Chapter 7 – Counters and Registers

ELEVENTH EDITION



Principles and Applications



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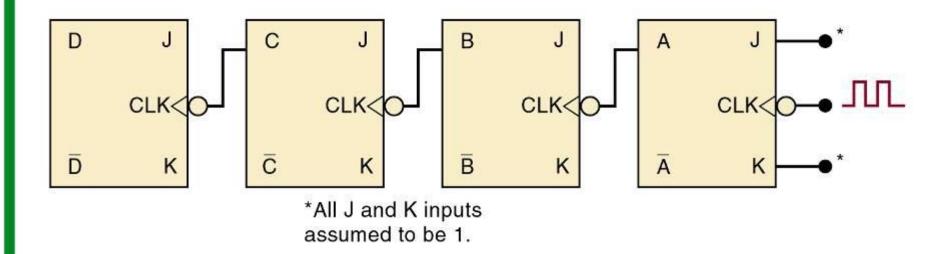
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Chapter 7 Objectives

- Selected areas covered in this chapter.
 - Operation & characteristics of synchronous and asynchronous counters.
 - Analyzing and evaluating various types of counters.
 - Schemes used to decode different types of counters.
 - Counter circuits using different levels of abstraction in HDL.
 - Operation of various types of IC registers.
 - Shift registers and shift register counters using HDL.
 - Troubleshooting techniques used for combinational logic systems to troubleshoot sequential logic systems.

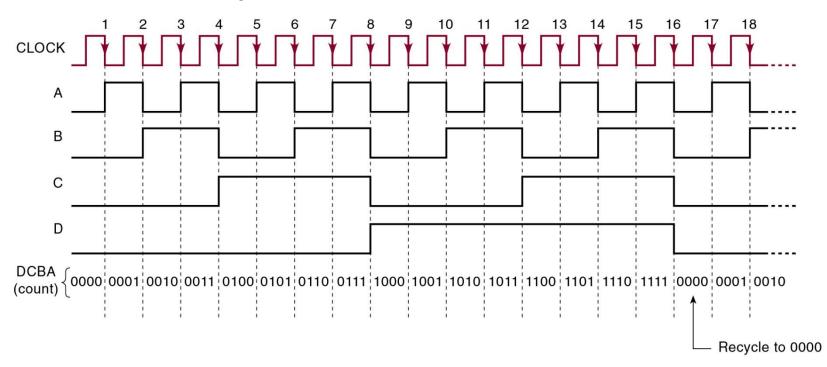
7-1 Asynchronous (Ripple) Counters

- Review of four bit counter operation:
 - Clock is applied only CLK input to FF A.
 - J & K are HIGH in all FFs.
 - Output of FF A is CLK of FF B, etc.
 - FF outputs *D*, *C*, *B*, and *A*, are a 4-bit binary number with *D* as the MSB.



7-1 Asynchronous (Ripple) Counters

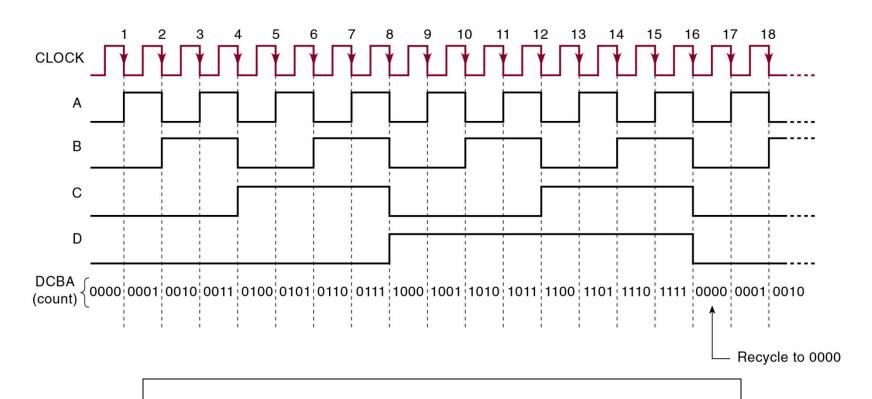
- Review of four bit counter operation:
 - After the NGT of the 15th clock pulse, the counter FFs are recycled back to 0000.



An asynchronous counter—state is *not* changed in exact synchronism with the clock.

7-1 Asynchronous (Ripple) Counters – MOD Number

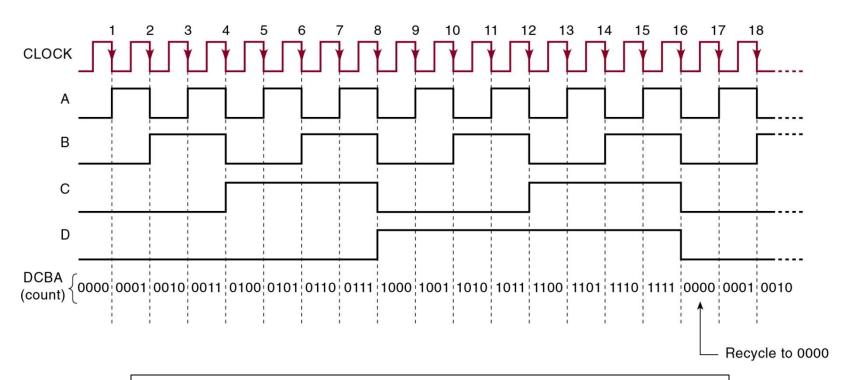
 MOD number is equal to the number of states the counter goes through before recycling.



Adding FFs will increase the MOD number.

7-1 Asynchronous (Ripple) Counters – MOD Number

 Frequency division – each FF will have an output frequency of 1/2 the input.



Output frequency of the last counter FF will be clock frequency divided by MOD of the counter.

7-1 Asynchronous (Ripple) Counters – Signal Flow

- Schematics are normally drawn from left to right.
 - Counters will be drawn from right to left so that the MSB and LSB appear in the appropriate positions.

7-2 Propagation Delay in Ripple Counters

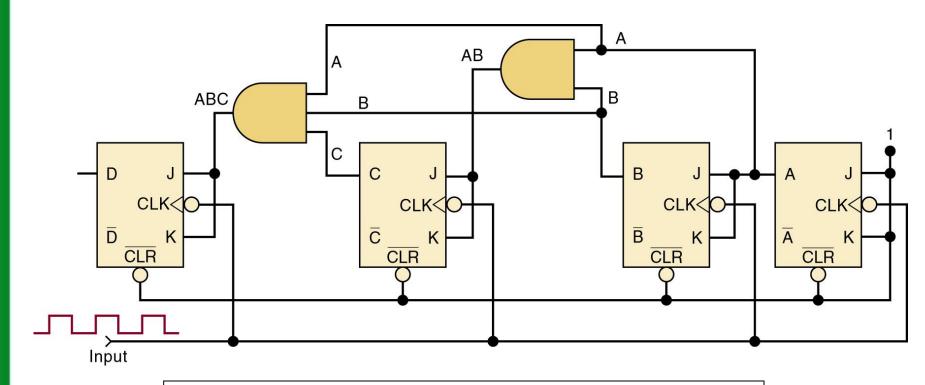
- Ripple counters are simple—requiring the fewest components to produce a given operation.
 - Cumulative propagation delay can cause problems at high frequencies.
- If the period between input pulses is made longer than the total propagation delay of the counter, problems can be avoided
 - For proper operation: T_{clock} ≥ N x t_{pd}
 - Maximum frequency: $F_{\text{max}}=1/N \times t_{\text{pd}}$

7-2 Propagation Delay in Ripple Counters

- Asynchronous counters are not useful at very high frequencies—especially for counters with large numbers of bits.
 - Erroneous count patterns can generate glitches
 - Signals produced by systems using asynchronous counters.

7-3 Synchronous (Parallel) Counters

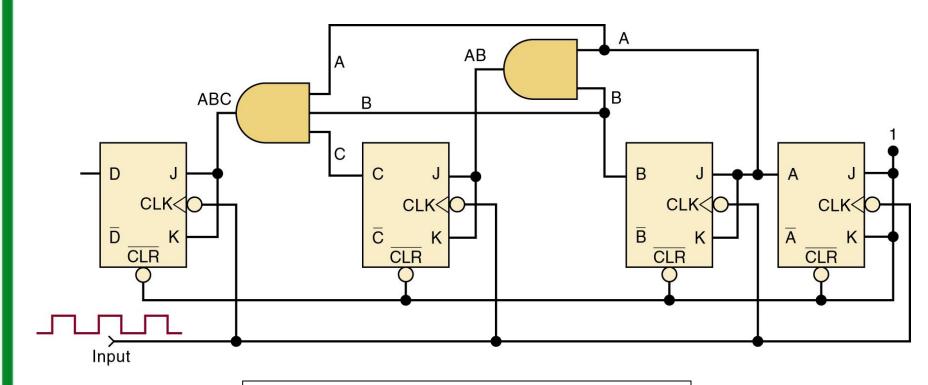
 In synchronous or parallel counters, all FFs are triggered simultaneously (in parallel) by the clock.



Synchronous counters can operate at much higher frequencies than asynchronous counters.

7-3 Synchronous (Parallel) Counters

 Each FF has J & K inputs which are HIGH only when outputs of all lower-order FFs are HIGH.



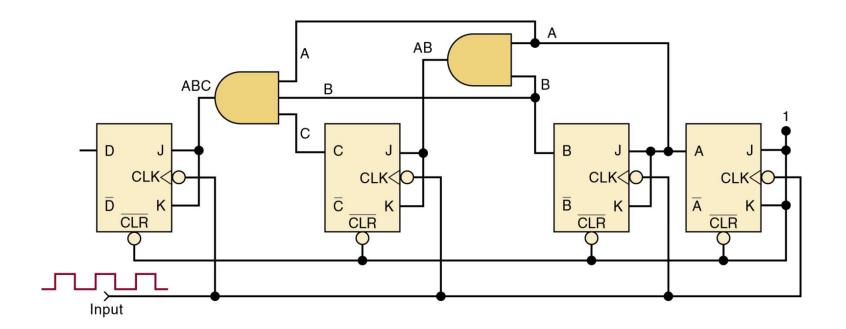
The total propagation delay will be the *same* for *any* number of FFs.

7-3 Synchronous (Parallel) Counters

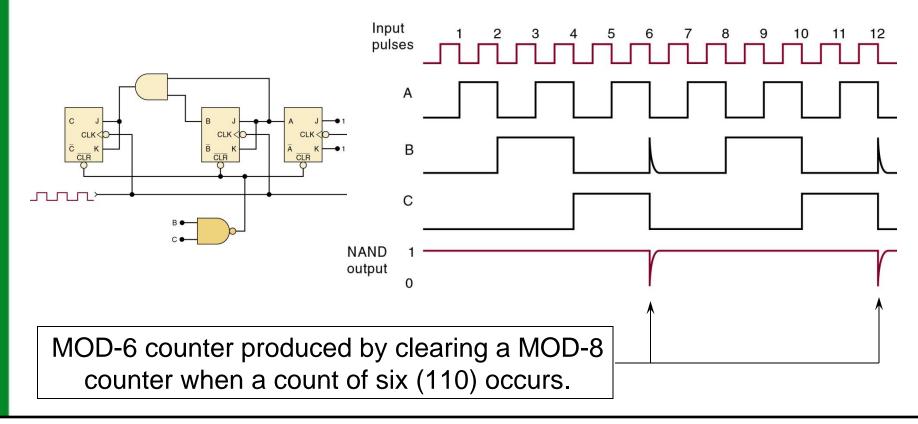
For this circuit to count properly, on a given NGT of the clock, only those FF that are supposed to toggle on that NGT should have J = K = 1 when NGT occurs.

Count	D	O	В	Α
0	0	0	0	0
1	0	0	0	1
1 2 3	0	0 0 0	1	0
3	0	0	1	1 0 1
4		1	0	0
4 5	0 0	1	0	1
6 7	0	1	1	0
7	0	1	1	1 0 1
8	1	0	0	0
9	1	0	0	
10	1	0 0	1	0
11	1	0	1	1 0 1
12	1	1		0
13	1	1	0	1
14	1	1	1	1 0 1
15	1	1	1	1
0	0	0	0	0
21479	160	13	20	*
626		33	22	*
		etc.		

- The basic synchronous counter shown is limited to MOD numbers that are equal to 2^N.
 - Where N is the number of FFs.



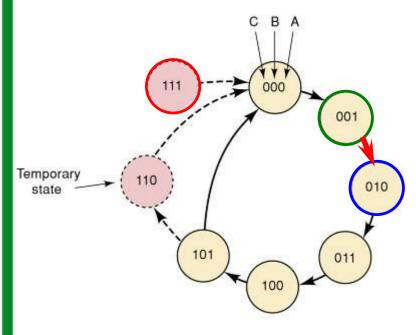
- The basic counter can be modified to produce MOD numbers less than 2^N.
 - By allowing the counter to skip states that are normally part of the counting sequence.



- •
- Changing the MOD number.
 - Find the smallest MOD required so that 2^N is less than or equal to the requirement.
 - Connect a NAND gate to the asynchronous CLEAR inputs of all FFs.

Determine which FFs are
HIGH at the desired count and connect the outputs of these
FFs to the NAND gate inputs.

State transition diagram for the MOD-6 counter

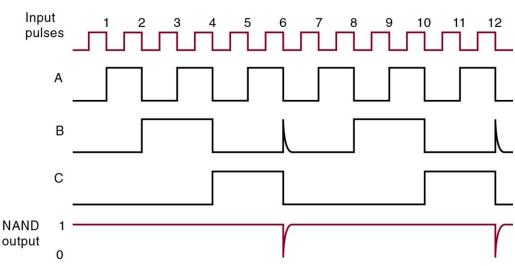


Each circle represents one of the possible counter states.

Arrows indicate how one state changes to another—in response to an input clock pulse.

There is no arrow to the 111 state as the counter can *never* advance to that state.

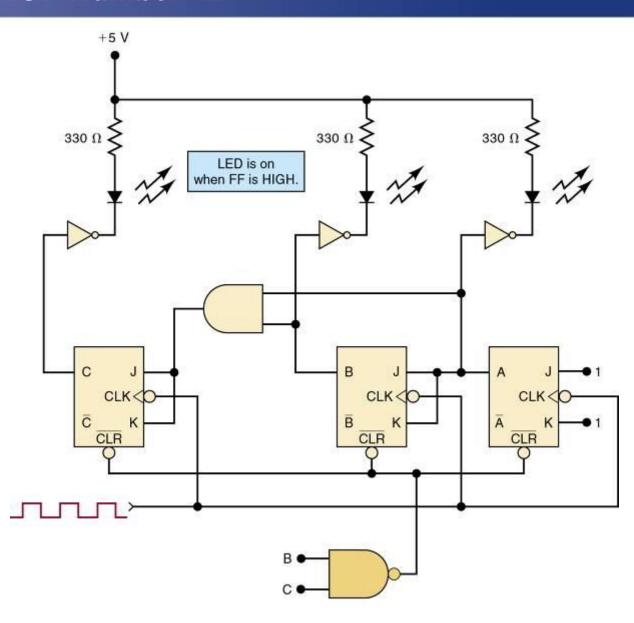
The 111 state *can* occur on power-up when the FFs come up in random states.



7-4 Counters with MOD Number <2^N

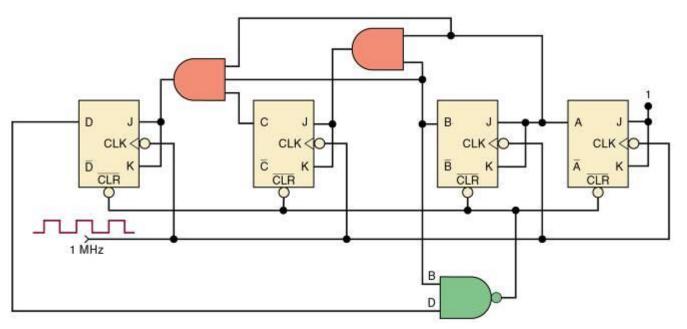
Display of counter states is often done with an LED

The MOD-6 counter lights the LED on HIGH output.



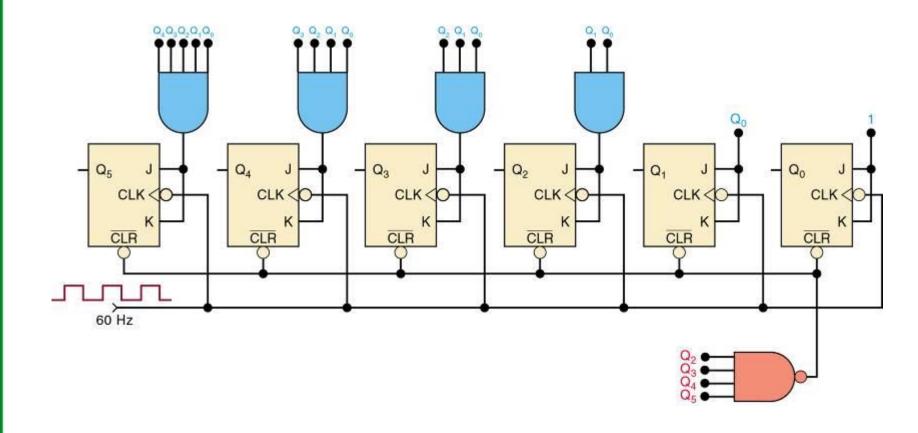
7-4 Counters with MOD Number <2^N

- Decade counters are widely used for counting events, and displaying results in decimal form.
 - A decade counter is any counter with 10 distinct states, regardless of the sequence.
 - A BCD counter is a decade counter that counts from binary 0000 to 1001.



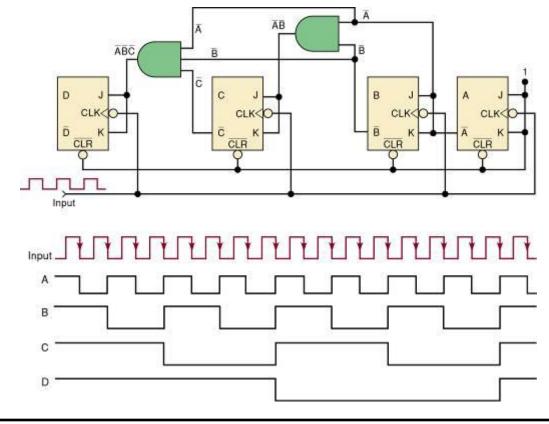
Any MOD-10 counter is a decade counter.

Mod-60 Counter

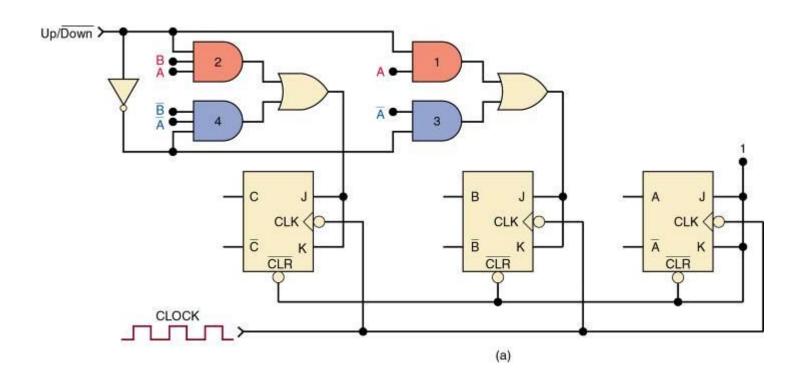


- A synchronous down counter is constructed in a similar manner to an up counter.
 - It uses the inverted FF outputs to control the higherorder J, K inputs.

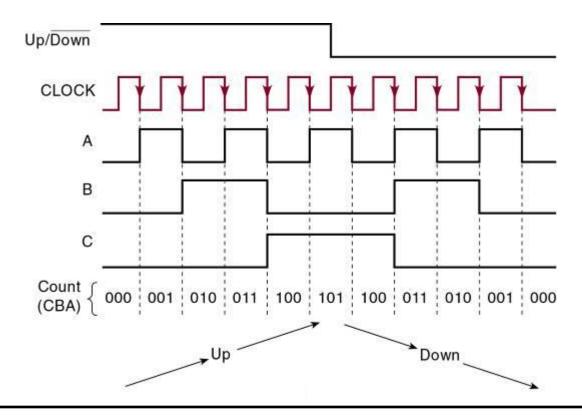
Synchronous, MOD-16, down counter and output waveforms.



- In a parallel up/down counter, the control input controls the values fed to the J and K inputs of the successive FFs.
 - The normal FF outputs or the inverted FF outputs.

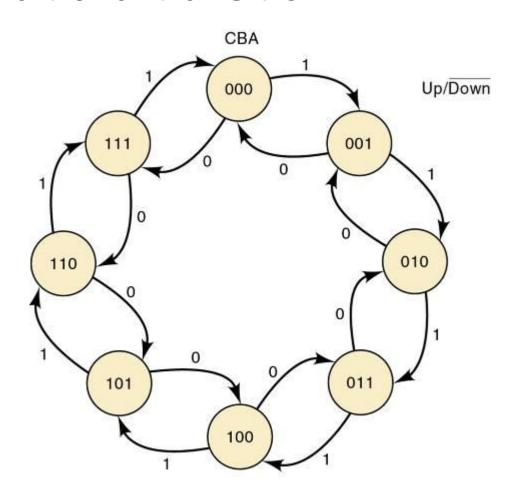


- For the first five clock pulses, Up/Down = 1.
 - The counter counts up.
- For the last five pulses, Up/Down = 0.
 - The counter counts down.



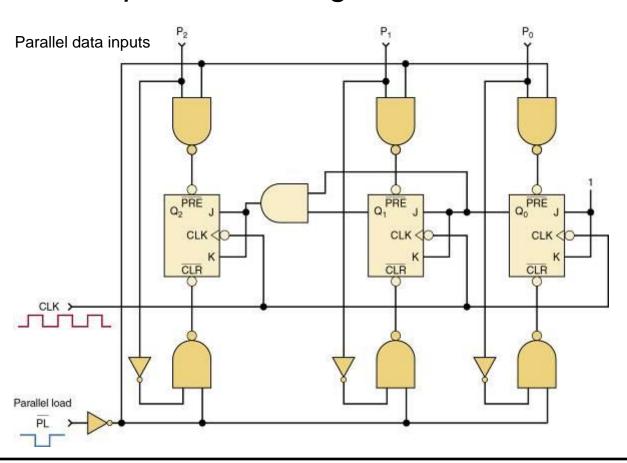
 Note that there are two arrows leaving each state's bubble—a conditional transition.

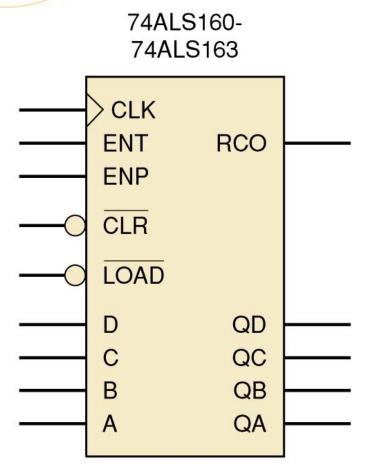
The next state for this counter is dependent upon the logic level applied to the control input.



- •
- A presettable counter can be set to any desired starting point—synchronously or asynchronously.
 - Preset is also called parallel loading the counter.

Synchronous counter with asynchronous parallel load.





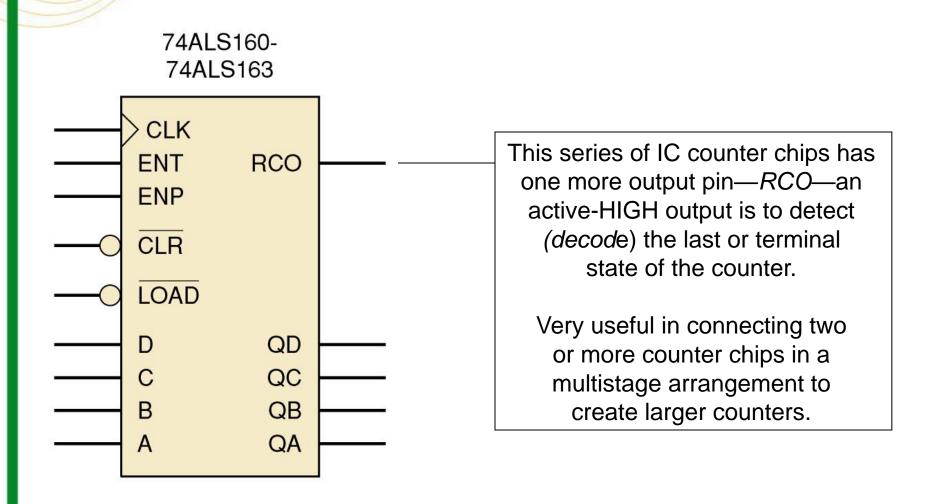
Counter contains four FFs.

FFs are triggered by a PGT at the *CLK* input.

Active-low asynchronous CLEAR input.

Can be preset to any value by applying an active-low LOAD input to the *A*, *B*, *C*, and *D* inputs .

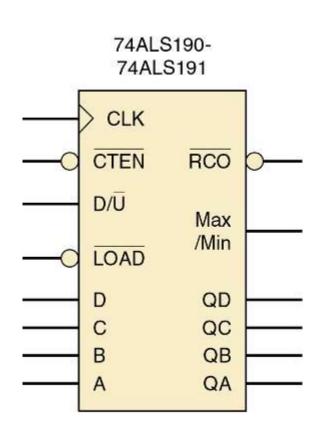
Part Number	Modulus
74ALS160	10
74ALS161	16
74ALS162	10
74ALS163	16



TTL 74ALS160 – 74ALS163 Function Table

CLR	LOAD	ENP	ENT	CLK	Function	Part Numbers
L	Х	Х	Х	Х	Asynch. Clear	74ALS160 & 74ALS161
L	Х	Х	X	1	Synchr. Clear	74ALS162 & 74ALS163
Н	L	Х	X	1	Synchr. Load	All
Н	Н	Н	Н	1	Count up	All
Н	Н	L	Х	Х	No change	All
Н	Н	×	L	X	No change	All

74ALS190 and 74ALS191 series ICs are recycling, four-bit counters.

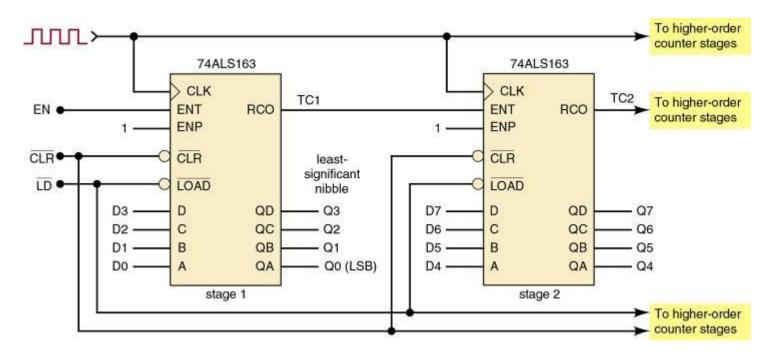


Part Number	Modulus
74ALS190	10
74ALS191	16

74ALS190-74ALS191 Function Table

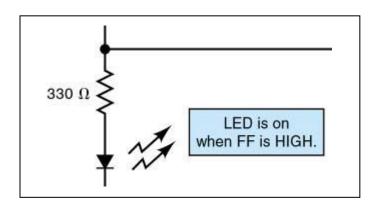
LOAD	CTEN	D/Ū	CLK	Function
L	Х	Х	Х	Asynch. Load
Н	L	L	1	Count up
Н	Ĺ	Н	1	Count down
Н	Н	Х	X	No change

- Many standard IC counters have been designed to make it easy to connect multiple chips to create circuits with a higher counting range.
 - A multistage or cascading arrangement.



74ALS163s in a two-stage arrangement to extend the maximum counting range.

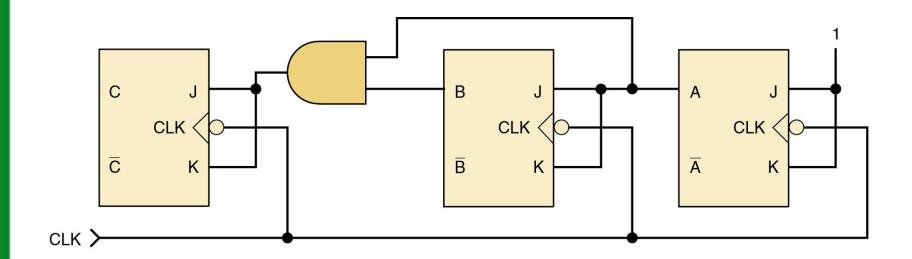
- Digital counters are often used in applications where the count represented by FF states must somehow be determined or displayed.
 - One of the simplest means for displaying contents of a counter is connecting the FF output to an LED.



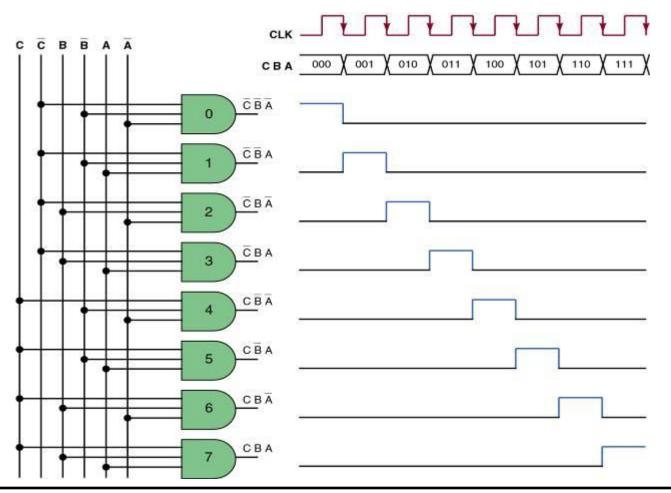
Active-HIGH decoder output.

The LED method becomes inconvenient as the size (number of bits) of the counter increases. It is much harder to decode the display mentally.

- Decoding is the conversion of a binary output to a decimal value—a form immediately recognized.
 - The active-HIGH decoder shown can be used to light an LED representing each decimal number 0 to 7.



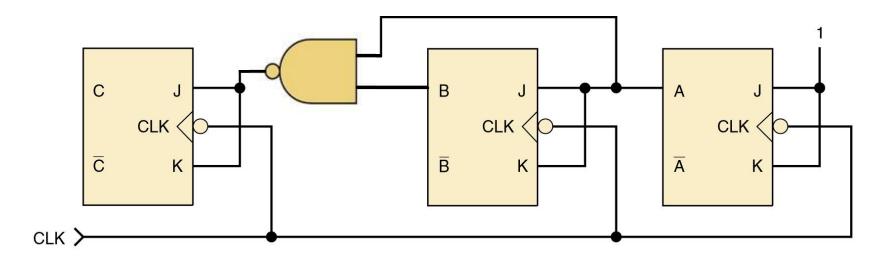
 Decoding is the conversion of a binary output to a decimal value—a form immediately recognized.



MOD-8
Active-HIGH
decoder output.

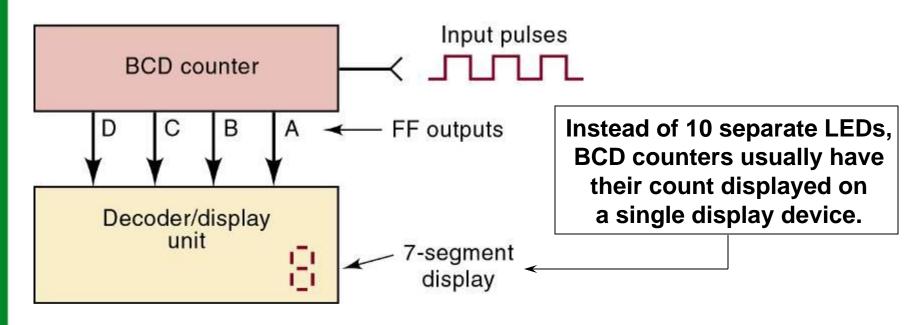
The active-HIGH decoder shown can be changed to an active-LOW type.

Active-LOW decoding is obtained by replacing the **AND** gates with **NAND** gates.



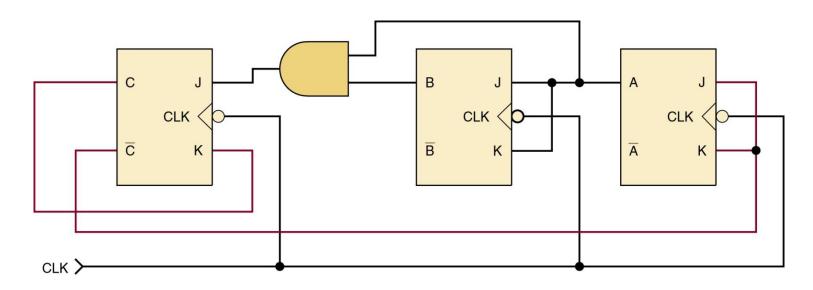
The decoder outputs now produce a normally HIGH signal, which goes LOW only when the number being decoded occurs.

- A BCD counter has 10 states, decoded to provide 10 outputs corresponding to decimal digits 0 – 9.
 - Represented by the states of the counter FFs.
 - The 10 outputs can control 10 individual indicator LEDs for a visual display.



7-9 Analyzing Synchronous Counters

Synchronous up counter.



Control input expressions.

$$J_C = A \cdot B$$

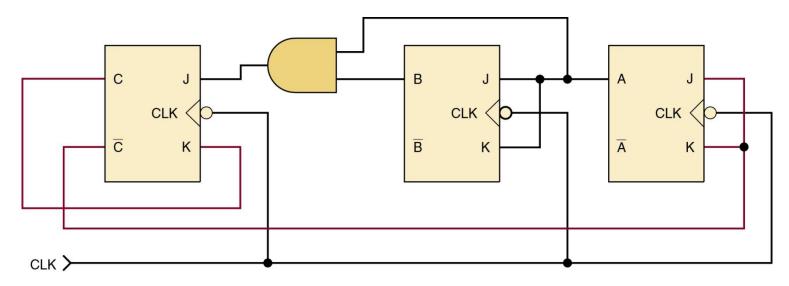
$$K_C = C$$

$$J_B = K_B = A$$

$$J_A = K_A = \overline{C}$$

7-9 Analyzing Synchronous Counters

 Synchronous counters can be custom-designed to generate any desired count sequence.



Synchronous up-counter.

$$J_C = A \cdot B$$
 $K_C = C$
 $J_B = K_B = A$
 $J_A = K_A = \overline{C}$
Control input expressions.

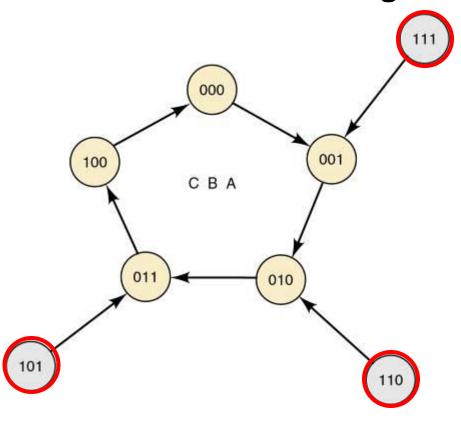
7-9 Analyzing Synchronous Counters

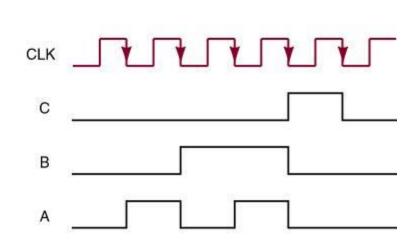
- Analyze counter designs of this type by predicting FF control inputs for each state of the counter.
 - A PRESENT state/NEXT state table is very useful for this purpose.

PRESENT State		Control Inputs					NEXT State				
С	В	A	J _C	Kc	J _B	K _B	J_A	KA	С	В	A
0	0	0	0	0	0	0	1	1	0	0	1
0	0	1	0	0	1	1	1	1	0	1	0
0	1	0	0	0	0	0	1	1	0	1	1
0	1	1	1	0	1	1	1	1	1	0	0
1	0	0	0	1	0	0	0	0	0	0	0
1	0	1	0	1	1	1	0	0	0	1	1
1	1	0	0	1	0	0	0	0	0	1	0
1	1	1	1	1	1	1	0	0	0	0	1

7-9 Analyzing Synchronous Counters

Synchronous up counter state transition diagram and waveform.



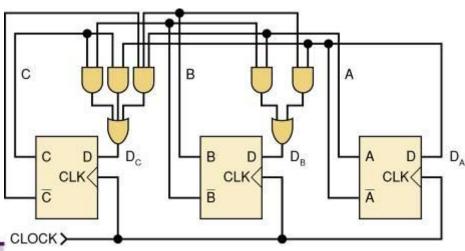


Highlighted information indicates this counter design is self-correcting.

7-9 Analyzing Synchronous Counters

Synchronous counter built using D-type FFs.

Control circuitry will typically be more complex than an equivalent JK-type counter,



PRESENT State			Control Inputs			NEXT State		
С	В	Α	D _C	D _B	DA	С	В	Α
0	0	0	0	0	1	0	0	1
0	0	1	0	1	0	0	1	0
0	1	0	0	1	1	0	1	1
0	1	1	1	0	0	1	0	0
1	0	0	1	0	1	1	0	1
1	0	1	1	1	0	1	1	0
1	1	0	1	1	1	1	1	1
1	1	1	0	0	0	0	0	0

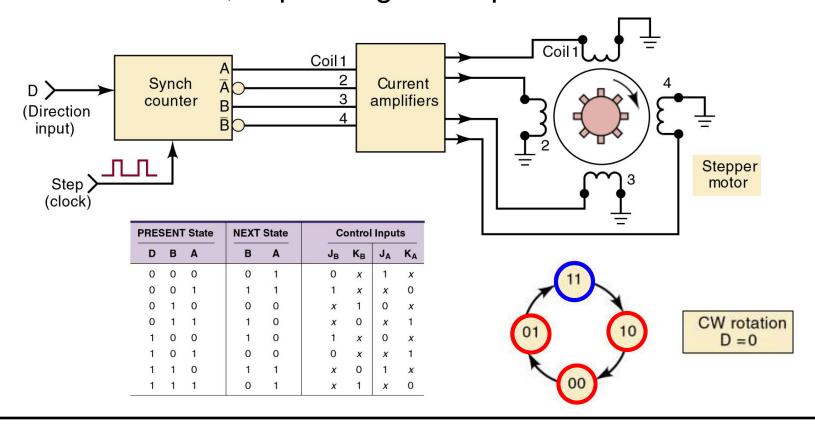
The number of synchronous inputs to control is reduced by half

7-10 Synchronous Counter Design

- Common design method using J-K flip-flops in a synchronous counter configuration.
 - Determine the desired number of bits (FFs) and the desired counting sequence.
 - Draw the state transition diagram showing all possible states—including those not part of the desired counting sequence.
 - Use the state transition diagram to set up a table that lists all PRESENT states and their NEXT states.
 - Add a column for each J and K input & indicate levels required to produce transition to the NEXT state.
 - Design the logic circuits to generate levels required at each input, and implement the final expressions.

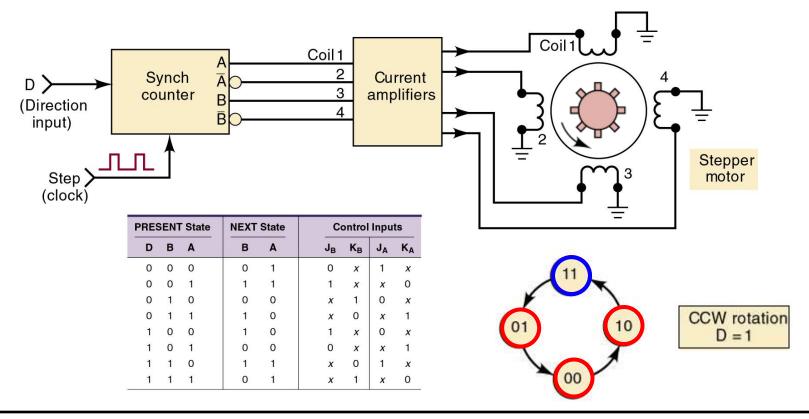
7-10 Synchronous Counter Design

- A stepper motor rotates in steps, not continuous motion—typically 15 degrees per step.
 - A practical application of synchronous counter design.
 - Reversible, depending on output level.



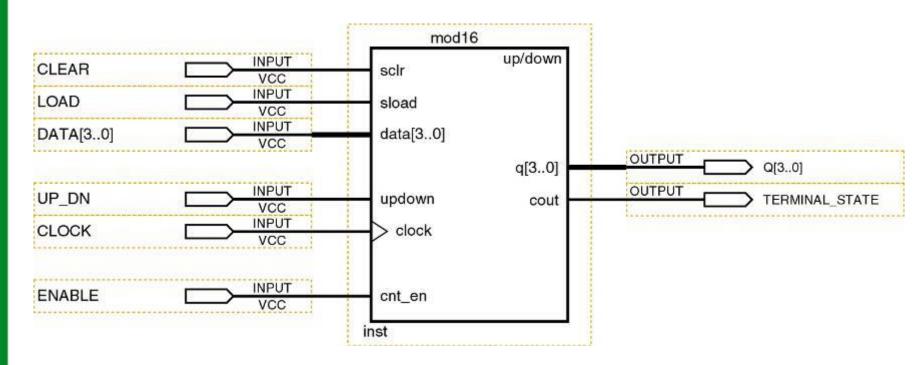
7-10 Synchronous Counter Design

- A stepper motor rotates in steps, not continuous motion—typically 15 degrees per step.
 - A practical application of synchronous counter design.
 - Reversible, depending on output level.



7-11 Altera Library Functions for Counters

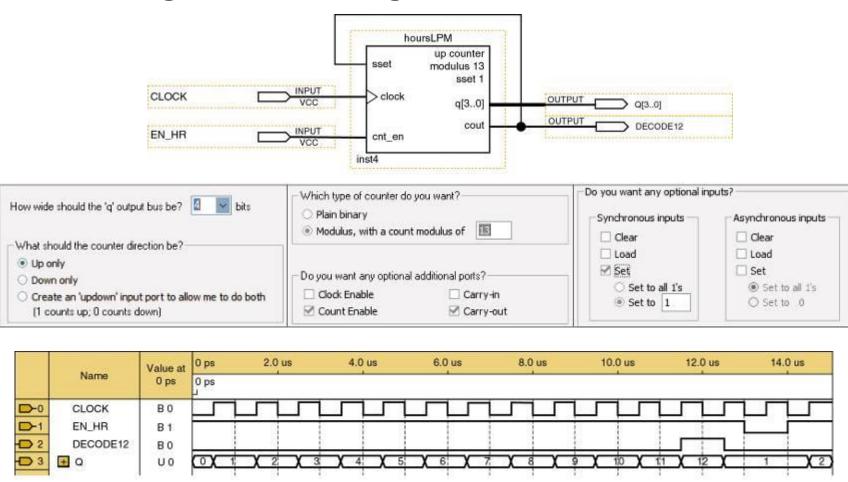
- The Quartus Block Editor can program a PLD with any counter using flip-flops and gates.
 - These macro-functions are in the maxplus2 library.



A full-featured MOD-16 up/down counter.

7-11 Altera Library Functions for Counters

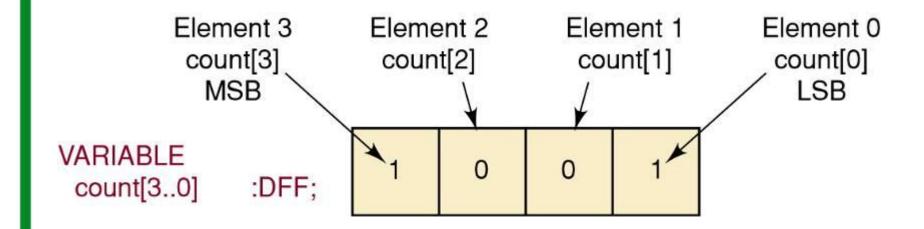
Digital clock hours counter—block diagram, MegaWizard settings & simulation results.



7-12 HDL Counters

- Methods to describe counter circuits using HDL primarily use synchronous techniques.
 - All flip-flops update simultaneously in response to the same clock event.
 - All bits in a count sequence go from their PRESENT state to their prescribed NEXT state simultaneously,
- State Transition Description Methods
 - The PRESENTstate/NEXT state table is the equivalent of the truth table.

- 0
- State descriptions in AHDL
 - The first important step is to declare the counter output pins properly— as a bit array.



State descriptions in AHDL

```
SUBDESIGN fig7 43
 3
       clock : INPUT;
       q[2..0] :OUTPUT; -- declare 3-bit array of output bits
4
 5
 6
    VARIABLE
7
       count[2..0] :DFF; -- declare a register of D flip flops.
8
    BEGIN
10
       count[].clk = clock; -- connect all clocks to synchronous source
11
       12
          count[].d = count[].q + 1; -- increment current value by one
       ELSE count[].d = 0; -- recycle to zero: force unused states to 0
13
14
       END IF;
15
       q[] = count[].q; -- transfer register contents to outputs
16
    END:
```

The current state of the counter is evaluated (count[].q) on line 11, and if it is less than the highest desired count value, it uses the description count[].d count.q + 1 (line 12).

State descriptions in AHDL

```
SUBDESIGN fig7 43
 3
       clock : INPUT;
       q[2..0] :OUTPUT; -- declare 3-bit array of output bits
4
 5
 6
    VARIABLE
7
       count[2..0] :DFF; -- declare a register of D flip flops.
8
    BEGIN
10
       count[].clk = clock; -- connect all clocks to synchronous source
11
       count[].d = count[].q + 1; -- increment current value by one
12
       ELSE count[].d = 0; -- recycle to zero: force unused states to 0
13
14
       END IF;
15
       q[] = count[].q; -- transfer register contents to outputs
16
    END:
```

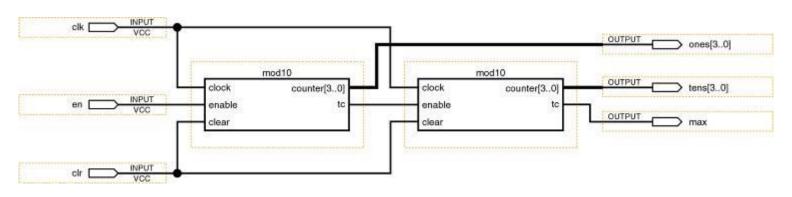
When the counter has reached the highest desired state (or higher), the *IF* statement test will be false, resulting in a NEXT-state input value of zero, which recycles the counter.

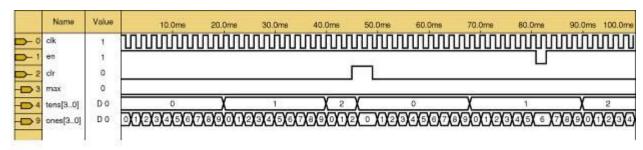
7-13 Wiring HDL Modules Together

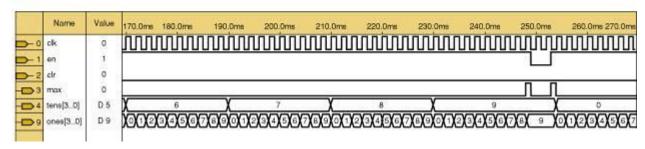
- Designing large digital systems is much easier if the system is subdivided into smaller, manageable modules that are interconnected.
 - The essence of the concept of hierarchical design.
- Consider a recycling, MOD-100 BCD counter with a synchronous clear.
 - Creating a MOD-10 BCD counter module, cascading synchronously two of thesein a higher-level design file is the easiest way to do this.

7-13 Wiring HDL Modules Together

Block diagram design and simulation results for MOD-100 BCD counter design.







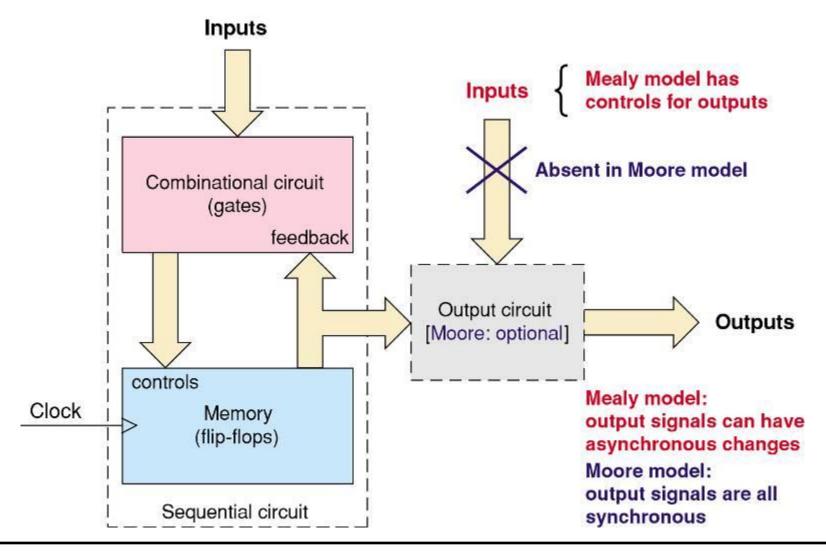
Decoding the AHDL MOD-5 counter

```
SUBDESIGN fig7 40
 1
 3
           clock
                       : INPUT;
           q[2..0]
                       :OUTPUT;
 6
     VARIABLE
           count[2..0] :DFF; --create a 3-bit register
     BEGIN
                                 --connect all clocks in parallel
 9
           count[].clk = clock;
10
11
                 CASE count [] IS
12
                       Present
                                   Next
13
14
                                        count [] .d = 1;
                       WHEN 0
                                        count[].d = 2;
15
                       WHEN 1
                                        count[].d = 3;
16
                       WHEN 2
17
                                        count[].d = 4;
                       WHEN
                                        count[].d = 0;
18
                       WHEN
19
                       WHEN OTHERS =>
                                        count[].d = 0;
20
                  END CASE;
21
            q[] = count[]; -- assign register to output pins
22
     END;
```

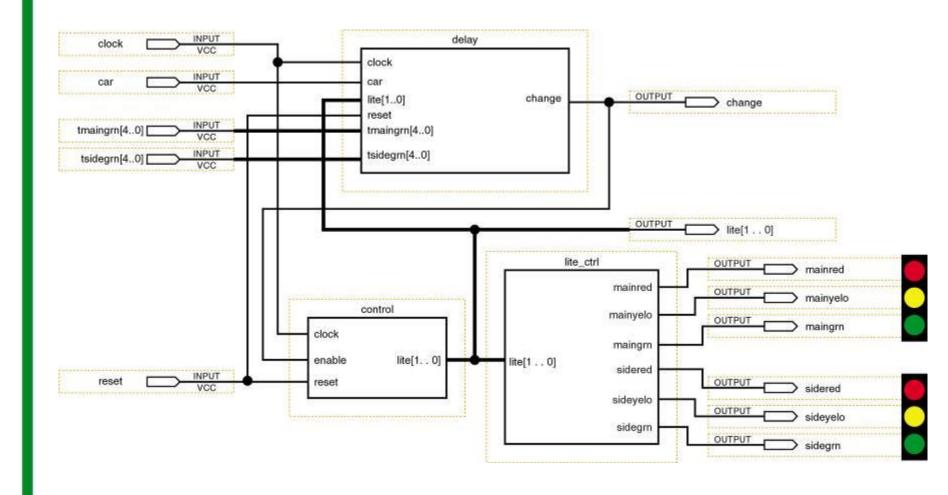
7-14 State Machines

- The term state machine refers to a circuit that sequences through a set of predetermined states.
 - Controlled by a clock and other input signals.
- The term *counter* is used for sequential circuits that have a regular numeric count sequence.
 - The things that are counted are actually clock pulses.
 - But the pulses may represent many kinds of events.
- The general distinction between the two terms:
 - A counter is commonly used to count events,
 - A state machine is commonly used to control events.

Block diagram for counters and state machines.



Traffic light controller state machine.

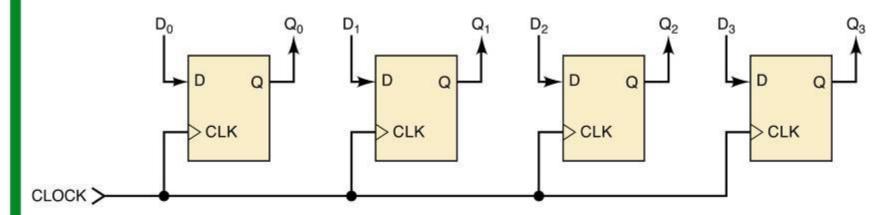


7-15 Register Data Transfer

- The various types of registers can be classified according to...
 - The manner in which data can be entered into the register for storage.
 - The manner in which data are outputted from the register.
- Serial data flow through a register is generally called shifting—either to the left or to the right.
 - Serial output data fed back to the input of the same register is called a *data rotate*.
- Parallel inputting of data is often described as a register load.

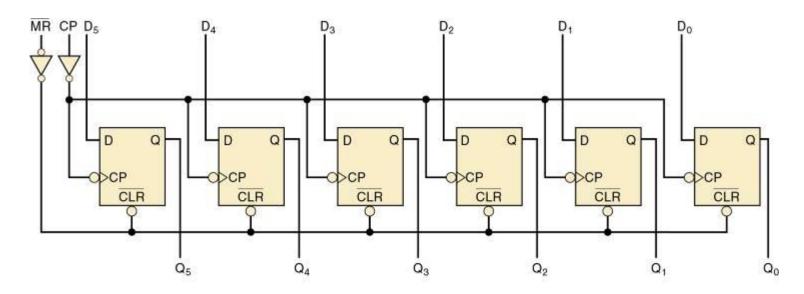


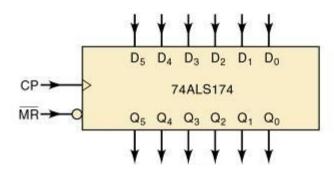
74ALS174/74HC174 Parallel in/parallel out (PIPO)



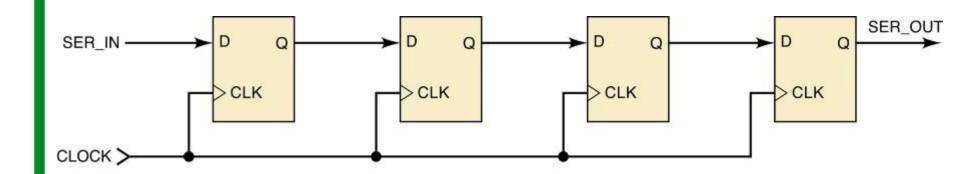
A group of flip-flops that can store multiple bits simultaneously and in which all bits of the stored binary value are directly available.

74ALS174/74HC174



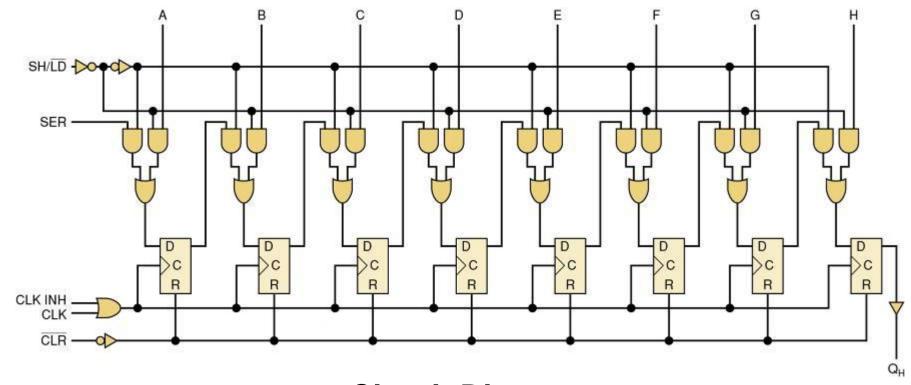


74ALS166/74HC166 Serial in/serial out (SISO)

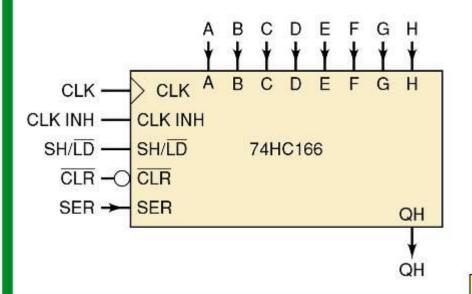


Data loaded one bit at a time moves one bit at a time, with each clock pulse through the flip-flops toward the other end of the register, and exit one bit at a time in the same order as originally loaded.

74ALS166/74HC166

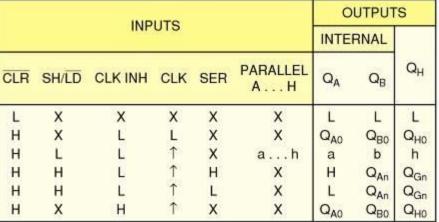


74ALS166/74HC166

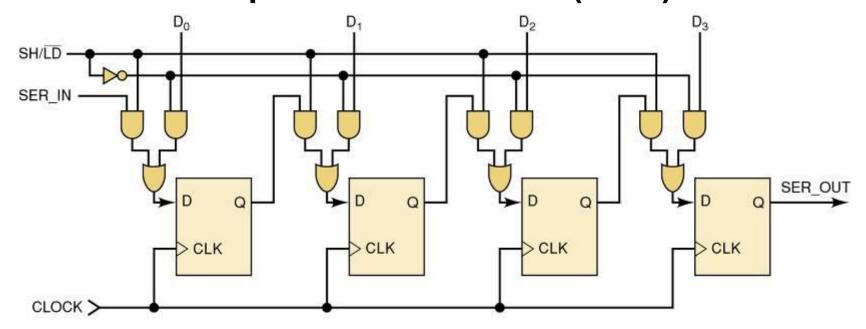


Logic Symbol

Function Table

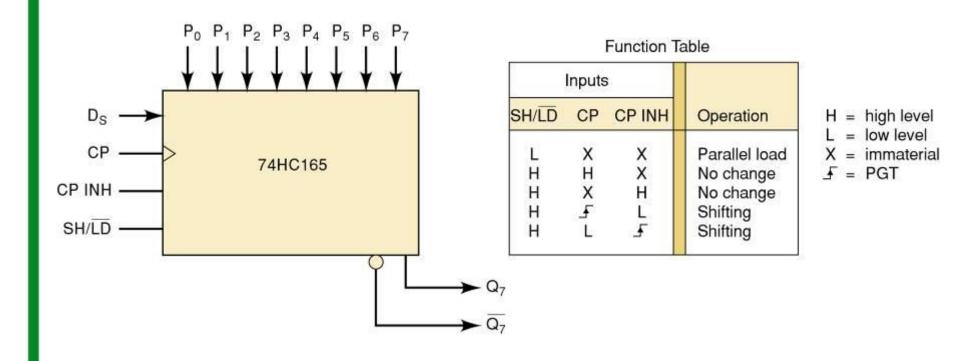


74ALS165/74HC165 8-bit parallel in/serial out (PISO)

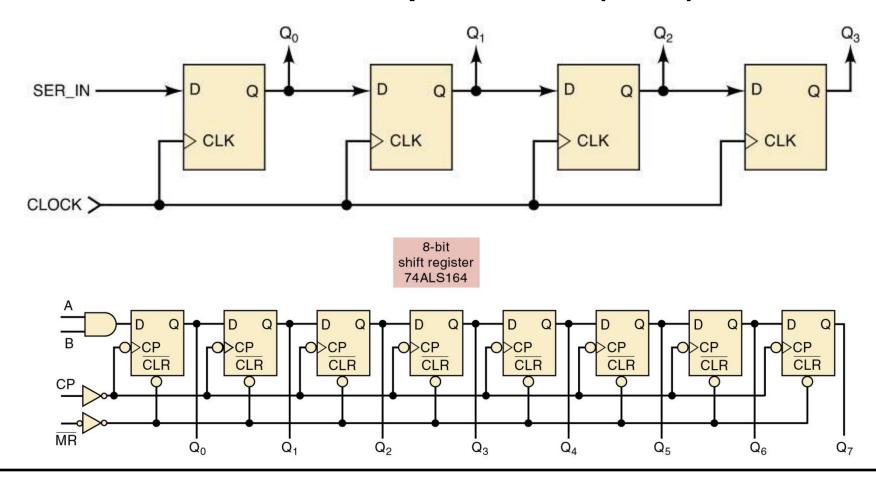


Serial shifting is always synchronous, as the clock is required to ensure the input data moves only one bit at a time with each appropriate clocking edge.

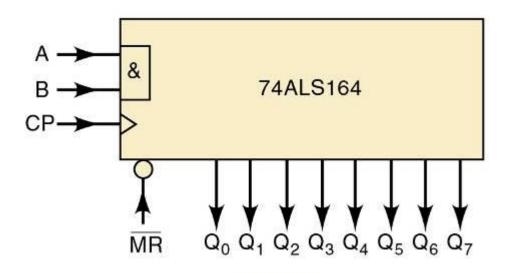
74ALS165/74HC165 8-bit parallel in/serial out (PISO)

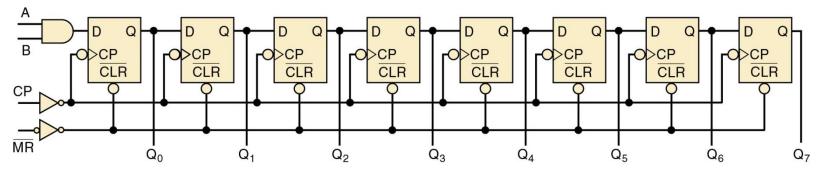


74ALS164/74HC164 8-bit serial in/parallel out (SIPO)



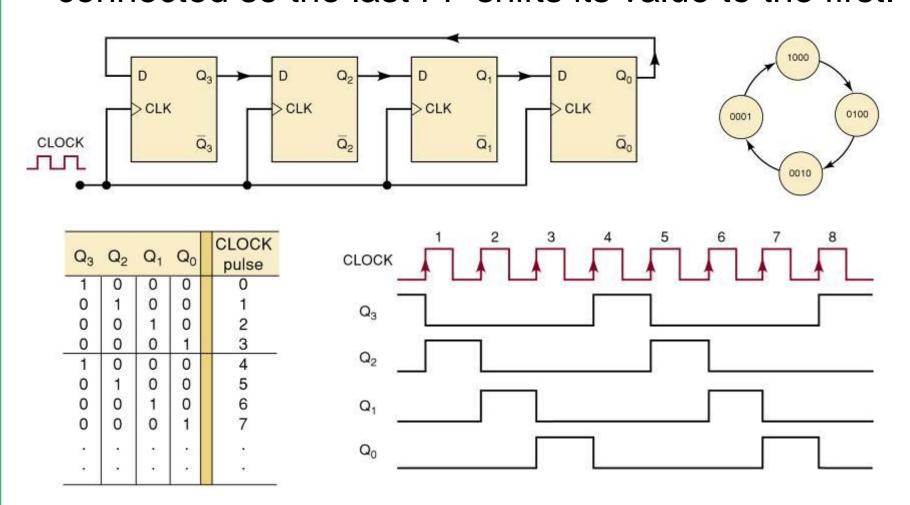
74ALS164/74HC164 8-bit serial in/parallel out (SIPO)





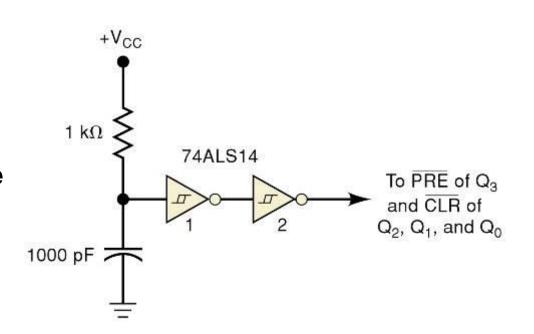
 Shift-register counters use feedback—the output of the last FF in the register is connected back to the first FF in some way.

A ring counter is a circulating shift register connected so the last FF shifts its value to the first.



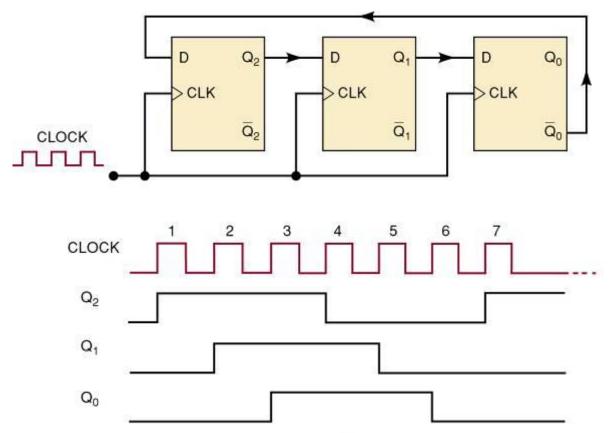
- To operate properly, a ring counter must start off with only one FF in the 1 state and all the others in the 0 state.
 - As power-up starting states will be unpredictable, the counter is preset *before* clock pulses are applied.

Circuit for ensuring the ring counter starts in the 1000 state on power-up.

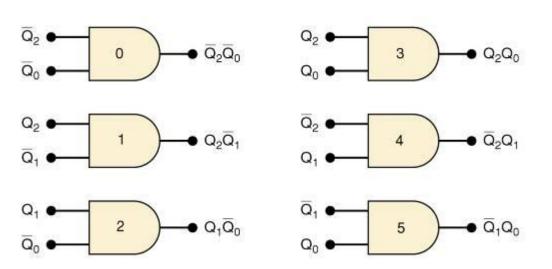


 In the Johnson or twisted-ring counter inverted output of the last FF is connected to the input of the first FF.

Q_2	Q ₁	Q ₀	CLOCK pulse
0	0	0	0
1	0	0	1
1	1	0	2
1	1	1	3
0	1	1	4
0	0	1	5
0	0	0	6
1	0	0	7
1	1	0	8
≅ •	1363	2.63	*6
	50.00	23.00	*
33	(*6)	200	



- For a given MOD number, a Johnson counter requires only half the FFs a ring counter requires.
 - It requires decoding gates—a ring counter does not.
- A Johnson counter uses one logic gate to decode for each count.
 - Each gate requires only two inputs, regardless of the number of FFs in the counter.



Q_2	Q ₁	Q_0	Active gate
0	0	0	0
1	0	0	1
1	1	0	2
1	1	1	3
0	1	1	4
0	0	1	5

- Very few ring counters or Johnson counters are available as ICs.
 - It is relatively simple to wire a shift-register IC as either a ring counter or a Johnson counter.
- Some of the CMOS Johnson-counter ICs include the complete decoding circuitry on the same chip as the counter.
 - (74HC4017, 74HC4022)

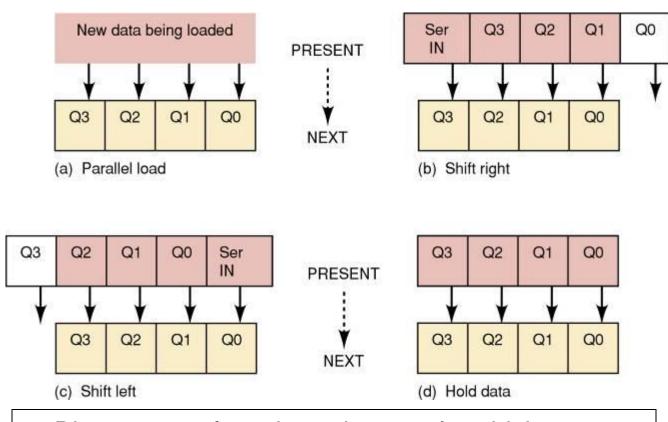
7-18 Troubleshooting

- Flip-flops, counters, and registers are the major components in sequential logic system.
 - Sequential systems suffer from the same types of failures as do combinational systems.
 - Open circuits, shorts, internal IC faults, etc.
- Basic troubleshooting procedures still apply.
 - Observe system operation.
 - Use analytical reasoning to determine possible causes.
 - Use test equipment to isolate the exact fault.

7-20 HDL Registers

- HDL techniques use bit arrays to describe register data & transfer the data in parallel or serial format.
- Concatenation—grouping together in a specific sequence—of desired set of data bits can be used to describe data movement for serial shifting.

Four flip-flops performing transfer operations of parallel load, shift right, shift left, and hold data.



Bits are transferred synchronously, which means they all move simultaneously on a single clock edge.

7-21 HDL Ring Counters

- A ring counter is a shift register that circulates a single active logic level through all its FFs.
 - Modulus is equal to the number of FFS in the register.
 - There are always many unused and invalid states.
- With planning, we can ensure the counter reaches the desired sequence—no matter the initial state.
 - Regardless of the state to which the counter initializes, it eventually fills with zeros.
 - At which time, logic shifts in a HIGH to start the ring sequence.

- 7-2
 - In the AHDL code shown, lines 11 & 12 control the serial input using the strategy just described.
 - The (==) operator evaluates whether the expressions on each side are equal or not.

```
SUBDESIGN fig7_92
 2
        clk : INPUT;
        q[3..0] :OUTPUT;
 5
 6
     VARIABLE
        ff[3..0] :DFF;
        ser in :NODE;
 9
     BEGIN
       ff[].clk = clk;
10
       IF ff[3..1].q == B"000" THEN ser_in = VCC; -- self start
11
12
       ELSE ser in = GND;
13
       END IF;
       ff[3..0].d = (ser in, ff[3..1].q); -- shift right
14
15
       q[] = ff[].q;
16
     END;
```

7-22 HDL One-Shots

- The concept of a counter can be applied to implement a digital one-shot using HDL.
 - A nonretriggerable one-shot ignores the trigger input pulse output is still active.
 - A retriggerable one-shot starts a pulse in response to a trigger.
 - Internal pulse timer restarts each time a subsequent trigger edge occurs before the pulse is complete.



END

Digital Systems

Principles and Applications



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