Week 4

Amplification

Sensor signals are in millivolts or milliamps
The analogue front end for a sensor is more complex than the digital control circuitry for the sensor actuator loop
The main issues for sensor interfaces are accuracy, noise, offset, drift, and impedance

Sensors that need amplification

- Process: flow, level, temp, pressure, vacuum
- Position: GPS, potentiometer, radar, sonar, altimeter
- Motion: gyroscopes, LVDT, accelerometer, speedometer
- Ergonomic: touch, optical, acoustic
- Chemical: mass spec, pH, conductivity, smoke, O_2, H_2, NO_2, CO
- Electrical: Voltmeter, ammeter, metal detector, Hall effect

Real Op Amps vary from the ideal

- Gain is not infinite especially at high frequency
- Input impedance is not infinite
- Output impedance is not zero
  Offset voltage is not zero
- Output voltage takes time to change (slew rate)
- Bandwidth is not infinite

Basic Amplifiers

- Open Loop Op Amp
- V1 inverting input
- V2 non-inverting input
- Very high input and very low output impedances
- The output voltage is equal to the gain times the difference between the input voltages
- Vout = A(V2-V1) Where A = open loop gain

Inverting Amplifier

- Assume that input terminals have infinite impedance and draw no current
- The summing junction has V=0
- Ohms law: i=Vin/R1 and -i = Vout/R2
- Solve gain A = Vout/Vin = -R2/R1

Non-Inverting Amplifier

- Assume input terminals have infinite impedance and draw no current
- Ohms law: i = Vout/(R2+R1) and i = Vin/R1

- Solving gain A = Vout/Vin = 1 +R2/R1

Summing Amplifier

- Sum of inverting amplifiers
- Input terminals have infinite impedance, draw no current
- Use supposition to calculate Vout from V1, V2, and Vn. Then sum the output voltages
- Ohms law: Vout/V1 = -R2/R1 = gain for loop 1, repeat for other loops

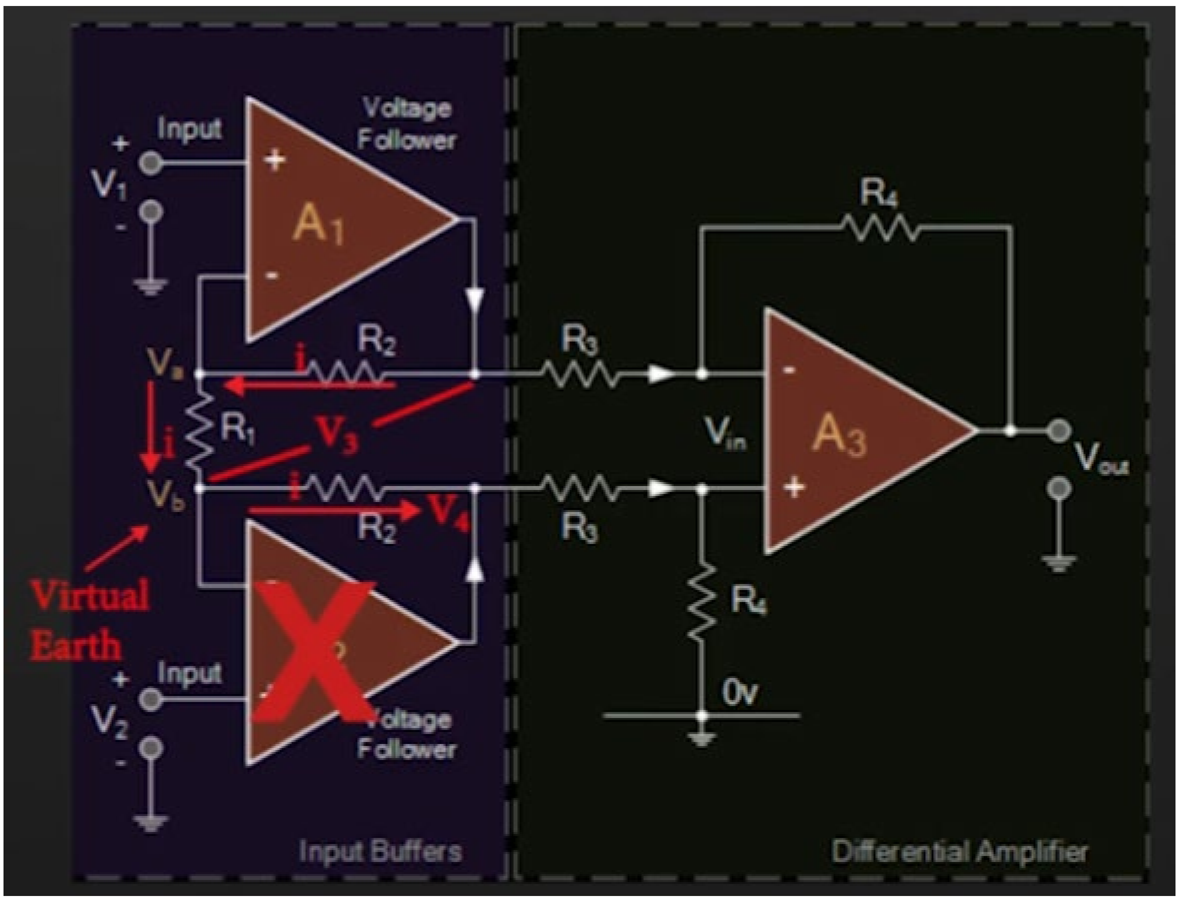
Differential Amplifier

- Calculate component of Vout from V1
- Find V+ in terms of V1
- Solving V+ = iR2, and V1 = i(R1+ R2)
- V+ = V1(R2/(R1+R2))
- Ohms law: i = Vout/(R3+R4) and i=V+/R3
- V1out = V+((R4+R3) /R3) = V1(R2/(R1+R2)) * ((R4+R3)/R3)
- Calculate component of Vout from V2
- Ohms law: V2 = iR3 and V2out = - iR4
- V2 out = - V2(R4/R3)
- Superposition, add components of Vout from V1 and V2
- Vout = V1out + V2out
- Vout = V1(R2/(R1+R2))*((R4+R3)/R3) – V2(R4/R3)
- Simplifying assumption: let R3 = R1 and R2=R4
- Vout = V1(R4/(R3+R4))*((R4+R3)/R3) – V2(R4/R3)
- Vout = V1(R4/R3) – V2(R4/R3)
- Vout = (V1-V2)(R4/R3)

Instrumentation Amplifier

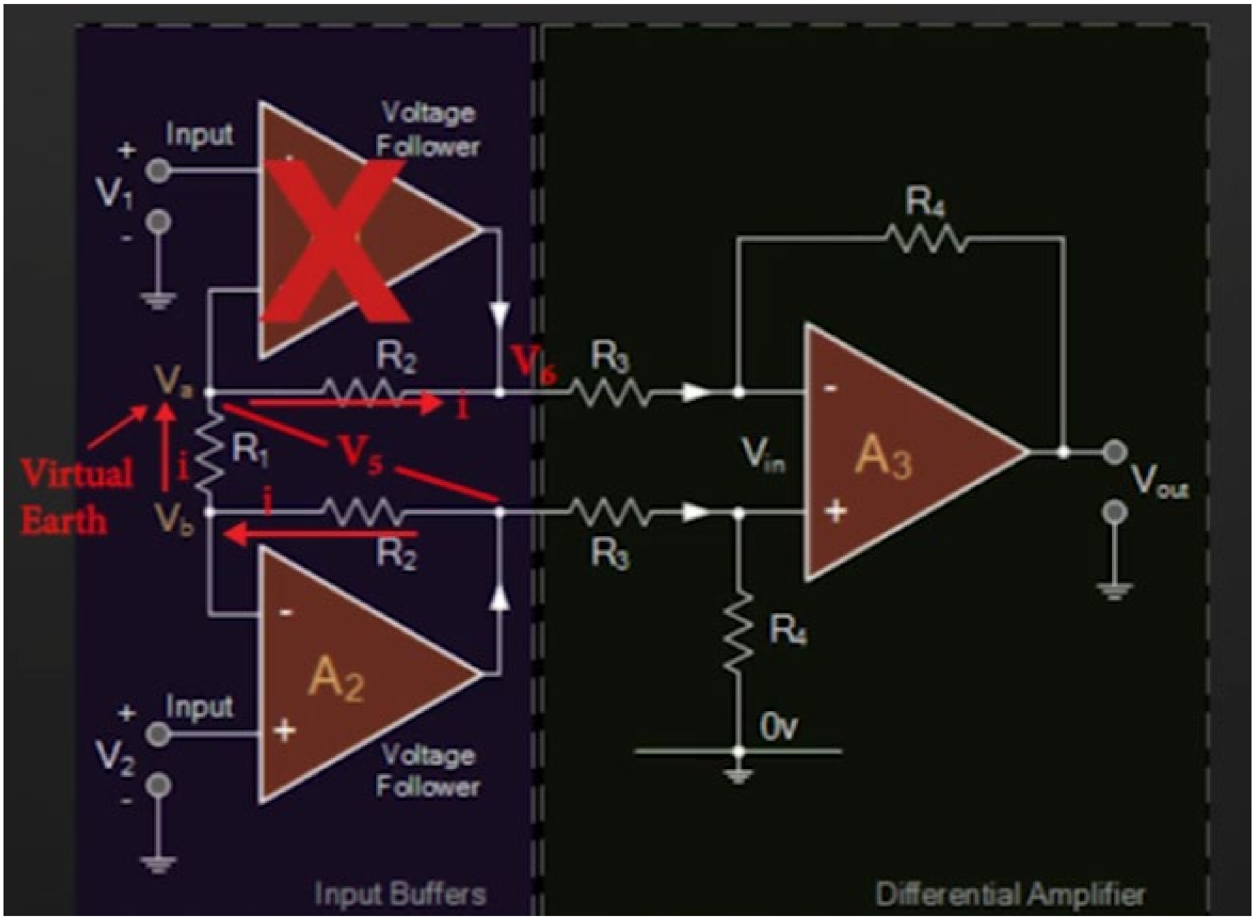
- Special type of variable gain, differential amplifier with high input impedance and a single output
- Commonly used to amplify small differential signals for thermocouples, strain gauges, and current sensors
- R1 or Rg is the variable gain resistor
- Gain may vary on commercial instrumentation amp from 1-1000
    - Set V2 = 0, calculate the component of Vout from V1
        - Use differential gain equation using V3 and V4
            - Vout1 = (R4/R3) * (V4-V3)
            - Solve for V3
            - Vb is a virtual earth
            - A1 acts as a non-inverting amplifier
            - V3 = V1*(1+R2/R1)
            - Solve for V4 in terms of V3

- i = V3/(R1+R2) = - V4 /R2
- V4 = - V3(R2/(R2+R1))
- Sub V4 and V3 for Vout
- Vout1 = (R4/R3) * (V4-V3)
- Vout1 = (R4/R3) (VF1(1+R2/R1)) – (V1(1+R2/R2)) (R2/(R2+R1))
- Vout1 = (R4/R3) (V1) ((R1+R2)/R1 + (R2/R1))
- Vout1 = -V1(R4/R3) (R1+2R2)/R1))



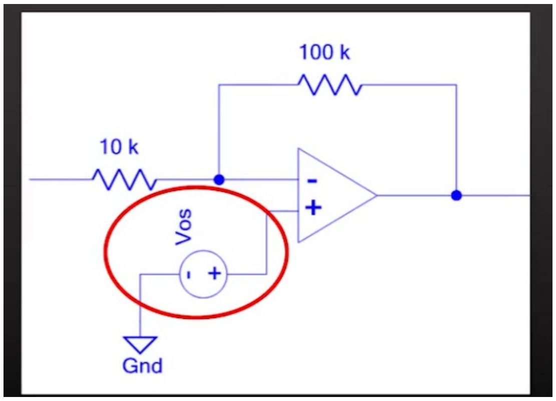
- Then set V1 = 0, calculate Vout from V2
- Use diff equation for V5 and V6
- Vout2 = (R4/R3) (V5-V6)
- Va = virtual earth
- A2 is the non-inverting amplifier
- V5 = -V2(1+R2/R1)
- i = V5/(R1+R2) = -V6/R2
- V6 = -V5(R2/(R2+R1))

- Sub for V6 and V5
- Vout2 = V2(R4/R3) ((R1+2R2)/R1)
- Vout = (V2-V1) (R4/R3) (R1+2R2)/R1))



Imperfection: Input Offset Voltage

- The ideal op amp output is zero when both inputs are at equal voltage
- A real op amp will saturate in one direction or another when both inputs are equal
- This voltage is called the input offset voltage (Vos)
- Vos gets multiplied by the gain to produce an error in the amplified signal
- Critical spec when you have small differential input and you need a high gain for the output
- Vos has a base component and a value that depends on temp

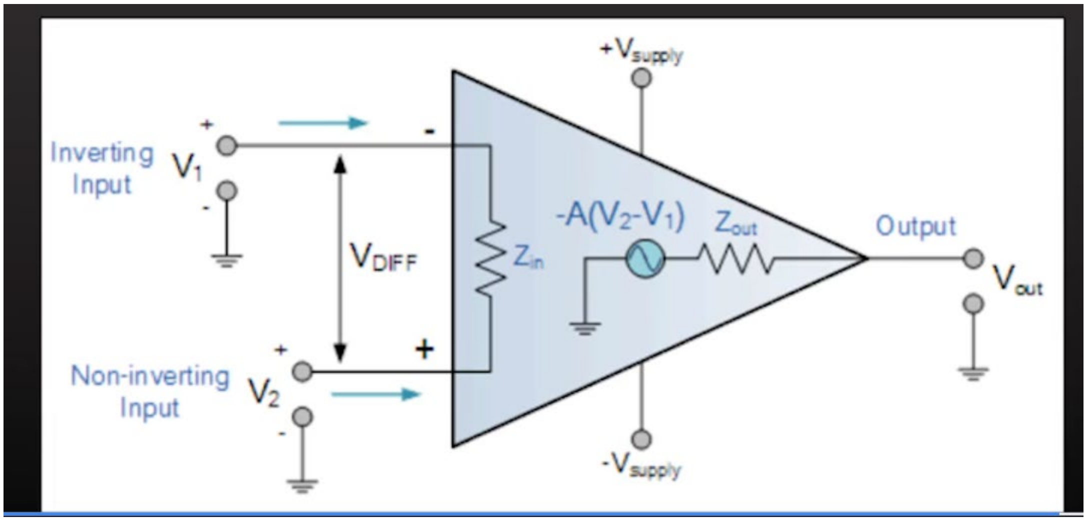


Imperfection: Input Bias Current

- The inputs of all op amps will draw a small amount of current unlike an ideal op amp
- This current draw cannot be accurately modeled as a simple resistive impedance
- It happens because the inputs to an op amp have finite impedance
- They are connected to a real transistor in their internal construction
- Input bias current causes a voltage drop across your input resistors
- The bigger the resistor, the more the voltage drop

Imperfection: Common Mode Rejection

- There should be no change in output signal if identical, in phase input signals (common mode) are applied
- In real op amps, the change in output consists of the sum of a large differential gain and a very small common mode gain
- The common mode rejection ratio (CMRR) of a differential amplifier measures its ability to reject common mode signals
- CMRR gets worse at high frequencies
- $V_{out} = A_{ol}(V2-V1)$ is the differential gain
- $V_{cm} = \frac{1}{2} A_{cm}(V2+V1)$ is the common mode gain
- $CMRR = A_{ol}/A_{cm} = 20 \log_{10} (A_{ol}/A_{cm})$ dB
- When measuring voltages, RF noise appears as an offset on both wire leads, making it a common mode signal
- The CMRR of the amplifier determines the attenuation applied to the noise
- High CMRRs reduce the impact of noise on the sensor accuracy



Open loop frequency response

- Real op amps do not have infinite bandwidth
- Open loop gain is the output amplification with no external feedback signals
- Gain bandwidth product (GBP) = Gain x Bandwidth

Frequency compensation

- Added to ensure that an op amp does not produce random high frequency oscillations
- Needed because stray capacities can cause unwanted phase shifts at frequencies > 1MHz
- Open loop gain is reduced at high frequencies by substituting an internal stage with a high pass filter

Slew rate

- Rate of change of the output voltage caused by a step change on the input
- Unit of measure is V/ microseconds
- Influenced by frequency compensation
- Capacitors used to reduce the high frequency response also slow down the speed of the response of the output
- Slew rate distortion
  - An op amp needs a minimum slew rate of 2 pie fVo to amplify an input signal Vo sin(2pieft) without distortion
  - Note that 2 pie fVo is the max slope of the input signal, occurring at the zero crossings

        - Running the op amp above the slew rate will distort the input signal

Sensor Noise

Sensor noise is the random addition of meaningless data added to your sensor signal
Noise stems from sources inside your sensor circuit
Interference comes from sources outside your circuit
Noise is expressed in signal to noise ratio
SNR = 20 log (Vsignal/Vnoise)

Noise in op amps is expressed statistically

- Op amp contributes their own noise to the sensor system
- The mean value of the noise waveform is zero
- The variance of the noise

$$(1/T) \int_T V_n(t)^2 \neq 0$$

Bandwidth

- The range of frequencies (highest to lowest) a signal uses in a given transmission device
- The higher the gain, the lower the bandwidth
- Noise in an op amp is a function of bandwidth
- Don't allow more bandwidth than needed in an op amp

4 main types of noise

- Johnson-Nyquist (thermal noise)
    - Occurs in all resistors due to the thermally induced motion of charge carriers inside the conductor
    - Happens regardless of applied voltage or current flow
    - Modeled as white noise
        - Power density is constant at all frequencies
    - Present in all electronic devices
    - Higher bandwidth circuits let in more noise
    - Voltage source in series with noiseless resistor
    - Because resistance increases with temp, so does thermal (JN) noise
    - Noise is a resistor can propagate

    - Max power transfer happens when the rest of the circuit's equivalent resistance = the resistor

- 1/f noise (pink noise)
    - The power frequency interval is inversely proportional to frequency
    - Each octave carries an equal amount of noise energy
    - This power spectrum looks pink when it occurs in visible light
    - Source of pink noise is very slow changes in metallurgy defects, semiconductor traps, and domain structures in inductors

- Shot noise (Schottky noise)
    - Occurs due to the random changes in the flow of discrete electrons in an otherwise constant DC current.
    - Independent of temperature and frequency

- Quantization noise
    - Occurs during the conversion by an ADC of the analog sensor signal to a digital signal
    - An ADC performs sampling and quantization
    - Sampling converts the sensor signal into a string of real numbers
    - Quantization replaces each number with a digital approximation needed for storage
    - Quantizing the sensor signal produces a string of errors
    - Noise is modeled as an additive random signal
    - The more digital levels an ADC uses, the lower the quantization noise
    - Noise is non-linear and signal dependent
    - Ideal noise is best seen in saw tooth and triangle waves
    - Sine wave quantization error is non-uniform

Noise is a sensor circuit is additive
Noise varies by temp and frequency
Sensor noise hurts both the accuracy and resolution
Resolution is the smallest increment of signal change that a sensor can reliably detect
Resolution is inversely related to noise
Accuracy is the error between the sensor reading and the true value of the reading
Accuracy cannot be better than the resolution
Accuracy is inversely related to noise

Reducing sensor noise

- You cannot filter out sensor noise in software without slowing down sensor response time
- Study the hardware to identify sources of noise and relative magnitudes
- Study source impedances, and see which frequencies may cause noise

- Use an op amp that gives the least sum of squares noise at the most likely input impedances