Chromatography & Measurement Systems

- Lectures
  - Two lectures with Sinead
    - These are in common with DNAF
  - One lecture with me
    - This is just us
    - Also frequent tutorial classes
- Laboratory
  - Wednesday 13:00 room 117/115/113/116/TDC
  - Class split in 3 groups
    - HPLC
    - GC
    - Instrumentation (room F3 or F6 in the TDC)

Assessment

- January exam 70%
- Midterm 30%
  - My midterm worth 10%
  - Three multiple choice quizzes scheduled for three weeks over course of semester

Contents

- Measurement
  - Signal characteristics
  - Noise
  - Signal conditioning (amplifying and filtering)
  - Signal conversion (digitising)
  - Signal transmission (computer cables)
- Sensors (selection from)
  - Temperature transmitters
  - Pressure Sensors
  - Light Sensors

Elements of a Measurement System

- generic model of measurement system

input → sensing element → signal conditioning → signal conversion → data display

- each element has an input (i/p) and an output (o/p)
- mostly signal conditioning, signal conversion, and signal transmission

- Sensing Element
  - Some kind of transducer
  - Examples: light detector, pH meter, thermocouple
  - Typically, turns environmental variable (e.g. temperature) into a voltage
- Signal Conditioning
  - Voltage might need to be amplified, cleaned up, compared to reference, etc
- Signal Conversion
  - Change signal into a digital format suitable for a PC
  - ADC’s
- Data Display
  - Screen, printer, hard disk, etc
  - Data analysed

Classification of Sensors

- Power supply requirements
  - Active or passive
- Nature of output signal
  - Digital or analogue
- Measurement operational mode
  - Deflection or null modes
- Input/output dynamic relationships
  - Zero/first/second order
- Measurand
  - Mechanical/thermal/magnetic/light/chemical
- Physical measurement variable
  - Voltage/resistance/capacitance

Passive / Active Sensors

- Passive
  - Don’t need external power supply
  - Output power supply comes from the stimulus
  - e.g. thermocouple
- Active
  - Needs power supply
  - e.g. chemical sensors, strain gauges

Analogue / Digital Sensors

- Analogue
  - Output signal varies continuously in magnitude and time. Value can adopt any value in range
  - Quantitative output
  - e.g. light sensor, thermometer
- Digital
  - Output can only be certain discrete values, it’s quantised
  - Qualitative output
  - e.g. any LED readout

Operational Mode

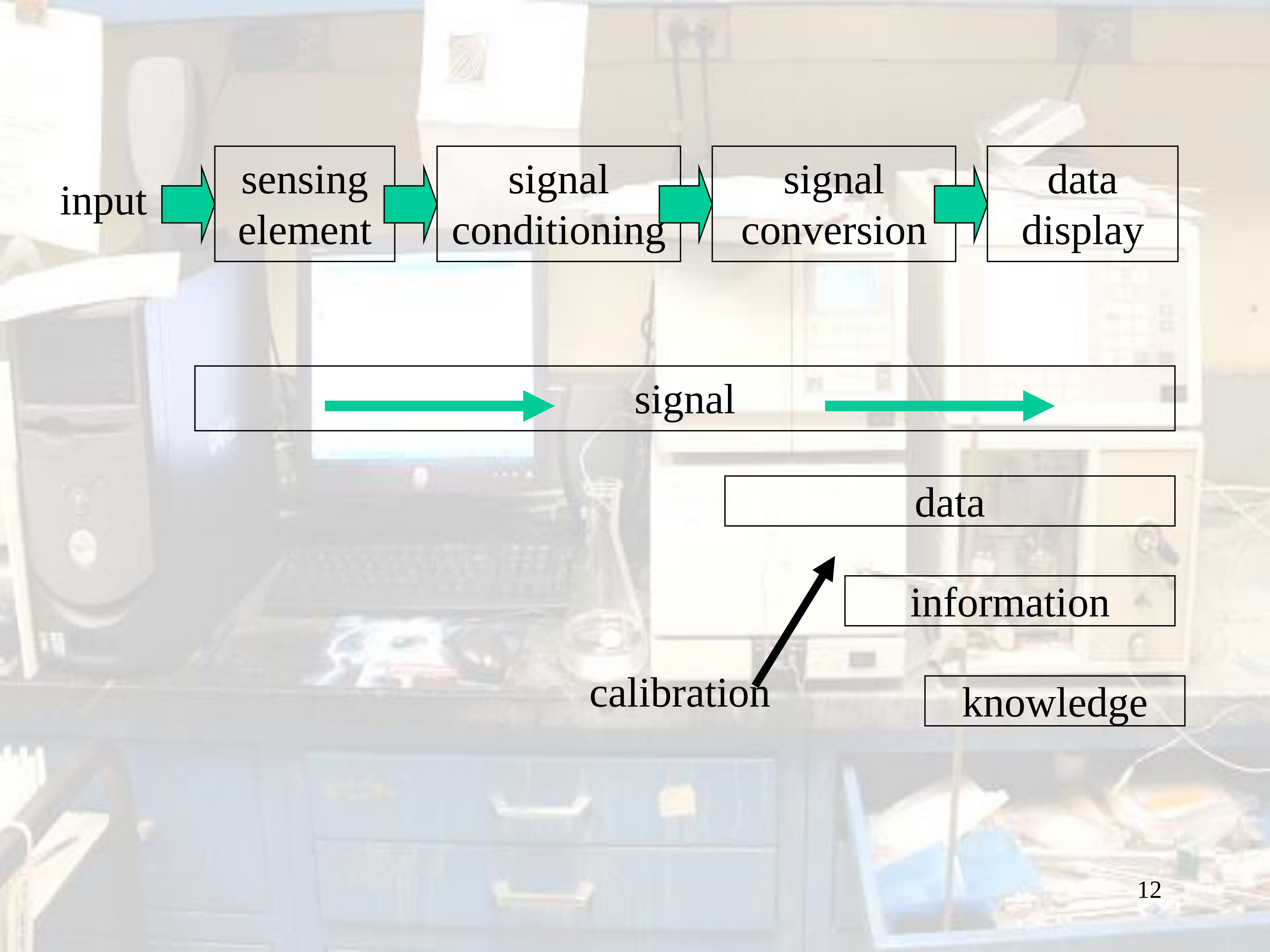
- Deflection mode
  - Response from sensor is deflection or deviation from initial condition
  - Deflection proportional to quantity to be measured
- Null mode
  - Sensor exerts a force to zero some quantity
  - Force required depends on quantity to be measured
- Null mode accurate but slow

Dynamics of Input/Output

- Zero Order Sensors
  - Output always directly proportional to input
  - If input changes then output responds immediately
  - e.g. none, pity though
- First Order Sensors
  - Time lag in response
  - When input changes the sensor takes a while to catch up with the new value
  - e.g. mercury thermometer
- Second Order Sensors
  - When input changes the sensor oscillates around new value, eventually settles down to steady reading
  - e.g. bathroom scales

Some Jargon

- Five important terms: signal, data, calibration, data, knowledge
- **Signal**: flows from item to be measured to eventual observer, often electrical
- **Data:** set of numbers associated with signal
- **Calibration:** turns data (signal) into information
- **Information:** representation of measured system in agreed format
- **Knowledge:** analysed information


input
sensing element
signal conditioning
signal conversion
data display
signal
data
information
knowledge
calibration

Signal Characteristics

- Two categories
  - Static response
    - Sensitivity
    - Range
    - Accuracy
    - Precision (repeatability)
    - Resolution
    - Hysterisis
    - Linearity
    - Drift
    - Monotanicity
    - Zero Stability
    - Error
    - Dynamic Range
  - Dynamic response
    - Frequency response
    - Rise time
    - Slew rate

Static Performance

This is when the transducer is allowed to reach a steady state

Sensitivity:

The sensitivity S of a transducer is defined as:

S = (change in output signal) / (change in input signal)

It is the slope of the input/output characteristic obtained by calibration. For example, a typical blood pressure transducer may have a sensitivity rating of 10 mV/V/mm Hg; that is, there will be a 10-mV output voltage for each volt of excitation potential and each mm Hg of applied pressure.

Not quite the same as sensitivity in Statistics

Range:

The range of the sensor is the maximum and minimum values of applied parameter that can be measured.

For example, a given pressure sensor may have a range of -400 to +400 mm Hg. Alternatively, the positive and negative ranges often are unequal.

For example, a certain medical blood pressure transducer is specified to have a minimum

(vacuum) limit of -50 mm Hg and a maximum (pressure) limit of +450 mm Hg.

This specification is common, incidentally, and is one reason doctors and nurses sometimes destroy blood pressure sensors when attempting to draw blood through an arterial line without being mindful of the position of the fluid stopcocks in the system. A small syringe can exert a tremendous vacuum on a closed system.

Dynamic Range is the total range of the sensor from minimum to maximum. From the example above, Rdyn = 400mm Hg to -400m Hg = 800 mm Hg

Accuracy:

The accuracy may be defined as the agreement of a measurement with the known true value for the quantity being measured.

Precision (repeatability):

This precision is a measure of the extent to which repeated measurements of the same true value agree with one another

Resolution:

The resolution is the smallest increment in the input that can be detected with certainty by the transducer

Hysterisis:

The difference in output value when a give measurand value is approached from increasing and decreasing directions

Linearity:

Linearity is the closeness of and input/output characteristic to a specified straight line

Drift:

Is the unidirectional variation in the transducer's output which is not caused by any changes in its input

<u>Dynamic Range</u>

Ratio of smallest detectable change to largest input value.
Measured in dB.

Dynamic Performance

- This is time dependent performance of transducers and is characterised by the transfer function
- The transfer function is the ratio of the output to the input expressed in the time or frequency domain
- The input stimulus must be carefully defined, commonly used are step input, linear ramp input and sinusoidal inputs.
- Generally sensors exhibit dynamic performances that enable them to be categorised into first order or second order systems
  - First order sensors provide an exponential character of the response
  - Second order systems have both an exponential character to the response in addition to a time dependent oscillation provided the system is not critically damped or over damped

Frequency Response

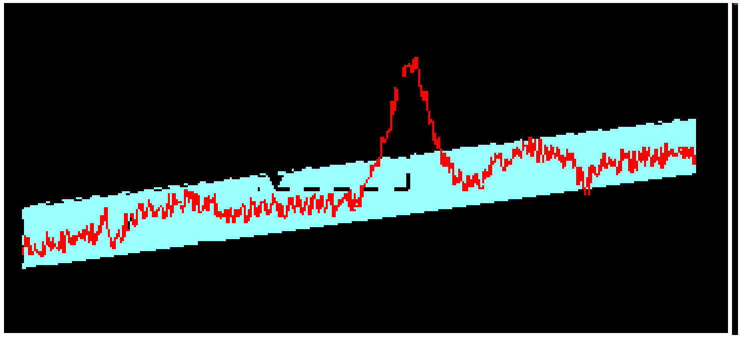
- A critical factor in assessing the full dynamic performance of a transducer is the frequency response.
- This is normally measured using a sinusoidally varying measurand
- The maximum output in the frequency response is called the resonant frequency and the useful frequency range is called the bandwidth.

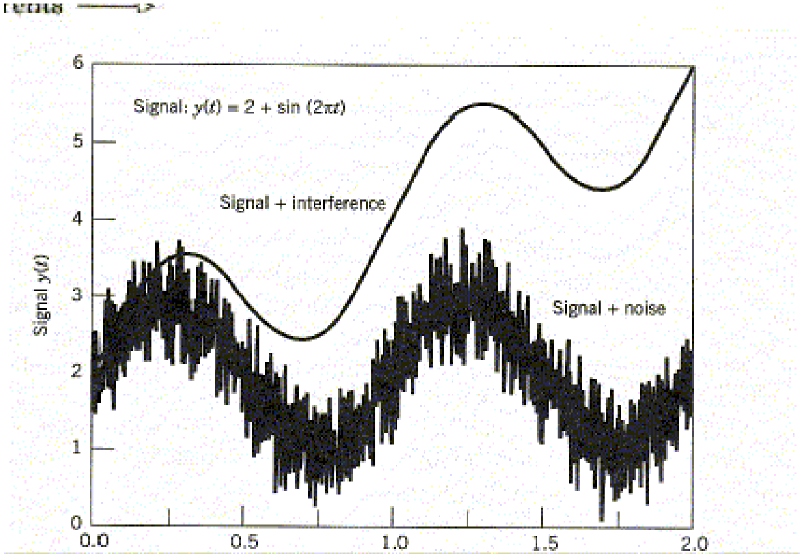
Rise Time

- Output response when sudden step change applied to input
- In general taken to be time to get from 10% to 90% of final steady value
- For exponential rise given by 2.2 times the time constant

Noise

- Origins
  - Nature
  - Man made
- Consequences – limited accuracy and precision of experiments
- Can it be avoided? – no, but tricks to make things better





Sources of Noise

- Thermal noise – nature is in chaotic motion
- Quantisation noise – things come in clumps
- Fluctuation noise – random deviations
- Instrument noise – badly built devices
- Digitisation noise – arises when signal converted from analogue to digital format

Thermal Noise

- Also called Johnson noise
- Consider an electrical resistor
- Thermal fluctuations of electrons in the resistor lead to transient voltages
- Time average is zero
- $|V_n| = (4kT\ \Delta f\ R)^{1/2}$

(because power = 1/2kT x degrees of freedom x bandwidth)

Quantisation Noise

- Also called shot noise
- Current not a continuum but made up of discrete electrons
- Light not a continuum but made up of discrete photons
- Statistical fluctuations in number of electrons / photons

Quantisation Noise 2

- Consider a current
- $I = Ne/t$ (saw this last year, defines current in amperes)

$\Rightarrow N = It/e$

$\Rightarrow \Delta N = (It/e)^{1/2}$

$\Rightarrow \Delta I = (It/e)^{1/2}\, e/t = (Ie/t)^{1/2} = (2Ie\, \Delta f)^{1/2}$

$\Rightarrow \Delta V = \Delta I\, R = (2Ie\, \Delta f)^{1/2}\, R = (2\, V/R\, e\, \Delta f)^{1/2}\, R$

$\Rightarrow \Delta V = (2\, e\, V\, R\, \Delta f)^{1/2}$

$$\Delta V = \sqrt{2\, e\, V\, R\, \Delta f}$$

Where Δf is the bandwidth, e is charge on electron ($=1.6\times10^{-19}$C), R is resistance in ohms

e.g. for 20mA current with 1Mhz bandwidth get

$\Delta I = 80\text{nA} = 4\text{ppm}$

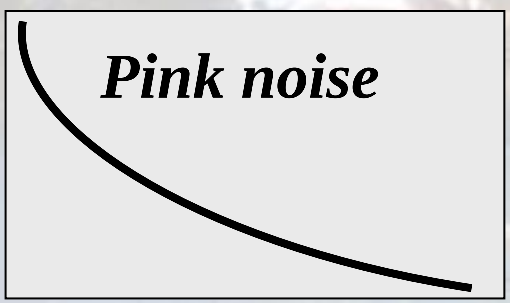
Fluctuation Noise

- Also called 1/f noise or “pink noise” (thermal and shot are examples of “white noise”)
- Phenomenon of nature (dripping taps, heartbeats, DNA sequences……)
- Power density decreases 3dB per octave, each octave contains the same amount of power

White / Pink Noise

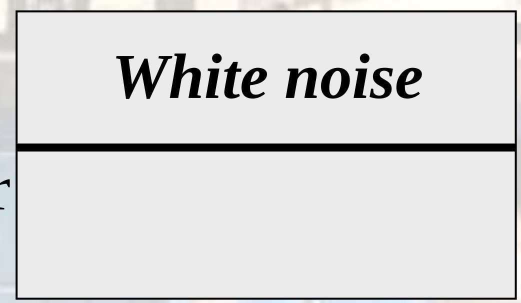
- Noise Power
  - White noise – same noise power in each hertz
  - Pink noise – same noise power in each octave
- Spectrum
  - White noise – flat spectrum
  - Pink noise – 1/f spectrum
- Pink noise a big problem at low frequencies

Noise power



frequency

Noise power



frequency

Instrument Noise

- Environment contains lots of extraneous signals at different frequencies
  - MHz – GHz TV, radio, computers
  - kHz Machinery
  - 50Hz ESB power supply
  - 1Hz Traffic
  - 10^{-5}Hz Day / night

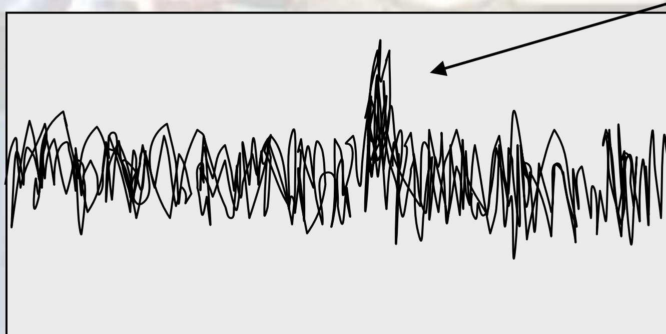
Digitisation Noise

- Process of digitising a signal “rounds off” voltages
- Gives rise to a noise component
  - $\Delta V = V_{range}/2^n$
    - V_{range} is digitized voltage range
    - n is number of bits
- More on this when we discuss voltage conversion later on.

Measuring Noise

- Signal to noise ratio (SNR)
- Average height of signal / average height of noise
- Often expressed in deciBels
- $SNR = 20 \log_{10} (V_{signal} / V_{noise})$
- Need signal to ~2.5 times the noise to be measureable

Is this a signal?



Reducing Noise

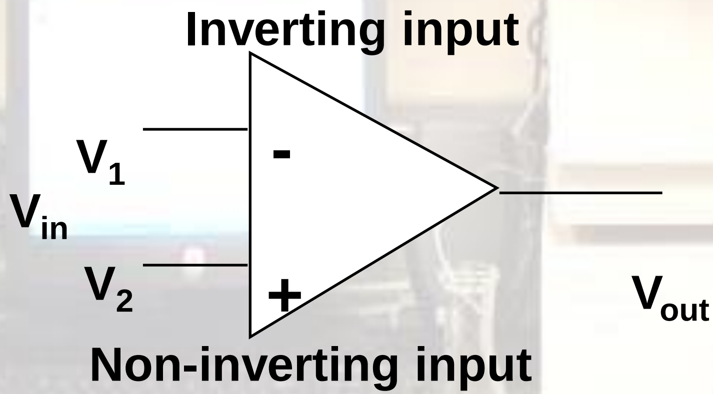
- Filter – e.g notch filter to get rid of 50Hz, comb filter to get rid of harmonics
- Shielding
  - Coax
  - Twisted pair
  - Isolate analog and digital signals
- Avoid long wires
- Layout of components on sensor, capacitors, inductors, transistors, all sources of magnetic and electric fields

Signal Conditioning

- Most sensors need to have their output signals conditioned as the next step in the measurement process
- Reasons for this is that the output from the sensor may be at low power levels and may be non linear with respect to the measurand.
- Typical examples of signal conditioning elements include
  - amplifier
  - filter

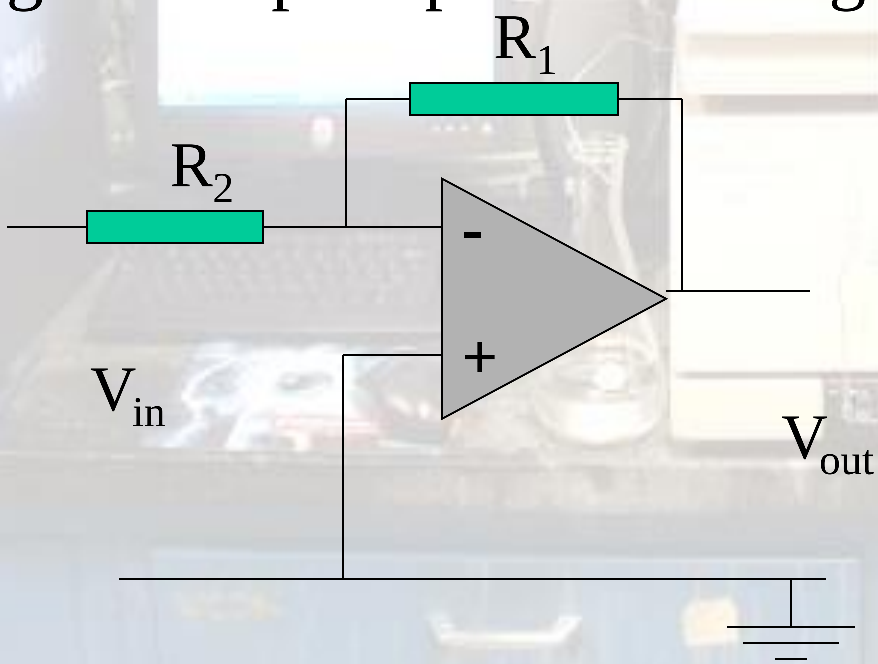
Amplifier

- Workhorse element is the op-amp
- in circuits represented by:



- Internal structure of an op-amp is very complicated (lots of transistors)
- always surrounded by other circuit elements (resistors, capacitors) that dictate how it performs

- Tricks to analysing op-amp circuits
  – no current goes through op-amp (huge input impedance)
  – two inputs at almost identical voltage (massive gain of op-amp ties them together)



  – Gain is $A = - R_1 / R_2$

- Op-amps can be rigged to have
  - A>1 boost signal
  - A<1 attenuate signal
  - A=1
- the latter two regimes is to increase the power output from the sensor (buffering the sensor from the load requirements of the output)
- Some transducers give an output signal when the measurand is set to zero
- This can be used as a “live zero” to show whether the sensor has suffered catastrophic failure. This offset must be removed before amplification

Filters

- Filters are useful conditioning devices where the noise and measurement signal are separable on the basis of frequency
- Four types:
  - high-pass
  - low-pass
  - band-pass
  - band-stop
- These can be either passive (resistors / capacitors / inductors) or active (amplifier / resistors / capacitors) the latter being termed tuned amplifiers