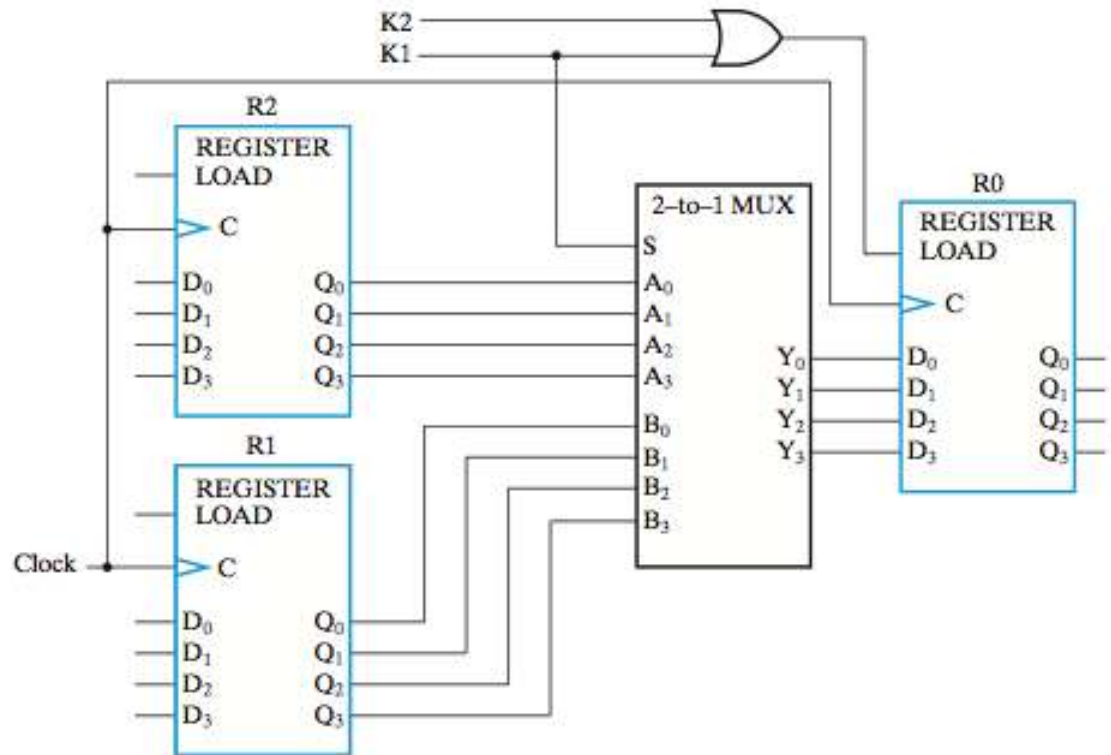
- Multiplexer-Based Transfers - Multiple inputs are selected by a multiplexer dedicated to the register
- Bus-Based Transfers - Multiple inputs are selected by a shared multiplexer driving a bus that feeds inputs to multiple registers
- Three-State Bus - Multiple inputs are selected by 3-state drivers with outputs connected to a bus that feeds multiple registers
- Other Transfer Structures - Use multiple multiplexers, multiple buses, and combinations of all the above

Multiplexer-Based Transfers

- ❑ Multiplexers connected to register inputs produce flexible transfer structures (Note: Clocks are omitted for clarity)
- ❑ The transfers are:
 - ▣ K1: $R0 \leftarrow R1$
 - ▣ $K2 \times K1$: $R0 \leftarrow R2$



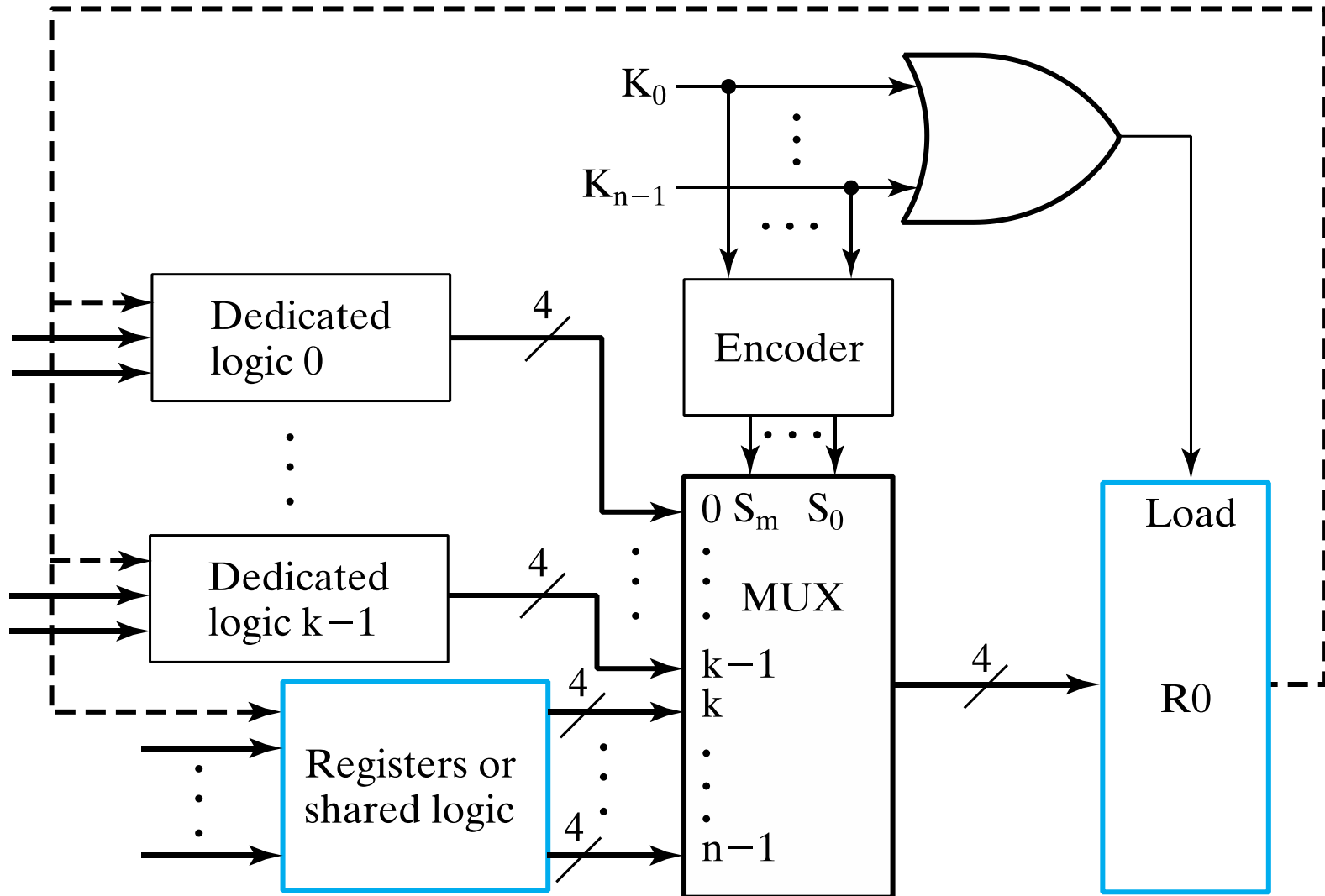
(a) Block diagram



(b) Detailed logic

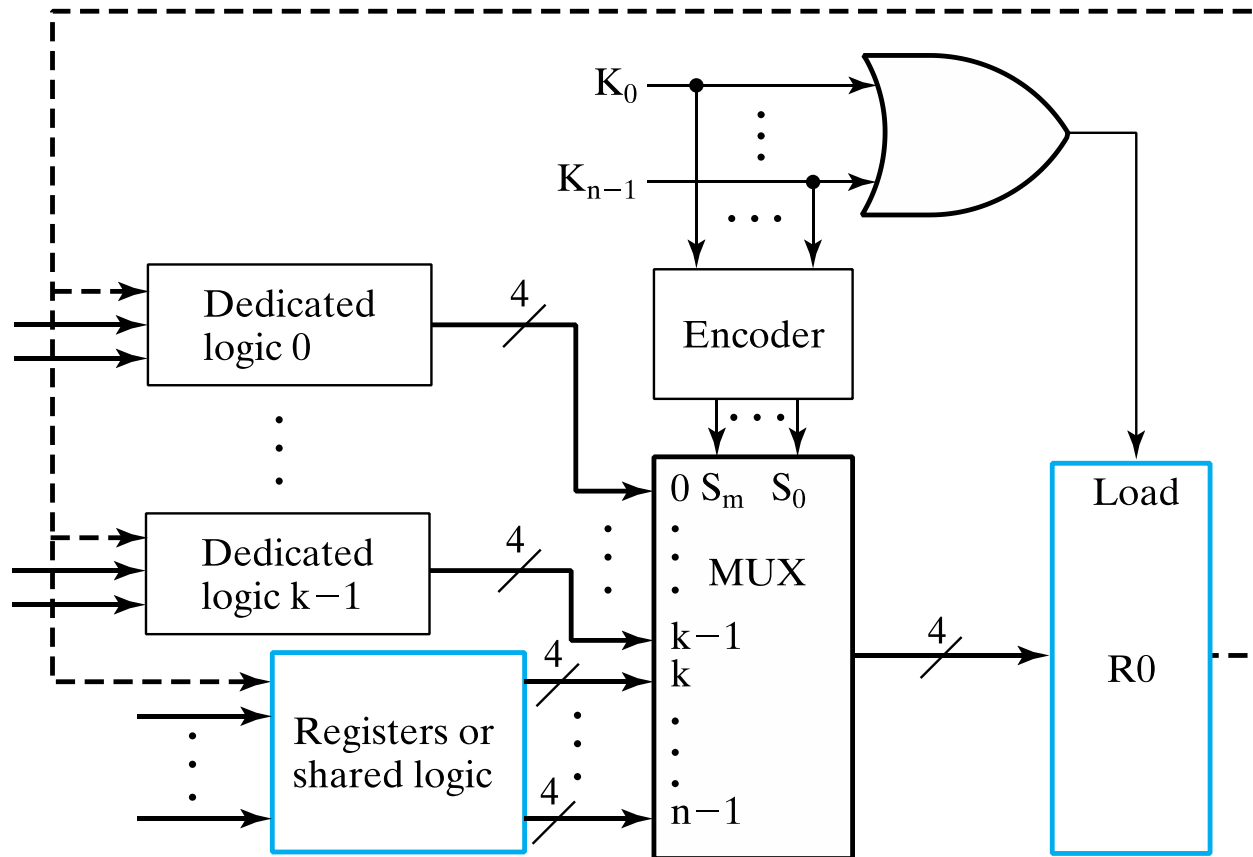
Multiplexer Approach

- Uses an n-input multiplexer with a variety of transfer sources and functions



Multiplexer Approach

- Load enable by OR of control signals K_0, K_1, \dots, K_{n-1}
 - assumes no load for 00...0
- Use Encoder + Multiplexer (shown) or $n \times 2$ AND-OR to select sources and/or transfer functions

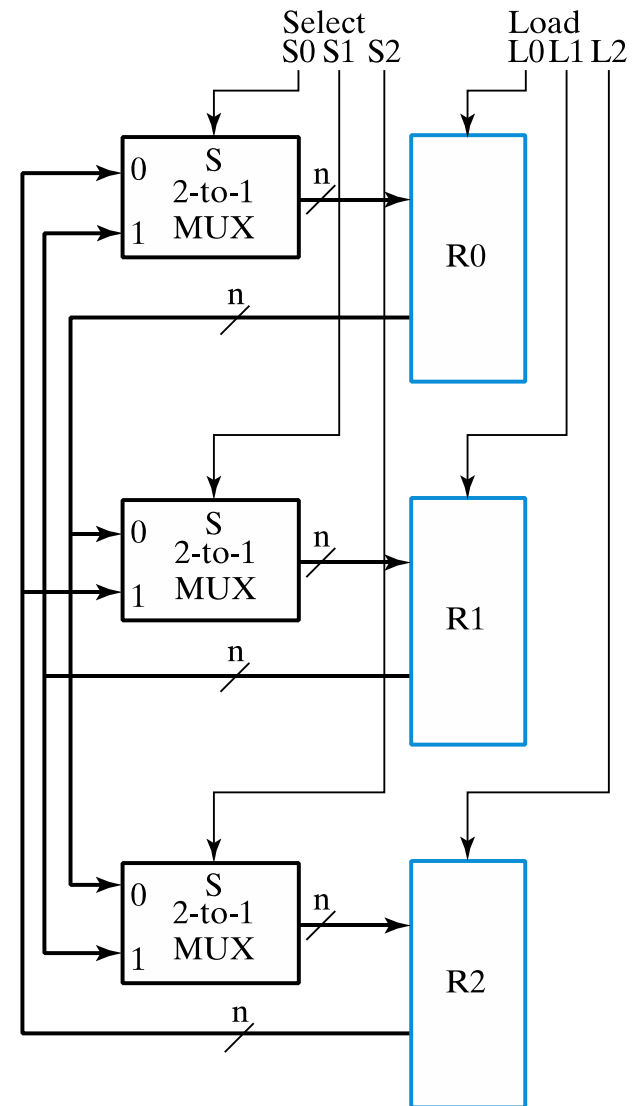


Multiplexer and Bus-Based Transfers for Multiple Registers

- Multiplexer dedicated to each register
- Shared transfer paths for registers
 - ▣ A shared transfer object is called a *bus* (Plural: *buses*)
- Bus implementation using:
 - ▣ multiplexers
 - ▣ three-state nodes and drivers
- In most cases, the number of bits is the length of the receiving register

Dedicated MUX-Based Transfers

- ❑ Multiplexer connected to each register input produces a very flexible transfer structure =>
- ❑ Characterize the simultaneous transfers possible with this structure.

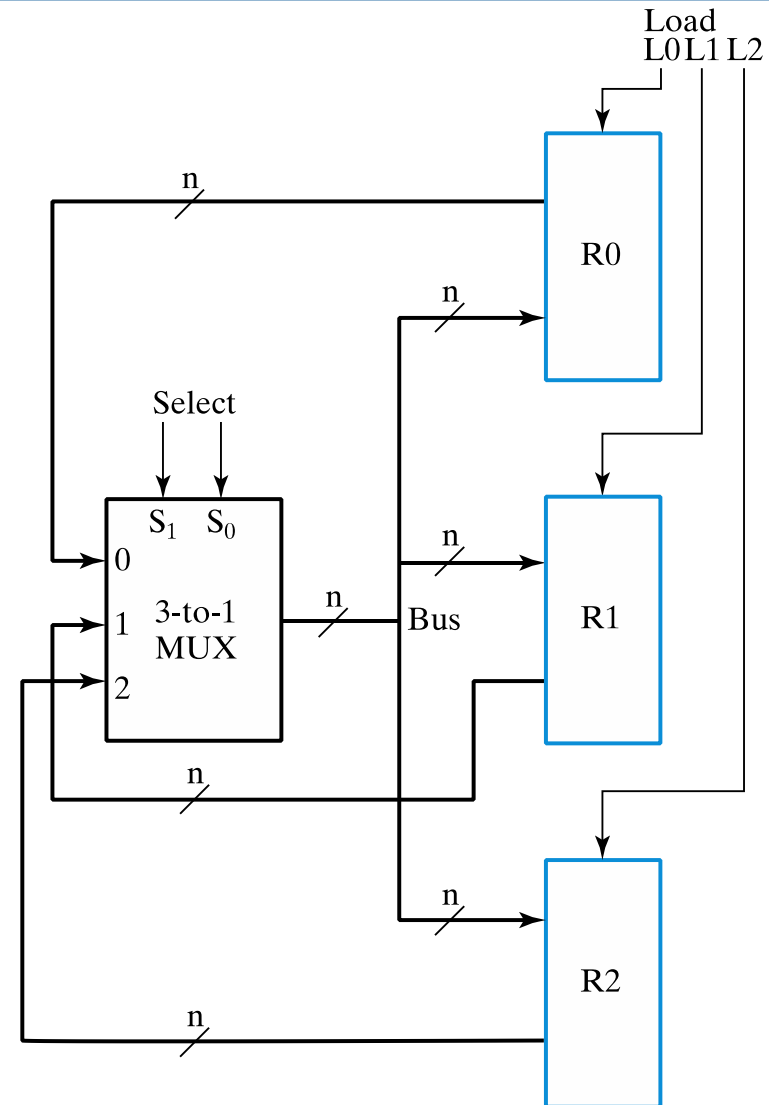


(a) Dedicated multiplexers

Multiplexer Bus

- A single bus driven by a multiplexer lowers cost, but limits the available transfers
=>
- Characterize the simultaneous transfers possible with this structure.
- Characterize the cost savings compared to dedicated multiplexers

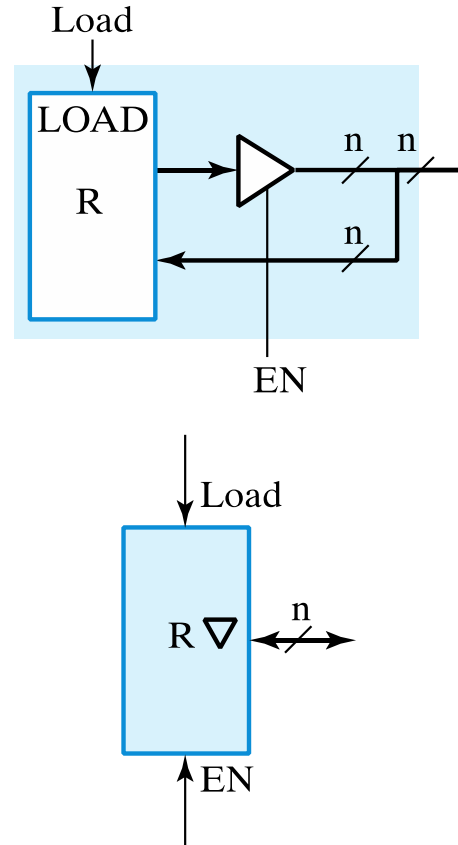
Register Transfer	Select		Load		
	S1	S0	L2	L1	L0
$R0 \leftarrow R2$	1	0	0	0	1
$R0 \leftarrow R1, R2 \leftarrow R1$	0	1	1	0	1
$R0 \leftarrow R1, R1 \leftarrow R0$	Impossible				



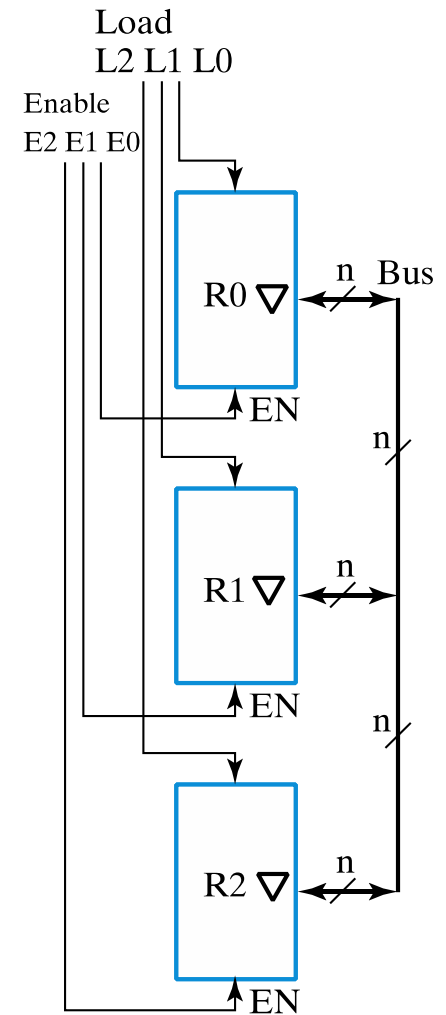
(b) Single bus

Three-State Bus

- The 3-input MUX can be replaced by a 3-state node (bus) and 3-state buffers.
- Cost is further reduced, but transfers are limited
- Characterize the simultaneous transfers possible with this structure.
- Characterize the cost savings and compare



(a) Register with bidirectional input-output lines and symbol



(c) Three-state bus using registers with bidirectional lines

Serial Transfers and Microoperations

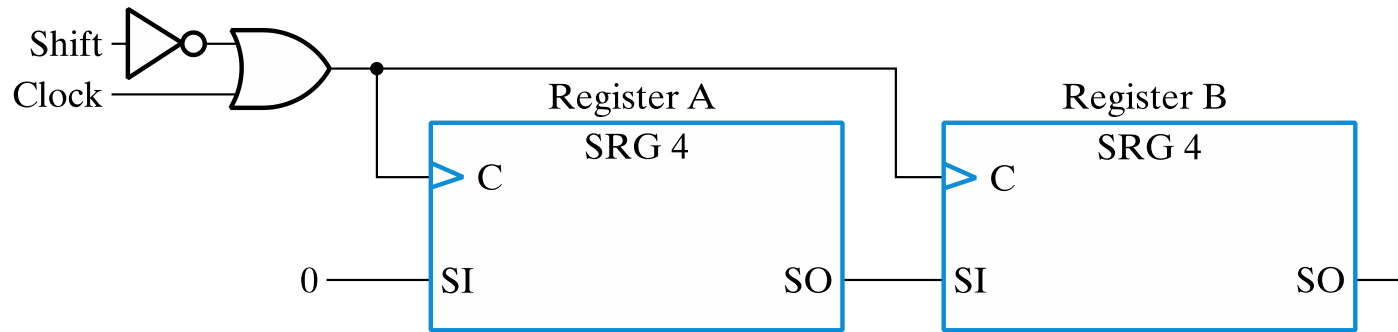
□ Serial Transfers

- ▣ Used for “narrow” transfer paths
- ▣ Example 1: Telephone or cable line
 - Parallel-to-Serial conversion at source
 - Serial-to-Parallel conversion at destination
- ▣ Example 2: Initialization and Capture of the contents of many flip-flops for test purposes
 - Add shift function to all flip-flops and form large shift register
 - Use shifting for simultaneous Initialization and Capture operations

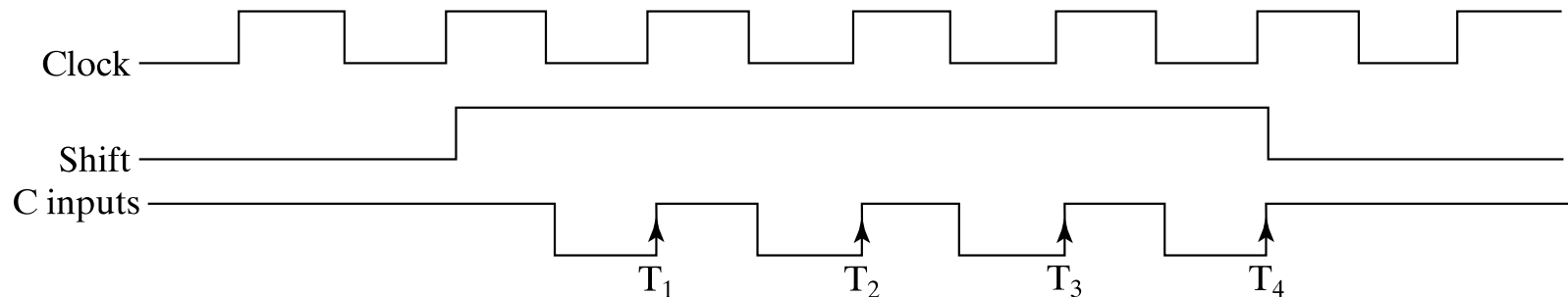
□ Serial microoperations

- ▣ Example 1: Addition
- ▣ Example 2: Error-Correction for CDs

Serial Transfer



(a) Block diagram



(b) Timing diagram

Example of Serial Transfer

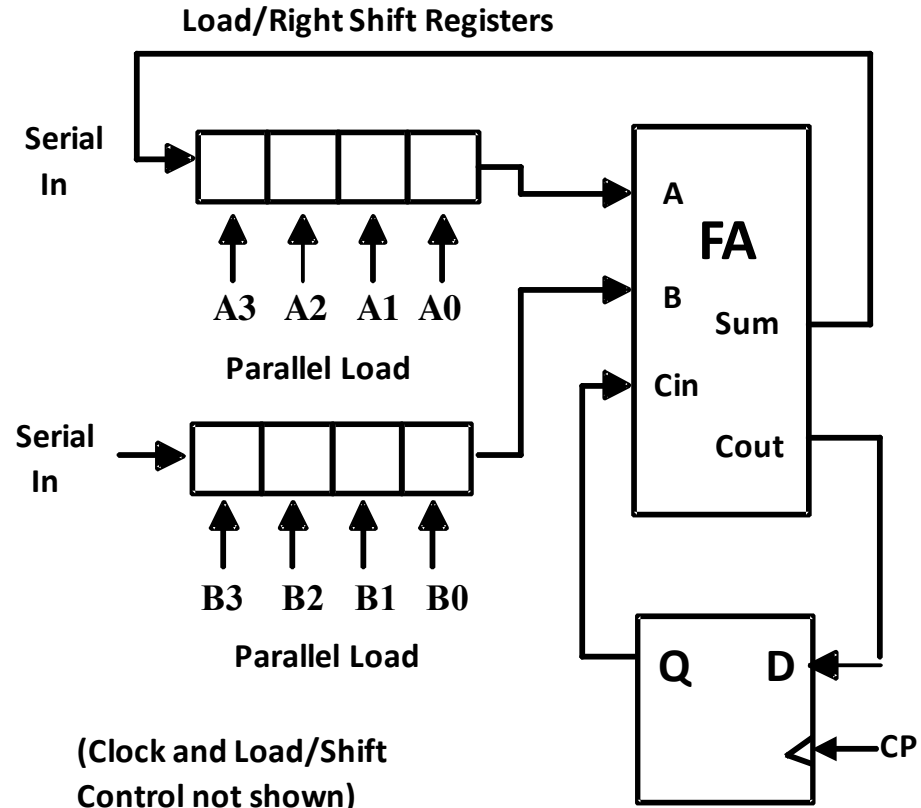
Timing pulse	Shift Register A				Shift Register B			
Initial value	1	0	1	1	0	0	1	0
After T_1	0	1	0	1	1	0	0	1
After T_2	0	0	1	0	1	1	0	0
After T_3	0	0	0	1	0	1	1	0
After T_4	0	0	0	0	1	0	1	1

Serial Microoperations

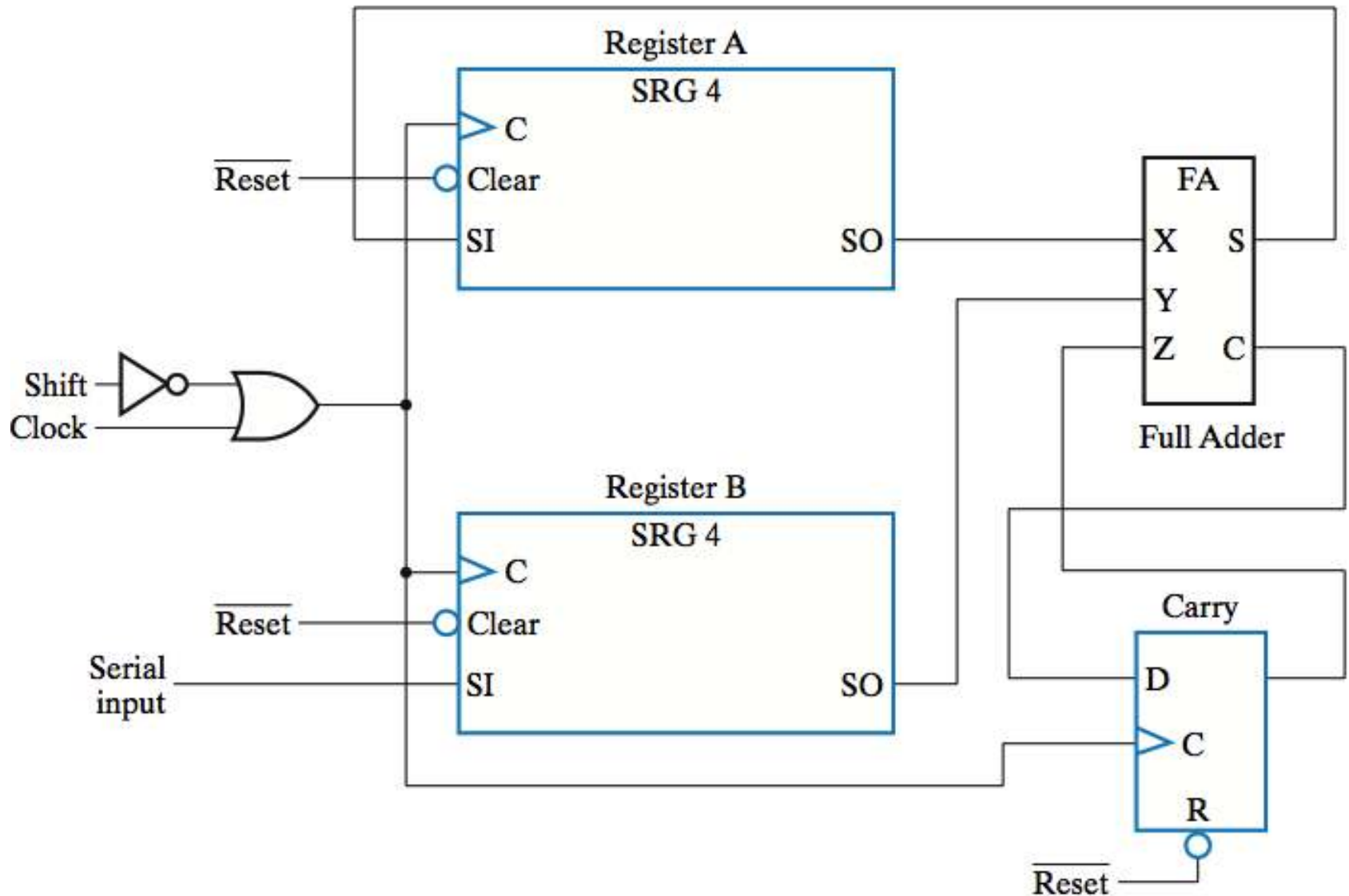
- By using two shift registers for operands, a full adder, and a flip flop (for the carry), we can add two numbers serially, starting at the least significant bit.
- Serial addition is a low cost way to add large numbers of operands, since a “tree” of full adder cells can be made to any depth, and each new level doubles the number of operands.
- Other operations can be performed serially as well, such as parity generation/checking or more complex error-check codes.
- Shifting a binary number left is equivalent to multiplying by 2.
- Shifting a binary number right is equivalent to dividing by 2.

Serial Adder

- The circuit shown uses two shift registers for operands A(3:0) and B(3:0).
- A full adder, and one more flip flop (for the carry) is used to compute the sum.
- The result is stored in the A register and the final carry in the flip-flop
- With the operands and the result in shift registers, a tree of full adders can be used to add a large number of operands. Used as a common digital signal processing technique.



Serial Adder

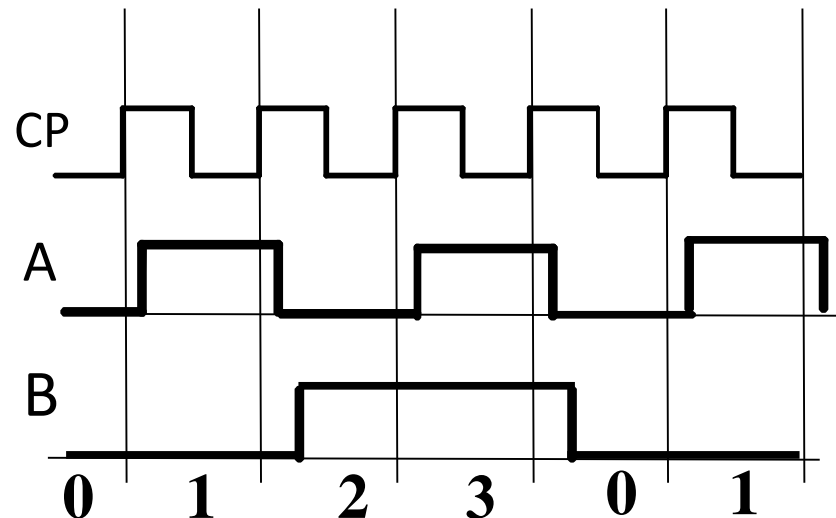
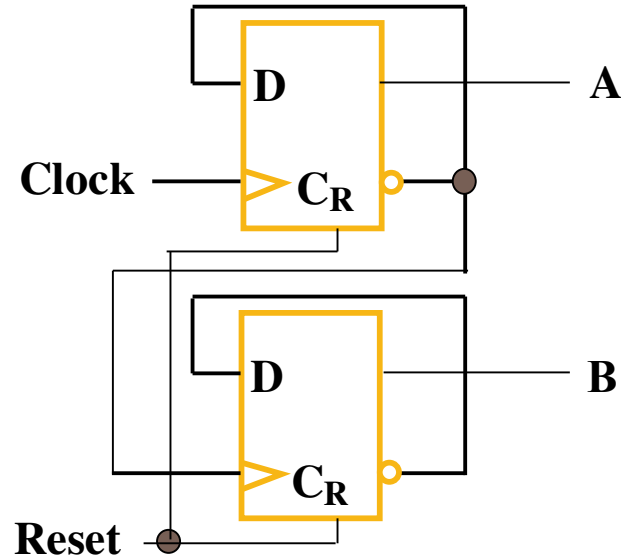


Counters

- Counters are sequential circuits which "count" through a specific state sequence. They can count up, count down, or count through other fixed sequences. Two distinct types are in common usage:
- **Ripple Counters**
 - ▣ Clock connected to the flip-flop clock input on the LSB bit flip-flop
 - ▣ For all other bits, a flip-flop output is connected to the clock input, thus circuit is not truly synchronous!
 - ▣ Output change is delayed more for each bit toward the MSB.
 - ▣ Resurgent because of low power consumption
- **Synchronous Counters**
 - ▣ Clock is directly connected to the flip-flop clock inputs
 - ▣ Logic is used to implement the desired state sequencing

Ripple Counter

- How does it work?
 - ▣ When there is a positive edge on the clock input of A, A complements
 - ▣ The clock input for flip-flop B is the complemented output of flip-flop A
 - ▣ When flip A changes from 1 to 0, there is a positive edge on the clock input of B causing B to complement



Ripple Counter (continued)

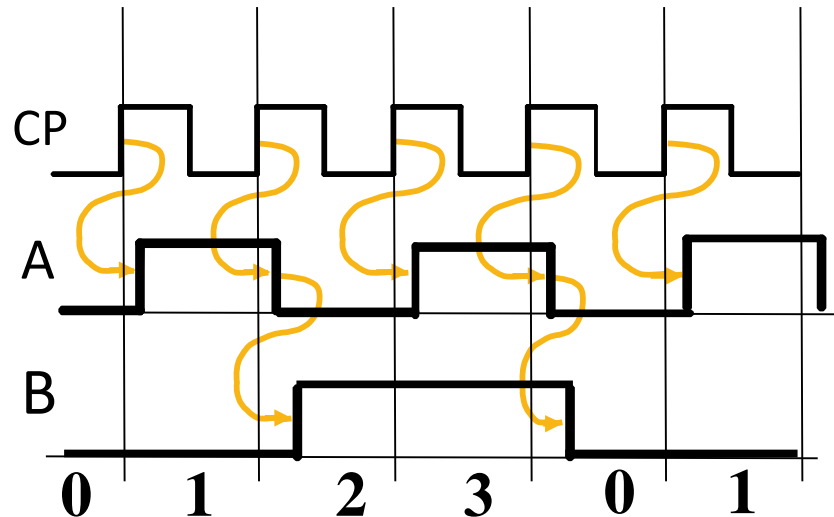
□ The arrows show the cause-effect relationship from the prior slide =>

□ The corresponding sequence of states =>

$(B,A) = (0,0), (0,1), (1,0), (1,1), (0,0), (0,1), \dots$

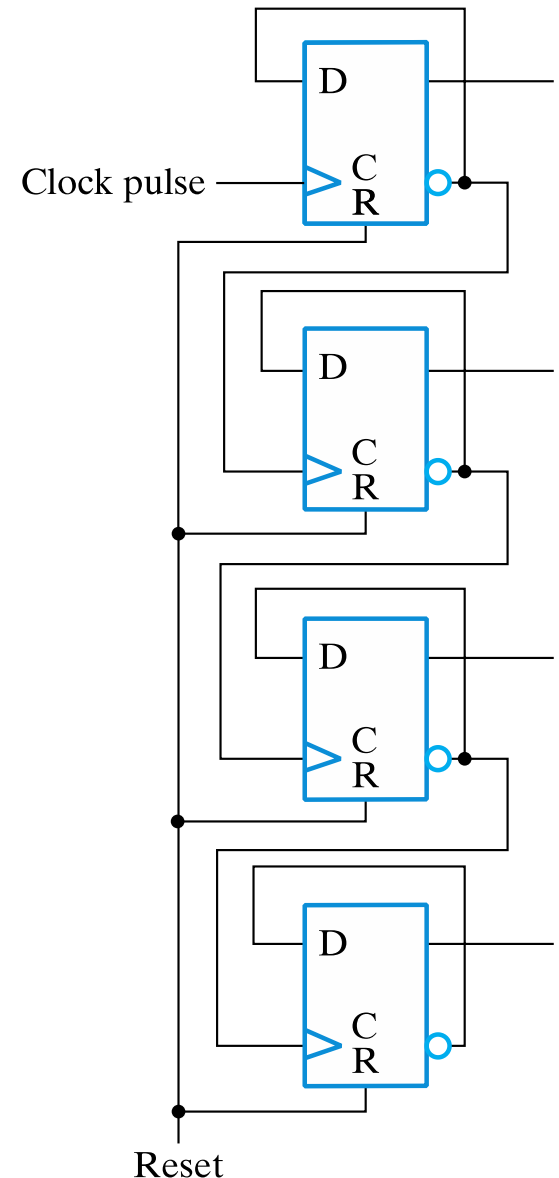
□ Each additional bit, C, D, ... behaves like bit B, changing half as frequently as the bit before it.

□ For 3 bits: $(C,B,A) = (0,0,0), (0,0,1), (0,1,0), (0,1,1), (1,0,0), (1,0,1), (1,1,0), (1,1,1), (0,0,0), \dots$



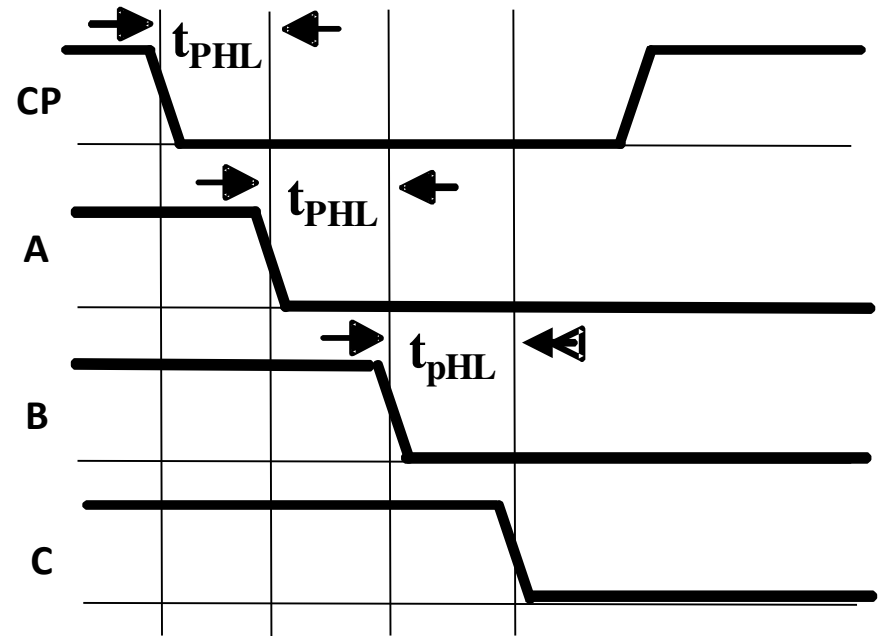
Ripple Counter (continued)

- These circuits are called *ripple counters* because each edge sensitive transition (positive in the example) causes a change in the next flip-flop's state.
- The changes “ripple” upward through the chain of flip-flops, i. e., each transition occurs after a clock-to-output delay from the stage before.
- To see this effect in detail look at the waveforms on the next slide.



Ripple Counter (continued)

- Starting with $C = B = A = 1$, equivalent to $(C,B,A) = 7$ base 10, the next clock increments the count to $(C,B,A) = 0$ base 10. In fine timing detail:
 - The clock to output delay t_{PHL} causes an increasing delay from clock edge for each stage transition.
 - Thus, the count “ripples” from least to most significant bit.
 - For n bits, total worst case delay is $n t_{PHL}$.

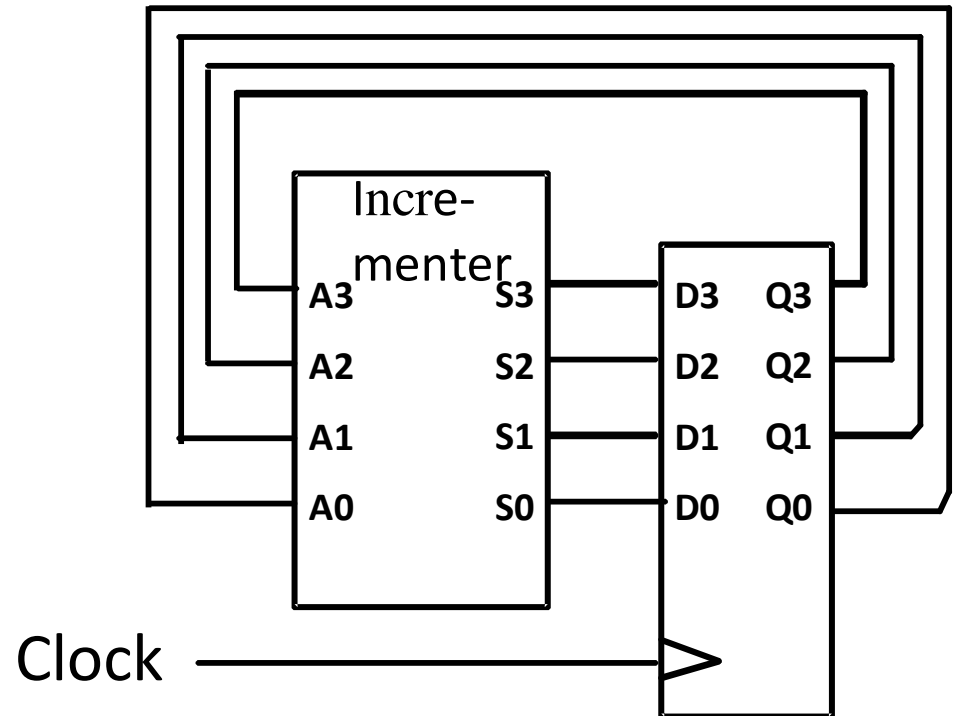


Synchronous Counters

- To eliminate the "ripple" effects, use a common clock for each flip-flop and a combinational circuit to generate the next state.
- For an up-counter, use an incrementer \Rightarrow

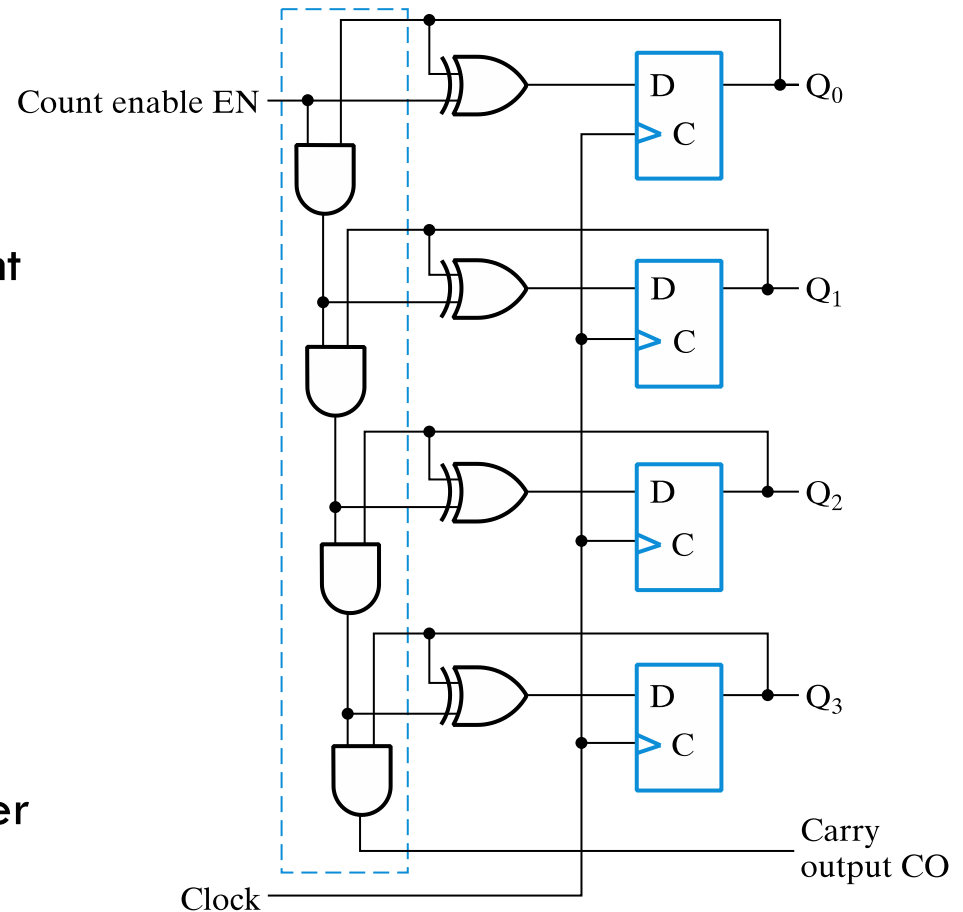
Counting Sequence of Binary Counter

Upward Counting Sequence				Downward Counting Sequence			
Q ₃	Q ₂	Q ₁	Q ₀	Q ₃	Q ₂	Q ₁	Q ₀
0	0	0	0	1	1	1	1
0	0	0	1	1	1	1	0
0	0	1	0	1	1	0	1
0	0	1	1	1	1	0	0
0	1	0	0	1	0	1	1
0	1	0	1	1	0	1	0
0	1	1	0	1	0	0	1
0	1	1	1	1	0	0	0
1	0	0	0	0	1	1	1
1	0	0	1	0	1	1	0
1	0	1	0	0	1	0	1
1	0	1	1	0	1	0	0
1	1	0	0	0	0	1	1
1	1	0	1	0	0	1	0
1	1	1	0	0	0	0	1
1	1	1	1	0	0	0	0



Synchronous Counters (continued)

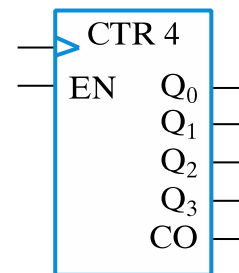
- Internal details =>
- Internal Logic
 - ▣ XOR complements each bit
 - ▣ AND chain causes complement of a bit if all bits toward LSB from it equal 1
- Count Enable
 - ▣ Forces all outputs of AND chain to 0 to “hold” the state
- Carry Out
 - ▣ Added as part of incrementer
 - ▣ Connect to Count Enable of additional 4-bit counters to form larger counters



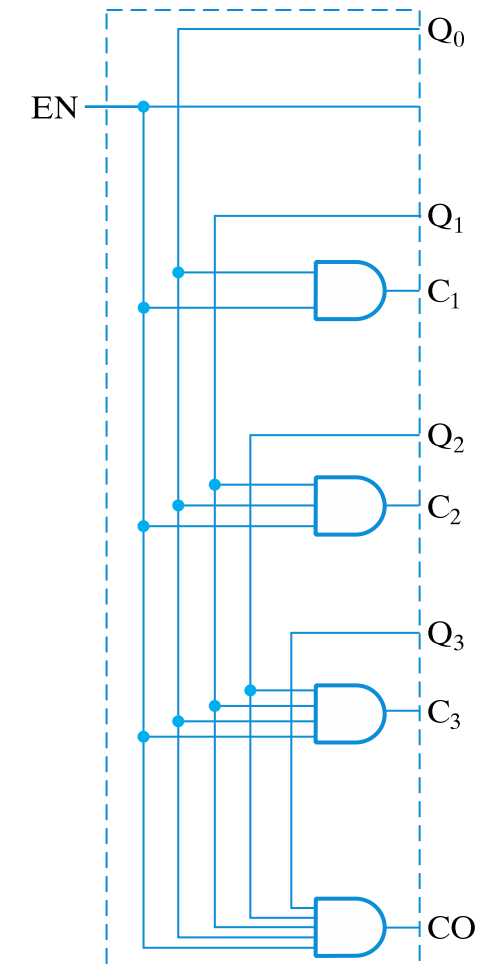
(a) Logic diagram-serial gating

Synchronous Counters (continued)

- Carry chain
 - ▣ series of AND gates through which the carry “ripples”
 - ▣ Yields long path delays
 - ▣ Called *serial gating*
- Replace AND carry chain with ANDs => in parallel
 - ▣ Reduces path delays
 - ▣ Called *parallel gating*
 - ▣ Like carry lookahead
 - ▣ Lookahead can be used on COs and ENs to prevent long paths in large counters
- Symbol for Synchronous Counter



(c) Symbol



(b) Logic diagram-parallel gating

Other Counters

□ See text for:

- *Down Counter* - counts downward instead of upward
- *Up-Down Counter* - counts up or down depending on value a control input such as Up/Down
- *Parallel Load Counter* - Has parallel load of values available depending on control input such as Load

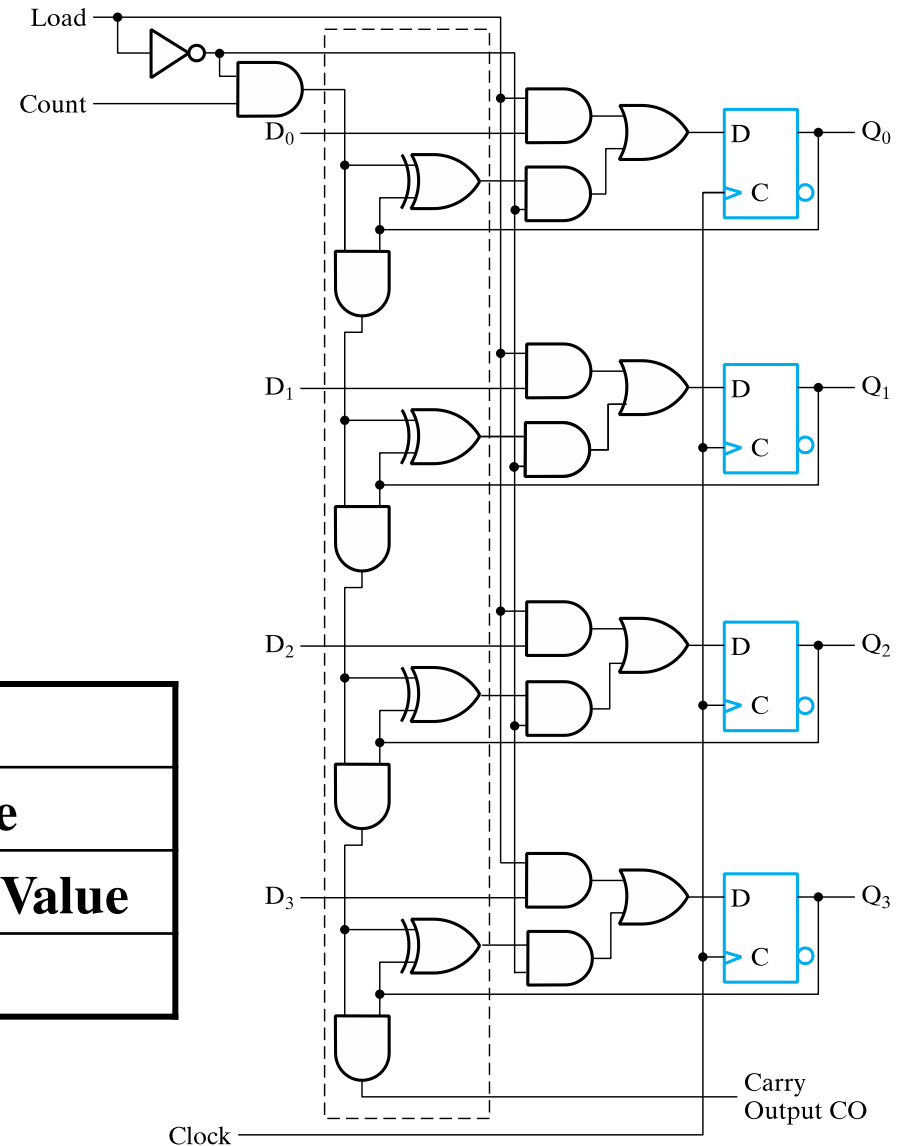
□ *Divide-by- n (Modulo n) Counter*

- Count is remainder of division by n ; n may not be a power of 2 or
- Count is arbitrary sequence of n states specifically designed state-by-state
- Includes modulo 10 which is the *BCD counter*

Counter with Parallel Load

- Add path for input data
 - ▣ enabled for Load = 1
- Add logic to:
 - ▣ disable count logic for Load = 1
 - ▣ disable feedback from outputs for Load = 1
 - ▣ enable count logic for Load = 0 and Count = 1
- The resulting function table:

Load	Count	Action
0	0	Hold Stored Value
0	1	Count Up Stored Value
1	X	Load D



Counter w/ Unused States

- n flip-flops $\Rightarrow 2^n$ binary states
- Unused states: — states that are not used in specifying the sequential ckt —
may be treated as don't-care conditions or
- may be assigned specific next states _ Self-correcting counter:
 - Ensure that when a ckt enter one of its unused states, it eventually goes into one of the valid states after one or more clock pulses so it can resume normal operation.
 - Analyze the ckt to determine the next state from an unused state after it is designed.

Counter w/ Unused States

□ Example:

State Table and Flip-Flop Inputs for Counter

Present State			Next State		
A	B	C	DA = DB = DC = A(t+1)B(t+1)C(t+1)		
0	0	0	0	0	1
0	0	1	0	1	0
0	1	0	1	0	0
1	0	0	1	0	1
1	0	1	1	1	0
1	1	0	0	0	0

The simplified f-f input eqs

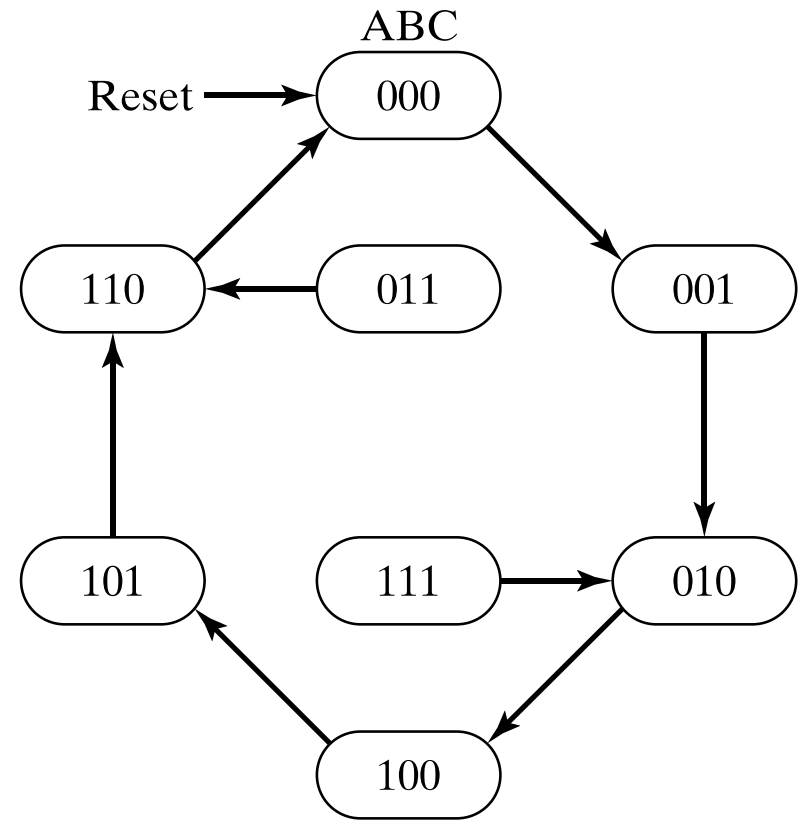
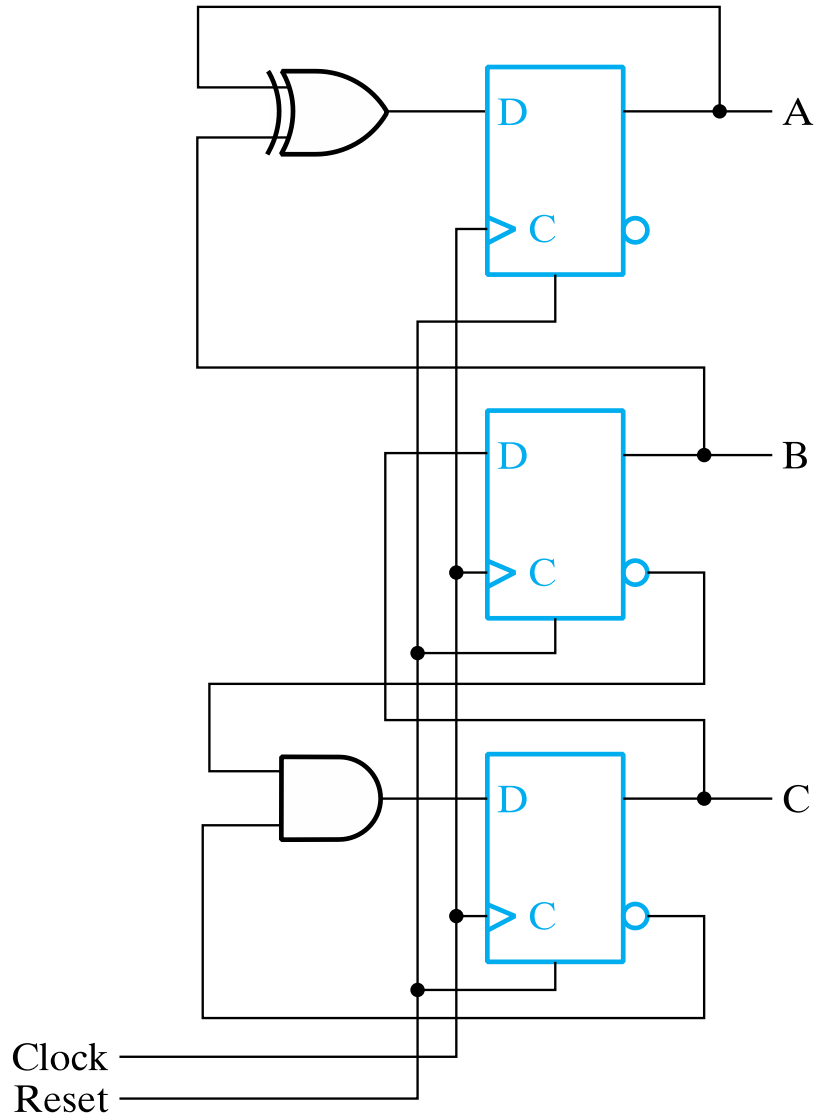
$$D_A = A \oplus B$$

$$D_B = C$$

$$D_C = \overline{B} \overline{C}$$

Two unused states: 011 & 111

Counter w/ Unused States



Design Example: Synchronous BCD

- Use the sequential logic model to design a synchronous BCD counter with D flip-flops
- Input combinations 1010 through 1111 are don't cares

State Table and Flip-Flop Inputs for BCD Counter

Present State				Next State				Output
Q_8	Q_4	Q_2	Q_1	$D_8 = Q_8(t+1)$	$D_4 = Q_4(t+1)$	$D_2 = Q_2(t+1)$	$D_1 = Q_1(t+1)$	Y
0	0	0	0	0	0	0	1	0
0	0	0	1	0	0	1	0	0
0	0	1	0	0	0	1	1	0
0	0	1	1	0	1	0	0	0
0	1	0	0	0	1	0	1	0
0	1	0	1	0	1	1	0	0
0	1	1	0	0	1	1	1	0
0	1	1	1	1	0	0	0	0
1	0	0	0	1	0	0	1	0
1	0	0	1	0	0	0	0	1

Synchronous BCD (continued)

- Use K-Maps to two-level optimize the next state equations and manipulate into forms containing XOR gates:

$$D1 = \overline{Q1}$$

$$D2 = Q2 \oplus Q1 \overline{Q8}$$

$$D4 = Q4 \oplus Q1 Q2$$

$$D8 = Q8 \oplus (Q1 Q8 + Q1 Q2 Q4)$$

- The logic diagram can be draw from these equations

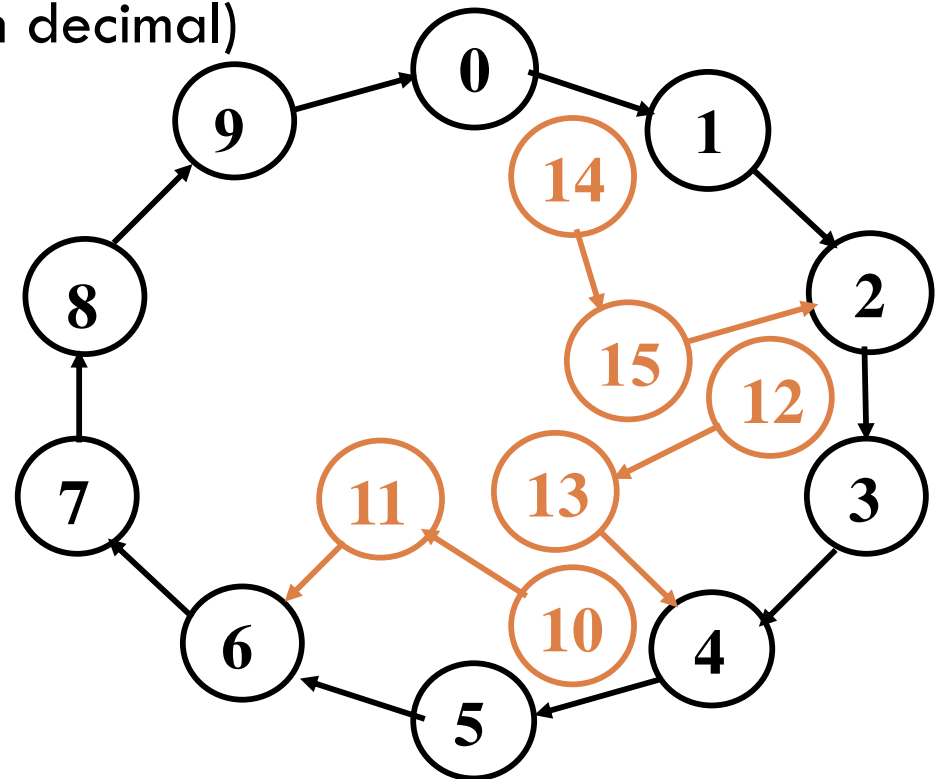
- An asynchronous or synchronous reset should be added

- What happens if the counter is perturbed by a power disturbance or other interference and it enters a state other than 0000 through 1001?

Synchronous BCD (continued)

- Find the actual values of the six next states for the don't care combinations from the equations
- Find the overall state diagram to assess behavior for the don't care states (states in decimal)

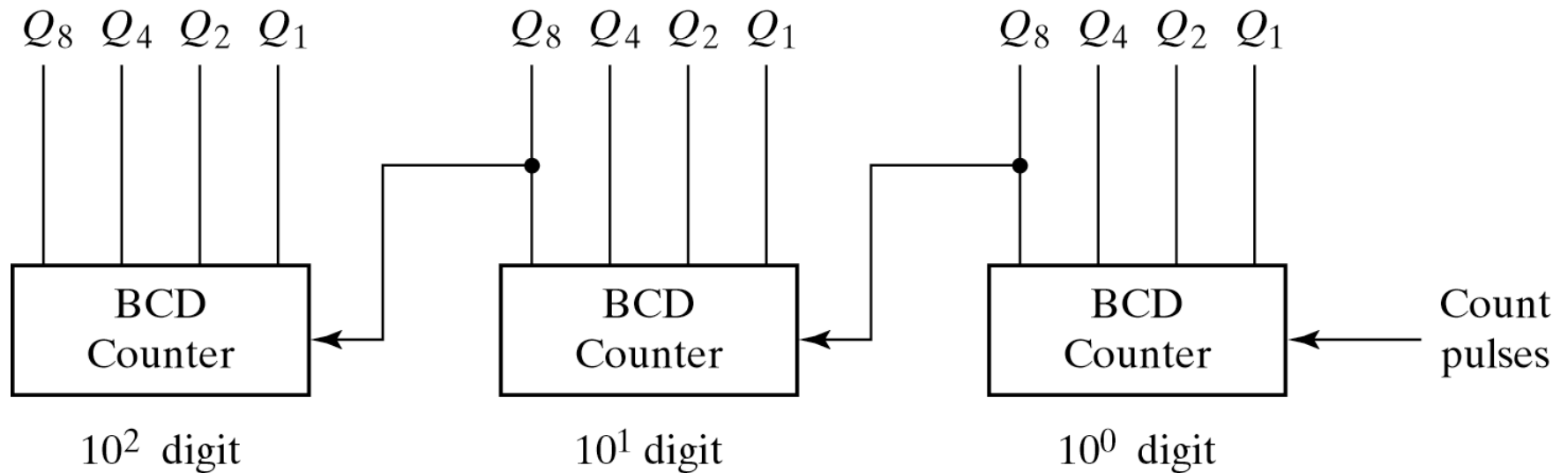
Present State				Next State			
Q8	Q4	Q2	Q1	Q8	Q4	Q2	Q1
1	0	1	0	1	0	1	1
1	0	1	1	0	1	1	0
1	1	0	0	1	1	0	1
1	1	0	1	0	1	0	0
1	1	1	0	1	1	1	1
1	1	1	1	0	0	1	0



Synchronous BCD (continued)

- For the BCD counter design, if an invalid state is entered, return to a valid state occurs within two clock cycles
- Is this adequate? If not:
 - ▣ Is a signal needed that indicates that an invalid state has been entered? What is the equation for such a signal?
 - ▣ Does the design need to be modified to return from an invalid state to a valid state in one clock cycle?
 - ▣ Does the design need to be modified to return from a invalid state to a specific state (such as 0)?
- The action to be taken depends on:
 - ▣ the application of the circuit
 - ▣ design group policy
- See pages 244 of the text.

Three Decade Decimal Counter



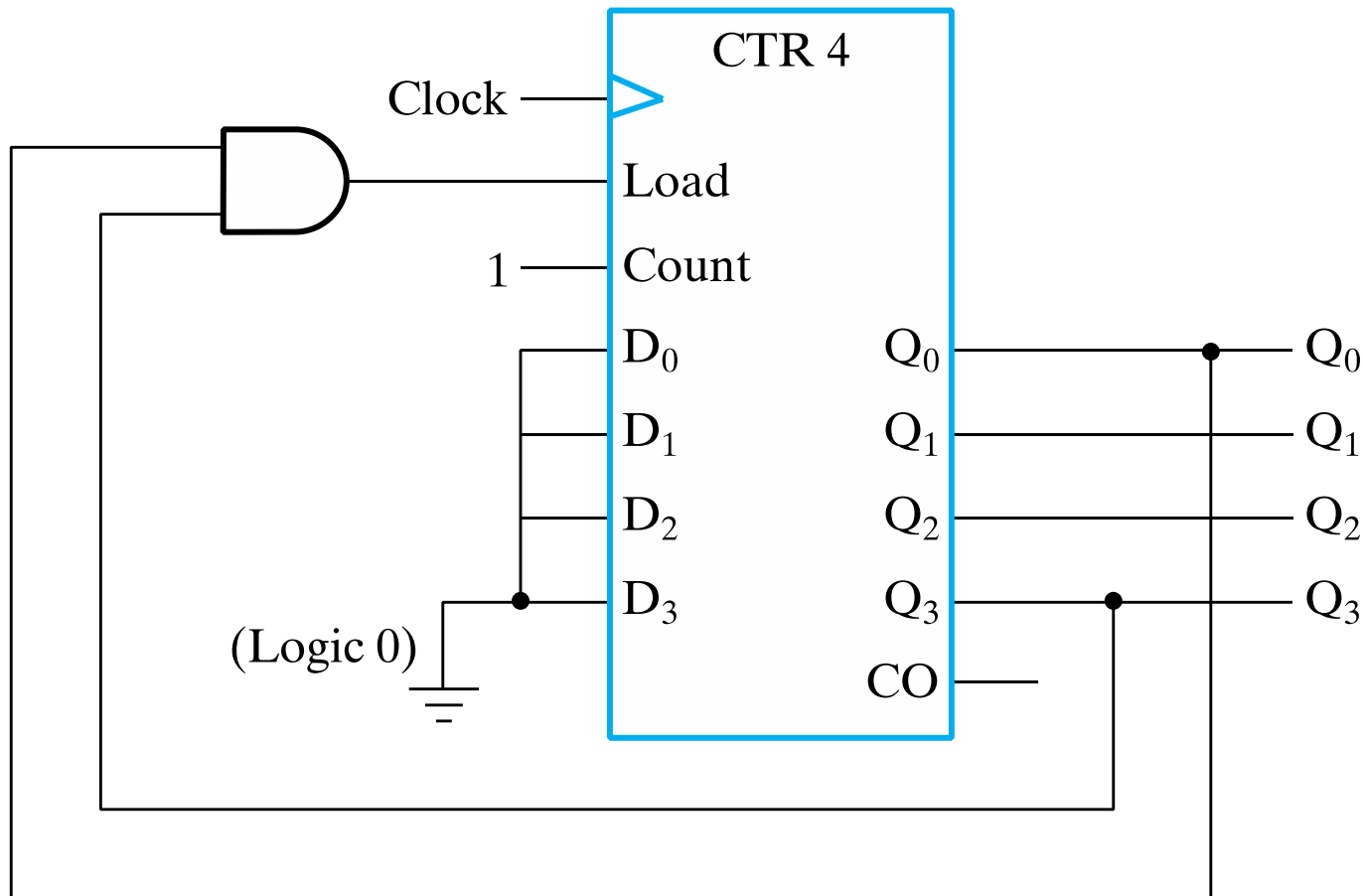
Block Diagram of a Three-Decade Decimal BCD Counter

Counting Modulo N

- The following techniques use an n -bit binary counter with asynchronous or synchronous clear and/or parallel load:
 - ▣ Detect a *terminal count* of N in a Modulo- N count sequence to asynchronously Clear the count to 0 or asynchronously Load in value 0 (These lead to counts which are present for only a very short time and can fail to work for some timing conditions!)
 - ▣ Detect a terminal count of $N - 1$ in a Modulo- N count sequence to Clear the count synchronously to 0
 - ▣ Detect a terminal count of $N - 1$ in a Modulo- N count sequence to synchronously Load in value 0
 - ▣ Detect a terminal count and use Load to preset a count of the terminal count value minus $(N - 1)$
- Alternatively, custom design a modulo N counter as done for BCD

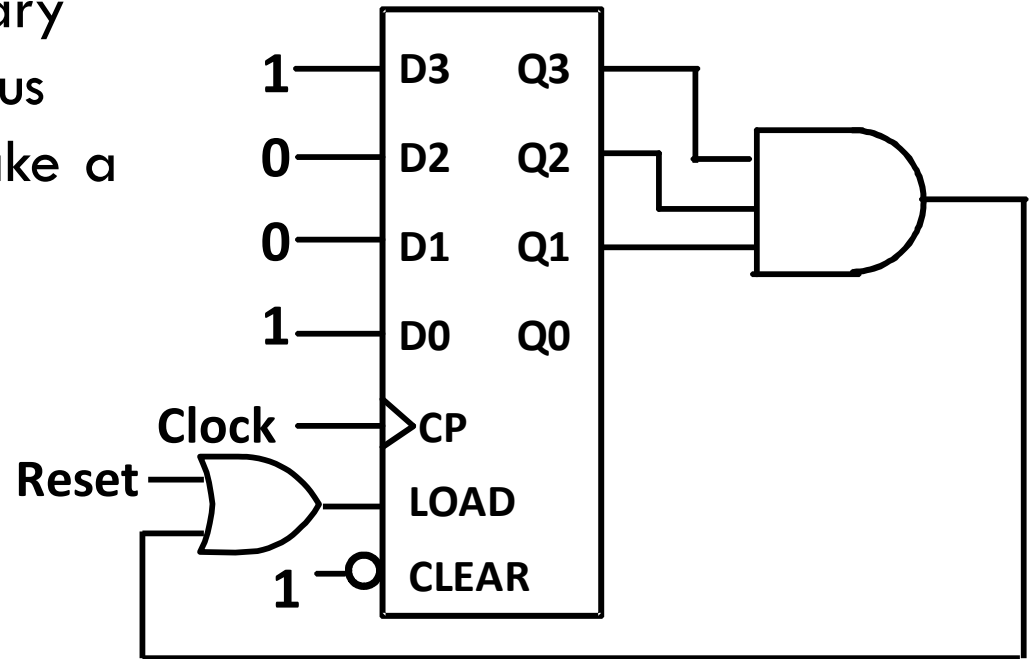
A BCD Counter

- Generate any count sequence:
 - ▣ E.g.: design a BCD counter by using a counter w/ parallel load & async clear



Counting Modulo 6: Synchronously Preset 9 on Reset and Load 9 on Terminal Count 14

- A synchronous, 4-bit binary counter with a synchronous Load is to be used to make a Modulo 6 counter.
- Use the Load feature to preset the count to 9 on Reset and detection of count 14.

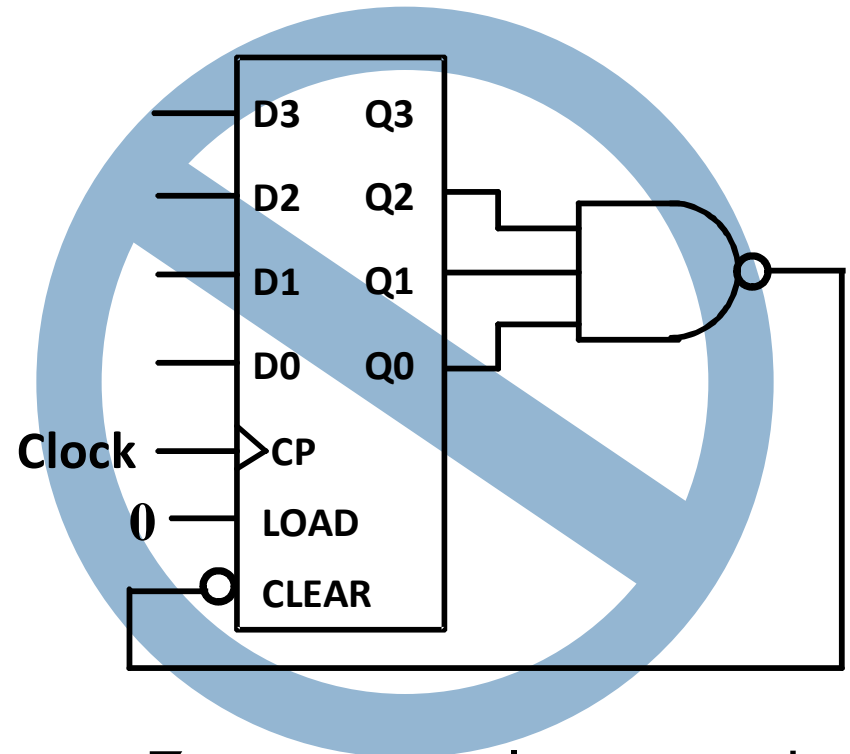


- This gives a count of 9, 10, 11, 12, 13, 14, 9, 10, 11, 12, 13, 14, 9, ...
- If the terminal count is 15 detection is usually built in as Carry Out (CO)

Counting Modulo 7: Detect 7 and Asynchronously Clear

- A synchronous 4-bit binary counter with an asynchronous Clear is used to make a Modulo 7 counter.

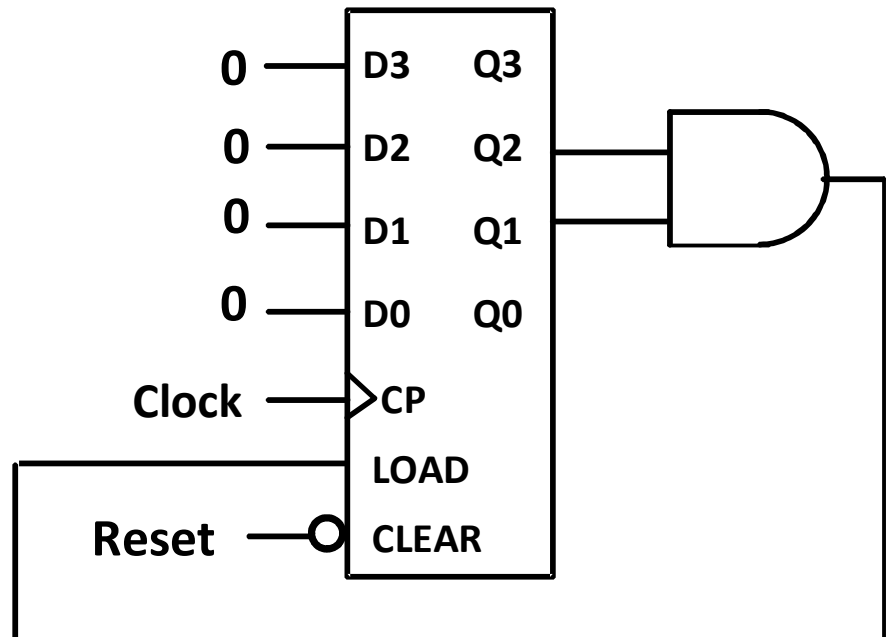
- Use the Clear feature to detect the count 7 and clear the count to 0. This gives a count of 0, 1, 2, 3, 4, 5, 6, 7(short)0, 1, 2, 3, 4, 5, 6, 7(short)0, etc.



- DON'T DO THIS! Existence of state 7 may not be long enough to reliably reset all flip-flops to 0. Referred to as a “suicide” counter! (Count “7” is “killed,” but the designer’s job may be dead as well!)

Counting Modulo 7: Synchronously Load on Terminal Count of 6

- A synchronous 4-bit binary counter with a synchronous load and an asynchronous clear is used to make a Modulo 7 counter
- Use the Load feature to detect the count "6" and load in "zero". This gives a count of 0, 1, 2, 3, 4, 5, 6, 0, 1, 2, 3, 4, 5, 6, 0, ...
- Using don't cares for states above 0110, detection of 6 can be done with Load = $Q_1 Q_2$



4-bit Shift Register with Reset

```
library ieee;  
use ieee.std_logic_1164.all;  
  
entity srg_4_r is  
    port(CLK, RESET, SI : in std_logic;  
        Q : out std_logic_vector(3 downto 0);  
        SO : out std_logic);  
end srg_4_r;
```


4-bit Shift Register with Reset

```
architecture behavioral of srg_4_r is
signal shift : std_logic_vector (3 downto 0);
begin
  process (RESET, CLK)
  begin
    if (RESET = '1') then
      shift <= "0000";
    elsif (CLK'event and (CLK = '1')) then
      shift <= shift(2 downto 0) & SI;
    end if;
  end process;
  Q <= shift;
  SO <= shift(3);
end behavioral;
```

4-bit Binary Counter with Reset

```
library ieee;  
use ieee.std_logic_1164.all;  
use ieee.std_logic_unsigned.all;  
  
entity count_4_r is  
    port(CLK, RESET, EN : in std_logic;  
        Q           : out std_logic_vector(3 downto 0);  
        CO           : out std_logic);  
  
end count_4_r;
```

4-bit Binary Counter with Reset

```
architecture behavioral of count_4_r is  
signal count : std_logic_vector(3 downto 0);  
begin  
  process (RESET, CLK)  
  begin  
    if (RESET = '1') then  
      count <= "0000";  
    elsif (CLK'event and (CLK = '1') and (EN = '1')) then  
      count <= count + "0001";  
    end if;  
  end process;  
  CO <= '1' when count = "1111" and EN = '1' else '0';  
  Q <= count;  
end behavioral;
```