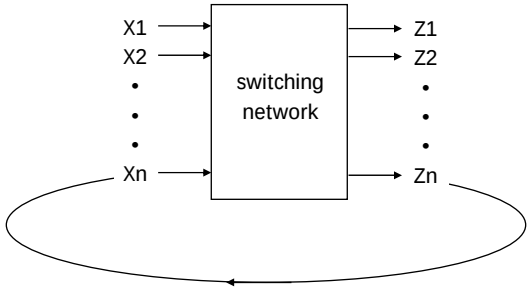
Sequential logic

- Sequential circuits
  - simple circuits with feedback
  - latches
  - edge-triggered flip-flops
- Timing methodologies
  - cascading flip-flops for proper operation
  - clock skew
- Basic registers
  - shift registers
  - simple counters
- Hardware description languages and sequential logic

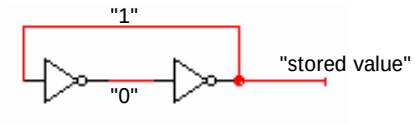
Circuits with feedback

- How to control feedback?
  - what stops values from cycling around endlessly

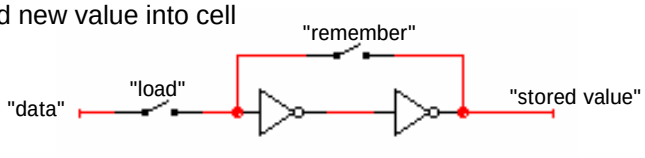


Simplest circuits with feedback

- Two inverters form a static memory cell
  - will hold value as long as it has power applied

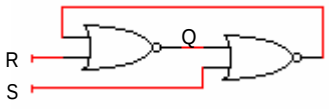


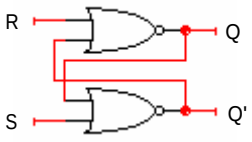
- How to get a new value into the memory cell?
  - selectively break feedback path
  - load new value into cell



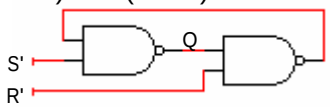
Memory with cross-coupled gates

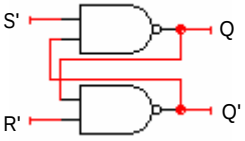
- Cross-coupled NOR gates
  - similar to inverter pair, with capability to force output to 0 (reset=1) or 1 (set=1)



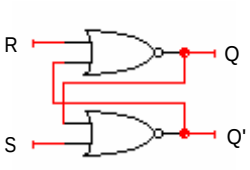


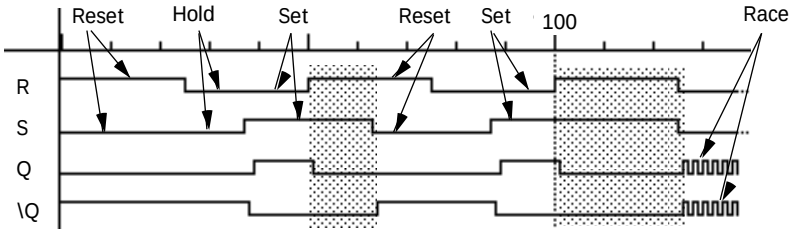
- Cross-coupled NAND gates
  - similar to inverter pair, with capability to force output to 0 (reset=0) or 1 (set=0)



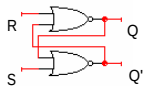


Timing behavior





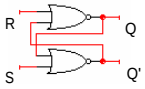
State behavior or R-S latch

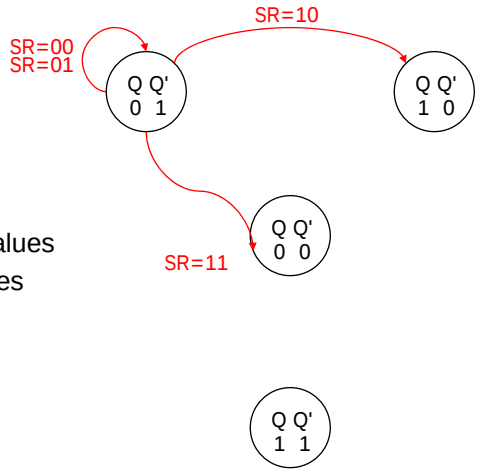


- Truth table of R-S latch behavior

S	R	Q
0	0	hold
0	1	0
1	0	1
1	1	unstable

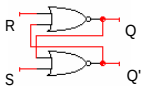
Theoretical R-S latch behavior

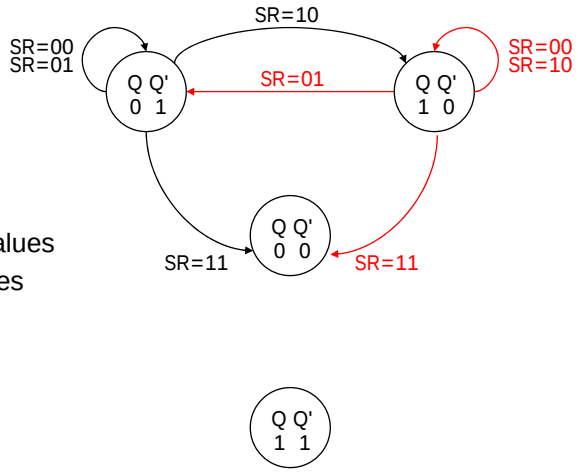




- State diagram
  - states: possible values
  - transitions: changes based on inputs

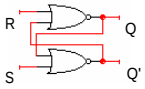
Theoretical R-S latch behavior



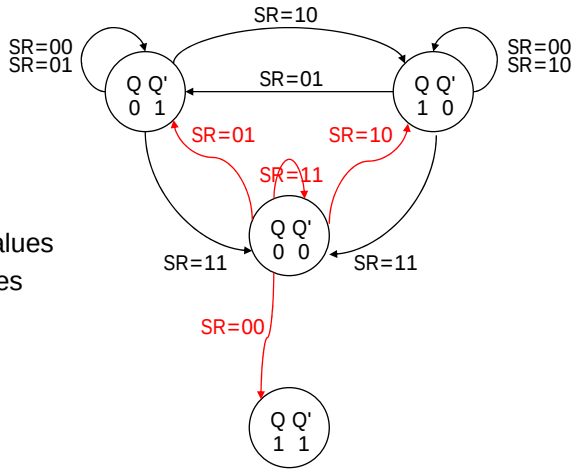


- State diagram
  - states: possible values
  - transitions: changes based on inputs

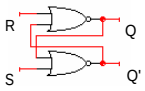
Theoretical R-S latch behavior



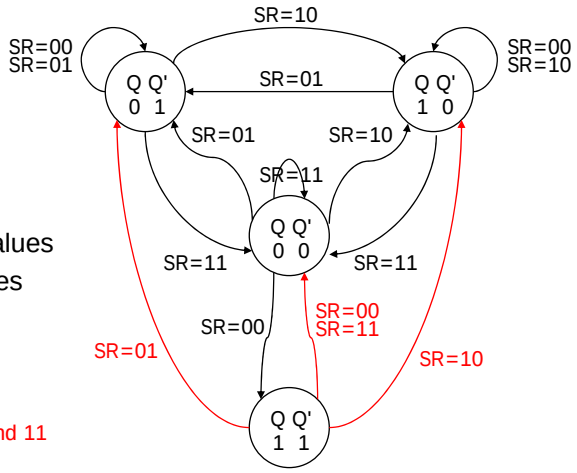
- State diagram
  - states: possible values
  - transitions: changes based on inputs



Theoretical R-S latch behavior

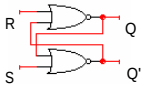


- State diagram
  - states: possible values
  - transitions: changes based on inputs

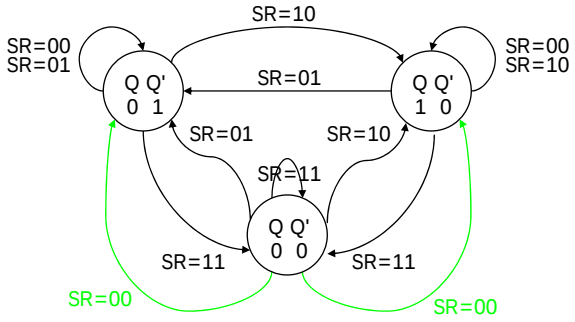


possible oscillation between states 00 and 11

Observed R-S latch behavior

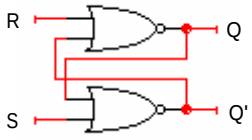


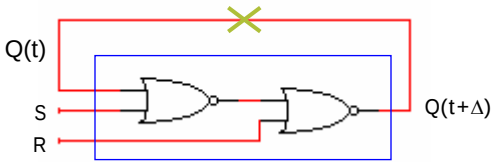
- Very difficult to observe R-S latch in the 1-1 state
  - one of R or S usually changes first
- Ambiguously returns to state 0-1 or 1-0
  - a so-called "race condition"
  - or non-deterministic transition



R-S latch analysis

- Break feedback path





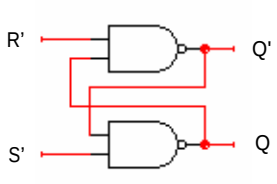
S	R	Q(t)	Q(t+Δ)	
0	0	0	0	hold
0	0	1	1	
0	1	0	0	reset
0	1	1	0	
1	0	0	1	set
1	0	1	1	
1	1	0	X	not allowed
1	1	1	X	

Q(t) \ SR	00	01	11	10
0	0	0	X	1
1	1	0	X	1

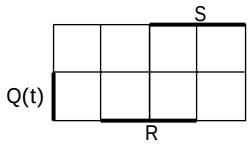
S (columns) / R (rows)

characteristic equation
$Q(t+\Delta) = S + R' Q(t)$

Activity: R-S latch using NAND gates

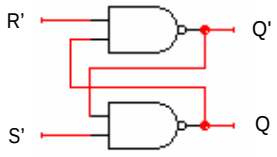


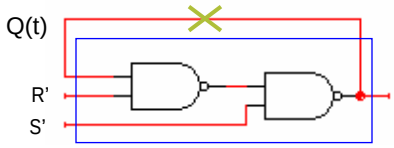
S	R	S'	R'	Q(t)	Q(t+Δ)
0	0	1	1	0	
0	0	1	1	1	
0	1	1	0	0	
0	1	1	0	1	
1	0	0	1	0	
1	0	0	1	1	
1	1	0	0	0	
1	1	0	0	1	



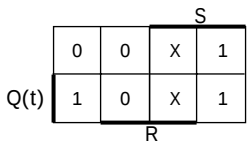
characteristic equation
Q(t+Δ) =

Activity: R-S latch using NAND gates





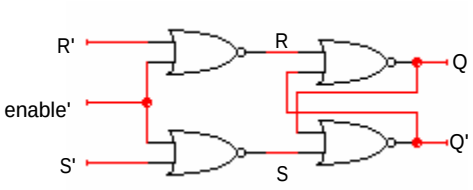
S	R	S'	R'	Q(t)	Q(t+Δ)	
0	0	1	1	0	0	hold
0	0	1	1	1	1	
0	1	1	0	0	0	reset
0	1	1	0	1	0	
1	0	0	1	0	1	set
1	0	0	1	1	1	
1	1	0	0	0	X	not allowed
1	1	0	0	1	X	

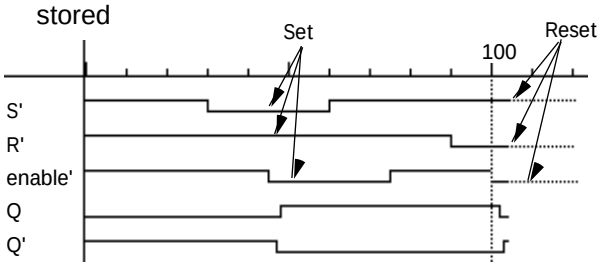


characteristic equation
Q(t+Δ) = S + R' Q(t)

Gated R-S latch

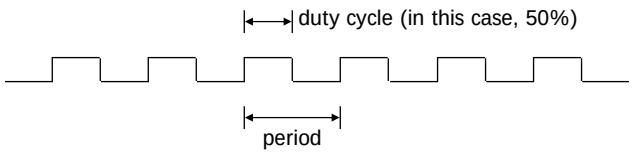
- Control when R and S inputs matter
  - otherwise, the slightest glitch on R or S while enable is low could cause change in value stored





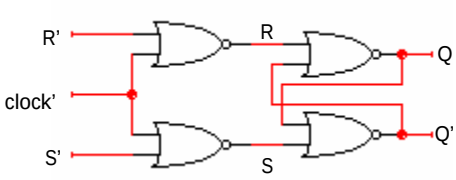
Clocks

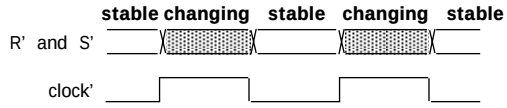
- Used to keep time
  - wait long enough for inputs (R' and S') to settle
  - then allow to have effect on value stored
- Clocks are regular periodic signals
  - period (time between ticks)
  - duty-cycle (time clock is high between ticks - expressed as % of period)



Clocks (cont'd)

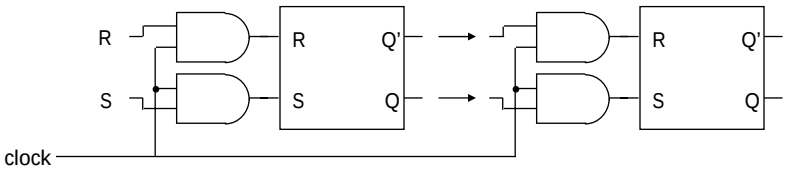
- Controlling an R-S latch with a clock
  - can't let R and S change while clock is active (allowing R and S to pass)
  - only have half of clock period for signal changes to propagate
  - signals must be stable for the other half of clock period





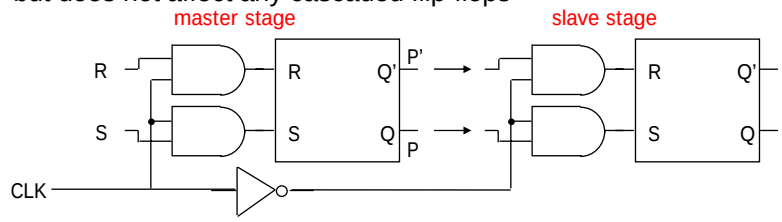
Cascading latches

- Connect output of one latch to input of another
- How to stop changes from racing through chain?
  - need to be able to control flow of data from one latch to the next
  - move one latch per clock period
  - have to worry about logic between latches (arrows) that is too fast



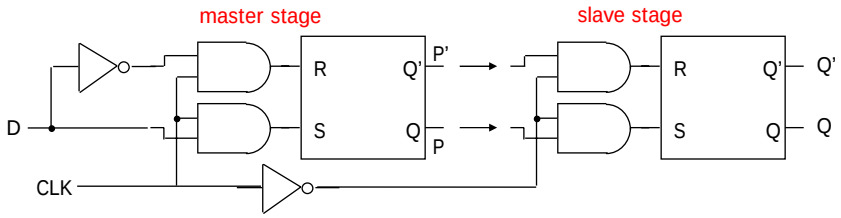
Master-slave structure

- Break flow by alternating clocks (like an air-lock)
  - use positive clock to latch inputs into one R-S latch
  - use negative clock to change outputs with another R-S latch
- View pair as one basic unit
  - master-slave flip-flop
  - twice as much logic
  - output changes a few gate delays after the falling edge of clock but does not affect any cascaded flip-flops



D flip-flop

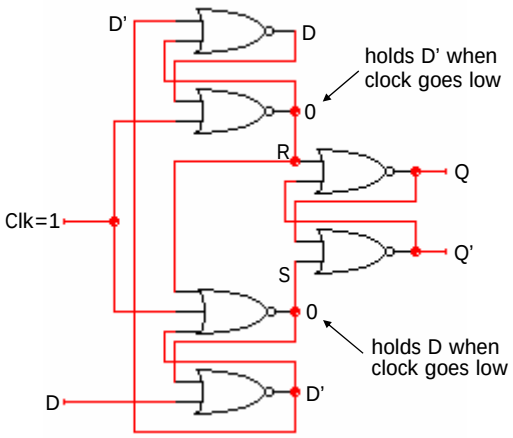
- Make S and R complements of each other
  - eliminates 1s catching problem
  - can't just hold previous value
    (must have new value ready every clock period)
  - value of D just before clock goes low is what is stored in flip-flop
  - can make R-S flip-flop by adding logic to make D = S + R' Q



10 gates

Edge-triggered flip-flops using gates

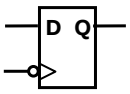
- Only 6 gates
  - sensitive to inputs only near edge of clock signal (not while high)



negative edge-triggered D flip-flop (D-FF)

4-5 gate delays

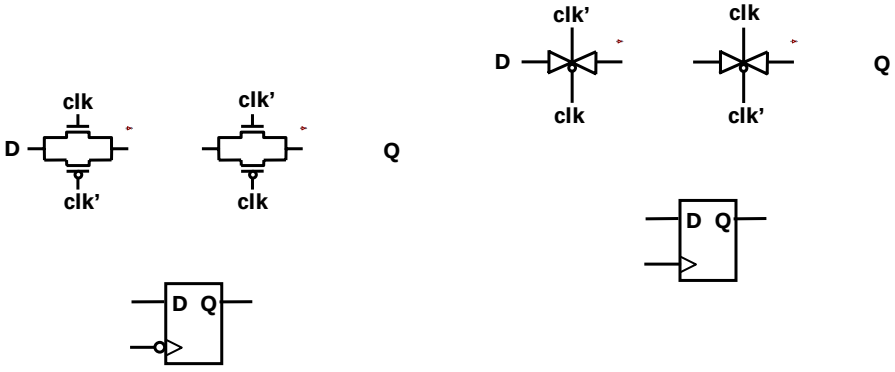
must respect setup and hold time constraints to successfully capture input



characteristic equation
Q(t+1) = D

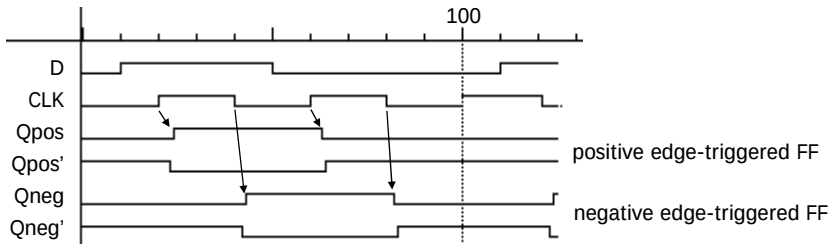
Edge-triggered flip-flops using transistors

- Only 8 transistors



Edge-triggered flip-flops (cont'd)

- Positive edge-triggered
  - inputs sampled on rising edge; outputs change after rising edge
- Negative edge-triggered flip-flops
  - inputs sampled on falling edge; outputs change after falling edge

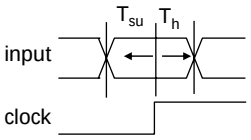


Timing methodologies

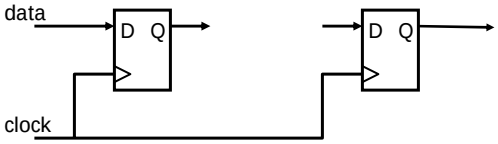
- Rules for interconnecting components and clocks
  - guarantee proper operation of system when strictly followed
- Approach depends on building blocks used for memory elements
  - we'll focus on systems with edge-triggered flip-flops
    - found in programmable logic devices
  - many custom integrated circuits focus on level-sensitive latches
- Basic rules for correct timing:
  - (1) correct inputs, with respect to time, are provided to the flip-flops
  - (2) no flip-flop changes state more than once per clocking event

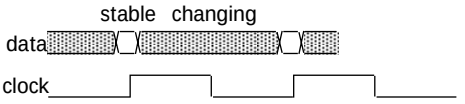
Timing methodologies (cont'd)

- Definition of terms
  - clock: periodic event, causes state of memory element to change
    can be rising edge or falling edge or high level or low level
  - setup time: minimum time before the clocking event by which the input must be stable (Tsu)
  - hold time: minimum time after the clocking event until which the input must remain stable (Th)



there is a timing "window" around the clocking event during which the input must remain stable and unchanged in order to be recognized

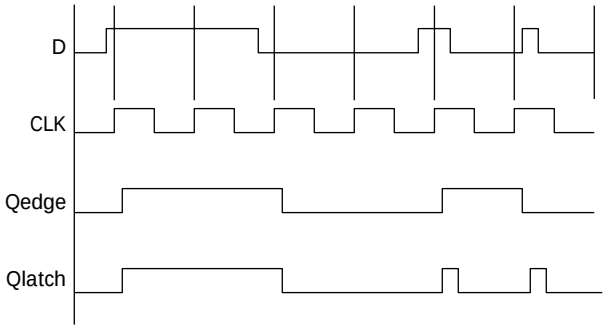




Comparison of latches and flip-flops

positive edge-triggered flip-flop

transparent (level-sensitive) latch



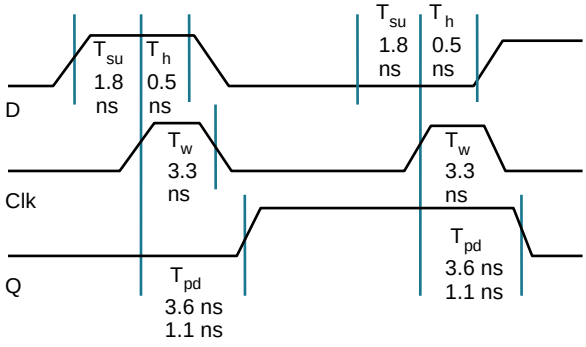
behavior is the same unless input changes while the clock is high

Comparison of latches and flip-flops (cont'd)

Type	When inputs are sampled	When output is valid
unclocked latch	always	propagation delay from input change
level-sensitive latch	clock high (Tsu/Th around falling edge of clock)	propagation delay from input change or clock edge (whichever is later)
master-slave flip-flop	clock hi-to-lo transition (Tsu/Th around falling edge of clock)	propagation delay from falling edge of clock
negative edge-triggered flip-flop	clock hi-to-lo transition (Tsu/Th around falling edge of clock)	propagation delay from falling edge of clock

Typical timing specifications

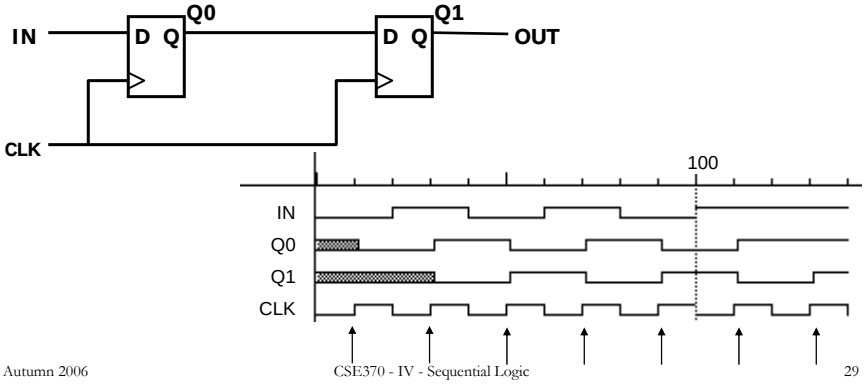
- Positive edge-triggered D flip-flop
  - setup and hold times
  - minimum clock width
  - propagation delays (low to high, high to low, max and typical)



all measurements are made from the clocking event (the rising edge of the clock)

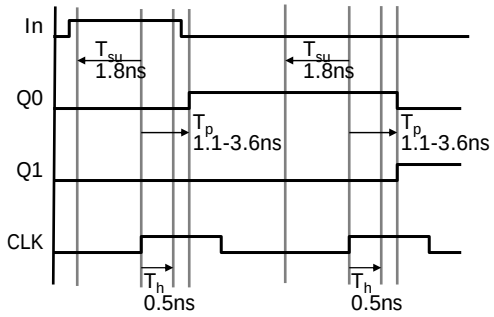
Cascading edge-triggered flip-flops

- Shift register
  - new value goes into first stage
  - while previous value of first stage goes into second stage
  - consider setup/hold/propagation delays (prop must be > hold)



Cascading edge-triggered flip-flops (cont'd)

- Why this works
  - propagation delays exceed hold times
  - clock width constraint exceeds setup time
  - this guarantees following stage will latch current value before it changes to new value

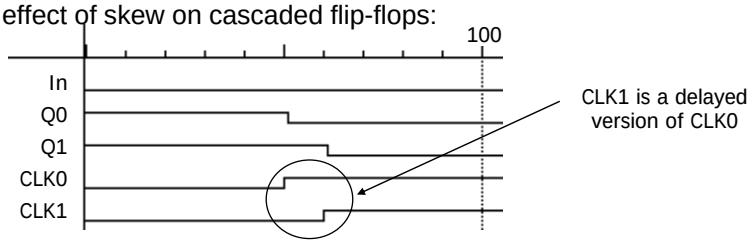


timing constraints guarantee proper operation of cascaded components

assumes infinitely fast distribution of the clock

Clock skew

- The problem
  - correct behavior assumes next state of all storage elements determined by all storage elements at the same time
  - this is difficult in high-performance systems because time for clock to arrive at flip-flop is comparable to delays through logic
  - effect of skew on cascaded flip-flops:



original state: IN = 0, Q0 = 1, Q1 = 1
due to skew, next state becomes: Q0 = 0, Q1 = 0, and not Q0 = 0, Q1 = 1

Summary of latches and flip-flops

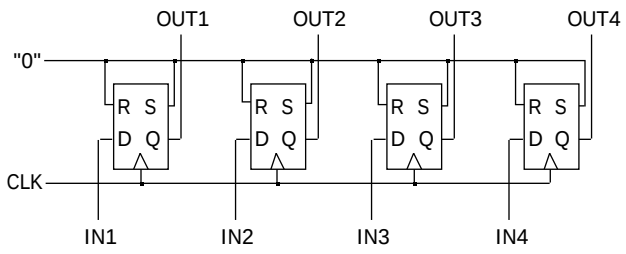
- Development of D-FF
  - level-sensitive used in custom integrated circuits
    - can be made with 8 switches
  - edge-triggered used in modern programmable logic devices
  - good choice for data storage register
- Historically J-K FF was popular but now never used
  - similar to R-S but with 1-1 being used to toggle output (complement state)
  - good in days of TTL/SSI (more complex input function: D = J Q' + K' Q
  - can always be implemented using D-FF
- Preset and clear inputs are highly desirable on flip-flops
  - used at start-up or to reset system to a known state

Flip-flop features

- Reset (set state to 0) – R
  - synchronous: Dnew = R' • Dold (when next clock edge arrives)
  - asynchronous: doesn't wait for clock, quick but dangerous
- Preset or set (set state to 1) – S (or sometimes P)
  - synchronous: Dnew = Dold + S (when next clock edge arrives)
  - asynchronous: doesn't wait for clock, quick but dangerous
- Both reset and preset
  - Dnew = R' • Dold + S (set-dominant)
  - Dnew = R' • Dold + R'S (reset-dominant)
- Selective input capability (input enable or load) – LD or EN
  - multiplexor at input: Dnew = LD' • Q + LD • Dold
  - load may or may not override reset/set (usually R/S have priority)
- Complementary outputs – Q and Q'

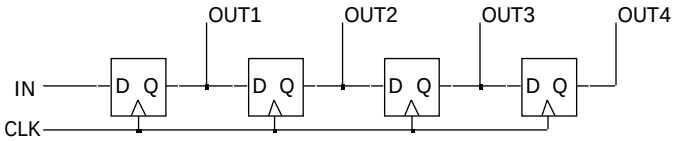
Registers

- Collections of flip-flops with similar controls and logic
  - stored values somehow related (for example, form binary value)
  - share clock, reset, and set lines
  - similar logic at each stage
- Examples
  - shift registers
  - counters



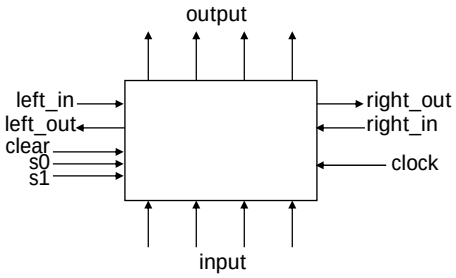
Shift register

- Holds samples of input
  - store last 4 input values in sequence
  - 4-bit shift register:



Universal shift register

- Holds 4 values
  - serial or parallel inputs
  - serial or parallel outputs
  - permits shift left or right
  - shift in new values from left or right



clear sets the register contents and output to 0

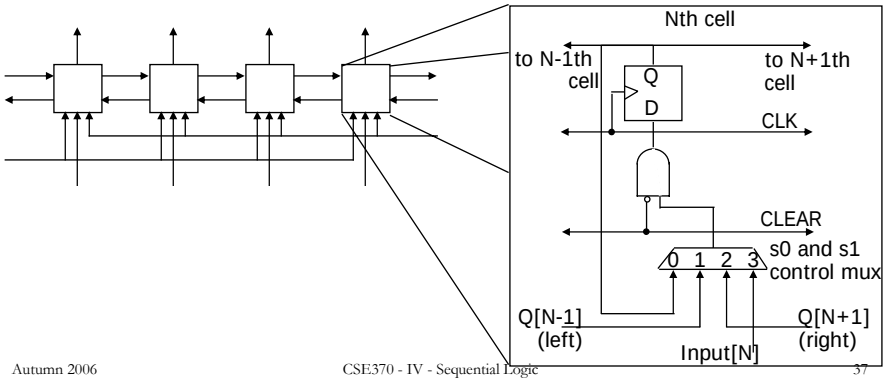
s1 and s0 determine the shift function

s0	s1	function
0	0	hold state
0	1	shift right
1	0	shift left
1	1	load new input

Design of universal shift register

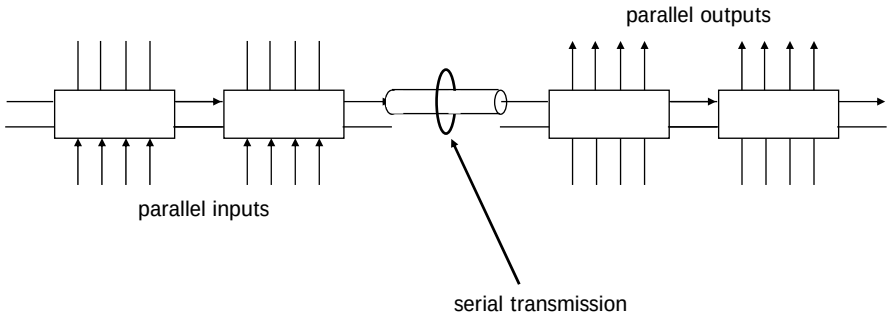
- Consider one of the four flip-flops
  - new value at next clock cycle:

clear	s0	s1	new value
1	–	–	0
0	0	0	output
0	0	1	output value of FF to left (shift right)
0	1	0	output value of FF to right (shift left)
0	1	1	input



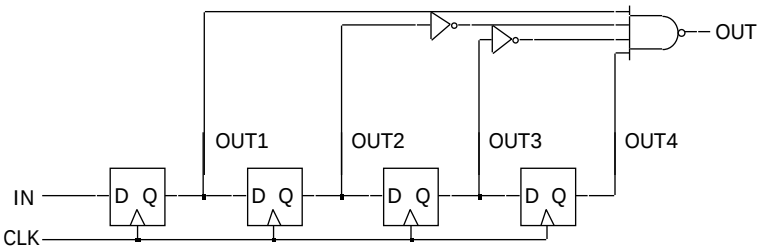
Shift register application

- Parallel-to-serial conversion for serial transmission



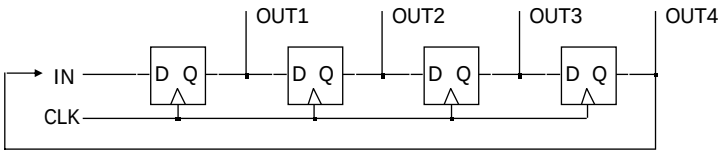
Pattern recognizer

- Combinational function of input samples
  - in this case, recognizing the pattern 1001 on the single input signal



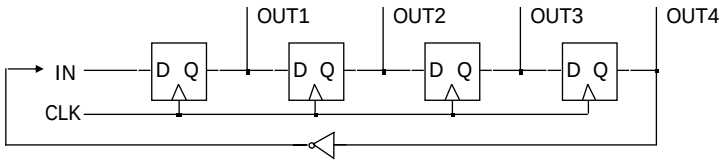
Counters

- Sequences through a fixed set of patterns
  - in this case, 1000, 0100, 0010, 0001
  - if one of the patterns is its initial state (by loading or set/reset)



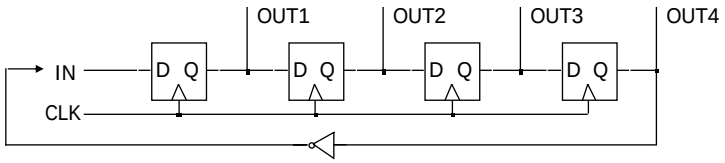
Activity

- How does this counter work?



Activity

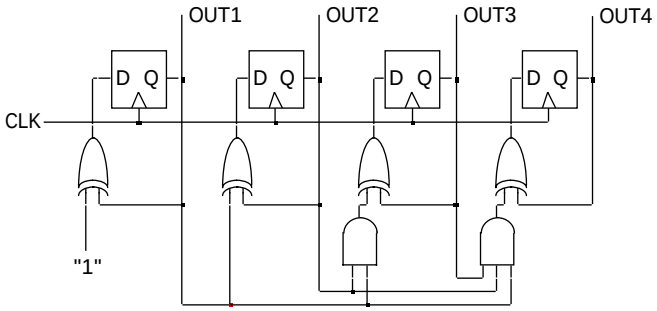
- How does this counter work?



- Counts through the sequence: 1000, 1100, 1110, 1111, 0111, 0011, 0001, 0000
- Known as Mobius (or Johnson) counter

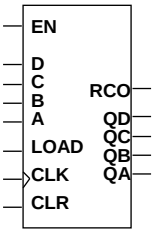
Binary counter

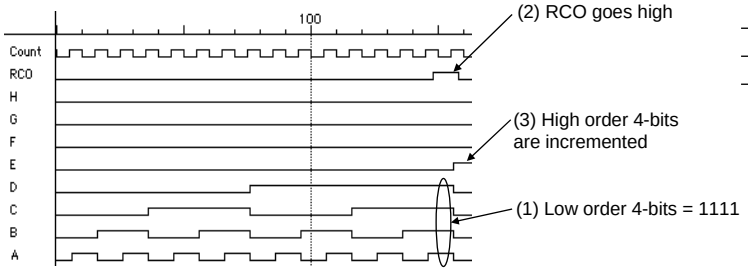
- Logic between registers (not just multiplexer)
  - XOR decides when bit should be toggled
  - always for low-order bit,
    only when first bit is true for second bit,
    and so on



Four-bit binary synchronous up-counter

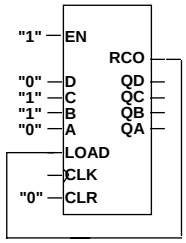
- Standard component with many applications
  - positive edge-triggered FFs w/ synchronous load and clear inputs
  - parallel load data from D, C, B, A
  - enable inputs: must be asserted to enable counting
  - RCO: ripple-carry out used for cascading counters
    - high when counter is in its highest state 1111
    - implemented using an AND gate



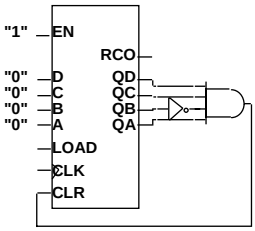


Offset counters

- Starting offset counters – use of synchronous load
  - e.g., 0110, 0111, 1000, 1001,
    1010, 1011, 1100, 1101, 1111, 0110, . . .



- Ending offset counter – comparator for ending value
  - e.g., 0000, 0001, 0010, ..., 1100, 1101, 0000



- Combinations of the above (start and stop value)

Hardware Description Languages and Sequential Logic

- Flip-flops
  - representation of clocks - timing of state changes
  - asynchronous vs. synchronous
- Shift registers
- Simple counters

Flip-flop in Verilog

- Use always block's sensitivity list to wait for clock edge

```
module dff (clk, d, q);

   input  clk, d;
   output q;
   reg    q;

   always @(posedge clk)
      q = d;

endmodule
```


More Flip-flops

- Synchronous/asynchronous reset/set
  - single thread that waits for the clock
  - three parallel threads – only one of which waits for the clock

Synchronous

```
module dff (clk, s, r, d, q);
    input  clk, s, r, d;
    output q;
    reg    q;

    always @(posedge clk)
        if (r)      q = 1'b0;
        else if (s) q = 1'b1;
        else        q = d;

endmodule
```

Asynchronous

```
module dff (clk, s, r, d, q);
    input  clk, s, r, d;
    output q;
    reg    q;

    always @(posedge r)
        q = 1'b0;
    always @(posedge s)
        q = 1'b1;
    always @(posedge clk)
        q = d;

endmodule
```

Incorrect Flip-flop in Verilog

- Use always block's sensitivity list to wait for clock to change

```
module dff (clk, d, q);

    input  clk, d;
    output q;
    reg    q;

    always @(clk)
        q = d;

endmodule
```

Not correct! Q will change whenever the clock changes, not just on an edge.

Blocking and Non-Blocking Assignments

- Blocking assignments (X=A)
  - completes the assignment before continuing on to next statement
- Non-blocking assignments (X<=A)
  - completes in zero time and doesn't change the value of the target until a blocking point (delay/wait) is encountered
- Example: swap

```
always @(posedge CLK)
    begin
        temp = B;
        B = A;
        A = temp;
    end
```

```
always @(posedge CLK)
    begin
        A <= B;
        B <= A;
    end
```

Register-transfer-level (RTL) Assignment

- Non-blocking assignment is also known as an RTL assignment
  - if used in an always block triggered by a clock edge
  - all flip-flops change together

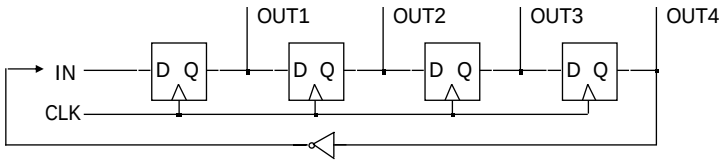
```
// B,C,D all get the value of A
always @(posedge clk)
   begin
      B = A;
      C = B;
      D = C;
   end
```

```
// implements a shift register
always @(posedge clk)
   begin
      B <= A;
      C <= B;
      D <= C;
   end
```


Shift register in Verilog

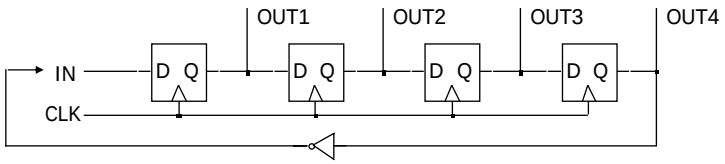
```
module shift_register (clk, in, out);

  input  clk;
  input  in;
  output [0:3] out;

  reg [0:3] out;

  initial begin
    out = 0;  // out[0:3] = {0, 0, 0, 0};
  end

  always @(posedge clk) begin
    out = {in, out [0:2]};
  end

endmodule
```

Activity: express in Verilog




```
always @(posedge clk)
   begin




   end
```


Mobius Counter in Verilog




```
initial
   begin
      A = 1'b0;
      B = 1'b0;
      C = 1'b0;
      D = 1'b0;
   end

always @(posedge clk)
   begin
      A <= ~D;
      B <= A;
      C <= B;
      D <= C;
   end
```

```
{A, B, C, D} <= {~D, A, B, C};
```

Binary Counter in Verilog

```
module binary_counter (clk, c8, c4, c2, c1);

   input  clk;
   output c8, c4, c2, c1;

   reg [3:0] count;

   initial begin
     count = 0;
   end

   always @(posedge clk) begin
     count = count + 4'b0001;
   end

   assign c8 = count[3];
   assign c4 = count[2];
   assign c2 = count[1];
   assign c1 = count[0];

endmodule
```

```
module binary_counter (clk, c8, c4, c2, c1, rco);

   input  clk;
   output c8, c4, c2, c1, rco;

   reg [3:0] count;
   reg rco;

   initial begin . . . end

   always @(posedge clk) begin . . . end

   assign c8 = count[3];
   assign c4 = count[2];
   assign c2 = count[1];
   assign c1 = count[0];
   assign rco = (count == 4b'1111);

endmodule
```


Sequential logic summary

- Fundamental building block of circuits with state
  - latch and flip-flop
  - R-S latch, R-S master/slave, D master/slave, edge-triggered D flip-flop
- Timing methodologies
  - use of clocks
  - cascaded FFs work because propagation delays exceed hold times
  - beware of clock skew
- Basic registers
  - shift registers
  - counters
- Hardware description languages and sequential logic