STANFORD UNIVERSITY

EE122B

Introduction to Biomedical Electronics

Bioinstrumentation Fundamentals

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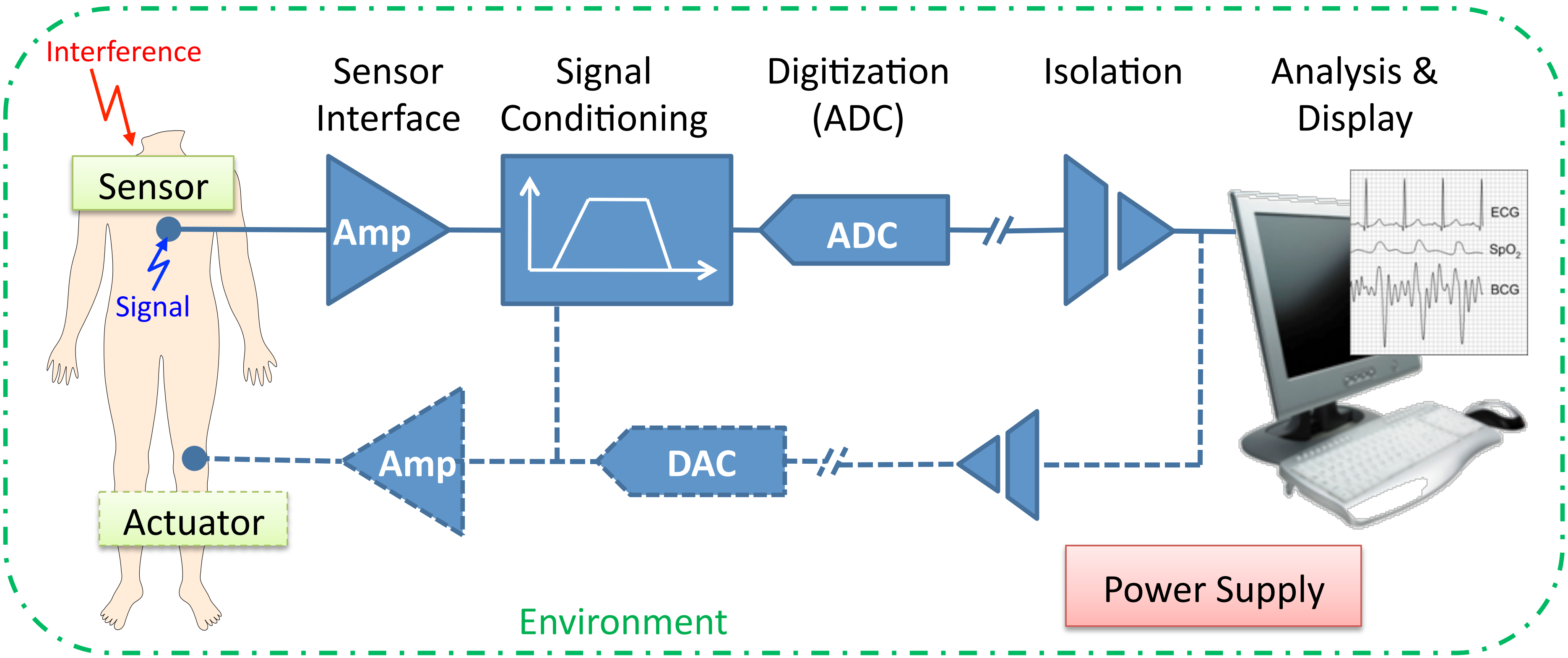
Content

- Components of a generic bioinstrumentation system
  - Sensors
  - Signal conditioning
  - Data acquisition
  - Post-processing/Display/Data Archiving
- Specifics of bioinstrumentation
  - Environment
  - Noise sources
  - Safety
  - Regulatory issues (not covered in EE122B)

Elements of a Biomedical Instrument



Sensor: electrodes, pressure sensor,…

Sensor interface: pre-amplifier, bias circuit, etc.

Signal conditioning: filter, amplifier, etc.

Digitization: analog-digital converter (ADC)

Isolation: optocoupler, inductive, et al.

Analysis: data processing (off- or on-line)

Sensors in Biomedical Instruments

- **Electrical**
  - Capacitive, resistive, inductive sensors (e.g. respiration)
- **Electrochemical**
  - Biopotential electrodes (e.g., ECG, EEG,…)
  - Electrochemical sensors (e.g., oxygen, pH sensors)
  - Enzymatic sensors (e.g., glucose)
- **Mechanical**
  - Strain gauge (e.g., force, weight, BCG)
  - Piezoelectric, capacitive sensors (e.g., heart sounds, blood flow)
  - Pressure sensors (e.g., blood pressure)
  - Acceleration sensors (e.g., activity, posture)

Sensors in Biomedical Instruments

(cont'd)

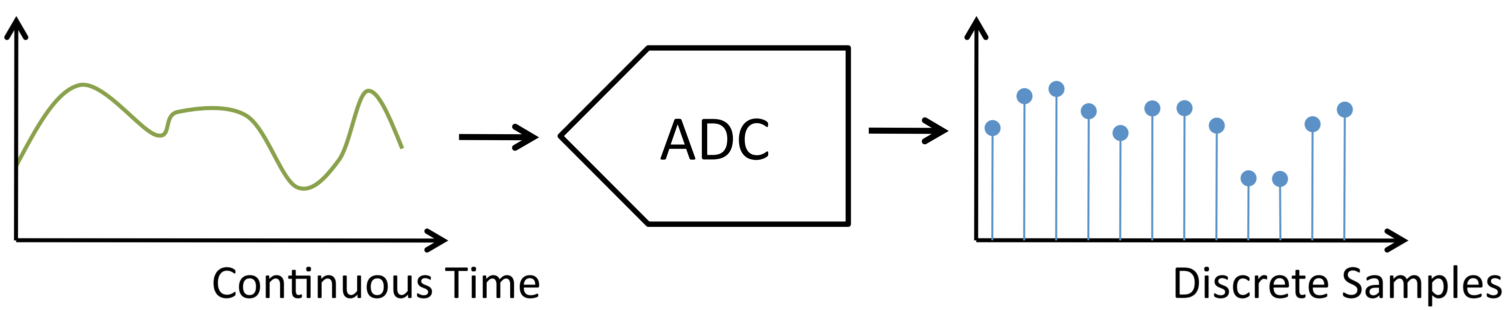
- **Thermal**
  - Thermocouple, thermistor, RTD sensors (e.g. temperature)
- **Optical**
  - Photodiode, phototransistors, photoconductive sensors (e.g. heart pulse, blood oxygen saturation)
  - Infrared sensors (e.g., temperature)
- **RF, High-energy radiation** (not covered in EE122B)
  - Imaging modalities (MRI, ultrasound)

Signal Conditioning

- Sensor interface (amplification, biasing, powering)
  - Some sensors (electrochemical sensors, piezoelectric) imposes specific requirements on front-end (e.g., low input bias current).
  - Some signals (e.g., EEG) require very low noise design.
- Signal filtering
  - Passive and active filters
- Demodulation, lock-in amplification
- Buffering/filtering for next stage (e.g. ADC)

Analog to Digital Conversion

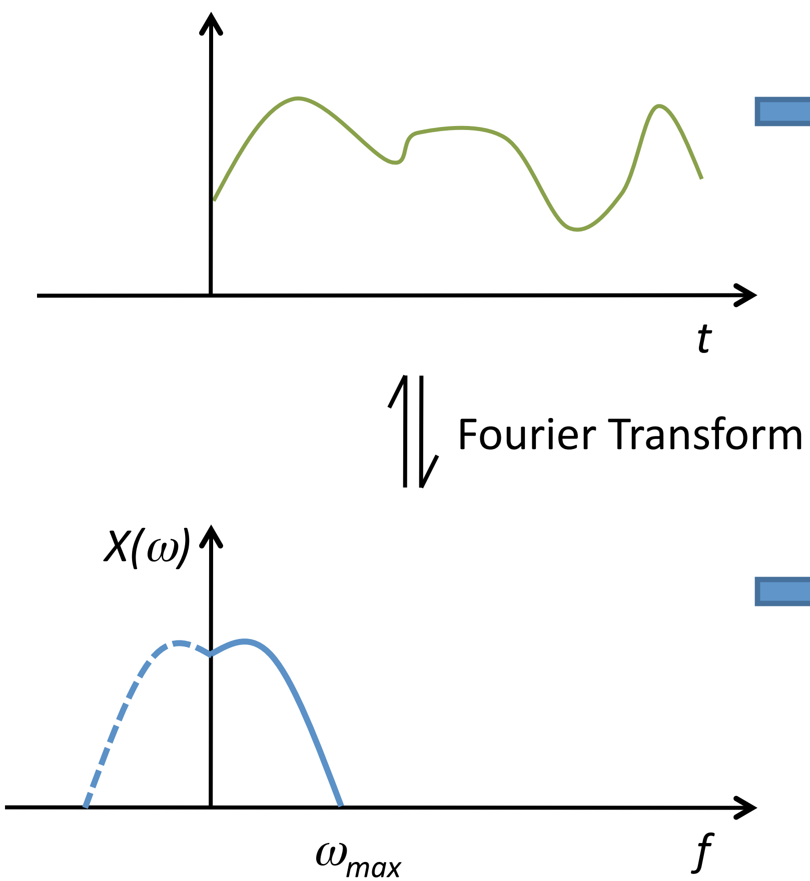
- Nowadays, digital processing of signals is ubiquitous. Biomedical instrumentation is no exception.
- EE122B will rely on data acquisition (digitization) and digital processing for the labs and most projects.
- A short review is given here.

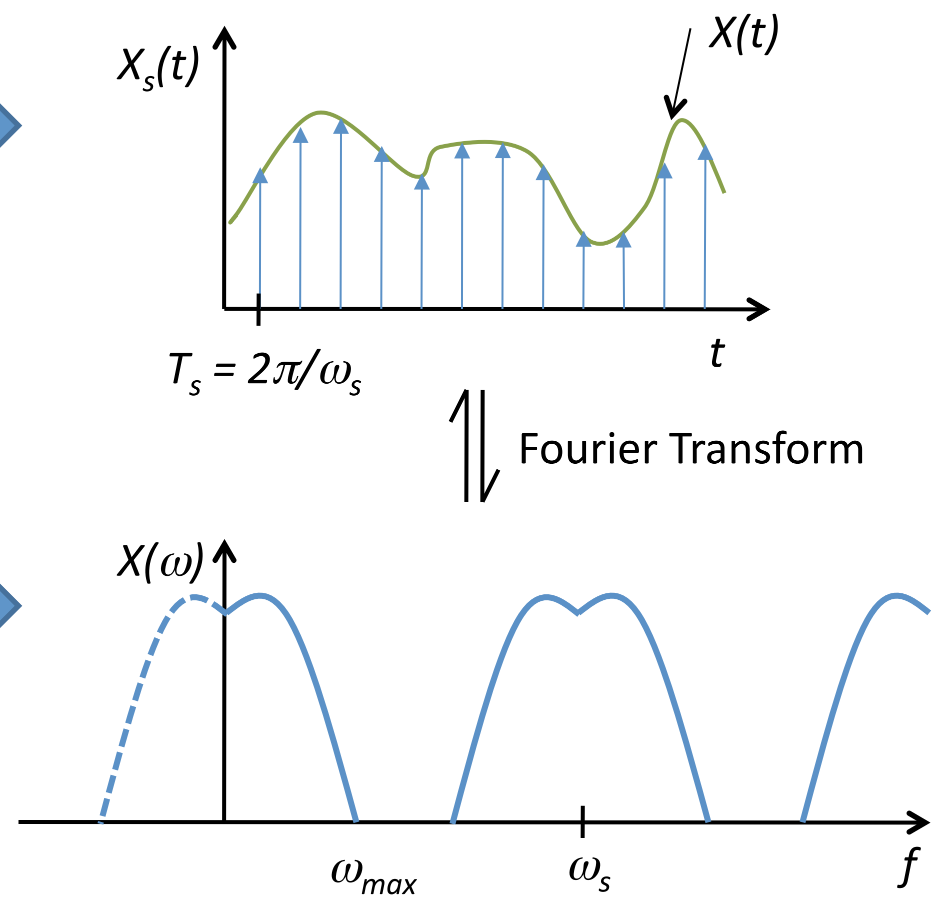


Digitization – Time/Frequency

$$x_s(t) = x(t)\sum_{k=-\infty}^{+\infty}\delta(t-kT_s)$$

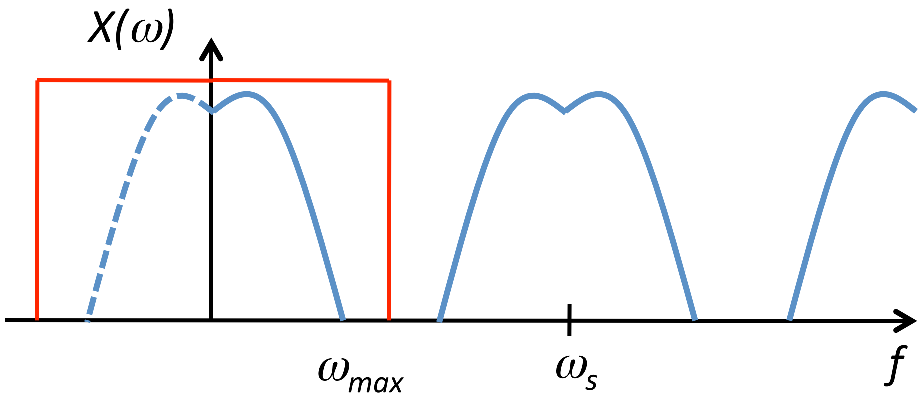
Sampling in time domain results in periodic spectra.



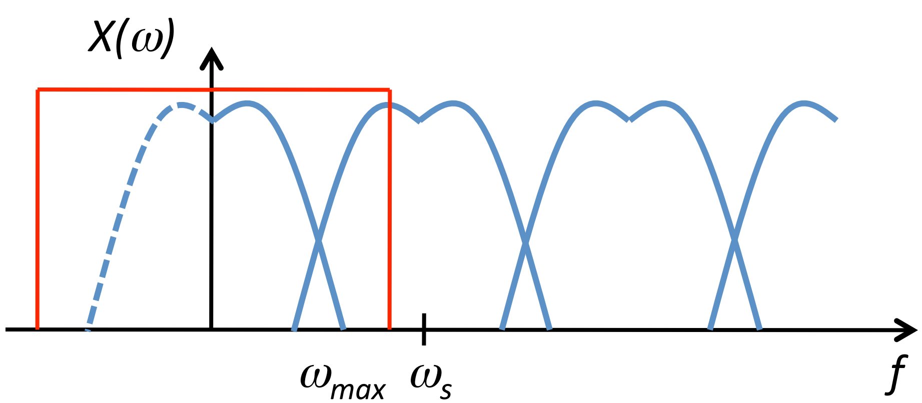


Multiplication in time domain is convolution in frequency domain.

Nyquist's Theorem



If $\omega_s \leq 2\omega_{max}$ (**Nyquist frequency**), the signal can be reconstructed accurately.



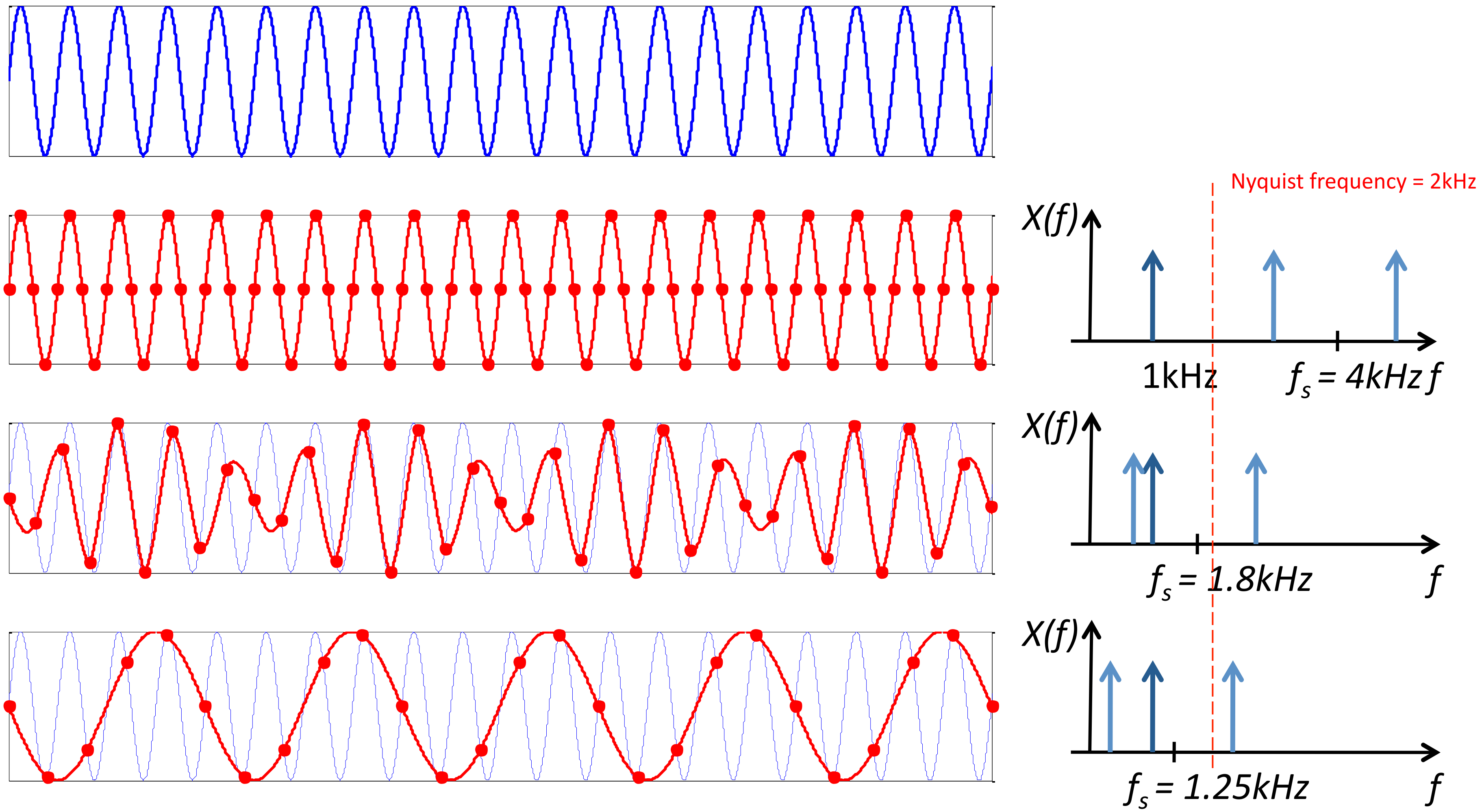
If $\omega_s < 2\omega_{max}$, the signal is irreversibly **corrupted**.

This is called **Aliasing.**

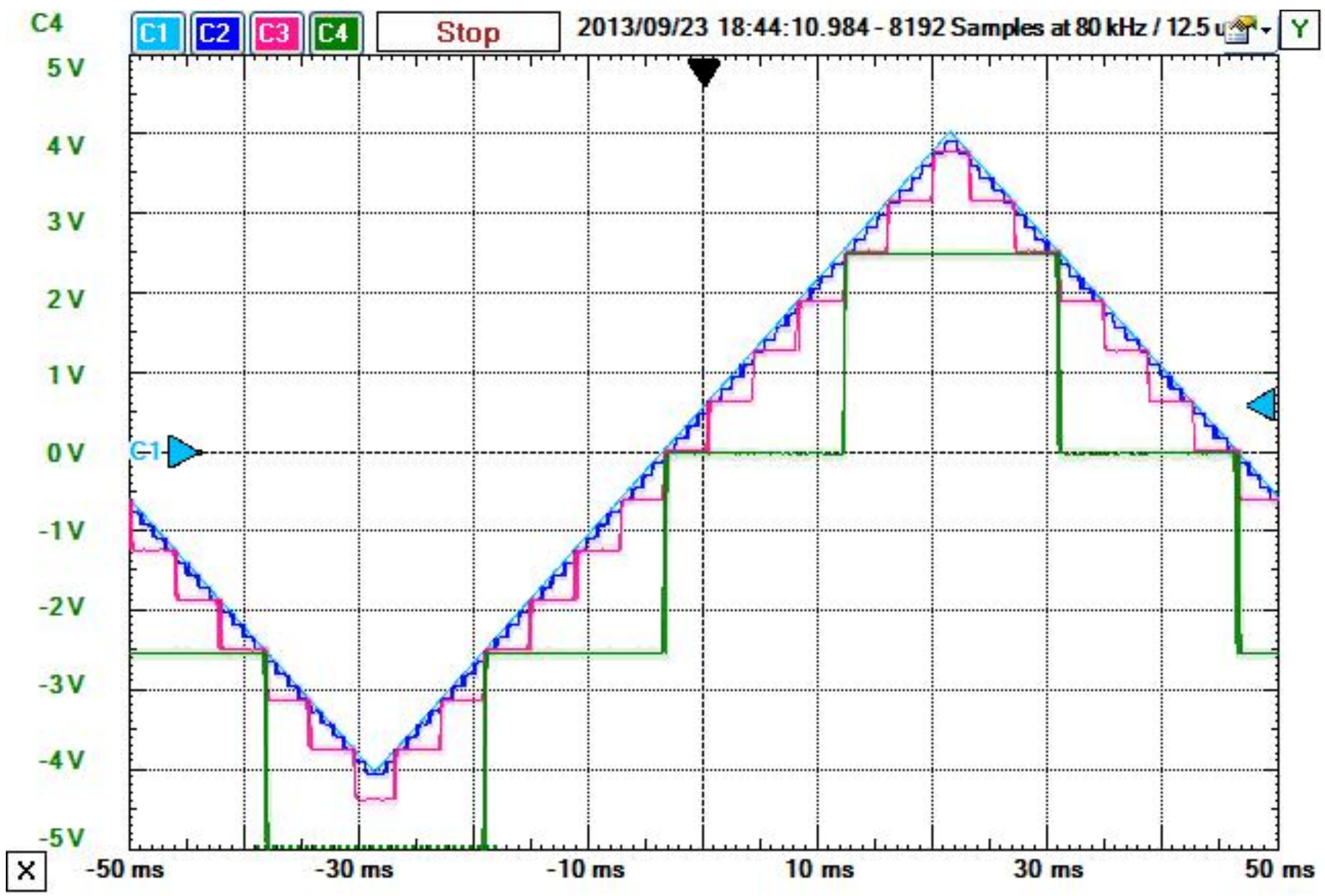
Reconstruction filter (low-pass filter)

Aliasing - Demonstration

A 1kHz sine wave (Nyquist frequency = 2 kHz) sampled at 4 kHz, 1.8 kHz, and 1.25 kHz

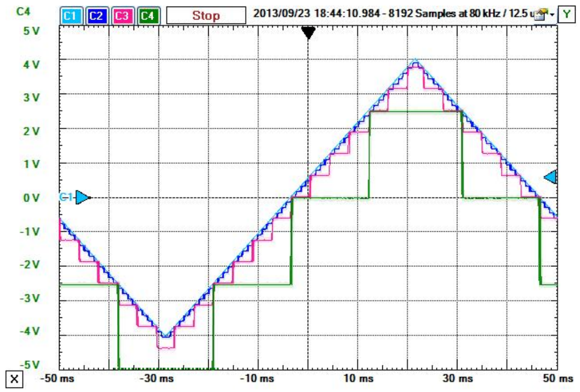


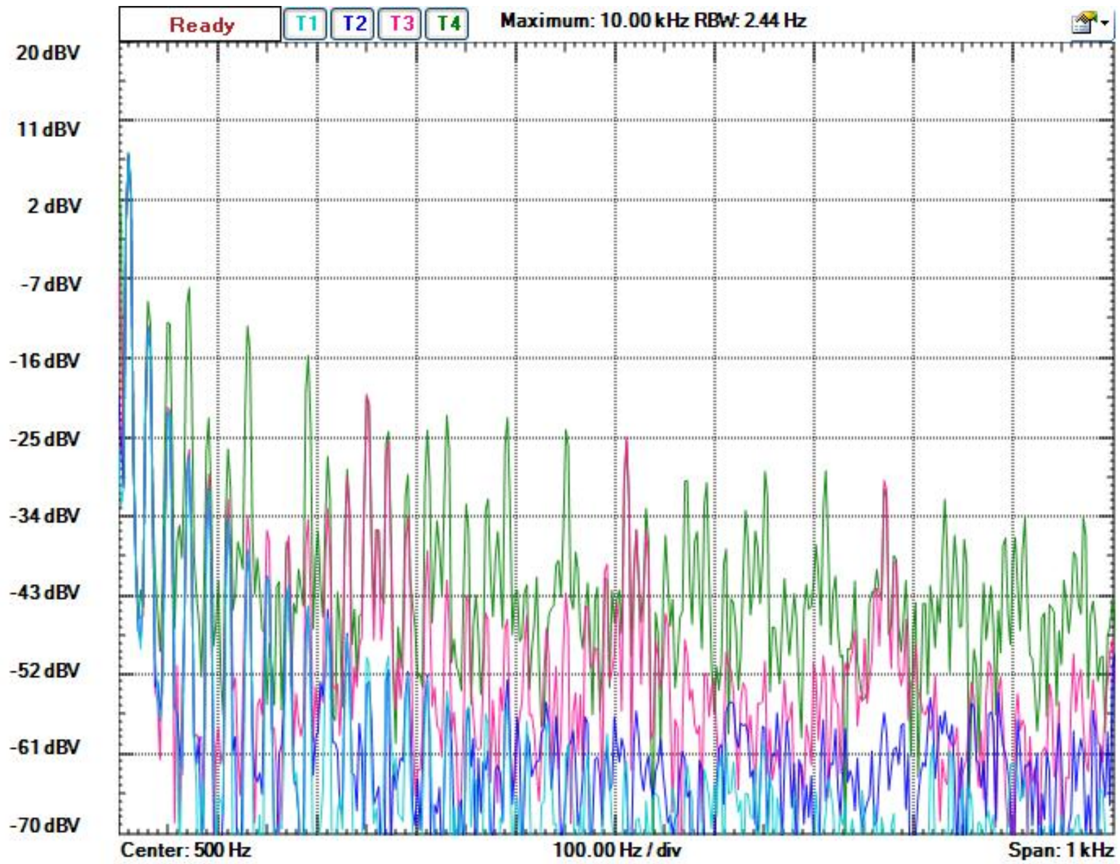
Quantization - Demonstration



A 10Hz triangle wave sampled at 6-, 4-, and 2-bit ADC resolutions (from EE122A Lab 1).

Quantization - Demonstration





Frequency spectra of 10Hz triangle wave sampled at 6-, 4-, and 2-bit ADC resolutions (from EE122A Lab 1).

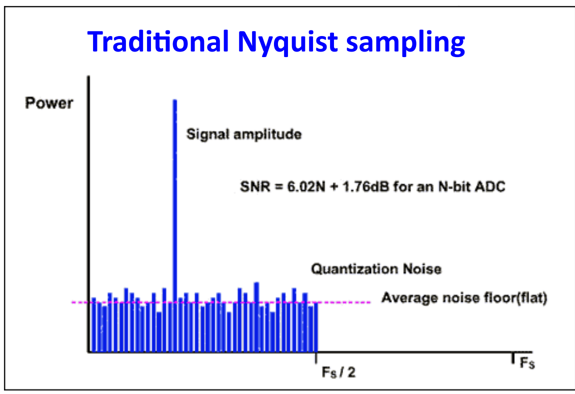
ADC Characteristics

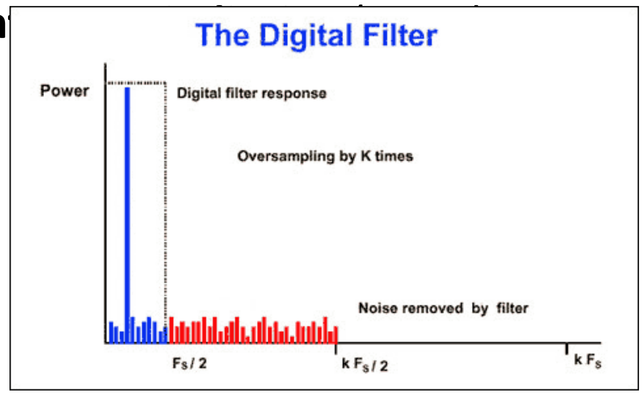
- Type (Integrating, SAR, Flash, Sigma-Delta,…)
- Resolution (e.g., 16-bit = 2^{16} = 65536 levels)
  - 16-bit resolution may not give 16 bits of accuracy!
  - ENOB (equivalent number of bits) is the important specification – the effective resolution you actually get.
- Dynamic range (e.g., ±5V)
  - Along with resolution, this defines voltage resolution.
- Linearity (e.g., 0.01%)
- Sampling rate (e.g., 2000 samples/second)
  - Along with resolution, set requirements on anti-aliasing filter for a given accuracy.
- Sequential vs. Simultaneous (multichannel)
  - Settling time consideration (multiplexed ADC)
  - Crosstalk

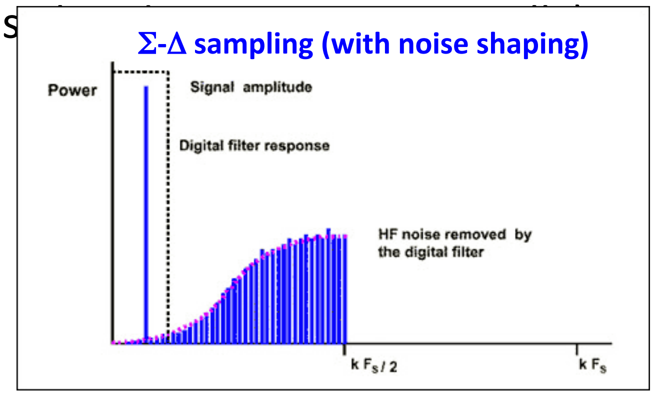
ADC Types

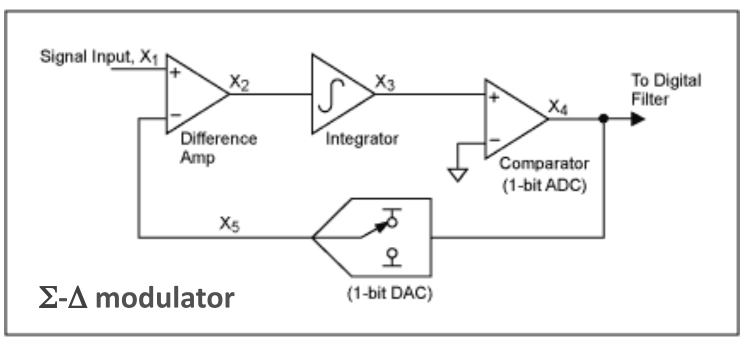
- **Flash**
  - Comparator bank with thermometer-code output and digital encoder
  - Ultra-fast, resolution limited to 8 bits and less due to complexity of circuit and yield (2^N-1 comparators, where N = number of bits)
  - Can be pipelined for higher resolutions
- **Integrating**
  - Single, dual-slope integrator with comparator and timer
  - Uses a current proportional to the input signal to linearly charge a capacitor to a preset level – the time taken is measured (other schemes are used also)
  - Simple, low-cost, high resolution
- **Successive-approximation (SAR)**
  - Voltage compared to a successively divided voltage reference (DAC)
  - Resolution proportional to number of steps
  - Good resolution, wide range of dynamic ranges

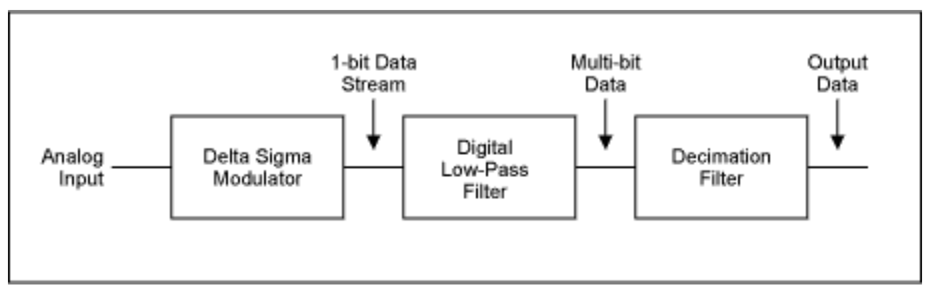
- **Sigma-Delta (Σ−Δ)-** Allows trade-off of resolution vs speed.
  - Oversample (96x typically) signal and convert with a 1-bit ADC at high frequency – get ≈ 3 dB per 2X oversampling **(≈1 bit per 4X oversampling)** which spreads noise energy over more bandwidth (note: ***SNR is unchanged***).
  - Sigma-Delta modulator maintains average output of integrator near comparator reference level and further shapes noise out of band (integrator acts as a lowpass for signal and high-pass for quantization noise).
  - High-resolution, slower data retrieved by digital low-pass and decimation.
  - Σ−Δ converters generally used for high-resolution, low-cost, with medium speed.











Source: Maxim App Note 1870

Anti-Aliasing Filter – How Steep?

- Resolution, accuracy, sampling rate and anti-aliasing are all related.
- Have to attenuate by ADC resolution (≈ 6 dB/bit by the time you reach Nyquist frequency).
- Signal-to-Noise ratio (or dynamic range) of an ideal ADC (accuracy = resolution) is:

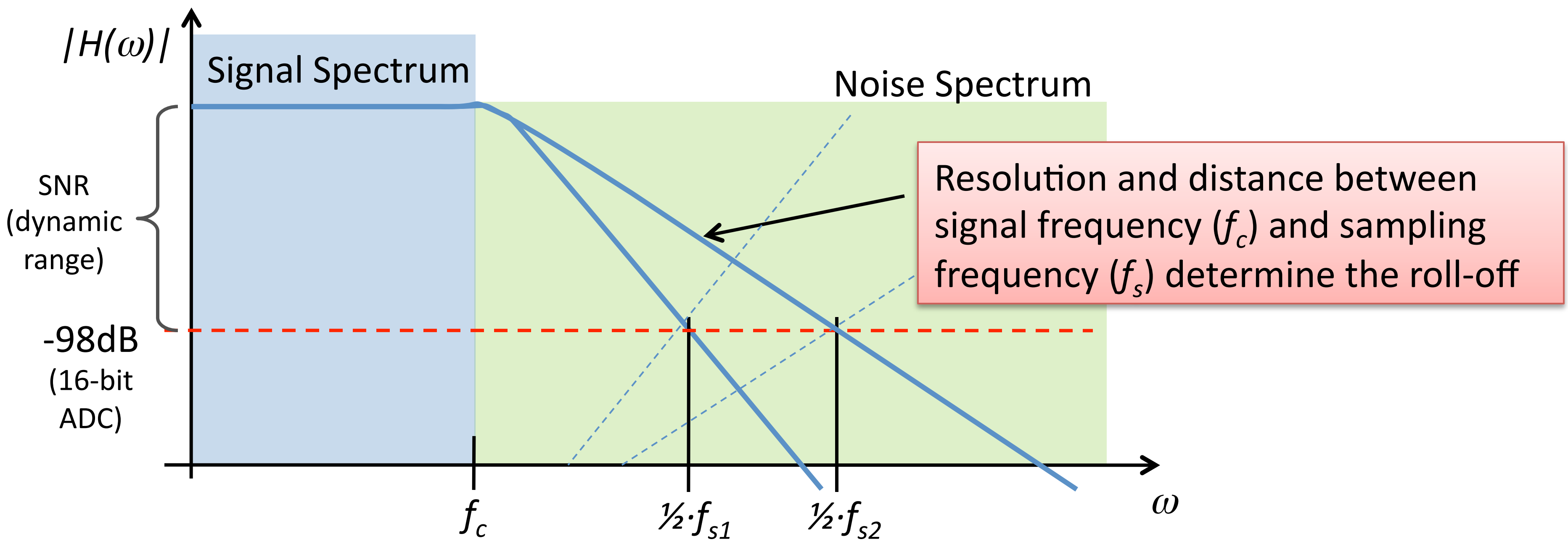
$$SNR = 6.02 \times \#bits + 1.76\ [dB]$$

ADC Resolution [bit]	SNR [dB]
8	49.9
10	62.0
12	74.0
14	86.0
16	98.1
20	122.2
24	146.2

← Comparable to human ear

Anti-Aliasing Filter – How Steep?

- Optimal filtering is when signal power is down at the ADC SNR, at half of the sampling frequency.
  - Higher sampling rate relative to Nyquist frequency lowers steepness requirements on filters.
  - In simple terms, you need a slope that drops from flat to 6dB/bit by f_N.

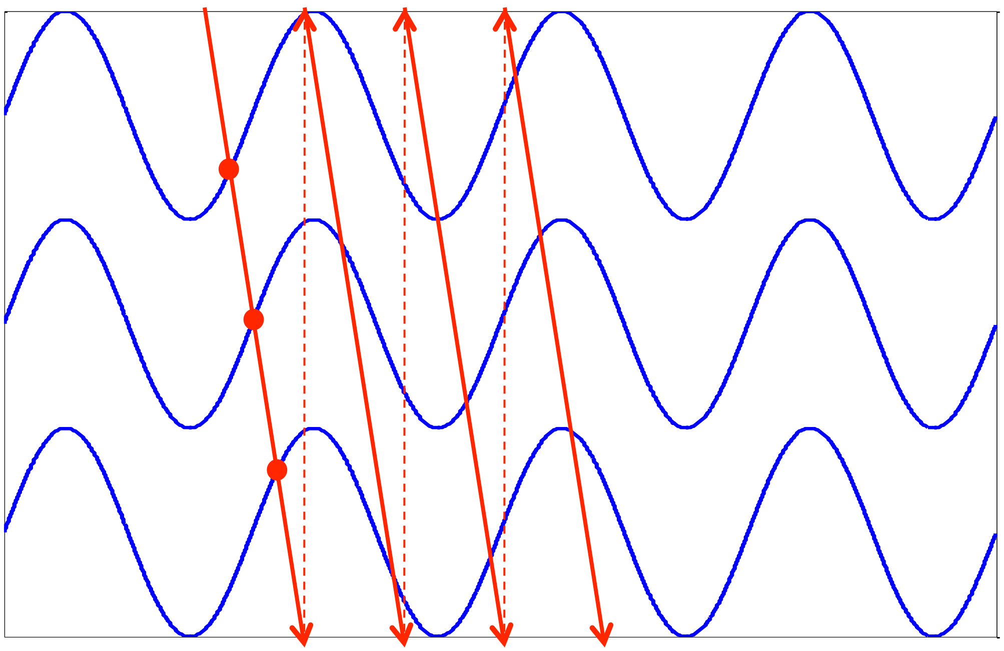


Note: Usually, the noise power decreases after f_c, so it is the **product** of the filter attenuation and the noise attenuation which must be at the SNR level at half of the sampling frequency.

Sequential and Simultaneous Sampling

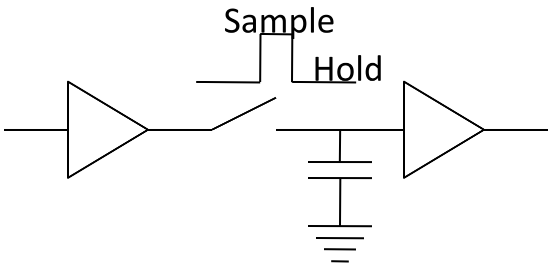
- Simultaneous sampling is ideal, but costly.
- Sequential sampling uses a multiplexer to feed a single ADC ("barber-pole" sampling).

Potential issue: signals are not sampled at exactly the same time:



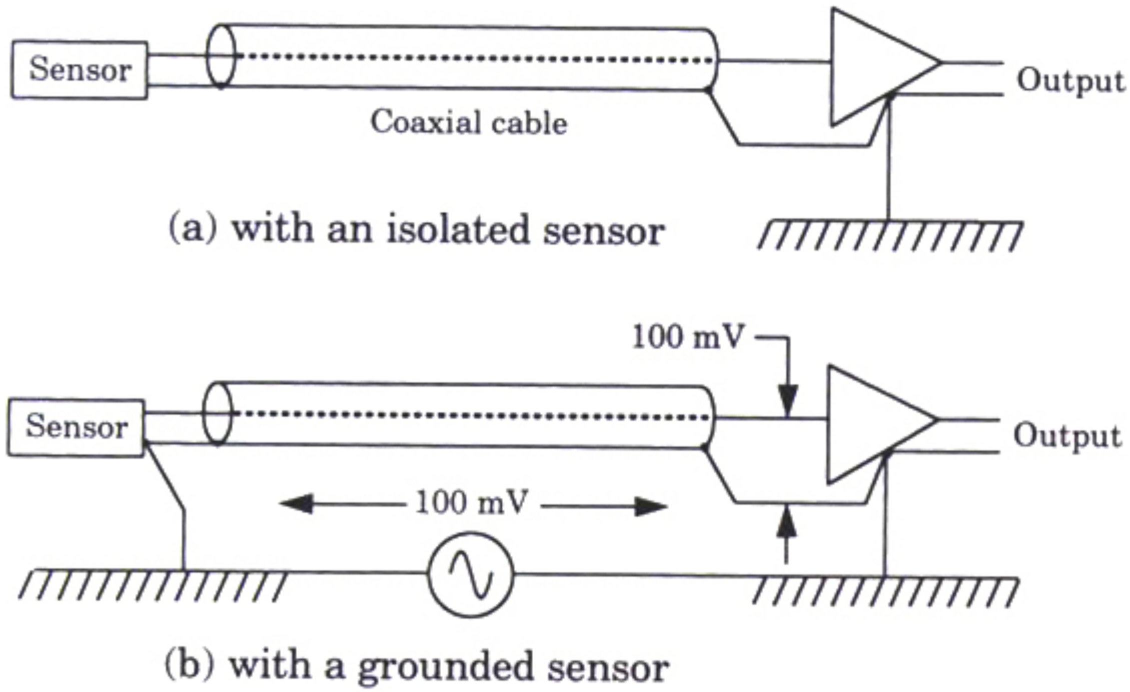
From http://www.barberpolesdirect.com/

Solution: **Sample and Hold**



Signal Connections to Front-End/ADC

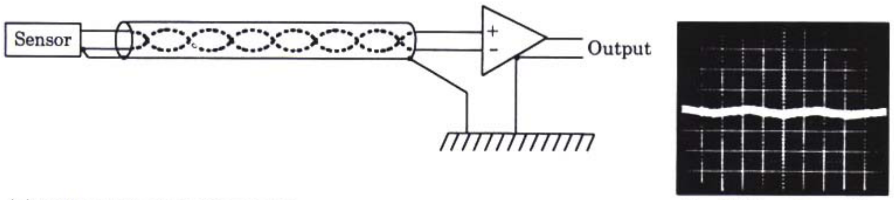
Single-Ended Connection



Beware of ground loops in signal-carrying cables ! These are unwanted currents that cause "ground" points to actually be a different potentials.

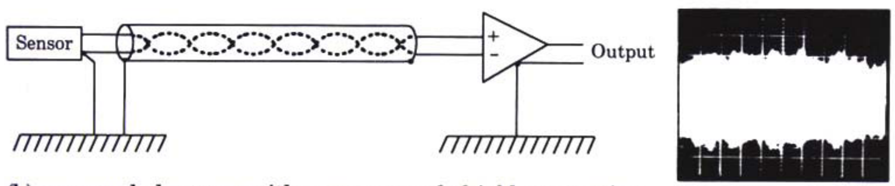
Source: KineticSystems, white paper "Analog Front-End "

Differential Connections



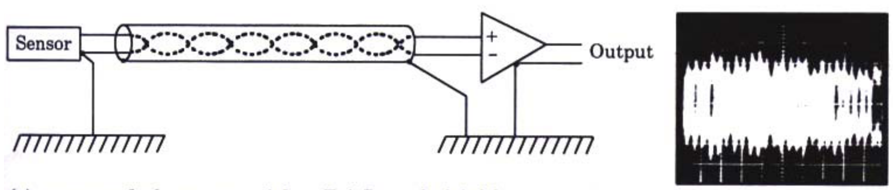
(a) with an isolated sensor — 5 mV/Div., 5 ms/Div.

Floating source (note sensor connection to shield)



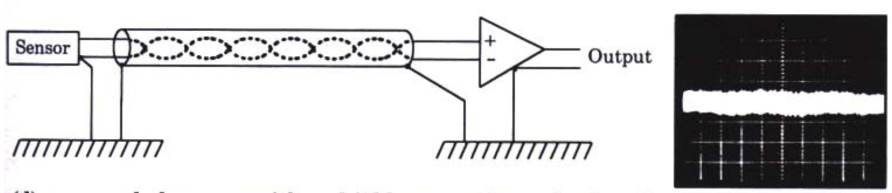
(b) a grounded sensor with a sensor-end shield connection — 100 mV/Div., 5 ms/Div.

Usually recommended – no ground loop



(c) a grounded sensor with a DAQ-end shield connection — 100 mV/Div., 5 ms/Div.

Usually recommended – no ground loop



(d) a grounded sensor with a shield connection at both ends — 5 mV/Div., 5 ms/Div.

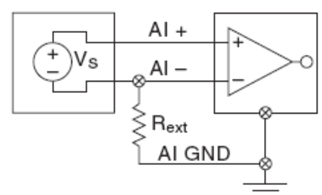
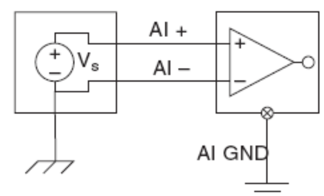
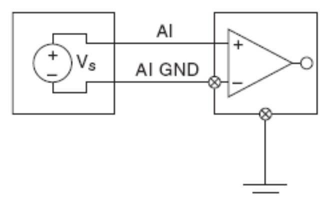
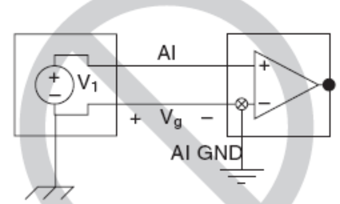
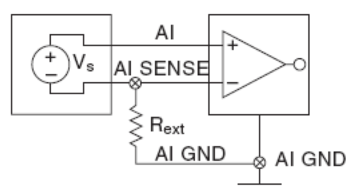
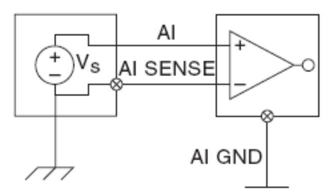
Usually not recommended – Ground loop, yet best **Why??**

There is such a thing as a good ground loop (as long as the loop **does not carry signals**)!

Think RF interference…

Source: KineticSystems, white paper "Analog Front-End "

Single-Ended vs. Differential

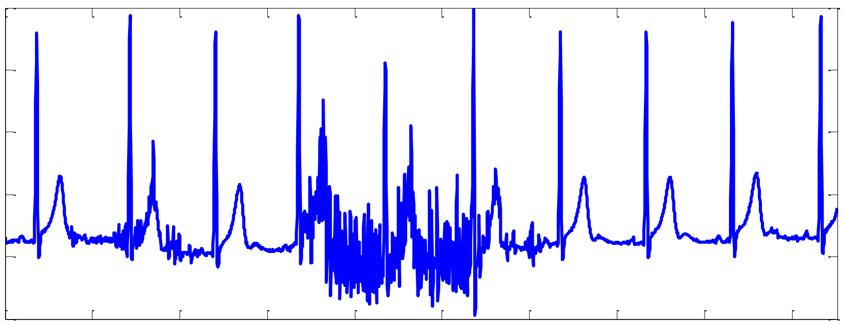
Input	Signal Source Type: Floating Signal Sources (Not Connect To Building Ground)	Signal Source Type: Ground-Referenced Signal Sources
	Examples • Ungrounded thermocouples • Signal conditioning with isolated outputs • Battery devices	Examples • Plug-in instruments with non-isolated outputs
Differential (DIFF)		
Single-Ended—Ground Referenced (RSE)		NOT RECOMMENDED  Ground-loop losses, V_g, are added to measured signal.
Single-Ended—Non-Referenced (NRSE)		

Source: National Instruments, E Series User Manual

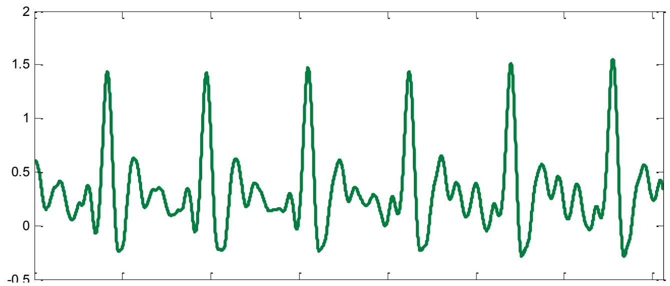
Source of Interference

- Any measurement includes signal & noise.
- Noise sources can be:
  - **Extrinsic**: 50/60 Hz, radio frequency (RF), magnetic,…
  - **Intrinsic Physiologic**: muscle noise, motion artifact, eye blink artifact, respiration,…
  - **Intrinsic Electronic**: Johnson (thermal) 1/f, shot, popcorn, et al.

Remember: noise for one person can be a signal for someone else…



EMG interference on an ECG



BCG on a weighing scale signal (~2 Newton "noise" on top of a 800 N "signal" [weight])

Safety in Biomedical Instrumentation

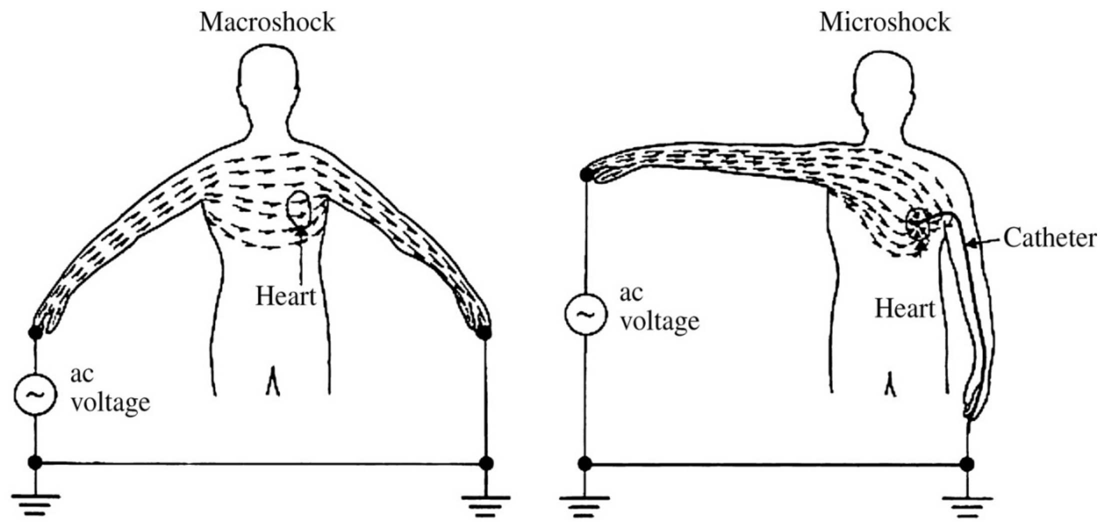
Remember:
Electricity can kill!

Source: Dennis MacDonald

Operating room of the Future (ORF) at Massachusetts General Hospital

Electric Hazards

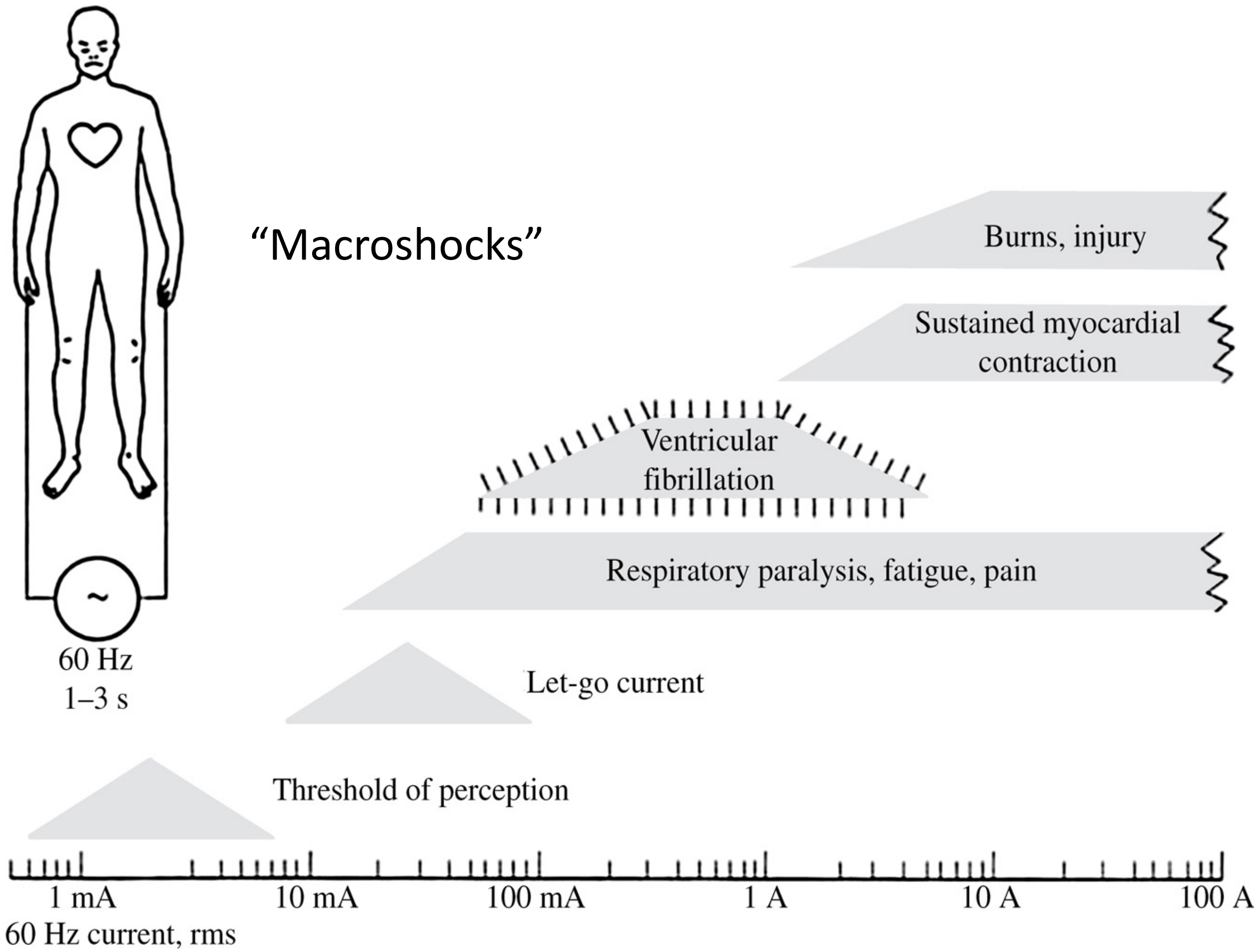
- Electrical shock can come from various sources, and are often the result of poor design, component failure, or misuse.
- They are usually categorized into two classes, based on the point-of-entry of the **current**:
  - Macroshock (instruments, electric chair)
  - Microshock (implantable catheters, leakage)



(a) (b)

  Source: Medical Instrumentation, J. Webster, 2009

Physiological Effect of Electricity



Risks are associated primarily with **currents**, not voltage. This is because currents are independent of the body and contact resistance.

Source: Medical Instrumentation, J. Webster, 2009

Gender Differences

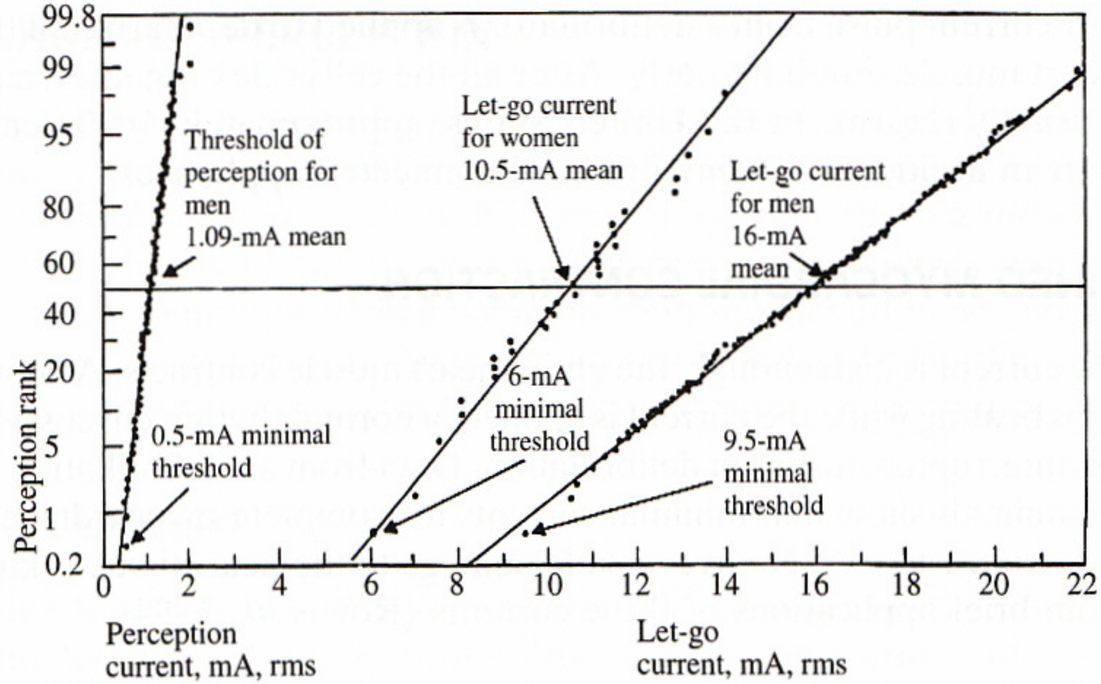
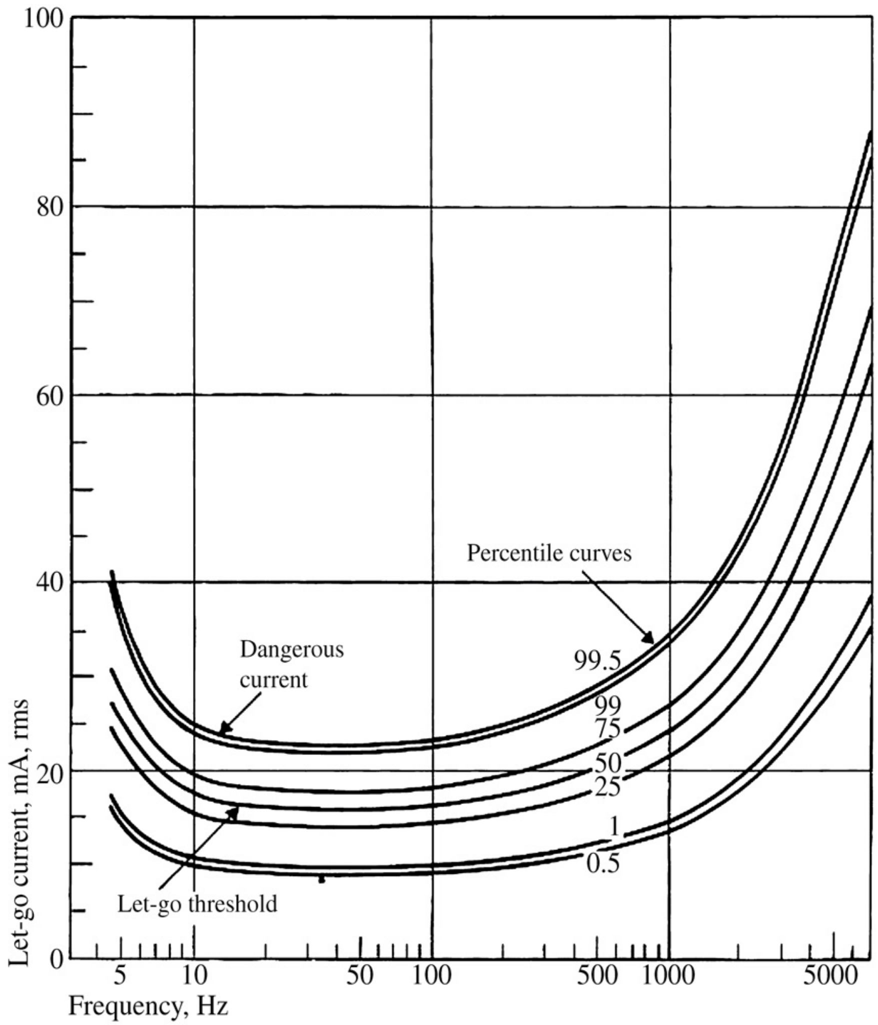


Figure 14.2 Distributions of perception thresholds and let-go currents These data depend on surface area of contact (moistened hand grasping AWG No. 8 copper wire). (Replotted from C. F. Dalziel, "Electric Shock," *Advances in Biomedical Engineering*, edited by J. H. U. Brown and J. F. Dickson III, 1973, 3, 223–248.)

  Source: Medical Instrumentation, J. Webster, 2009

Susceptibility versus Frequency

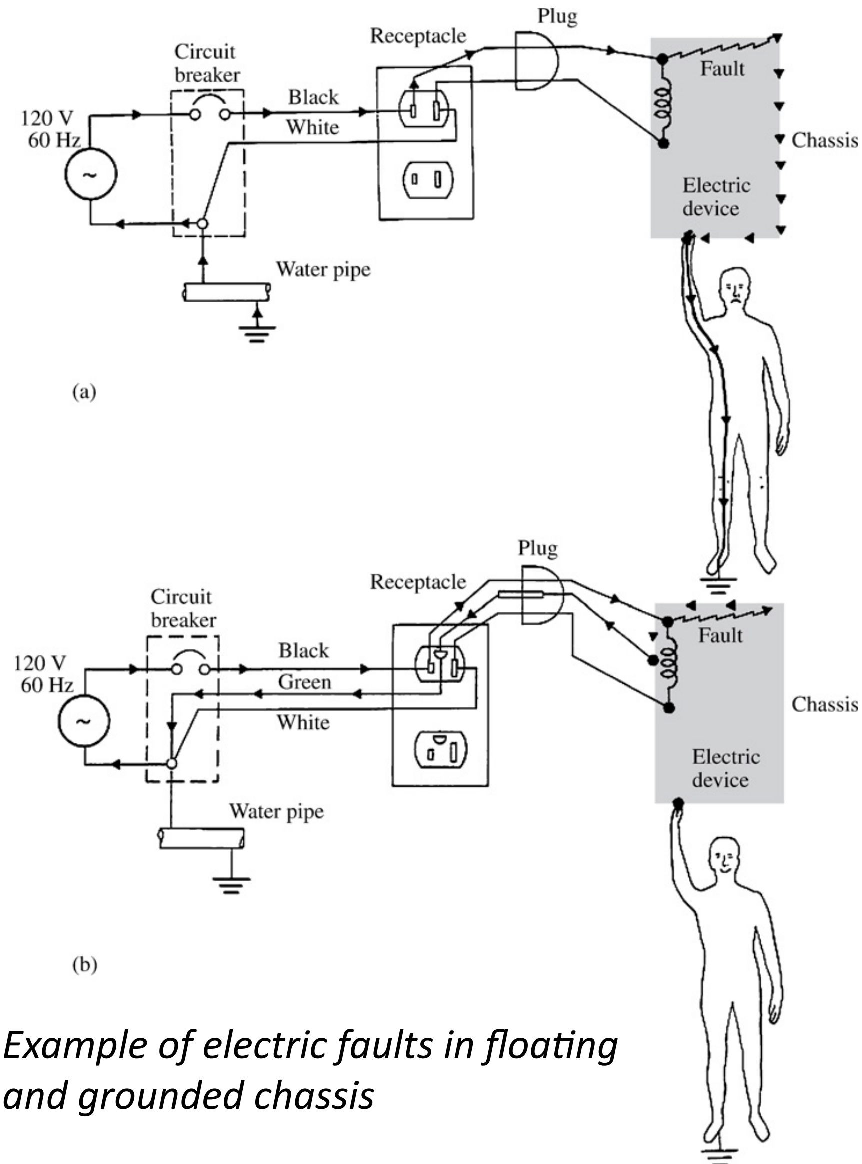
Let-go current as a function of frequency:



- Large difference between DC and AC
- **50/60Hz is the worst !!**
- Low susceptibility at high frequencies, used in several medical applications:
  - Impedance plethysmography
  - impedance cardiography
  - Body-area-networks

Source: Medical Instrumentation, J. Webster, 2009

Macroshock Hazards

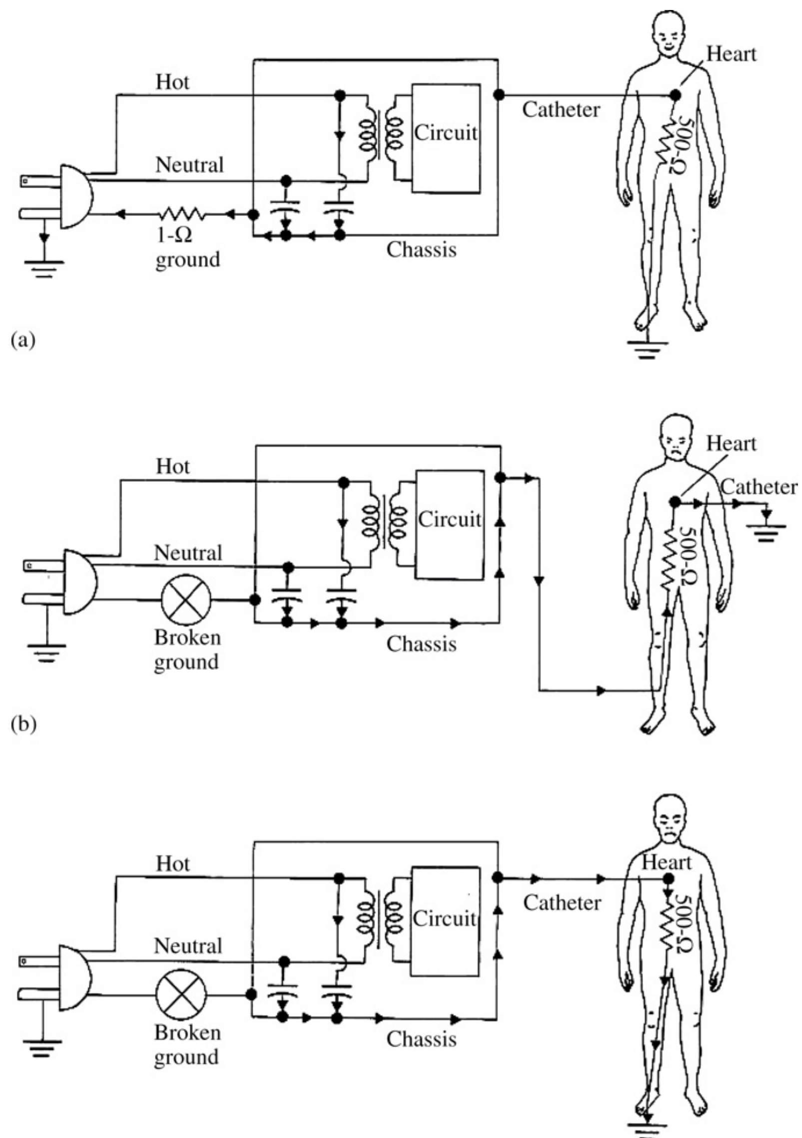


Example of electric faults in floating and grounded chassis

- Point of Entry: Skin
- Skin resistance 15kΩ – 1MΩ/cm²
- Usually results from ***ground faults*** *(short between hot and ground)*.
- Can be prevented by proper grounding, insulation, isolation.
- All medical equipments are required to use three-terminal (hot, neutral, ground) plugs/sockets.

Source: Medical Instrumentation, J. Webster, 2009

Microshock Hazards

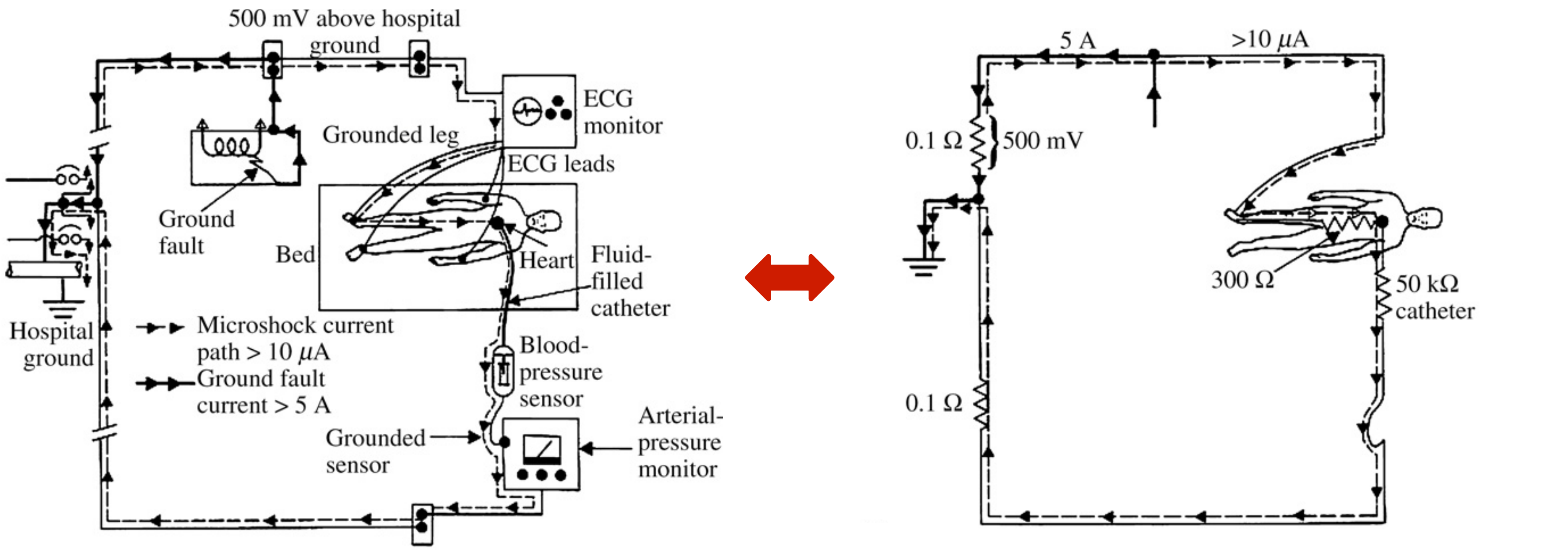


Examples of leakage-induced microshocks.

- Point of Entry: Devices in contact with the heart.
- Body resistance 100Ω (trunk) – 200Ω (limbs)
  - Much lower than for macroshocks
- Usually results from ***leakage currents, ground faults***.
- Can be prevented by proper grounding, insulation, isolation.

Source: Medical Instrumentation, J. Webster, 2009

Ground Fault-Induced Microshocks



- Equipments on separate grounds are vulnerable to ground-faults.
  - Ground potential can shift if ground faults, inducing ground potential differences.
  - Potential between conductive (grounded) surfaces must never be larger than **40mV** (critical care areas) or **500mV** (general care areas).
- Can be prevented by single patient grounding point.

  Source: Medical Instrumentation, J. Webster, 2009

Regulations

Several associations regulates admissible currents and limits, in particular:

- Association for the Advancement of Medical Instrumentation (AAMI)
  - "Safe current limits for electromedical apparatus", ANSI/AAMI ES1, 1993
- International Electrotechnical Commission (IEC)
  - "Medical electrical equipment", IEC-601 (adopted in Europe as EN-60601)

Extract from ANSI/AAMI ES1 for admissible current leakage:

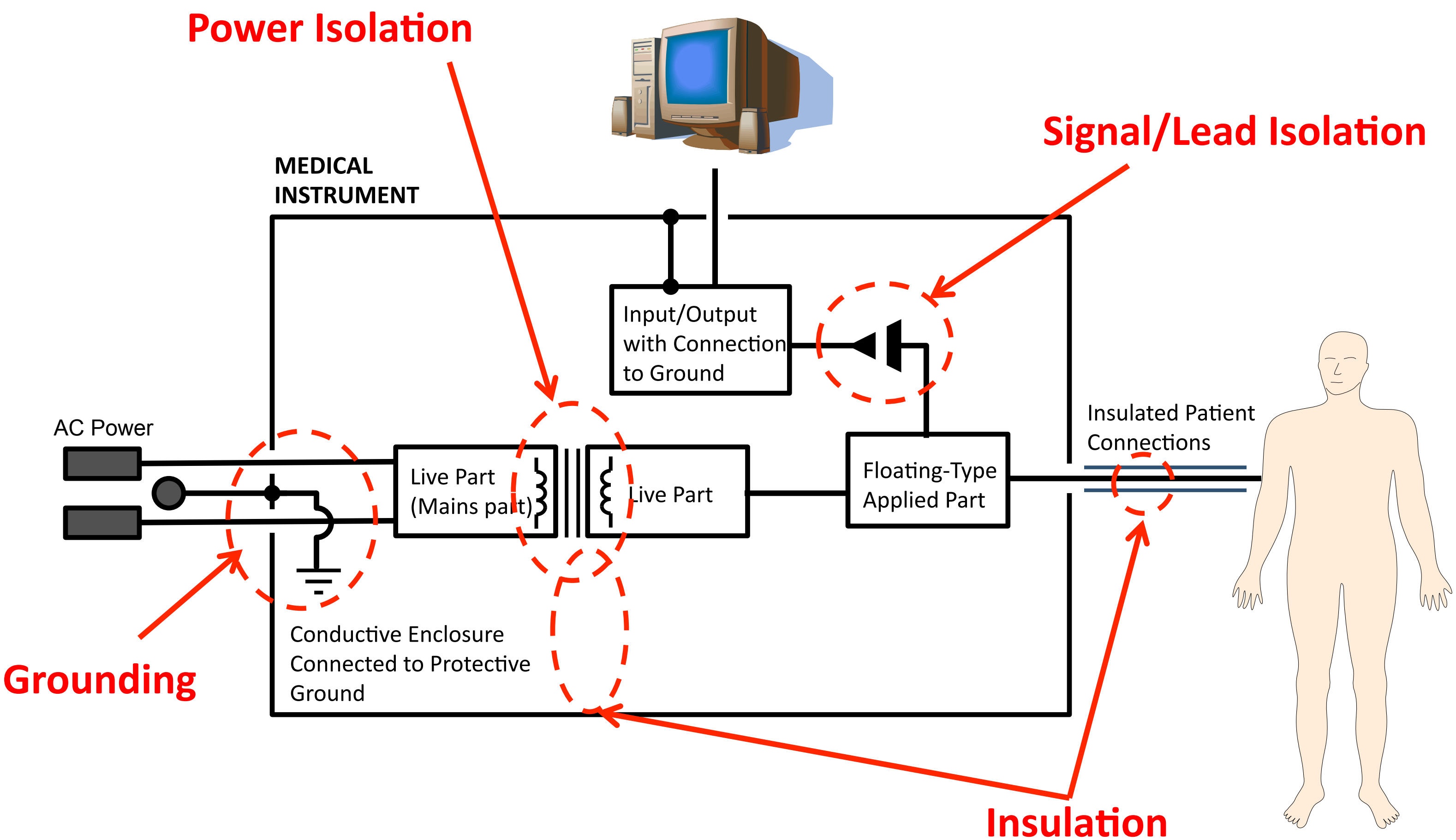
Electric Appliance	Chassis Leakage, μA	Patient-lead Leakage, μA
Not intended for patient contact	100	-
Not intended for patient contact and single fault	500	-
With nonisolated patient leads	100	10
With nonisolated leads and single fault	300	100
With isolated patient leads	100	10
With isolated leads and single fault	300	50

Protection Strategies

- To avoid shocks, ideally:
  - No contact (complete insulation), or
  - Contact equipotential surfaces only (perfect ground)
- In practice, neither can be fully achieved
  - Grounding system (single-point, low impedance)
  - Power supply isolation
  - Equipment design (reduced leakage currents)
  - Isolated connections

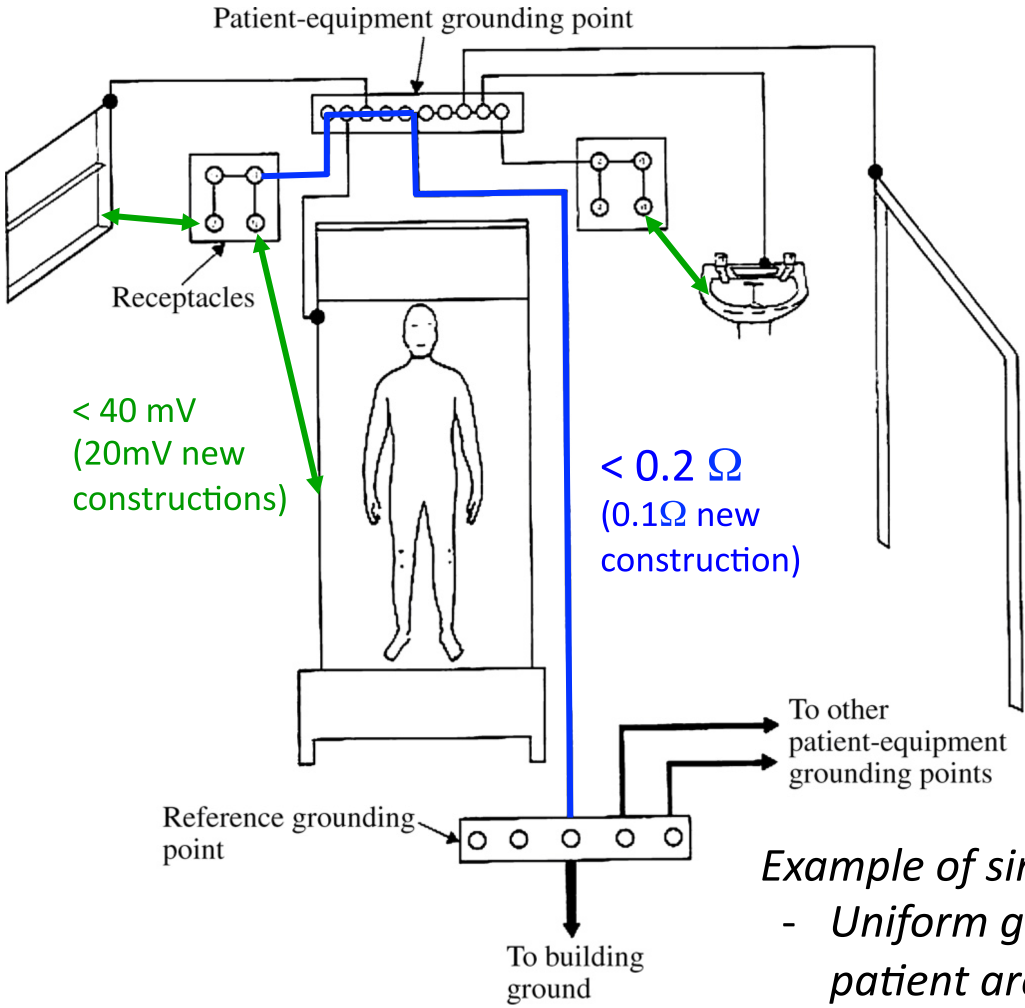
Protection Strategies

The best protection is a multi-level approach:



After Prutchi and Norris, "Design and Development of Medical Electronic Instrumentation", John Wiley & Sons, 2005

Protection: Grounding Systems



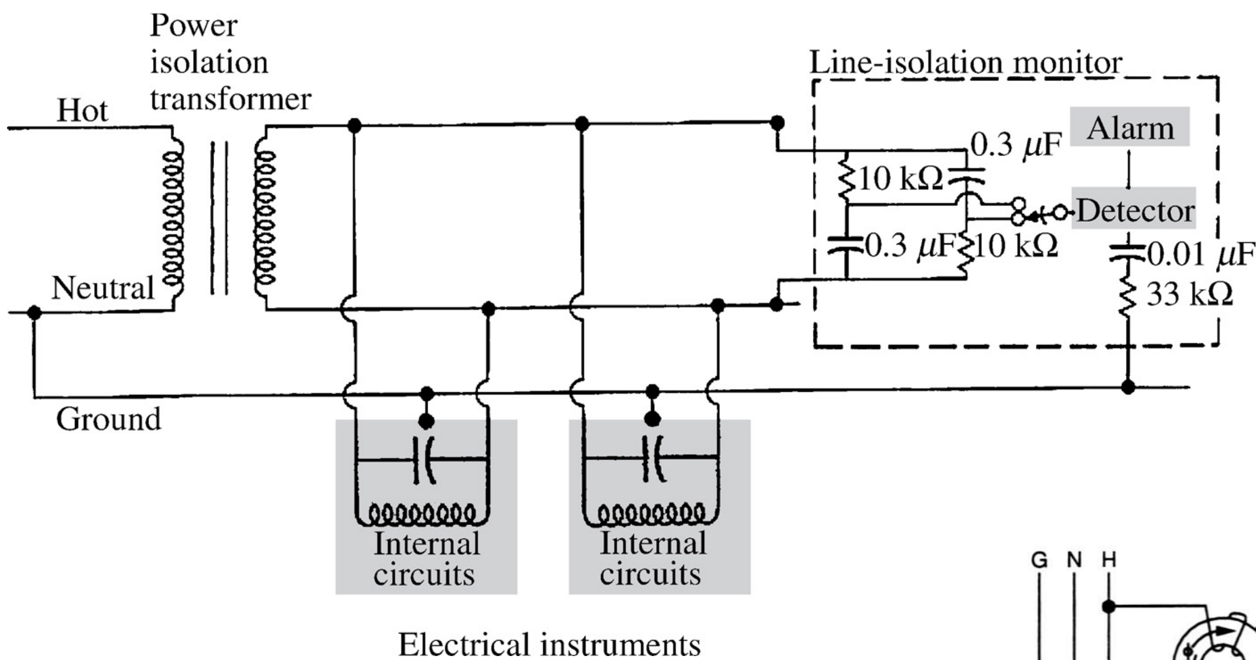
- Low resistance path to building ground.
- Keep all conductive surfaces to within **40mV** (critical care areas) or 500mV (general care areas).
  New constructions: **20mV**
- Protects from macroshocks and microshocks (ground-fault induced).

Example of single patient grounding point:
- *Uniform ground shift if ground fault within this patient area.*
- *No ground shift if ground fault occurs in another patient area.*

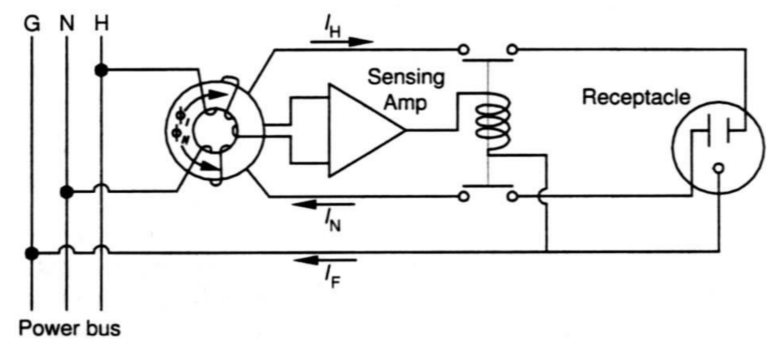
Source: Medical Instrumentation, J. Webster, 2009

Isolated Power Supply

- Isolated power supplies help reducing risks of large ground faults.
- Prevent macroshocks, but not microshocks (leakage currents).



Isolation transformer with line-isolation monitor (continuously check quality of isolation).



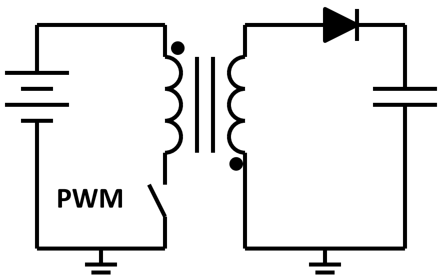
Ground-fault circuit interrupter (disconnect power if ground fault detected).

Source: Medical Instrumentation, J. Webster, 2009

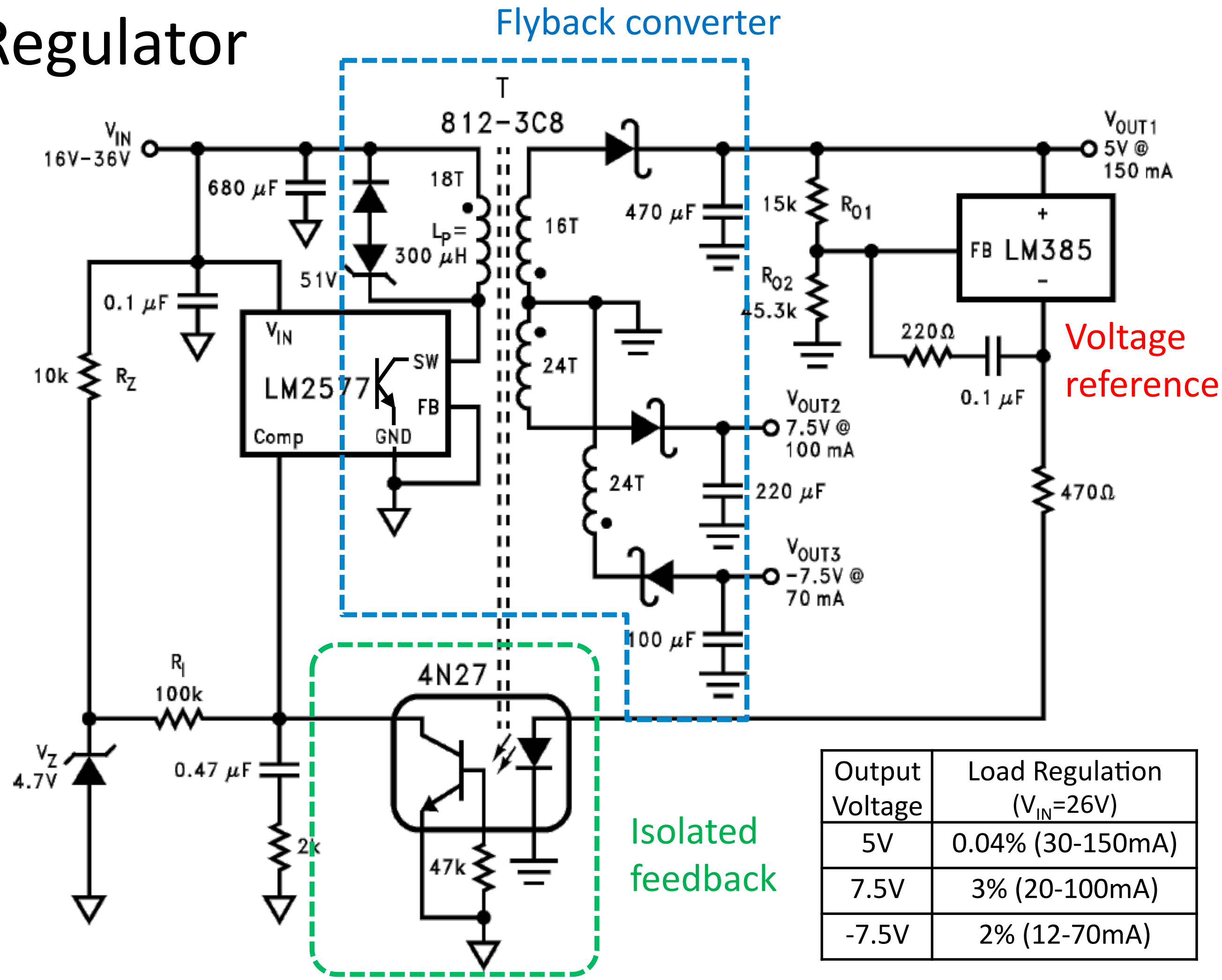
Isolated Power Supply

Isolated Flyback Regulator

Basic flyback topology



- Complete galvanic isolation
- Switching at 10-200kHz
- Typically for power under 100W (more efficient designs are sought for higher power)

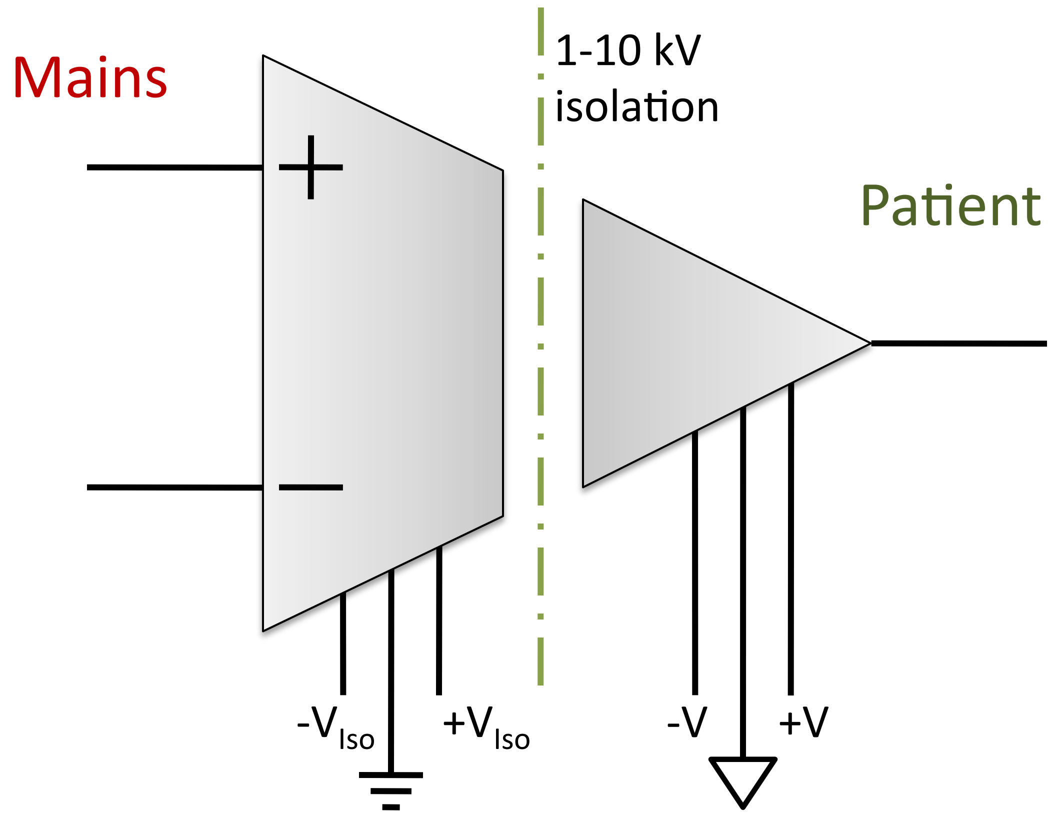


Output Voltage	Load Regulation (V_{IN}=26V)
5V	0.04% (30-150mA)
7.5V	3% (20-100mA)
-7.5V	2% (12-70mA)

Three-output isolated regulator (source: National Semiconductor AN-777, and Application Info by Chester Simpson)

Signal Isolation

- Lead isolation can be used to decouple ground and signals, protect from ESD/EMI, and prevent microshocks.
- Isolation can be applied to analog or digital signals.



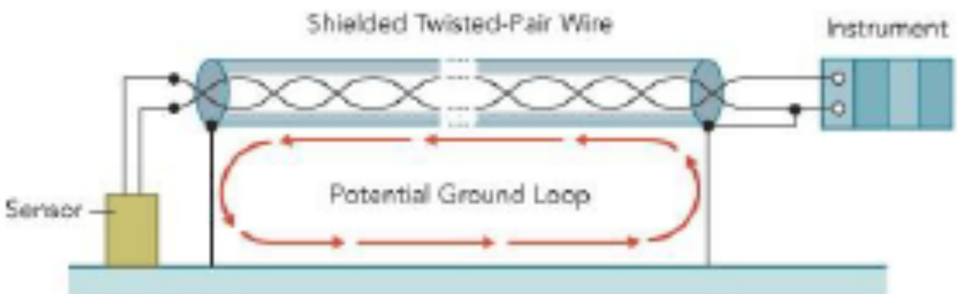
Common chip or hybrid isolation methods:

- Capacitive
- Inductive (transformer)
- Optical (linear and non-linear)

Some devices provide isolated power supply (limited current).

Why do we need Isolation?

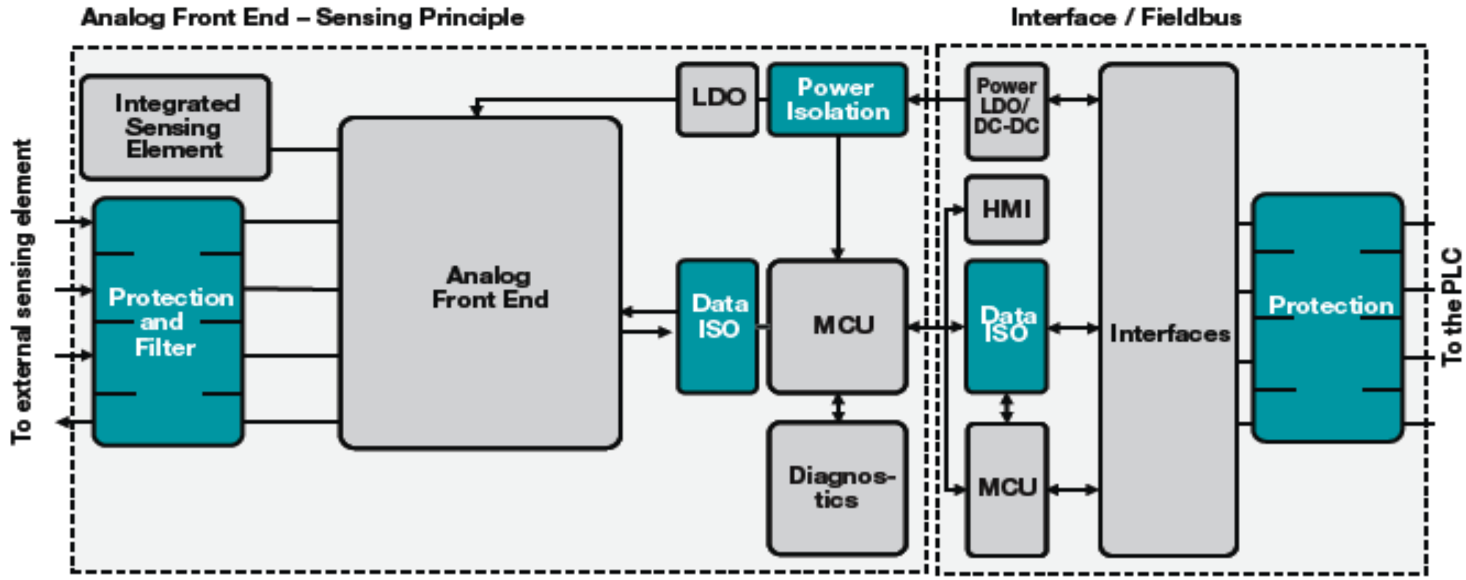
- Hazardous voltages : Equipment damage or Human Safety
- Transients : Measurement accuracy , Ground loop noise
- Common mode fluctuations : level shifter

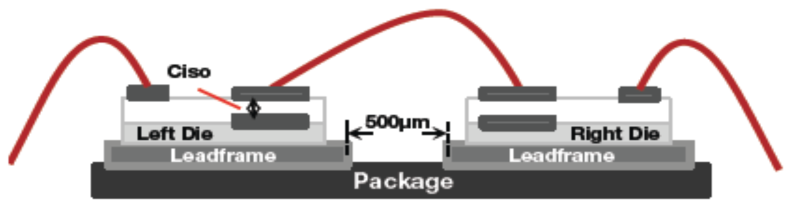


APEC 2013 ADI

Where is Isolation needed?

- Industrial
- Sensor Interfaces
- Automotive - HEV
- Medical
- Motor Control / Drives

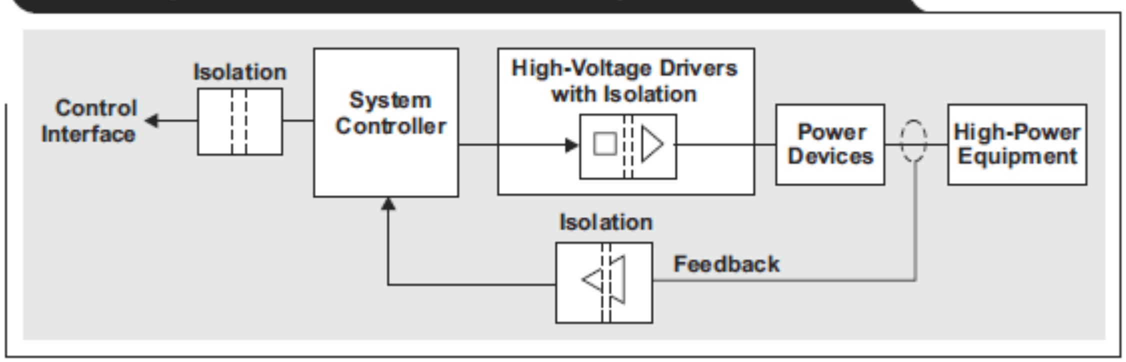




TI White paper

Figure 3. Block diagram of MCM with isolation capacitors

Figure 1. Typical isolation configuration for a power drive system

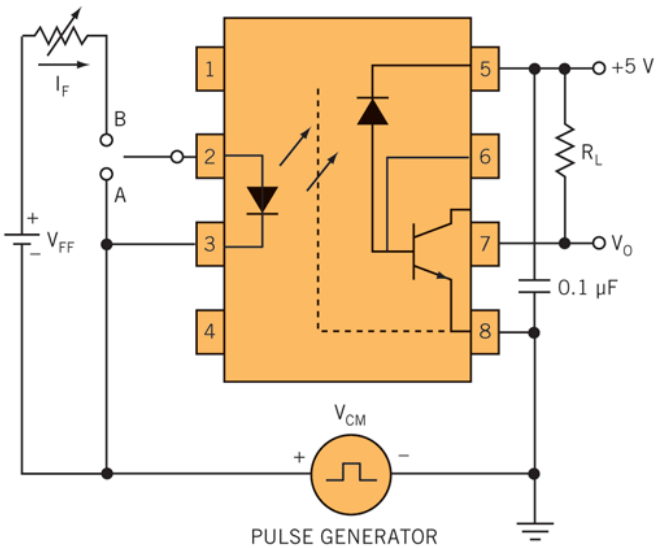


Key Performance Parameters

- **Voltage Isolation Rating**
  - **UL1577, VDE 0884-10, IEC 60747-17, CSA (component level)**
- **Power : Amount / Efficiency**
- **Data Rate : Currently limited to 150Mbps**
- **Latency : Delay across barrier**
- **Common Mode Transient Immunit**

  Specifies how fast a common mode transient can occur without data errors

  Example: 25kV/us



- **EMI /Immunity : FCC standards radiated / conducted**

Isolation Ratings

- **Working Voltage**
  - Continuous operation : steady state voltage
  - Example : 1kV$_{RMS}$ for 25 years

- **Transient Voltage (Withstand, Isolation Rating)**
  - Measure of protection against short term Common Mode variation
  - 60Hz - 60 second test : UL1577
  - Example: 5kV$_{RMS}$ (1 second test at 120%)

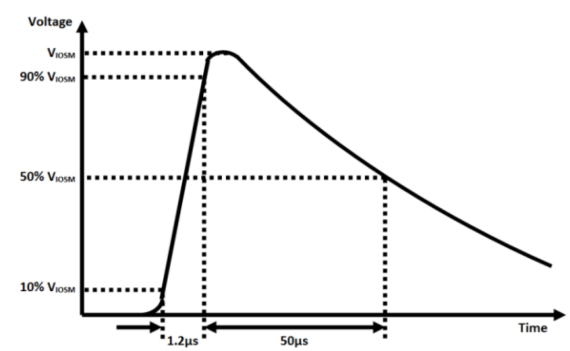
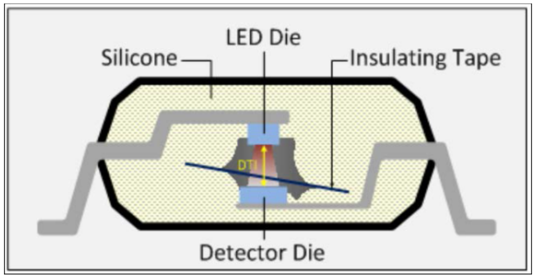


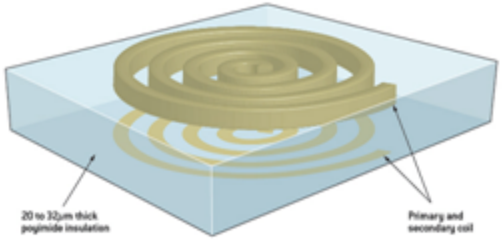
Figure 1. Surge Voltage Waveform

- **Surge Voltage**
  - Repetitive series of high voltage pulses
  - Example: 10kV (= Reinforced Insulation Rating; VDE0884-10)

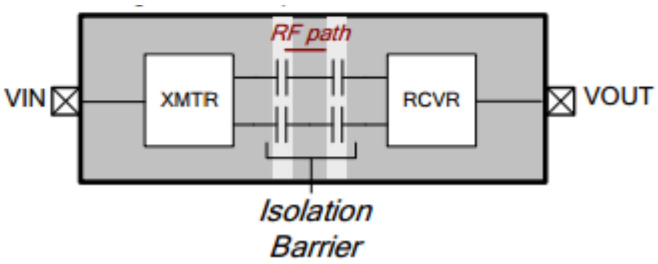
Current Techniques for Isolation



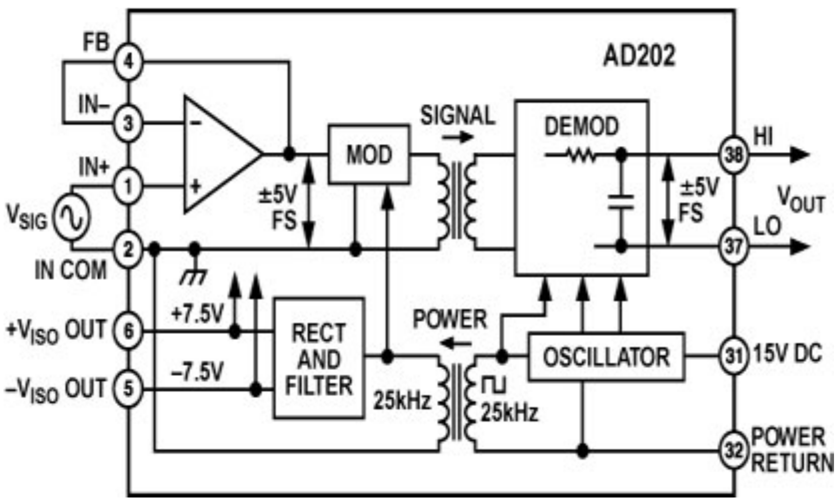
- **Opto Couplers (Avago, others)**
  - Uses light to transmit info across barrier
  - LED -> Photo diode
  - Wide usage
  - Disadvantage: Slow, wear out, wide performance variation



- **Transformers (ADI, Infineon, TI)**
  - On Chip – used in apps with AC signals
  - Signal and Power – higher data rates
  - Disadvantage: Magnetic Immunity, Low Isolation ratings
- **Capacitors (SiLabs, TI)**
  - No wear out, stable over temp
  - Disadvantage: Common Mode Transient

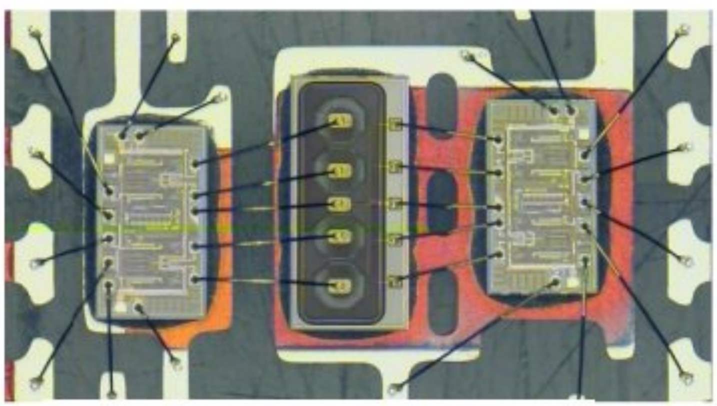


Example Hybrid Isolation Amplifier

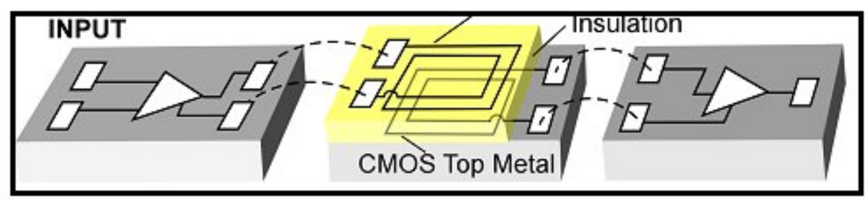


Analog Device AD202

- Inductive coupling
- Up to ±2000 V_{peak} continuous isolation
- ±7.5V/400µA power supply
- 5kHz Bandwidth
- ≈ $50 each



Multi-chip packaging picture

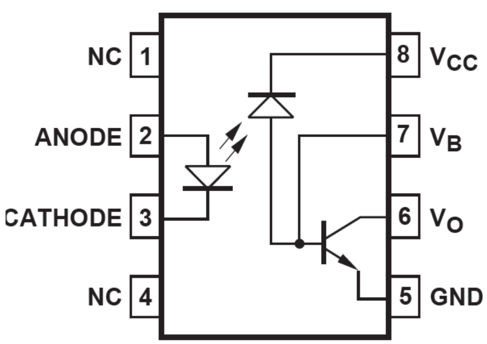


Proper board layout is required to meet the isolation specs!

Source: http://www.analog.com/en/interface/digital-isolators/products/CU_over_iCoupler_Digital_Isolation/fca.html

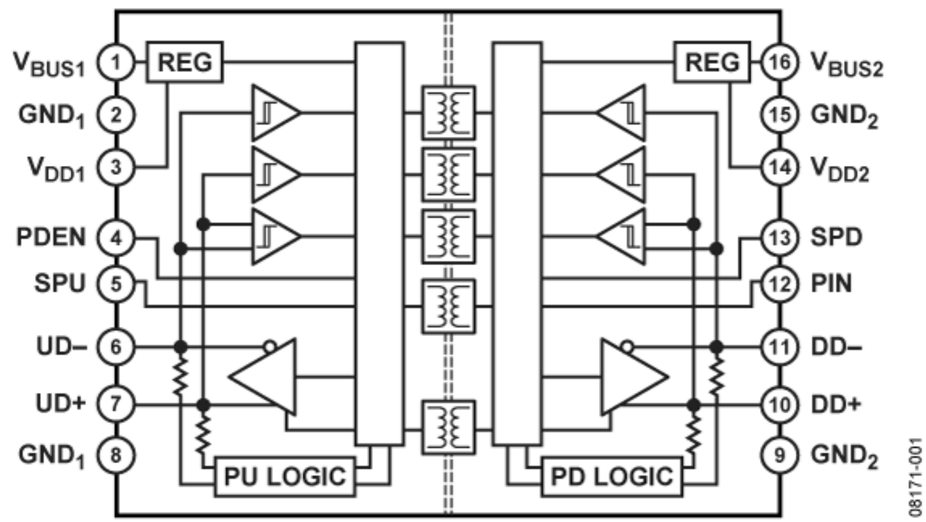
Digital Isolation

- Digital signal isolation can also be done post-ADC, if applicable.
  - More flexibility (signal-independent)
  - Simpler circuitry (non-linear isolator)
  - Sometimes less expensive



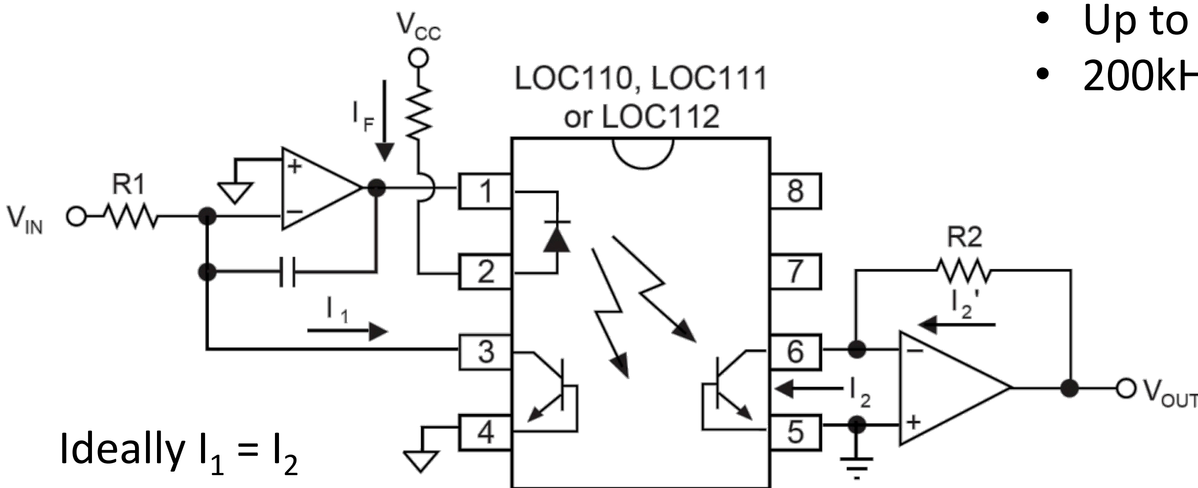
Avago HCNW135
(fast, TTL/CMOS optocoupler, not approved for medical use)

Analog Device iCoupler® ADUM4160
- *Single-chip,* ***USB 2.0 Isolator***
- *Comply with IEC 60601-1 (5kV$_{RMS}$)*



Linear Optocoupler

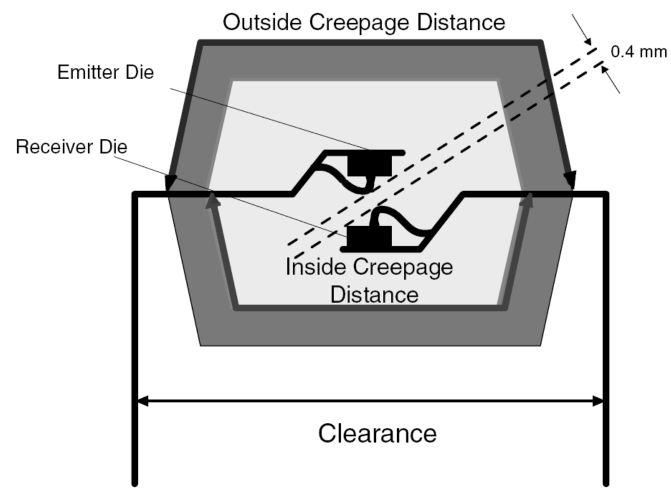
Note op-amp feedback loop around closely-matched phototransistors.



Ideally $I_1 = I_2$

Example: Clare LOC110

- High linearity opto-isolator
- Up to ±3750 V continuous isolation
- 200kHz Bandwidth



Also popular: Avago HCNR-200

First lab…

Optoisolation