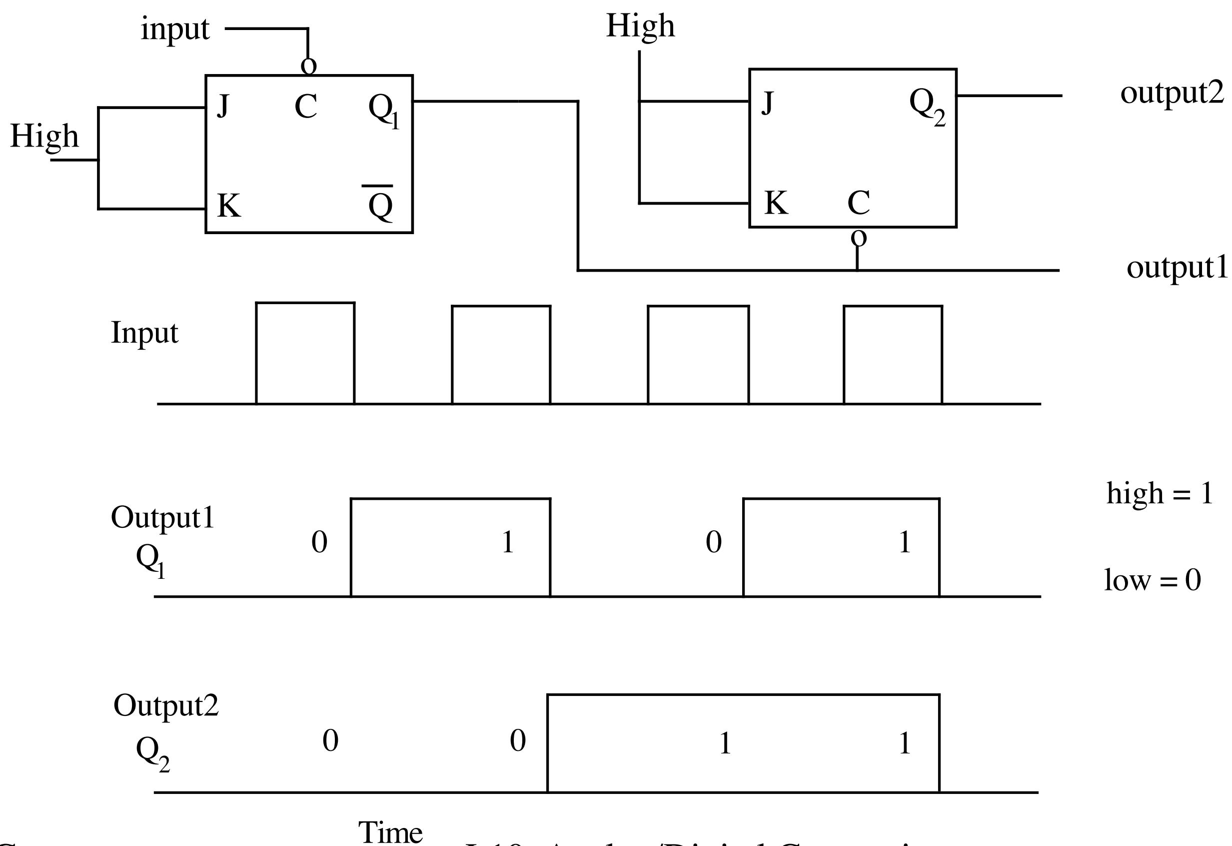
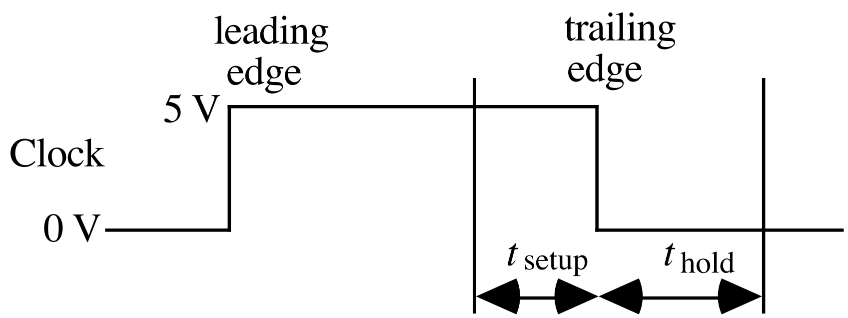
Lecture 10: Analog/Digital Conversion

- Example: Counter made from two JK flip-flops.
  - This circuit counts from 0 1 2 3 0 1 2 3 0…
  - Q_1 is the lowest order bit, Q_2 is the higher order bit.
  - The output is a binary number = Q_2Q_1.
  - The o's on the clock means that the output transition occurs on the trailing edge of the clock pulse.
  - Output of circuit is most conveniently displayed using a timing diagram:

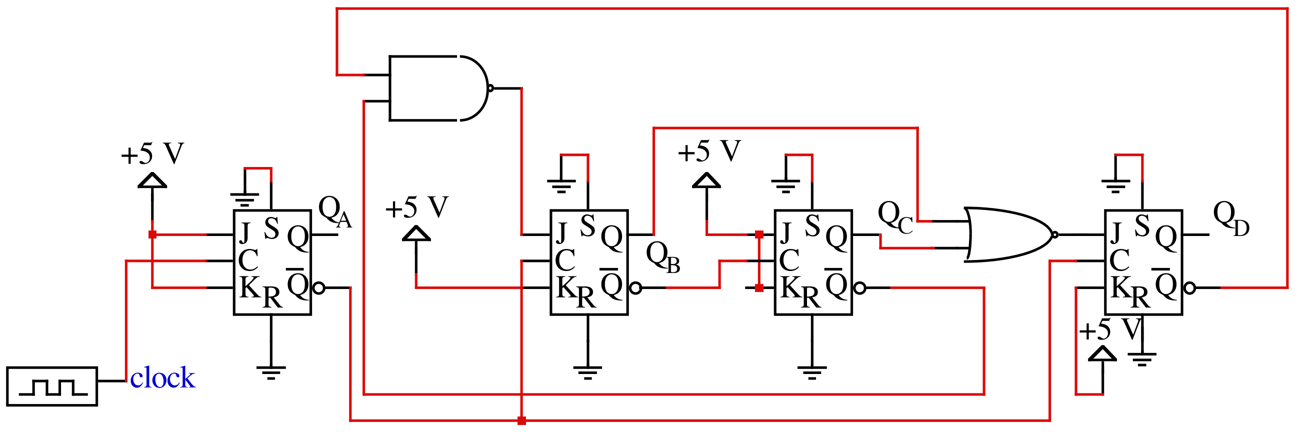


- A few words about clocking the flip-flops and timing of inputs.
  - Setup time:
    For each type of flip-flop there is a minimum specified time relative to the clock pulse during which time the input(s) to the FF must be stable (i.e. not change logic levels).
  - Hold time:
    For each type of flip-flop there is a minimum specified time after Q changes state that the input(s) to the FF must be stable (i.e. not change logic levels).
  - Example: 74LS112 JK flip-flop (the one we use in lab)
    - This FF changes state (Q) relative to the trailing edge of the clock.
    - The setup time is 20 nsec (2×10^{-8} sec) while the hold time is ≈ 0 nsec.
    - The maximum clock speed of this FF is 30 MHz.



☞ the data on J and K must be stable for at least $t_{setup} + t_{hold}$.

- Sometimes circuits with flip-flops are classified according to how the clock is distributed to the FF's.
  - There are two clocking schemes:
    - Synchronous: All FF's are clocked at the same time.
      - The easiest way to do this is to use one clock and distribute it to all the FF's.
    - Asynchronous: FF's are clocked at different times, usually by different clocks.
      - The previous circuit with two flip-flops was an example of this type of circuit.
        - The first FF was clocked by a “clock”.
        - The second FF was clocked by the output (Q) of the first FF.

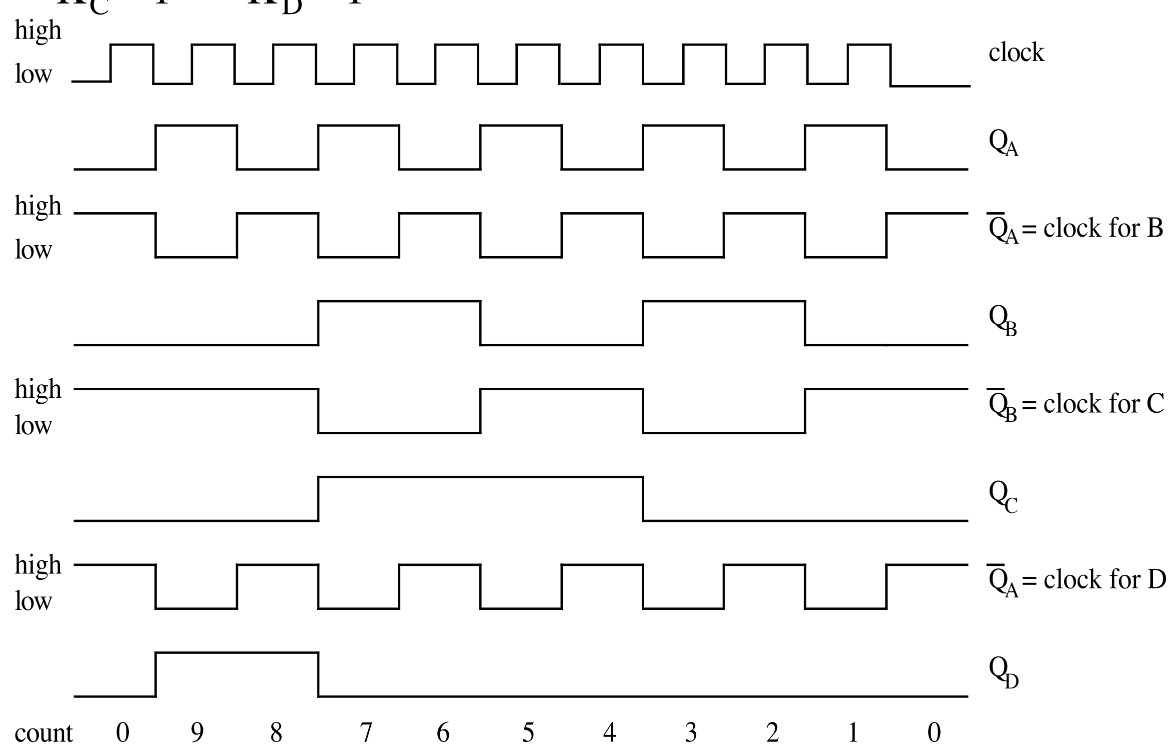


$J_A = 1$ $J_B = \overline{\bar{Q}_C \bar{Q}_D} = Q_C + Q_D$ $J_C = 1$ $J_D = \overline{Q_B + Q_C} = \bar{Q}_B \bar{Q}_C$

$K_A = 1$ $K_B = 1$ $K_C = 1$ $K_D = 1$

Divide by 10 ripple down counter
(counts from 9 to zero)

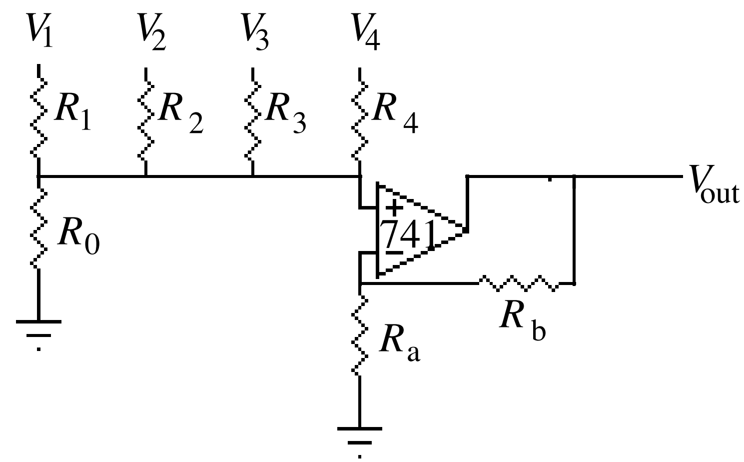
Asynchronous counter



Digital to Analog Conversion (DAC):

- There are two simple circuits commonly used to convert a digital signal to an analog voltage.
  - Weighted Resistor Ladder:
    - We assume that the input voltages (V_1, V_2, V_3, and V_4) are logic levels.
    - Let us use TTL levels and assume a high = 3 V and a low = 0 V.
    - The output voltage is given by:

$$V_{out} = \frac{\frac{R_b}{R_a}+1}{\frac{1}{R_0}+\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}+\frac{1}{R_4}}\left[\frac{V_1}{R_1}+\frac{V_2}{R_2}+\frac{V_3}{R_3}+\frac{V_4}{R_4}\right]$$



    - If we choose the resistors as follows:

      $R_1 = R_a = 1$ kΩ, $R_2 = 2$ kΩ, $R_3 = 4$ kΩ,

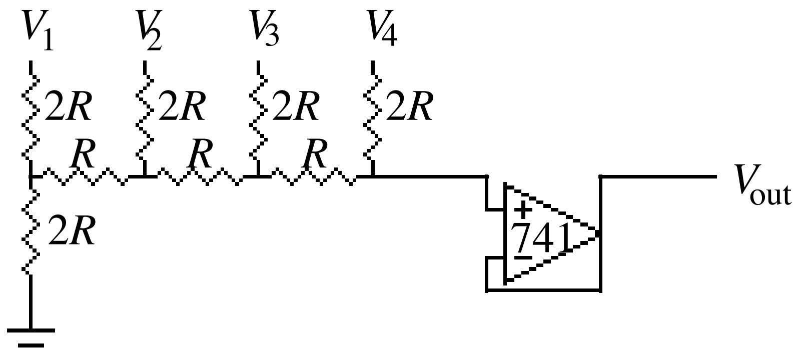
      $R_4 = R_0 = 8$ kΩ and $R_b = 15$ kΩ,

    ☞ we get the following simple relationship for V_{out}:

      $V_{out} = 8V_1 + 4V_2 + 2V_3 + V_4$

    - If V_{in} represents a binary number (e.g. 1001 = $V_1V_2V_3V_4$ with V_1 being the highest order bit)
      - the output voltage varies from 0 to 45 Volts (remember $V_1..V_4$ are all either 0 or 3 V)
      - example: the digital input 1001 has an analog output of 27 V = (3x8 + 3) V.
    - Unfortunately there are several bad points with this conversion scheme:
      - the output can be a large voltage (e.g. 45 V)
      - circuit needs 5 high precision resistors (expensive)
      - the current (and therefore power) in the resistors varies by a factor of 15

- Binary Ladder Network (R-2R Network):

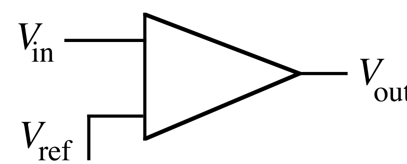


This circuit fixes up many of the problems in previous circuit

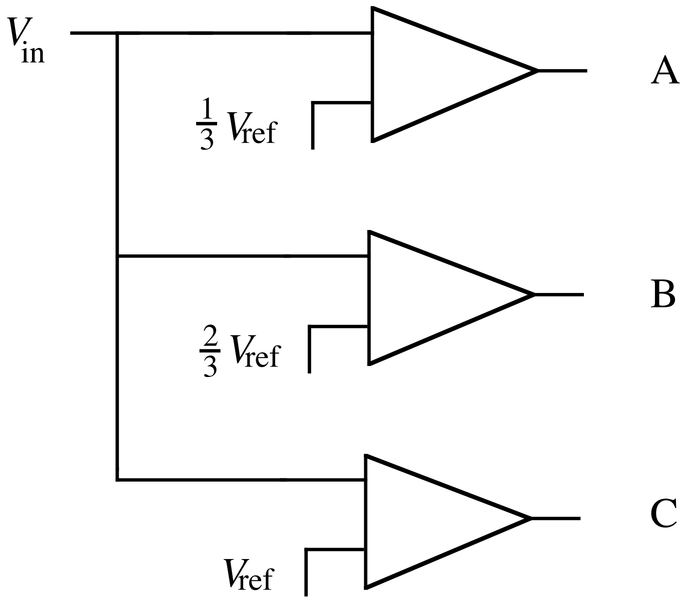
- The output voltage for this circuit is:
  $V_{out} = V_1/2 + V_2/4 + V_3/8 + V_4/16$
- This circuit needs only 2 precision resistors compared with the 5 in the previous design.
  - Power dissipated in the resistors varies by a factor of 2, compared with 15 in the previous design.
- There are still some bad points:
  - need precision components
  - the output voltage will usually be a fraction of the input (low noise immunity)
    - Example: if V_{in} = 1001, then V_{out} = 3/2 + 0/4 + 0/8 + 3/16 = 27/16 V for TTL logic levels.

Analog to Digital Conversion (ADC)

- Parallel A to D conversion ("Flash Encoder" or Flash ADC)
  - very fast and very simple method
  - use comparators for the conversion
  - Example: one bit ADC using one comparator
    - V_{out} = 1 (high) if $V_{in} > V_{ref}$
    - V_{out} = 0 (low) if $V_{in} < V_{ref}$



- How many comparators do we need for a given accuracy?
  - Suppose we want to convert an analog number into a 2 bit digital number.
    - For 2 bits there are 4 possible outcomes (00, 01, 10, 11), it takes 3 comparators.
- Example: 2 bit parallel converter



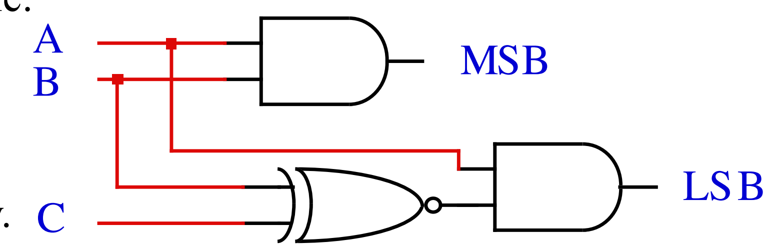
Truth Table

V_{in}	A	B	C	Output
$< \frac{1}{3}V_R$	0	0	0	0
$\frac{1}{3}V_R < V_{in} < \frac{2}{3}V_R$	1	0	0	1
$\frac{2}{3}V_R < V_{in} < V_R$	1	1	0	2
$> V_R$	1	1	1	3

  - Logic gates are needed to implement the truth table:

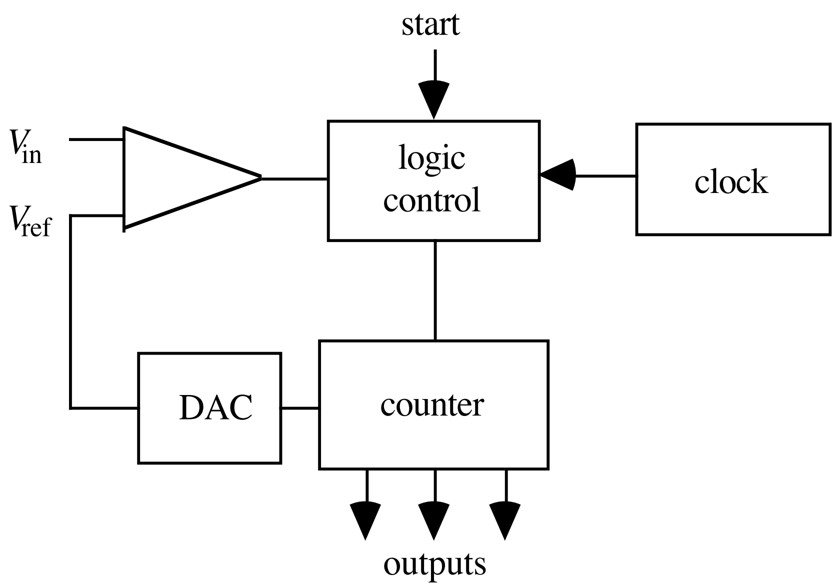
$$\text{LSB} = A\bar{B}\bar{C} + ABC = A(\bar{B}\bar{C} + BC)$$

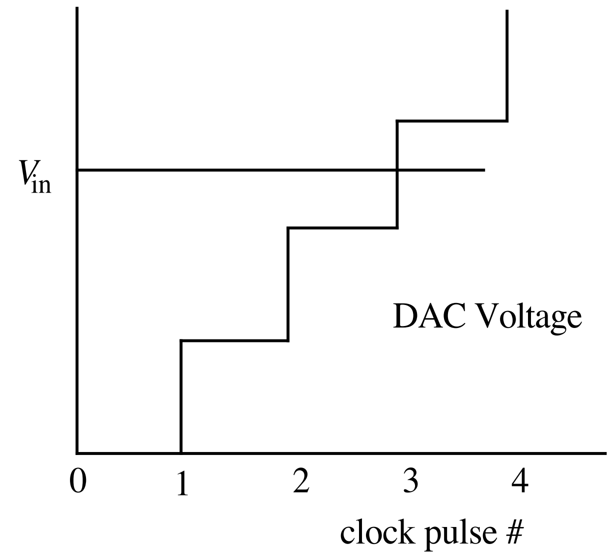
$$\text{MSB} = AB\bar{C} + ABC = AB(C + \bar{C}) = AB$$



- There are two problems with this scheme:
  - Need lots of comparators: $2^n - 1$ for n bit accuracy.
    - If we want 1 part in 1000 accuracy (0.1%), it takes 10 bits
      - ☞ $2^{10} - 1 = 1023$ comparators!
  - Number of logic gates necessary to code the output is large and the logic gets complicated.

- Counter ADC (staircase method):
  - Good news: only uses one comparator
  - Bad news: much more complicated than parallel method





- When $V_{DAC} > V_{in}$
  - ☞ the logic circuit stops the clock
  - ☞ the counter outputs a binary number which is just the number of clock pulses
- The DAC could be:
  - an integrator
  - a resistor ladder
  - a voltage reference

- Problems with this system:
  - control logic is complicated (use microprocessors + gates +...)
  - time to digitize depends on V_{in}.
  - Example: suppose clock runs at 5 MHz, and you want 10 bit accuracy.
    - 10 bits = 1024 clock pulses.
      - ☞ Can only digitize at 5 MHz/1024 ~ 5 kHz, *which is fairly slow!*

- Successive Approximation ADC:
  - Control logic is very complicated, but easy to program, like a binary search.
  - Conversion time is fast and almost independent of V_{in}.
  - Example: 5 bit ADC:
    - Steps for converting V_{in} into a binary number:
      - turn on MSB in DAC and compare with V_{in}.
        - output = 0 if $V_{DAC} > V_{in}$ (steps 1, 2, 5)
        - output = 1 if $V_{DAC} < V_{in}$ (steps 3, 4)
      - turn on next highest bit, output = 1 if $V_{DAC} > V_{in}$
      - repeat until least significant bit is checked
      - ☞ *n* comparisons for *n* bit accuracy
      - staircase approach requires $2^n - 1$ comparisons
      - parallel ADC requires 1 step, independent of accuracy
      - Time for a 10 bit conversion for the three methods:

        parallel : success approx. : staircase 1:10:1023