Digital to Analog Converters and Diodes

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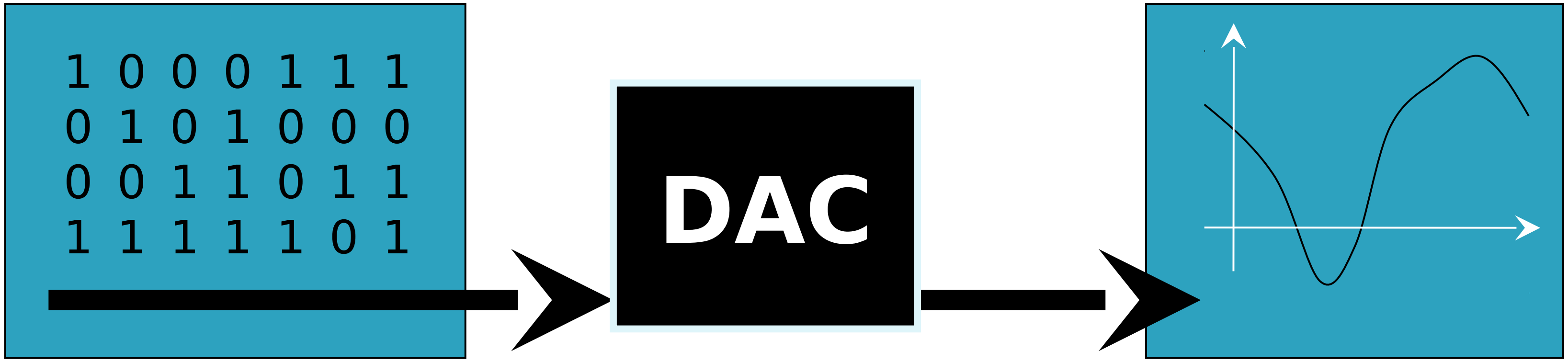
Outline:

- What is digital to analog converter (DAC)?
- Types of DAC
  - Binary Weighted Resistor
  - R-2R Ladder
- Discuss Specifications:
  - Reference Voltages
  - Resolution
  - Speed
  - Settling Time
  - Linearity
  - Errors
- Applications
- Diodes: Theory and applications
  - Ideal vs. real
  - Types: Junction and Zener

What is Digital-to-Analog Converter (DAC) ?

- A DAC converts a binary digital signal into an analog representation of the same signal
- Typically the analog signal is a voltage output, though current output can also be used



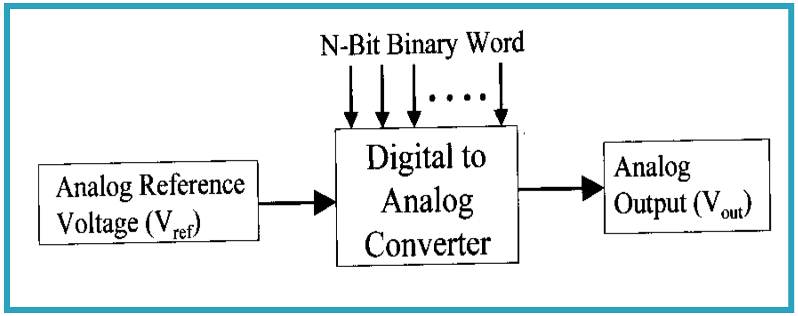
DAC vs. ADC

- ADCs are used in systems to capture “real world” signals and convert them to “digital” signals.

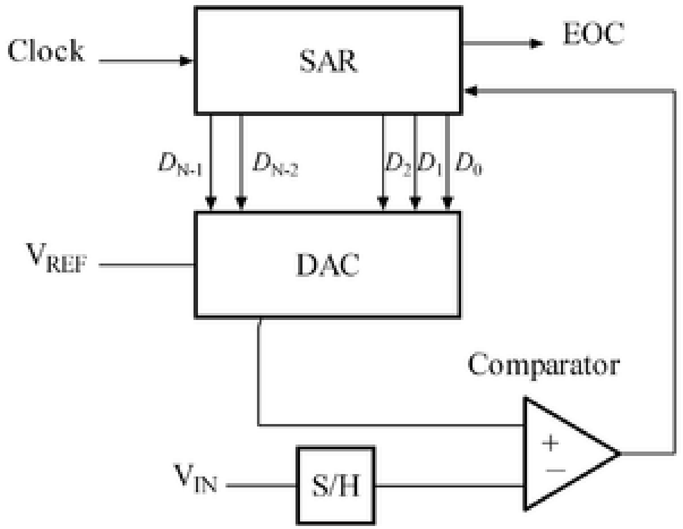
- DACs are used in systems to capture “digital” signals and convert them to “real world” signals that humans can interpret.

Significance of Reference Voltage in DACs

- DACs rely on an input reference voltage to generate analog output from digital signals.



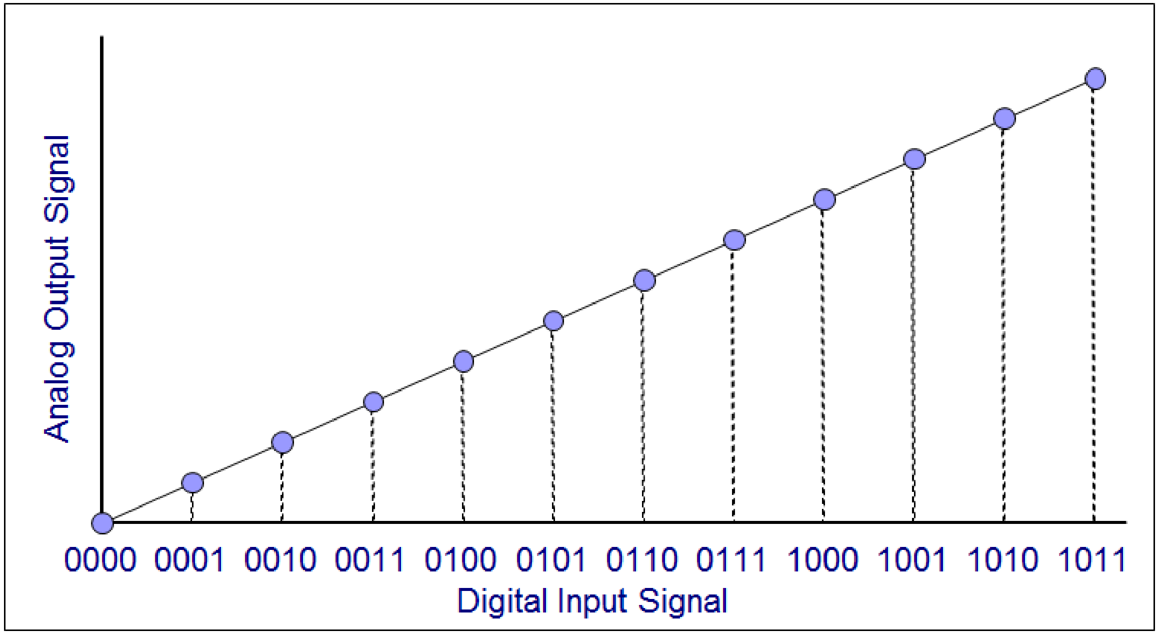
DAC



DAC (using Vref and bits as input) inside an SAR ADC
As explained in earlier student lecture on ADC

Analog Levels For Sampled Digital Values

- Each binary number sampled by a DAC corresponds to a different output analog level between 0 and V_{ref} for Unipolar and V_{ref} and $-V_{ref}$ for Bipolar.

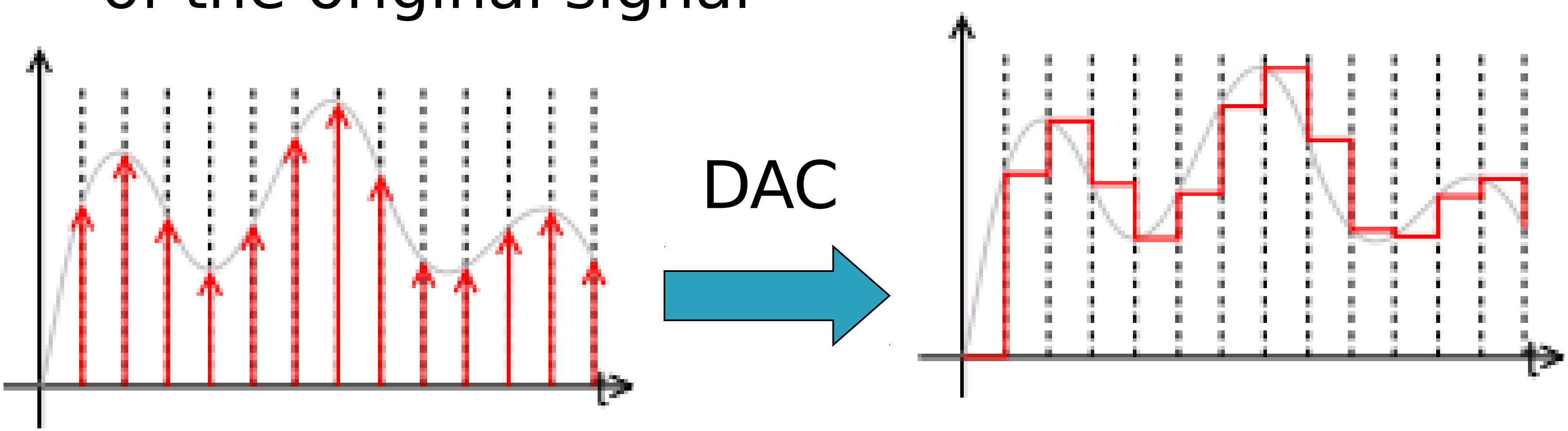


Sampling Frequency

- Sampling frequency is the number of data points sampled per unit time
- Sampling frequency must be twice the frequency of the sampled signal to avoid aliasing, per Nyquist criteria
- A higher sampling frequency decreases the sampling period, allowing more data to be transmitted in the same amount of time

Output is a Piecewise Function

- This is due to finite sampling frequency
- The analog value is calculated and “held” over the sampling period
- This results in an imperfect reconstruction of the original signal

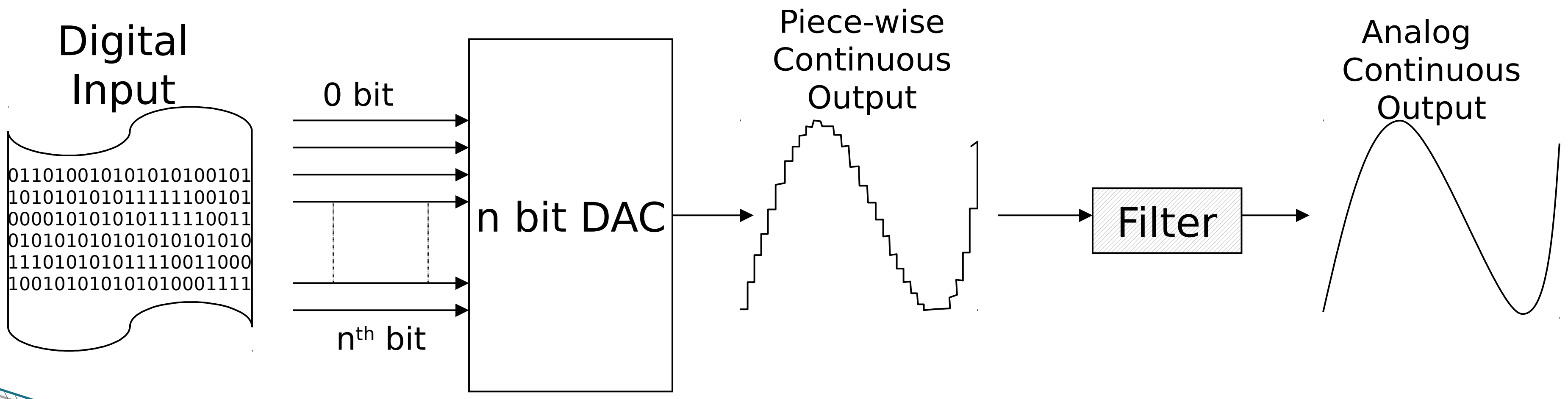


Ideally Sampled Signal

Output typical of a real, practical DAC due to sample & hold

Filtering

- The analog signal generated by the DAC can be smoothed using a low pass filter
- This removes the high frequencies required to sustain the sharp inclines making up the edges

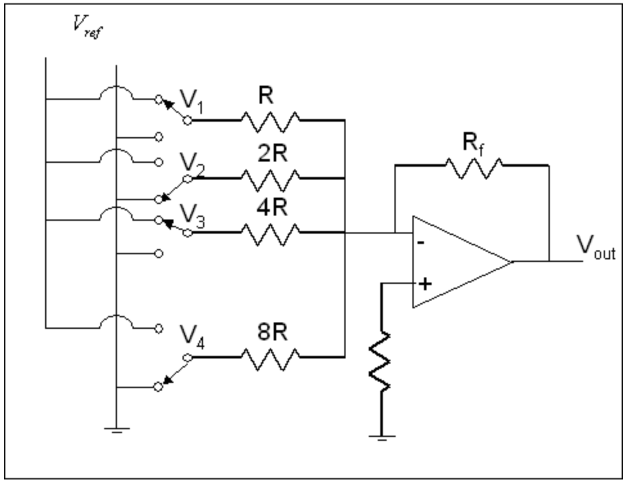


Types of DAC Implementations

- There can be several types of DAC implementations. Some of them are:

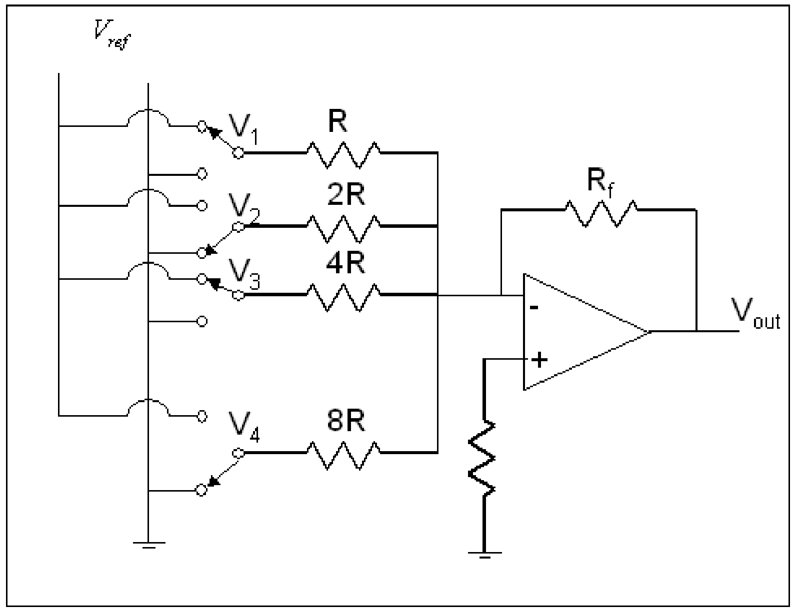
  1. Binary-weighted resistor
  2. R-2R ladder
  3. Pulse-width modulation
  4. Oversampling DAC (in EVB used in lab)
  5. Thermometer-coded DAC
  6. Hybrid DAC

1. Binary-weighted resistor DAC



- *Assumptions:*
  - Virtual Ground at Inverting Input
  - $V_{out} = -IR_f$
- *Details*
  - Use V_{ref} as input voltage
  - Use transistors to switch between high and ground
  - Use resistors scaled by two to divide voltage on each branch by a power of two
  - V_1 is MSB, V_4 LSB in this circuit

1. Binary-weighted resistor DAC



For Resistors Parallel

$$\frac{1}{R_{eq}} = \left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

$$V_{out} = -\frac{R_f}{R_{eq}} V_{ref} = -R_f V_{ref} \left(\frac{B_{n-1}}{R} + \frac{B_{n-2}}{2R} + \cdots + \frac{B_1}{2^{n-2}R} + \frac{B_0}{2^{n-1}R}\right)$$

$$V_{out} = -V_{ref} \frac{R_f}{R} \sum_{i=0}^{n-1} \frac{B_i}{2^{(n-1)-i}}$$

1. Binary-weighted resistor DAC

- Example: take a 4-bit converter,
- R_f /R= a; a = gain.

$$V_{out} = -aV_{ref}\left(\frac{B_3}{1}+\frac{B_2}{2}+\frac{B_1}{4}+\frac{B_0}{8}\right)$$

- Input parameters:
  - Input voltage V_{ref} = -2V
  - Binary input = 1011
  - Coefficient a = ½

$$V_{out} = -\frac{1}{2}\left(-2\right)\left(\frac{1}{1}+\frac{0}{2}+\frac{1}{4}+\frac{1}{8}\right)=\frac{11}{8}=1.375V$$

1. Binary-weighted resistor DAC

- **Resolution:** Making LSB as 1 and all other inputs as 0,

$$\left|V_{\min}\right| = \frac{R_{\mathrm{f}}\left|V_{ref}\right|}{R2^{\mathrm{n-1}}}$$

- If R_f = R/2 then resolution is $\dfrac{\left|V_{ref}\right|}{2^{\mathrm{n}}}$

- **Max $\mathbf{V_{out}}$** can be obtained making all input bits equal to 1 and it can be obtained solving geometric series in equation (1) as

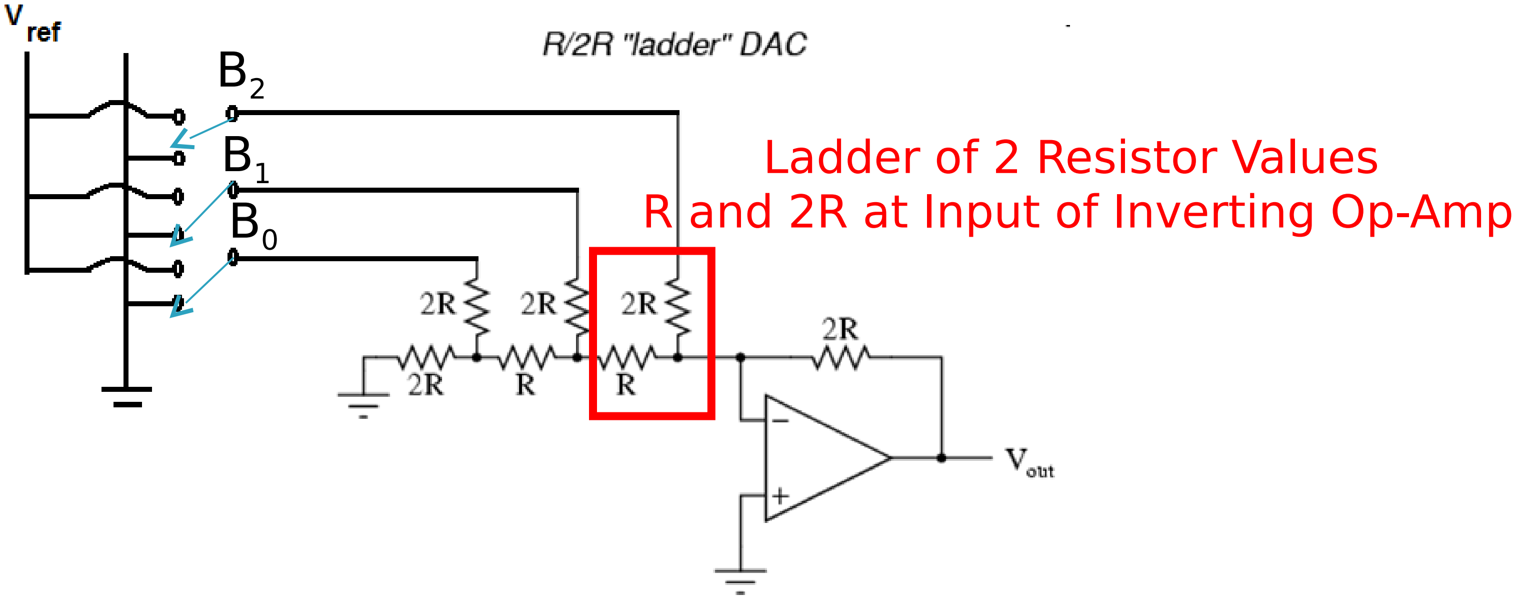
$$\left|V_{\max}\right| = \left|V_{ref}\right|\left(1-\frac{1}{2^{n}}\right)$$

1. Binary-weighted resistor DAC

- Advantages:
  - Simple
  - Fast

- Disadvantages
  - Need large range of resistor values (2048:1 for 12-bit) with high precision in low resistor values.
  - Need very small switch resistances.

2. R-2R Ladder DAC



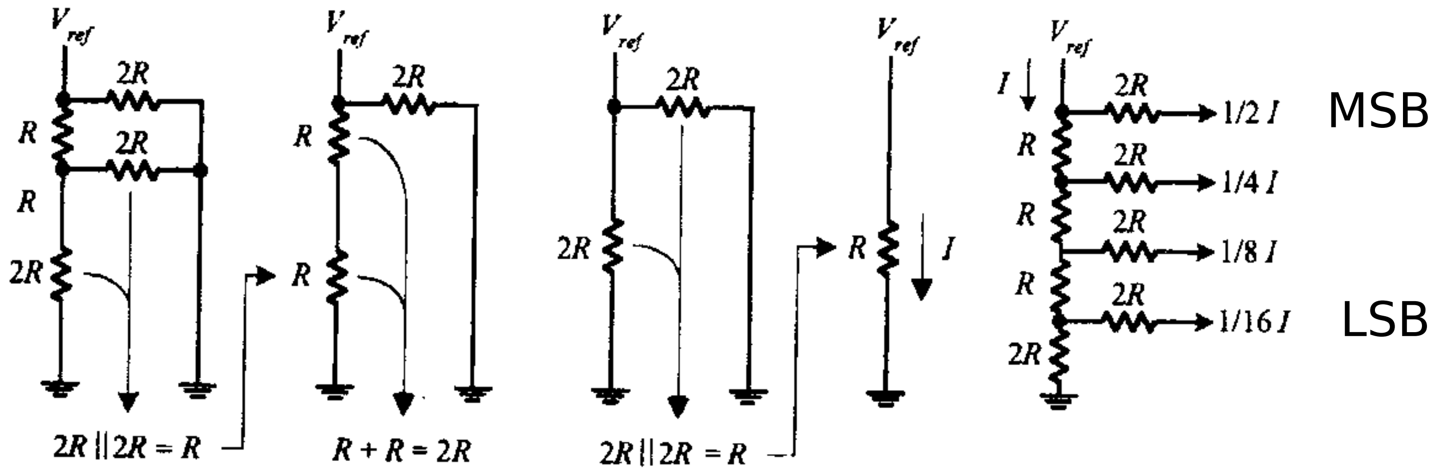
- All the inputs are V_{ref} followed by switches. Output of switches is B2, B1 and B0 in above circuit.
- Similar to binary weighted DAC, status of switches would define if input bits to DAC are V_{ref} or 0.

2. R-2R Ladder DAC

By adding resistance in series and in parallel we can derive an equation for the R-2R ladder.

$$\frac{1}{R_{eq}} = \frac{1}{2R} + \frac{1}{2R}$$

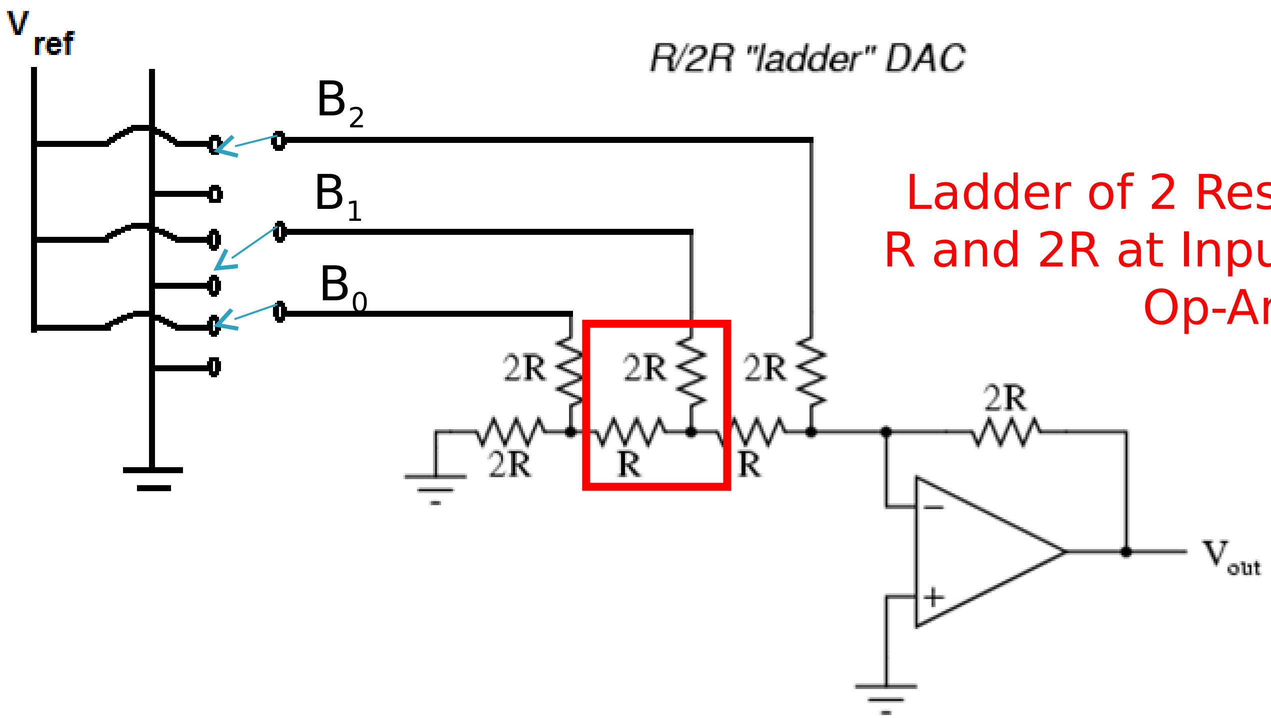
$$\rightarrow R_{eq} = R$$



By knowing how current flows through the ladder we can come up with a general equation for R-2R DACs.

$$V_{out} = -I_{sum} R_f = -I\left(\frac{B_3}{2} + \frac{B_2}{4} + \frac{B_1}{8} + \frac{B_0}{16}\right) R_f$$

2. R-2R Ladder DAC



- Circuit may be analyzed using *Thevenin's theorem* (replace network with equivalent voltage source and resistance).
- Final result is:

$$I = \frac{V}{R}$$

$$V_{\text{out}} = -V_{\text{ref}} \frac{R_f}{R} \sum_{i=0}^{n-1} \frac{B_i}{2^{n-i}}$$

2. R-2R Ladder DAC

- Example
  - Input: 101101
  - V_{ref} = -5.5 Volts
  - a = 1
  - R_f /R= a; a = gain.

$$V_{out} = -V_{ref} \frac{R_f}{R} \sum_{i=0}^{n-1} \frac{B_i}{2^{n-i}}$$

$$V_{out} = -(-5.5)(1)\left[\frac{1}{2^1} + \frac{0}{2^2} + \frac{1}{2^3} + \frac{1}{2^4} + \frac{0}{2^5} + \frac{1}{2^6}\right]$$

$$V_{out} = 3.867$$

2. R-2R Ladder DAC

- **Resolution:** Making LSB as 1 and all other inputs as 0,

$$\left|V_{\min}\right| = \frac{R_{\mathrm{f}}\left|V_{ref}\right|}{R2^{\mathrm{n}}}$$

- If R_f = R then resolution is $\dfrac{\left|V_{ref}\right|}{2^{\mathrm{n}}}$

- **Max V_{out}** can be obtained making all input bits equal to 1 and it can be obtained solving geometric series in equation (1) as

$$\left|V_{\max}\right| = \left|V_{ref}\right|\left(1 - \frac{1}{2^{n}}\right)$$

2. R-2R Ladder DAC

- Advantages:
  - Only 2 resistor values
  - Lower precision resistors acceptable

- Disadvantages
  - Slower conversion rate

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Reference Voltage (V_{ref})

- The reference voltage determines the range of outputs from the DAC

- Non-Multiplying DAC
  - V_{ref} is internally set by the manufacturer and is a constant (fixed) value
  - Sometimes V_{ref} is external from manufacturer

- Multiplying DAC
  - V_{ref} is externally set and can be varied during operation
  - Most DACs use this type

Full Scale Voltage and Resolution

- Full Scale Voltage (V_{fs}) is the output voltage when all bits are set high

$$V_{fs} = V_{ref}\frac{2^N - 1}{2^N} = V_{ref} - V_{LSB}$$

- The DAC resolution is the amount of variance in output voltage for every change of the LSB in the digital input
  - How closely we can approximate the desired output signal
    - Higher resolution Finer Detail Smaller Voltage Divisions
  - Data sheets list the resolution in bits
  - Typical resolution is 8 – 16 bits

$$^{*}V_{LSB} = \frac{V_{ref}}{2^N} = Resolution$$

N = # of Bits

*Resolution depends on ratio of R_f and R as explained in previous section. This case is similar to R-2R ladder resolution with R_f=R

Sampling Rate (f_s)

- The sampling rate is the rate at which the DAC can convert the digital input into an output voltage

- The Nyquist Criterion is used to ensure the output correctly represents the digital input

$$f_s \geq 2f_{max}$$

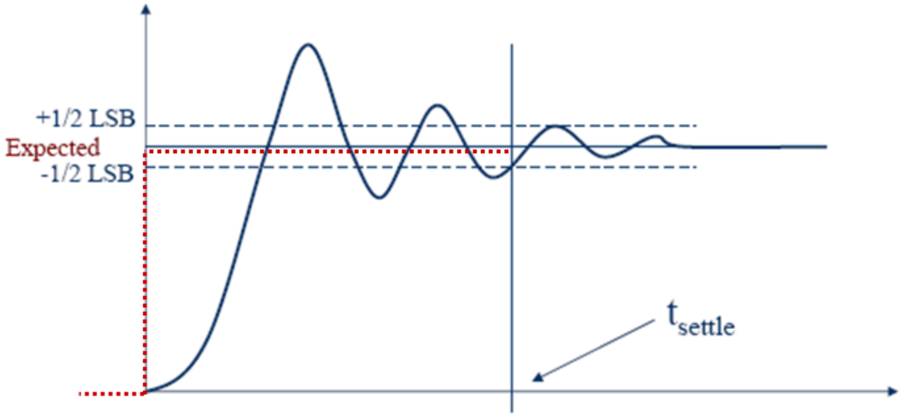
- f_{max} is the max frequency of the analog signal to be reconstructed

- f_s is limited by the input signal clock speed and DAC settling time

Settling Time

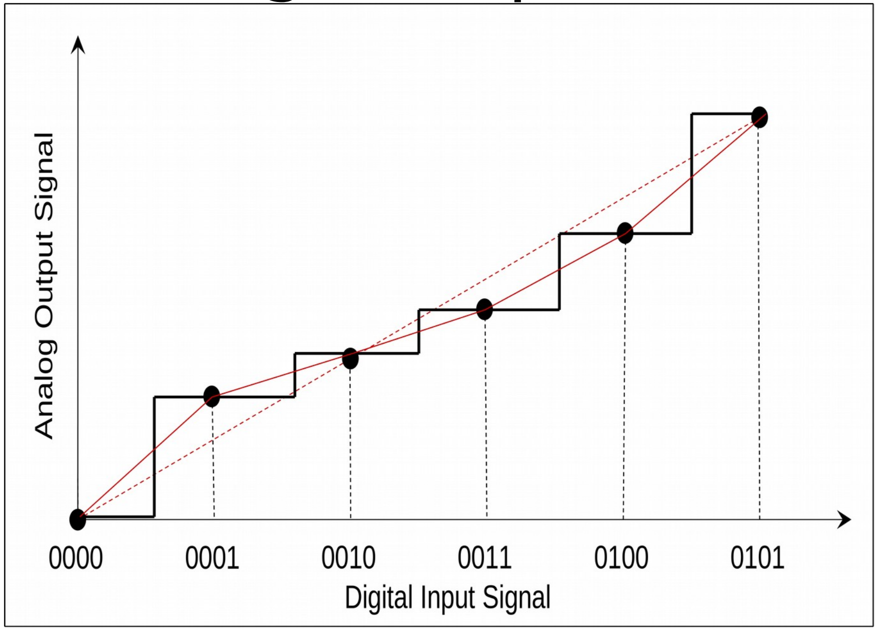
- The settling time is the interval between a command to update (change) its output value and the instant it is within a specified percentage of its final value

- Any change in the input state will not be reflected in the output state immediately. There is a time lag between the two events.



Linearity

- The linearity is the difference between the desired analog output and the actual output over the full range of expected values
- Ideally, a DAC should produce a linear relationship between a digital input and the analog output



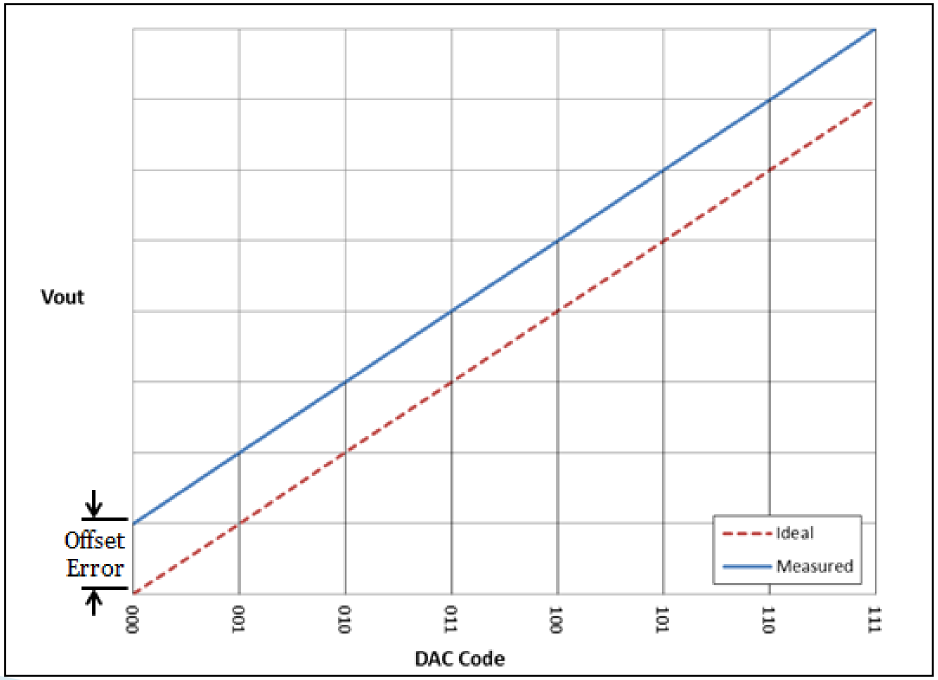
Errors

Common DAC Errors:

- Offset Error
- Gain Error
- Full Scale Error
- Resolution Errors
- Non Linearity
- Non-Monotonic
- Settling Time and Overshoot

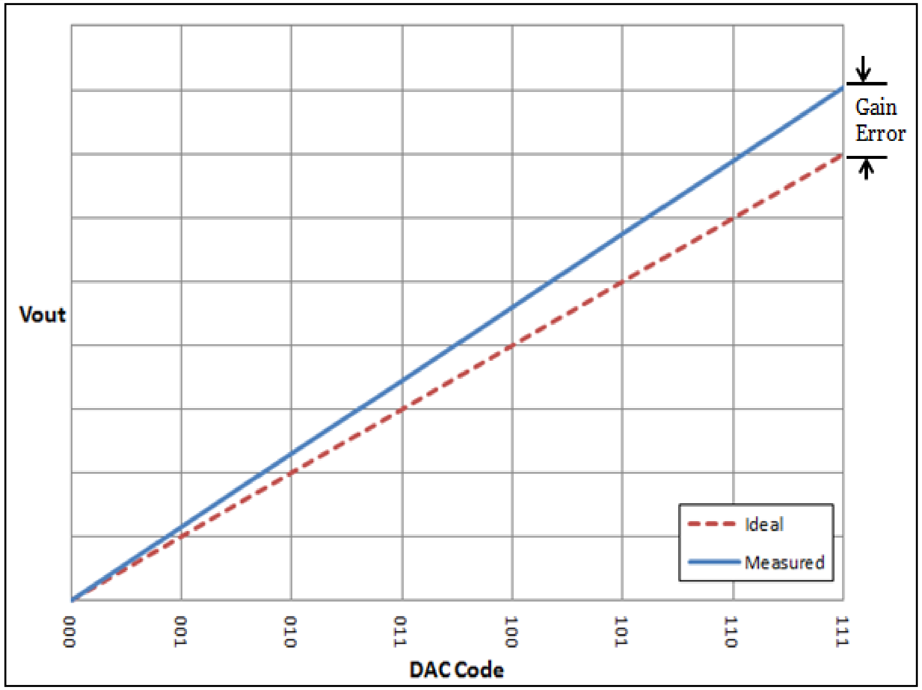
Offset Error

- An offset error will cause all the output voltages to be different from the ideal output by the error
  - It can be determined by measuring the output voltage for a digital input of zero.



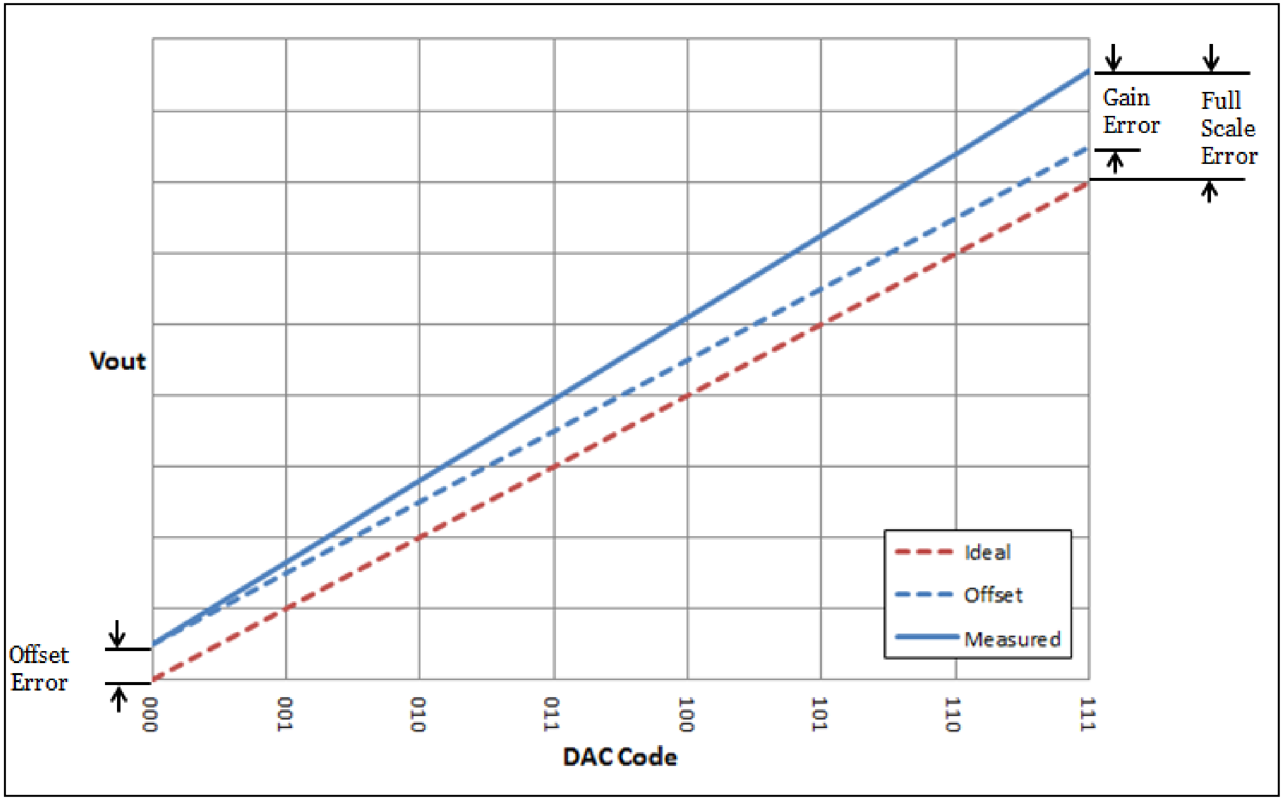
Gain Error

- The gain error is how well the slope of the actual transfer function matches the slope of the ideal transfer function
  - It can be determined by measuring the output voltage for a digital input of all 1’s



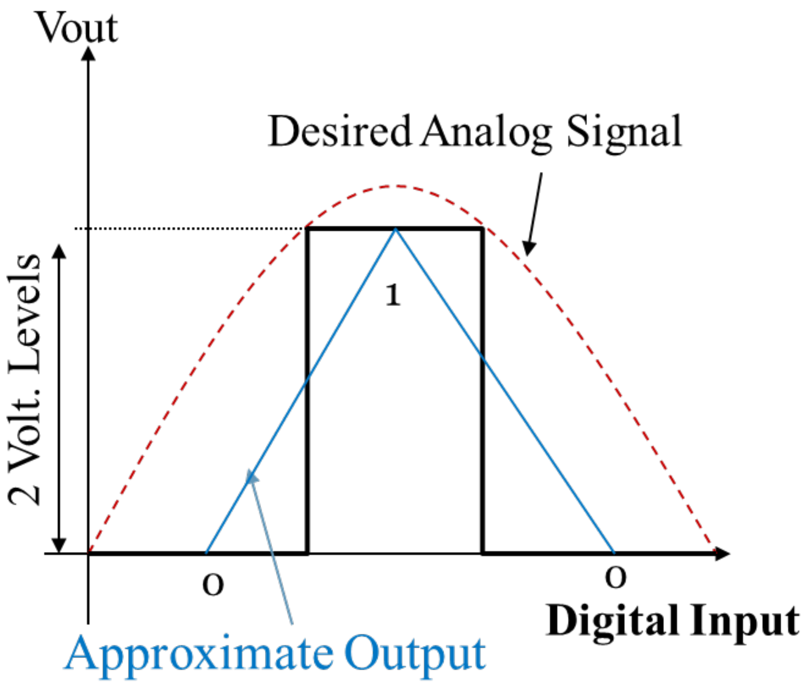
Full Scale Error

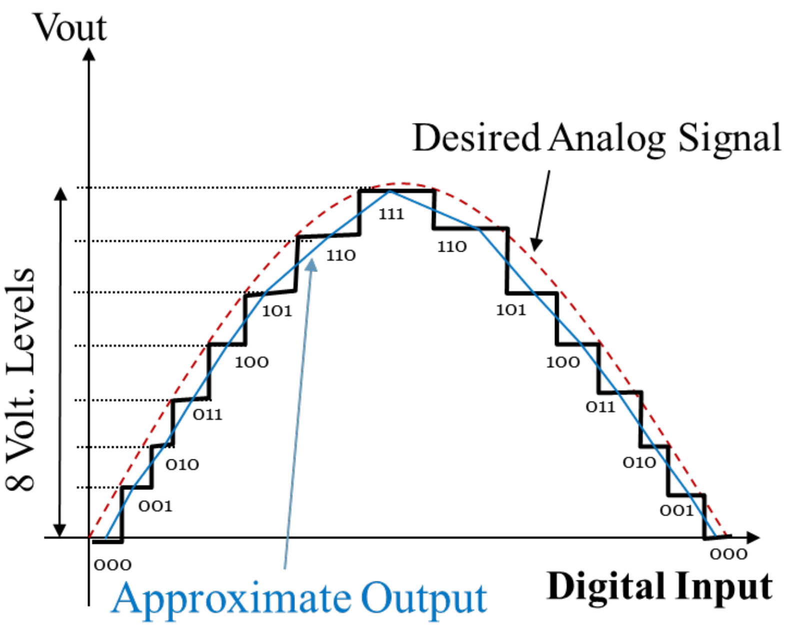
- Full Scale error is the combination of the Gain Error and the Offset Error



Resolution Error

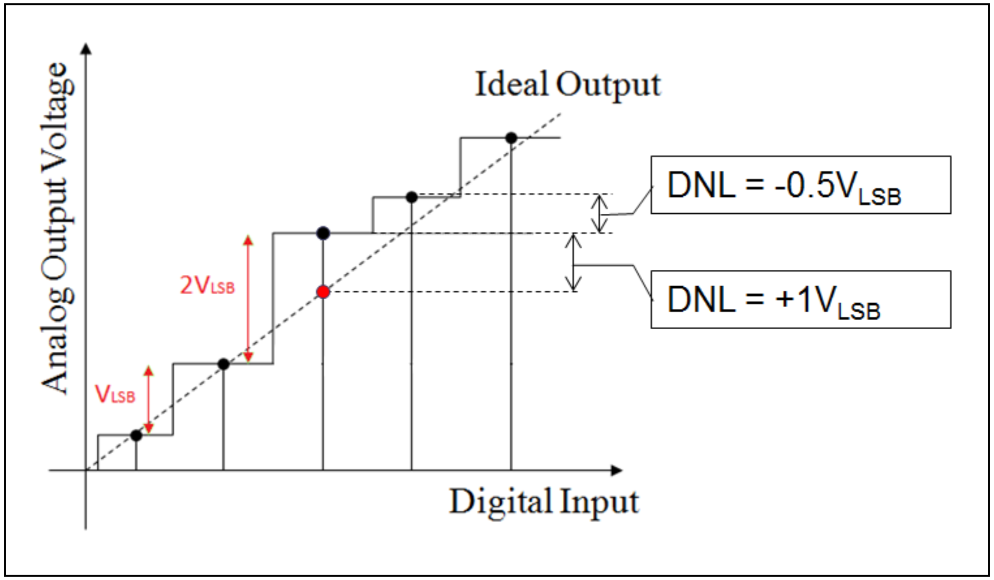
- The resolution will determine how close your output will match the desired signal





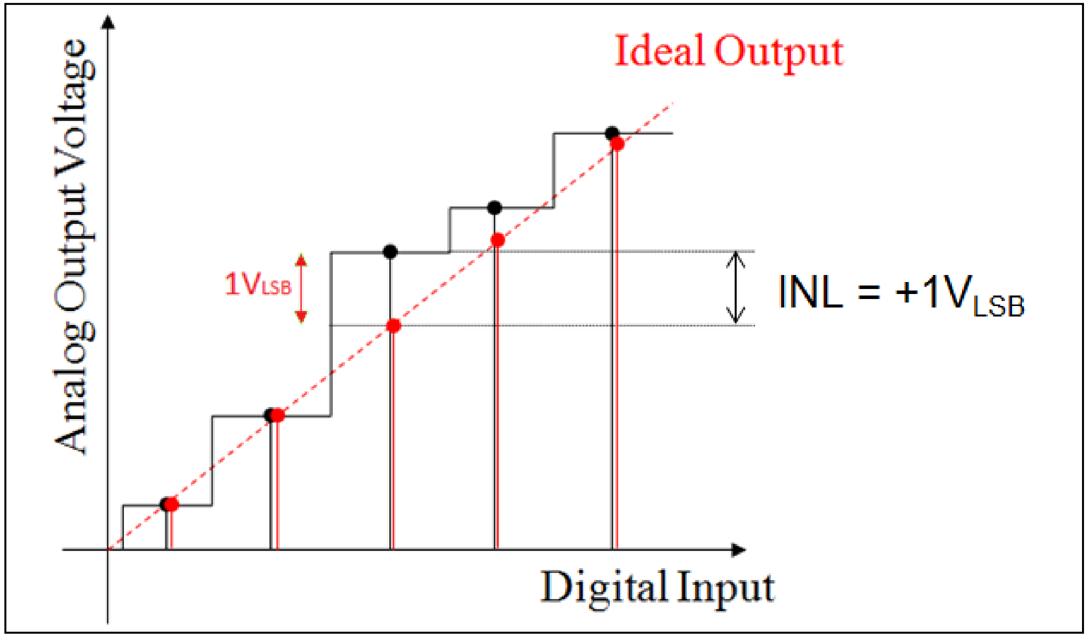
Differential Nonlinearity Error (DNL)

- The difference between two successive digital output codes is ideally 1 V_{LSB}
- The deviation from a step of 1 V_{LSB} is the DNL error
  - Manufacturers will specify the maximum DNL error



Integral Linearity Error (INL)

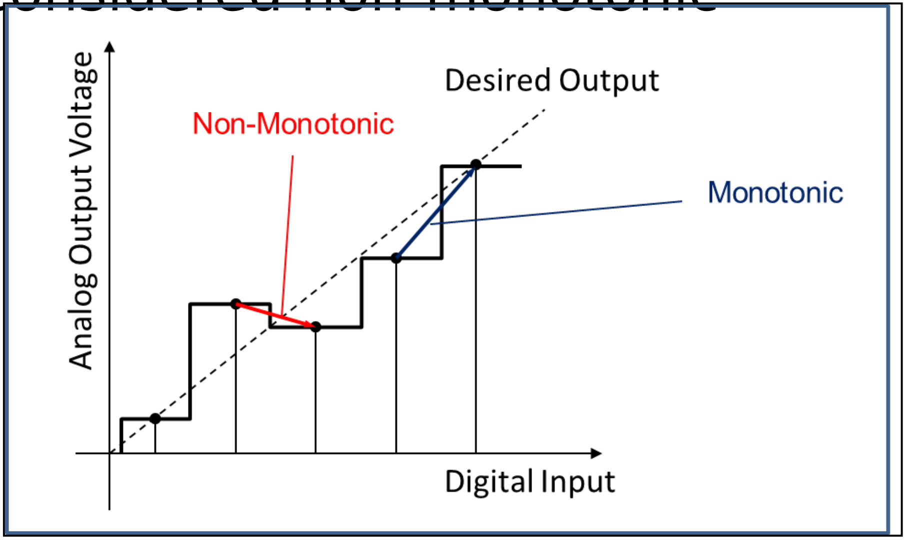
- The INL is the difference in the ideal linear voltage and the actual output voltage for a given digital code
  - Manufactures will specify the max INL error



Non-Monotonic

- Monotonic Function
  - A monotonically increasing function will always increase or remain constant (non-decreasing)
  - A monotonically decreasing function will always decrease or remain constant (non-increasing)

- If an increase in the digital input results in a decrease in the output voltage the DAC is considered non-monotonic
  - If the DNL error is less than ± 1 LSB the DAC is guaranteed to be monotonic



Applications

- Audio/Video
  - MP3 Players
  - CD Players
  - Cellphones
  - USB Speakers
  - Analog Monitors
- Signal Generators
  - Sine Wave generation
  - Square Wave generation
  - Random Noise generation

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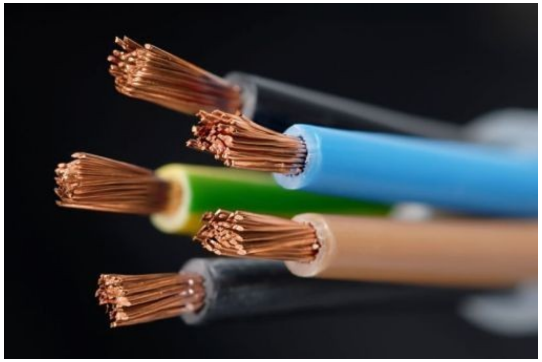
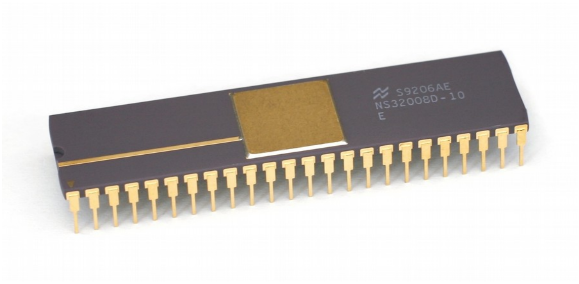
- Diodes: Theory and applications
  - Ideal vs. real
  - Types: Junction and Zener

Diodes

- Review of semiconductors
- Ideal Diode Characteristics
- Types of Diodes
  - Semiconductor Diodes
    - P-n Junction Diode
    - Zener Diode
    - Light Emitting Diode (LED)
    - Photodiode

Semiconductors

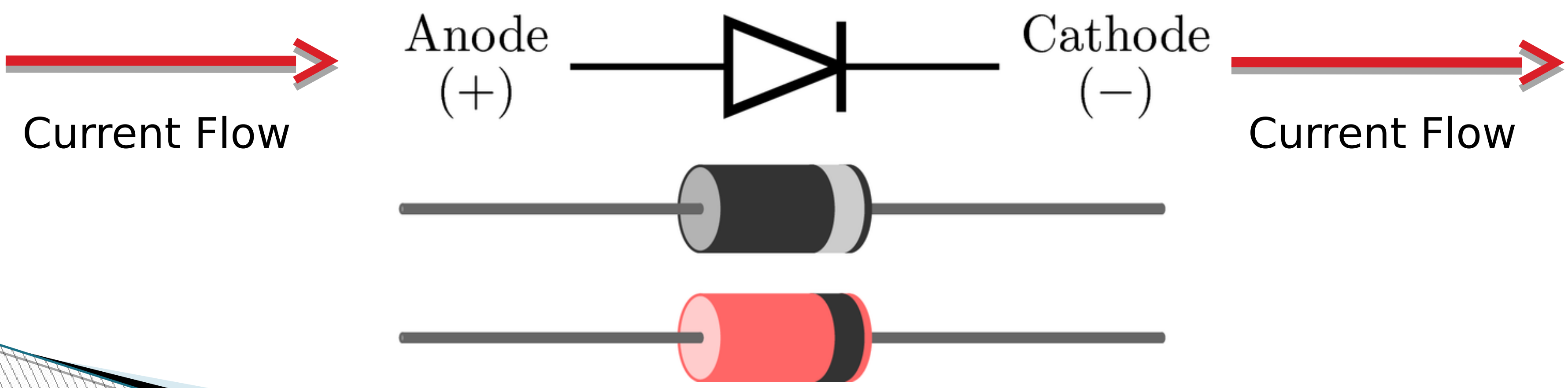




- **Conductors**
  - Material which allows flow of electric charge (current). Ex) Copper wiring, silver (contactor for electric motor)
- **Insulators**
  - Material does not allow flow of electric charge (current). In theory have an infinite resistivity. Ex) ceramic, glass, Teflon
- **Semiconductors**
  - A material whose electrical conductivity is poor at low temperatures but is improved by the application of heat, light, or voltage.
  - Electrical conductivity can be increased and precisely controlled by adding small impurities in a process called ***doping***

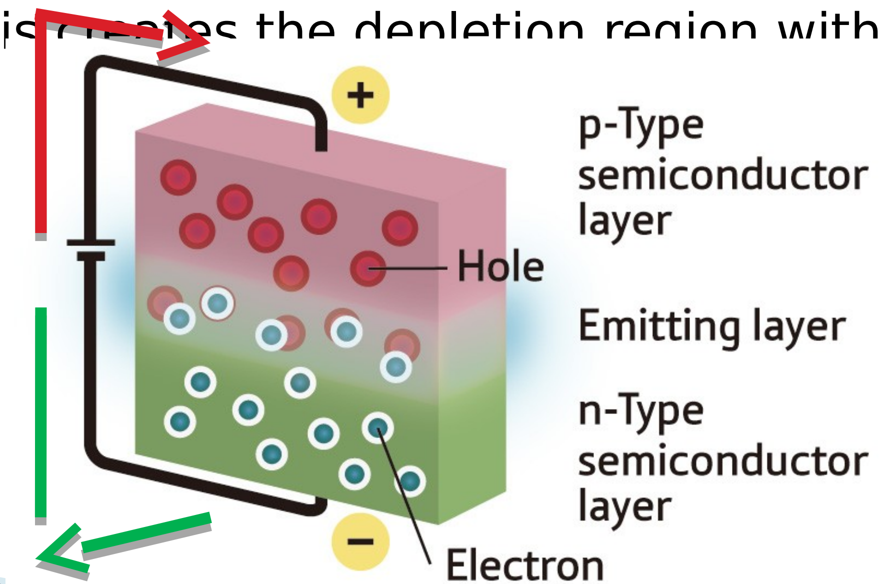
What is a diode?

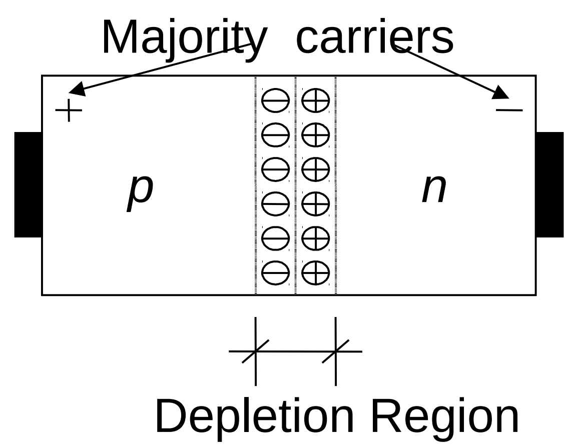
- A diode is a two-terminal electronic component with asymmetric conductance
- It has low (ideally zero) resistance to current flow in one direction (**forward**), and high (ideally infinite) resistance in the other (**reverse**)



Solid State Diode

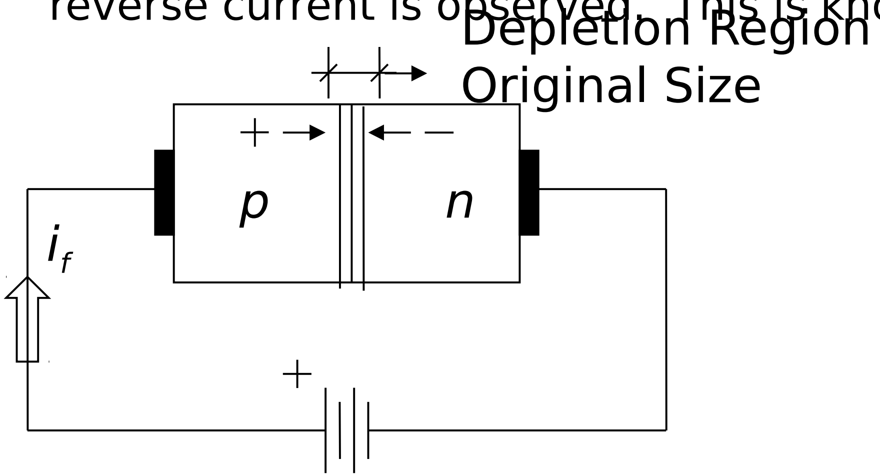
- A diode is created when a p-type semiconductor is joined with and n-type semiconductor by the addition of thermal energy.
- When both materials are joined, the thermal energy causes positive carriers in the *p*-type material to diffuse into the *n*-type region and negative carriers in the *n*-type material to diffuse into the *p*-type region.
- This creates the depletion region within the diode



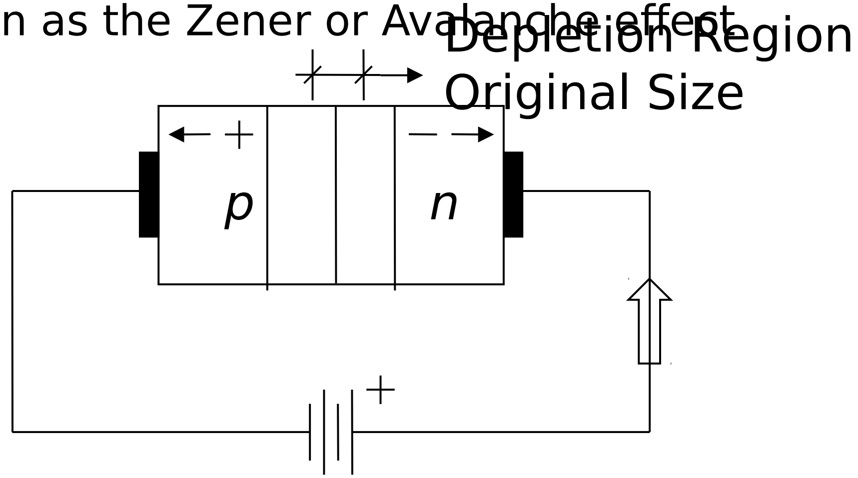


Forward and Reverse Bias

- A diode is forward biased if the positive terminal of the battery is connected to the p-type material.
  - Current is sustained by the majority carriers.
- A diode is reverse biased if the positive terminal of the battery is connected to the n-type material.
  - There is a small reverse current or leakage current sustained by the minority carriers
- If reverse bias is sufficiently increased, a sudden increase in reverse current is observed. This is known as the Zener or Avalanche effect.



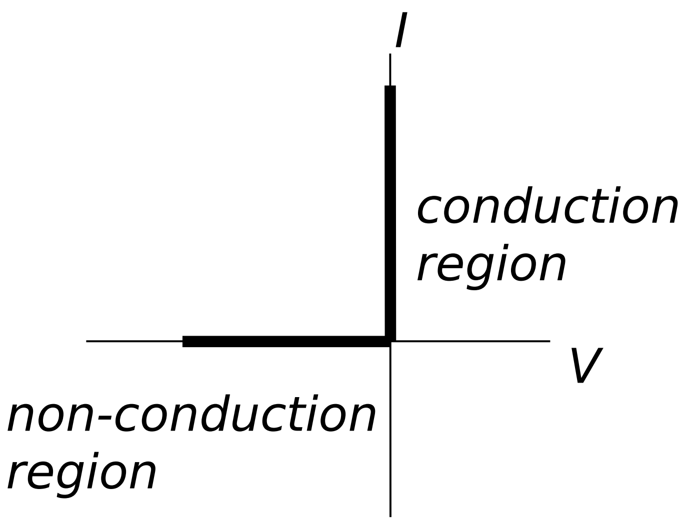
Forward Biased



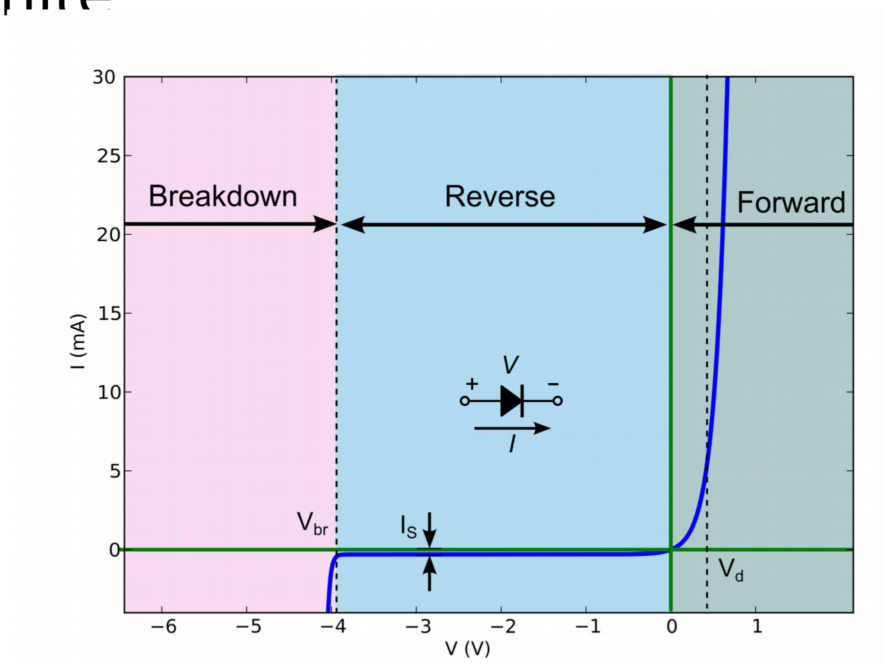
Reverse Biased

Diode Characteristic Curve

- Ideal Diode - no resistance to current flow in the forward direction and infinite resistance in the reverse direction
- Actual Diode – forward resistance not quite zero and reverse resistance not infinite

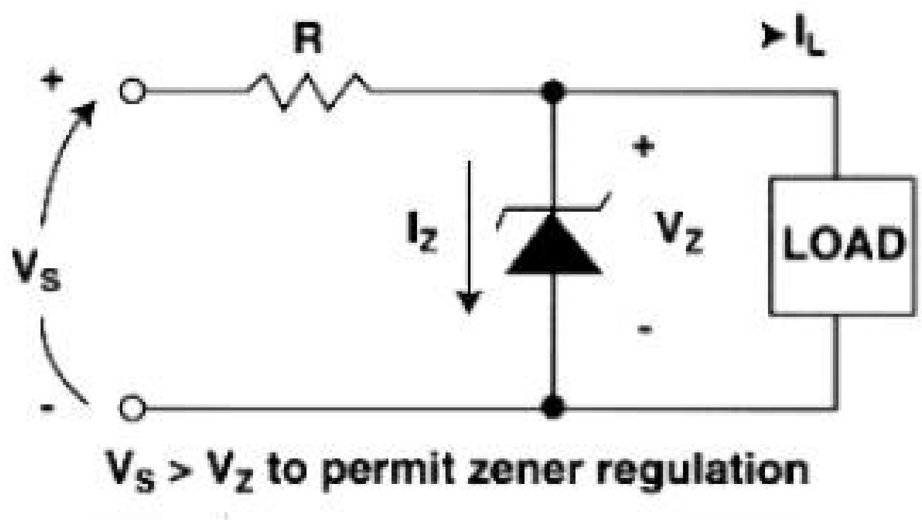


Ideal Curve



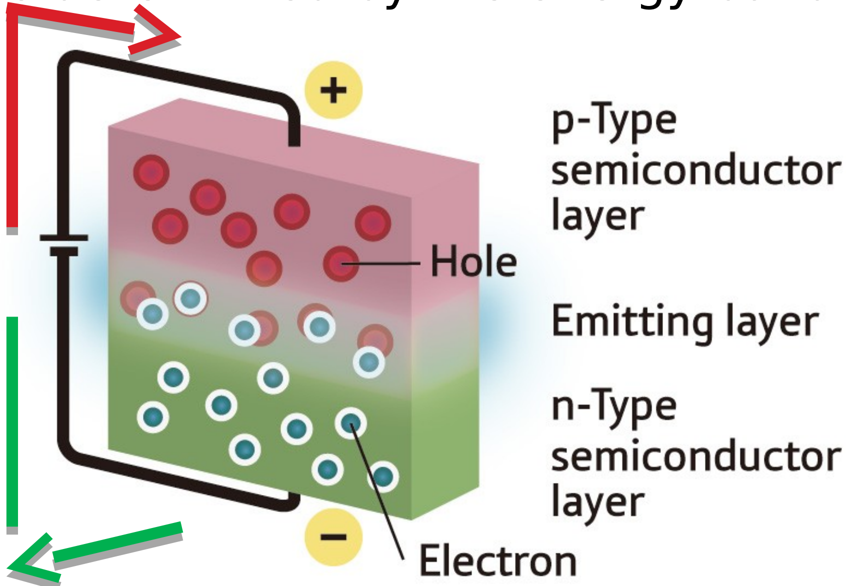
Zener Diode

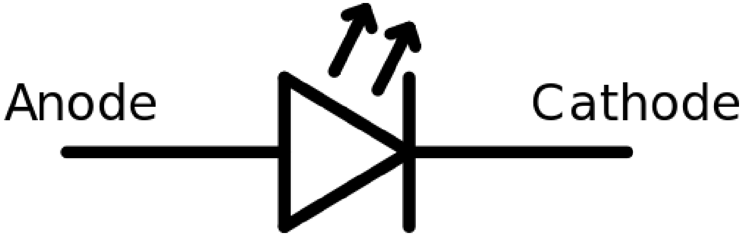
- A diode which allows current to flow in the forward direction in the same manner as an ideal diode
- But also permits it to flow in the reverse direction when the voltage is above a certain value known as the breakdown voltage
- Zener diodes have a specified voltage drop when they are used in reverse bias.
- Every p-n junction (i.e. diode) will break down in reverse bias if enough voltage is applied.
- Able to maintain a nearly constant voltage under conditions of widely varying current.
- Zener diodes are operated in rever



Light Emitting Diode (LED)

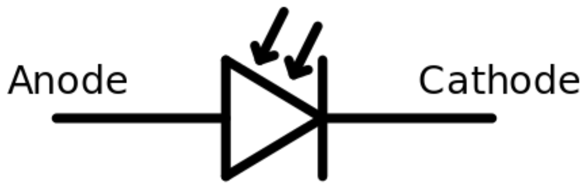
- Semiconductor device with a p-n junction
- When a forward bias is applied, electrons are able to recombine with holes within the device, releasing energy in the form of photons (electroluminescence).
- The color of the light (corresponding to the energy of the photon) is determined by the energy band gap of the semiconductor

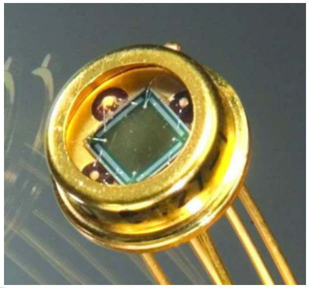


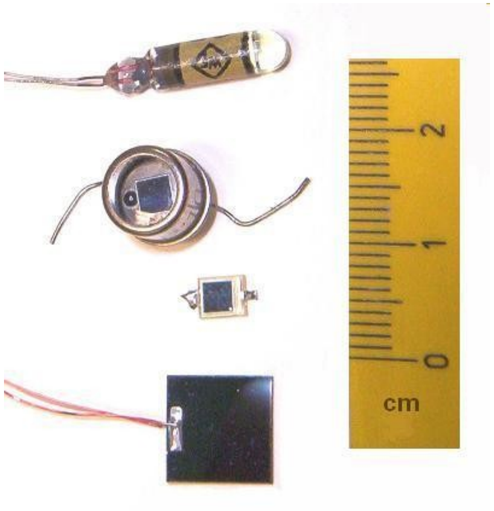


Photodiode

- Converts light into voltage or current
- Ex) a solar cell is a large area photodiode operating in zero bias
- Designed to operate in reverse bias
- Many use a P-I-N junction rather than a P-N junction
  - PIN diode: a diode with a wide, lightly doped 'near' intrinsic semiconductor region between a p-type semiconductor and an n-type semiconductor region







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