Amplifiers in systems

- Amplification

  single gain stage rarely sufficient

  add gain to avoid external noise eg to transfer signals from detector

  practical designs depend on detailed requirements

  constraints on power, space,... cost in large systems

  e.g. ICs use limited supply voltage which may constrain dynamic range

- Noise will be an important issue in many situations

  most noise originates at input as first stage of amplifier dominates

  often refer to Preamplifier = input amplifier

  may be closest to sensor, subsequently transfer signal further away

- In principle, several possible choices

  V sensitive

  I sensitive

  Q sensitive

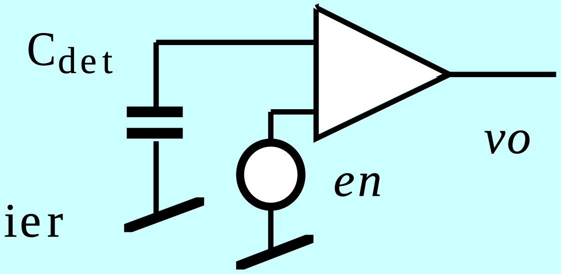
Voltage sensitive amplifier

- As we have seen many sensors produce current signals but some examples produce voltages - thermistor, thermocouple,...

  op-amp voltage amplifier ideal for these

  especially slowly varying signals - few kHz or less

- For sensors with current signals voltage amplifier usually used for secondary stages of amplification



- Signal $V_{out} = Q_{sig}/C_{tot}$

  C_{tot} = *total input capacitance*

  C_{tot} will also include contributions from wiring and amplifier

  V_{out} depends on C_{tot}

  not desirable if C_{det} is likely to vary

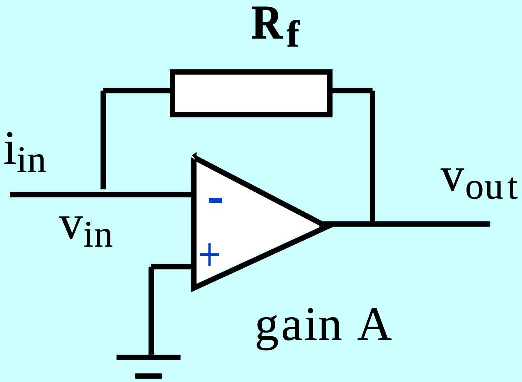
  eg with time, between similar sensors, or depending on conditions

- Noise to be discussed more later

  contribution from amplifier, and possibly sensor

  $S/N = Q_{sig}/(C_{tot}.v_{noise})$ can it be optimised?

Current sensitive amplifier



- Common configuration, eg for photodiode signals

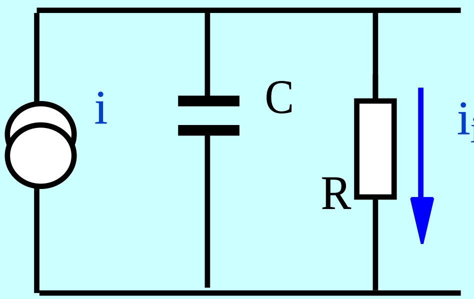
  $v_{out} = -Av_{in}$

  $v_{in} - v_{out} = i_{in}R_f$

  $v_{out} = -[A/(A+1)].i_{in}R_f \approx -i_{in}R_f$

- Input impedance

  $v_{in} = i_{in}R_f/(A+1) \qquad Z_{in} = R_f/(A+1)$



- Effect of C & R_{in} - consider in frequency domain

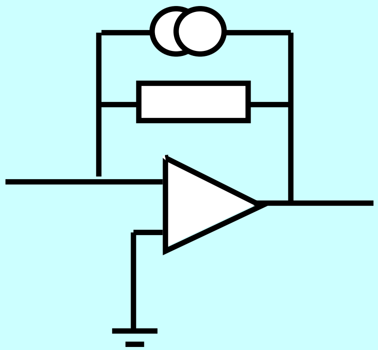
  $v_0 = i(1/j\omega C||R_{in})$

  $= i(\omega)R/(1 + j\omega\tau)$

  input signal convoluted with falling exponential

  increasing R_f to gain sensitivity will increase τ

  fast pulses will follow input with some broadening



- Noise

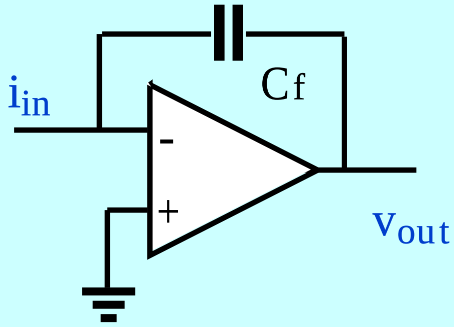
  will later find that feedback resistor is a noise source

  contributes current fluctuations at input ~ $1/R_f$

Charge sensitive amplifier

- Ideally, simple integrator with C_f

  but need means to discharge capacitor - large R_f



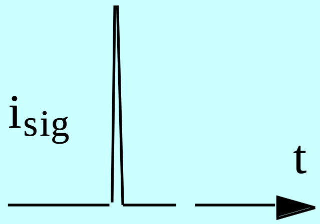
- Assume amplifier has Z_{in} very high (usual case)

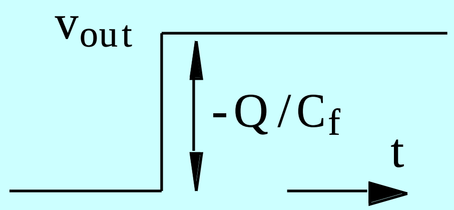
$v_{out} = -Av_{in}$

$v_{out} - v_{in} = i_{in}/j\omega C_f$

$v_{out} = -[A/(A+1)].i_{in}/j\omega C_f \approx i_{in}/j\omega C_f$

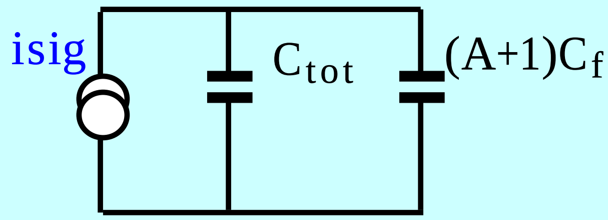
$\Rightarrow -Q/C_f$





- Input impedance

$v_{in} = i_{in}/(A+1)j\omega C_f$ $\qquad C=(A+1)C_f$ at low f



so amplifier looks like large capacitor to signal source

low impedance but some charge lost

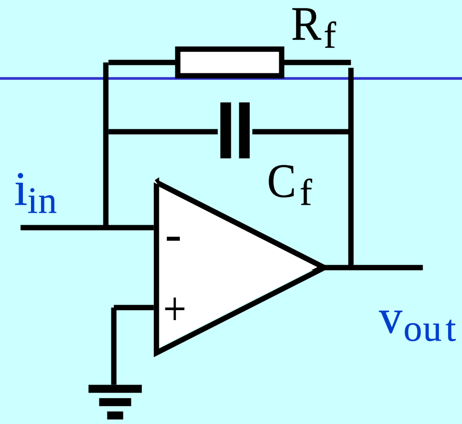
e.g. $A = 10^3$ $\quad C_f = 1pF$

$Q_A = Q/[1 + C_{tot}/(A+1)C_f]$

$C_{tot} = 10pF$ $\quad Q_A/Q = 0.99$

$C_{tot} = 100pF$ $\quad Q_A/Q = 0.90$

Feedback resistance



•Must have means to discharge capacitor so add R_f

$Z_f = R_f||1/j\omega C_f$

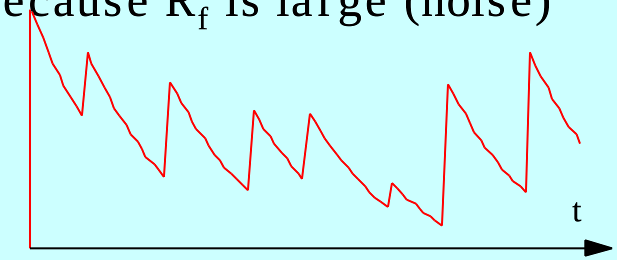
$v_{out} = -[A/(A+1)].i_{in}Z_f$

$= i(\omega)R_f/(1 + j\omega\tau_f) \qquad \tau_f = R_fC_f$

step replaced by decay with ~ $\exp(-t/R_fC_f)$ τ is long because R_f is large (noise)

easiest way to limit pulse pileup - differentiate

ie add high pass filter



•Pole-zero cancellation

exponential decay + differentiation => unwanted baseline undershoot

introduce canceling network

$v_0 = 1/(1 + j\omega\tau_f)$

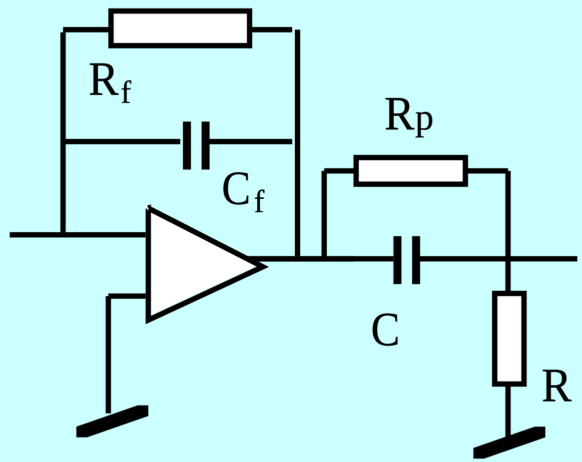
$v_1 = 1/(1 + j\omega\tau_f)(1 + j\omega\tau_1)$

$\tau_1 = RC < \tau_f$

add resistor R_p so $R_pC = \tau_f$

then

$v_1' = 1/(1 + j\omega\tau_3)$ with $\tau_3 = (R||R_p)C < \tau_f$



Effect of finite bandwidth

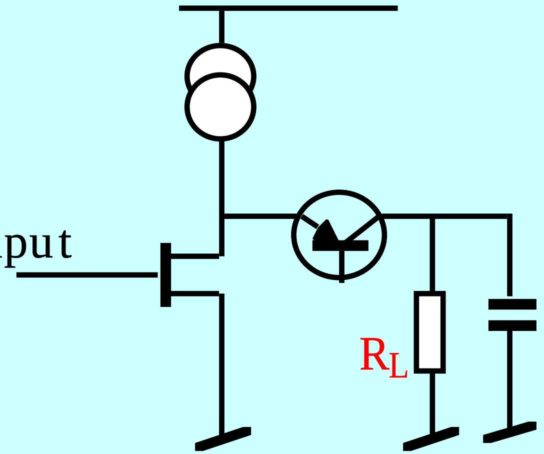
- Realistic input stage of amplifier

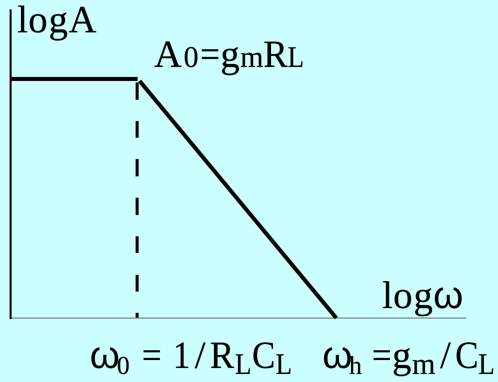
$v_{out} = i_d(R_L||C_L)$ $\quad$ $i_d = g_m v_{in}$

$A = g_m R_L$ $\quad$ low f

$A = g_m/j\omega C_L$ $\quad$ high f

(NB phase change)



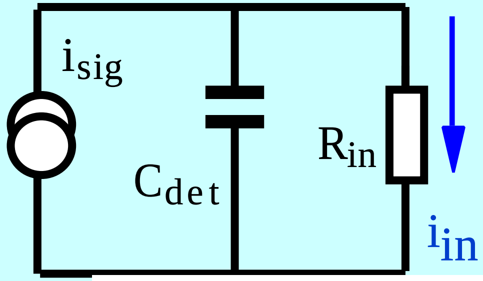


$Z_{in} \approx 1/A.j\omega C_f = C_L/g_m C_f$ resistive!

Irrespective of detailed design

$A \approx A_0\omega_h/j\omega$ $\quad$ ω_h = gain-bandwidth product

$= 1/A_0\omega_h C_f$



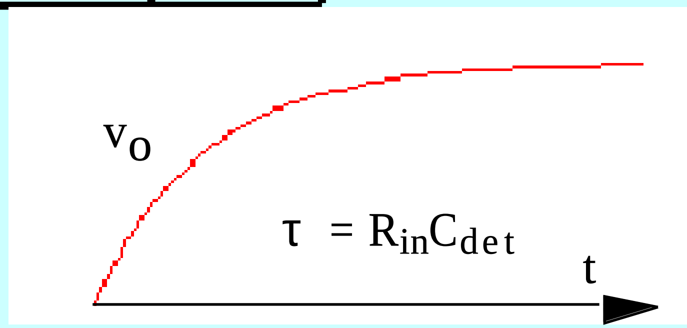
- Effect of R_{in}

signal current shared between R_{in} & C_{det}

$v_{out} = i_{in}Z_f \approx i/[j\omega C_f(1 + j\omega\tau_{rise})]$

$\sim 1 - \exp(-t/\tau)$

high frequencies in leading edge



leading edge of output pulse

Output impedance

- Usual method of varying v_{out} and finding i_{out} - generally messy algebra
- Current sensitive amplifier, open loop gain = A

$v_{out} = i_2(R_2 + R_{in})$

$v_{in} = i_2 R_{in}$

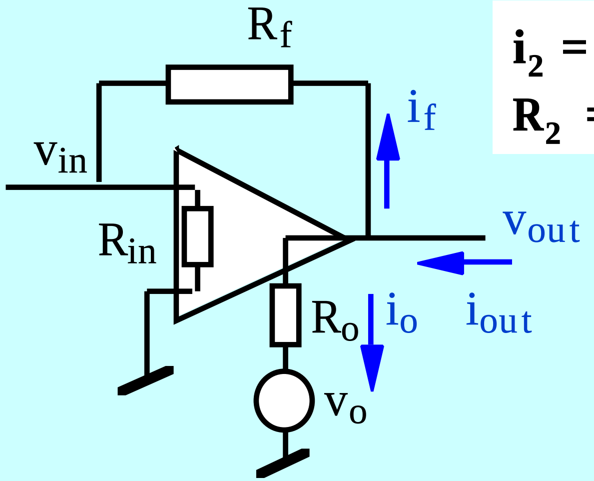
$v_o = -A v_{in} = -A i_2 R_{in}$

$i_o = (v_{out} - v_0)/R_o = (v_{out} - A i_2 R_{in})/R_o$

$Z_{out} = v_{out}/i_{out} = R_o (R_2 + R_{in})/[Ro + R_2 + R_{in}(A+1)]$

$\approx R_o/(A+1)$

since $R_{in} \gg R_2, R_o$



$i_2 = i_f$

$R_2 = R_f$

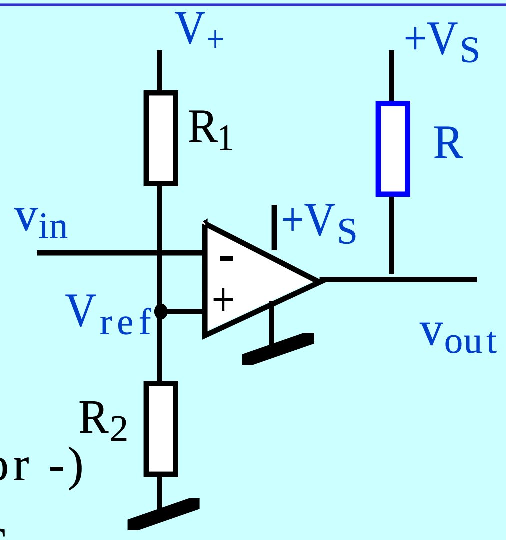
R_o = open loop output impedance

- In general

$Z_{out} = R_o/(1+Ab)$ if voltage is sampled at output b = feedback fraction

$Z_{out} = R_o(1+Ab)$ if current is sampled at output

Comparators



- Frequently need to compare a signal with a reference
  - eg temperature control, light detection, DVM,...
  - basis of analogue to digital conversion -> 1 bit
- Comparator
  - high gain differential amplifier,
    - difference between inputs sends output to saturation (+ or -)
  - could be op-amp - without feedback - or purpose designed IC
  - Sometimes ICs designed with open-collector output so add pull-up R to supply
    - also available with latch (memory) function
- NB
  - no negative feedback so $v_- \neq v_+$
  - saturation voltages may not reach supply voltages - check specs
  - speed of transition
- Potential problem
  - multiple transitions as signal changes near threshold

Hysteresis

- Add positive feedback (Schmitt trigger)

  V_{ref} changes as v_{out} -> $+V_S$

  ie threshold falls once transition is made

  preventing immediate fall

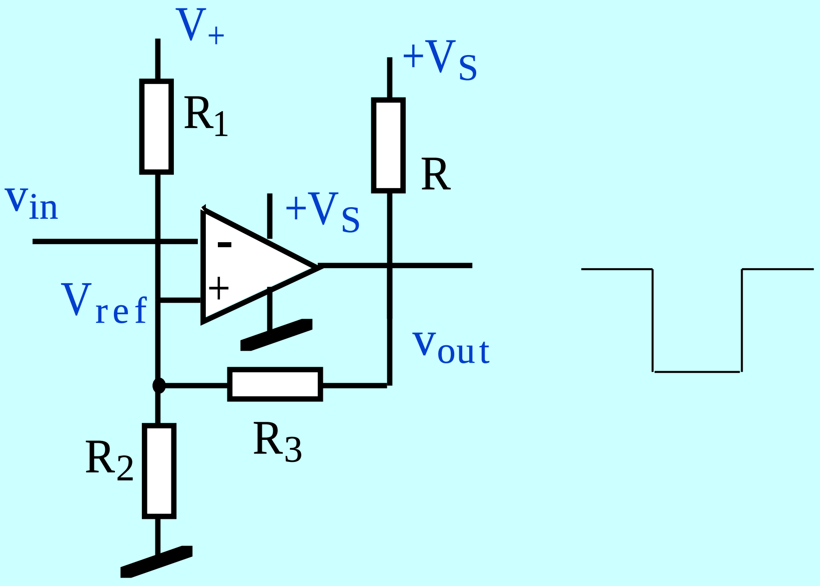
  positive feedback speeds transition

  $v_{out} = A(V_{ref} - v_-)$

  $V_{ref} > v_-$ => $v_{out} = V_s$ $V_{ref} = V_{high}$

  $V_{ref} < v_-$ => $v_{out} = 0V$ $V_{ref} = V_{low}$

  here, signal => logical "1": $v_{out} = 0V$



- Output depends on history

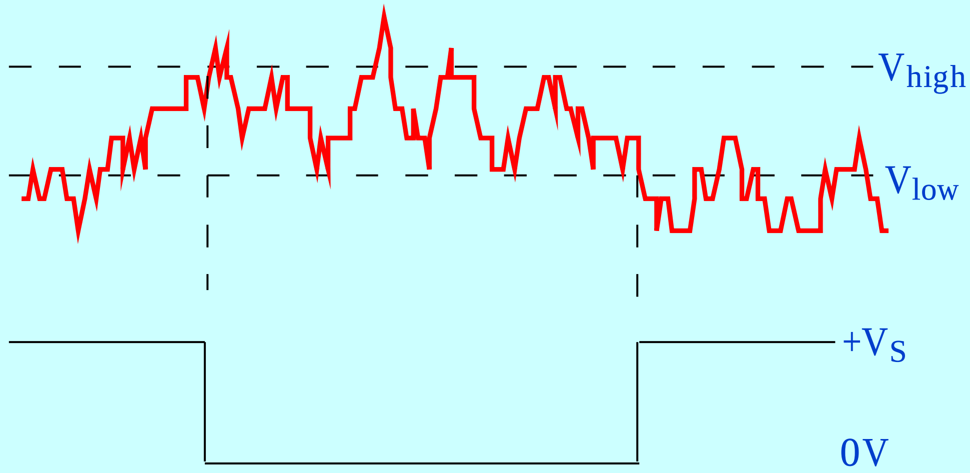
  eg $V_+ = 10V$, $V_S = +5V$, $0V$

  $R_1 = 10k\Omega$, $R_2 = 10k\Omega$, $R_3 = 100k\Omega$

  $V_{out} = 0V$, $V_{ref} = 4.76V$

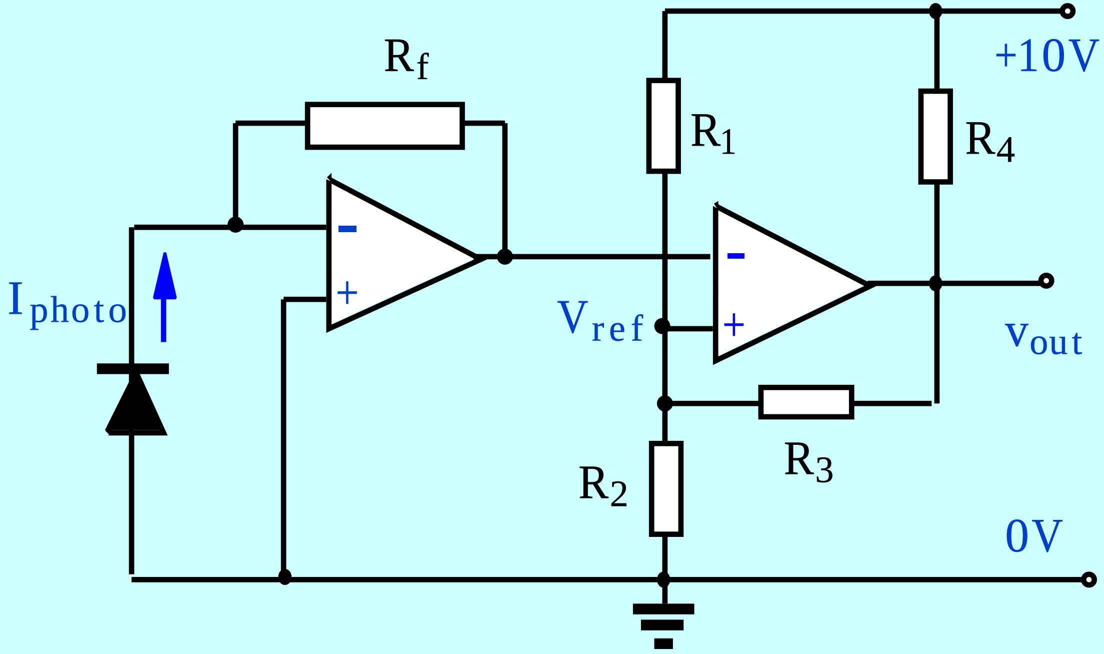
  $V_{out} = 5V$, $V_{ref} = 5V$

  hysteresis = $\Delta V_{ref} = 0.24V$



Example - alarm

•



Oscillators

•Basic building block of many systems

clock or timer, signal generators, function generators,...

can exploit positive feedback

•Relaxation oscillator

charge capacitor C through R ~exp(-t/RC)

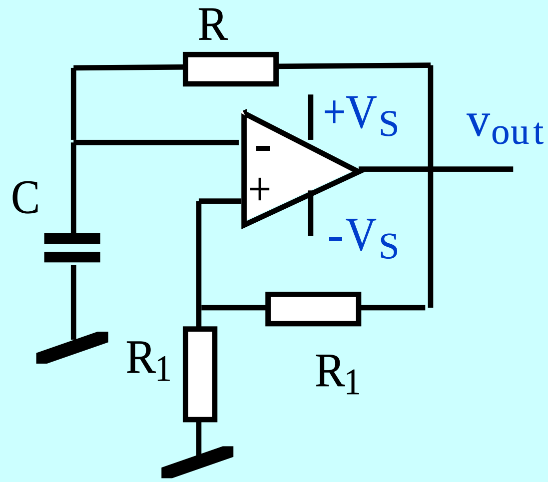
v_- crosses threshold at V_{ref}, V_{out} => $\pm V_S$

V_{ref} changes sign

etc, etc...

square wave output: $[+V_S,-V_S]$

Period T = 2.2RC



•many more types of oscillator design available

IC classic = 555 (many versions)

external components set period and duty cycle

Wien bridge oscillator

- Sine wave oscillators also often required

favourite circuit for audio test applications:

low harmonic distortion at f ~ few kHz

Gain = real at $\omega_0 = 1/RC$

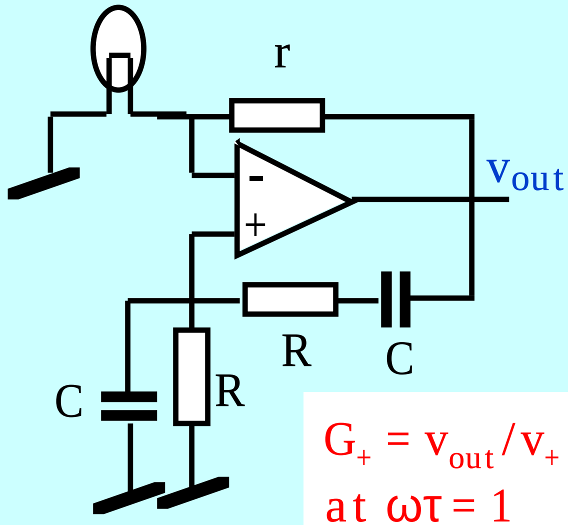
so positive feedback

Lamp provides temperature dependent resistor

so negative feedback controls amplitude

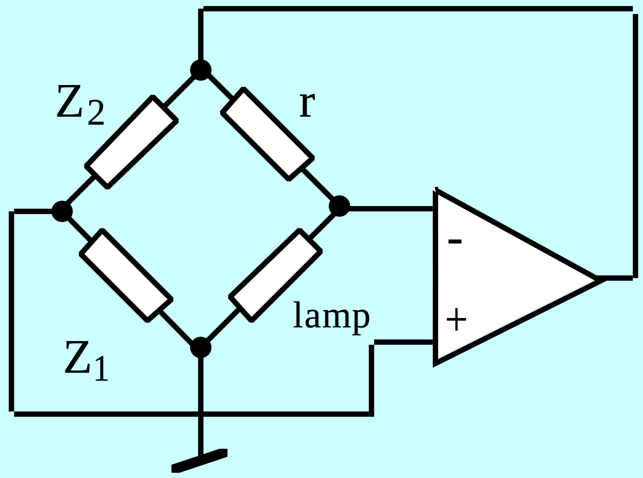
What values to choose for lamp resistance and r?

What determines amount of harmonic distortion?



$G_+ = v_{out}/v_+ = 3$

at $\omega\tau = 1$



Temperature controller

•A frequent requirement - similar to many other control applications

eg cryostat with stable temperature maintained by resistive heater, or oven, ...

•On-Off control

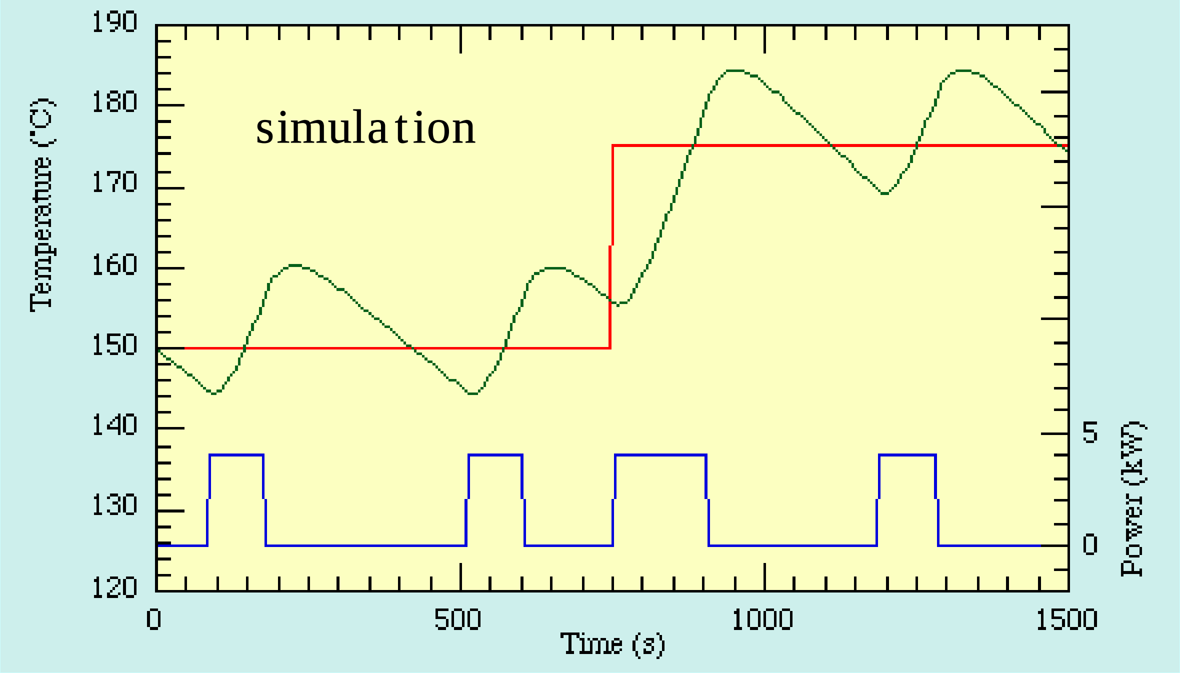
$T < T_0$

set heater to maximum power

add hysteresis (T_{01}, T_{02})

to prevent noise from

switching too rapidly



ok for central heating or

domestic oven but not good

for stable measurements - try to improve

P & PD Temperature control

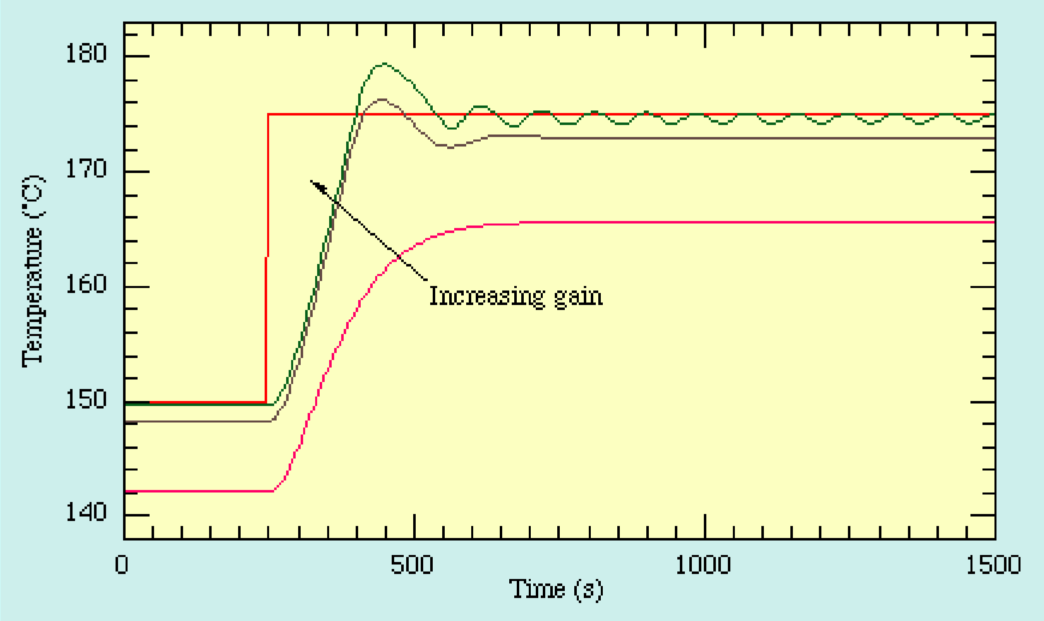
•Set heater power, proportional to temperature difference (P)

$W = P(T_{meas} - T_0)$

T still oscillates and

undershoots desired value

unstable if heat too fast

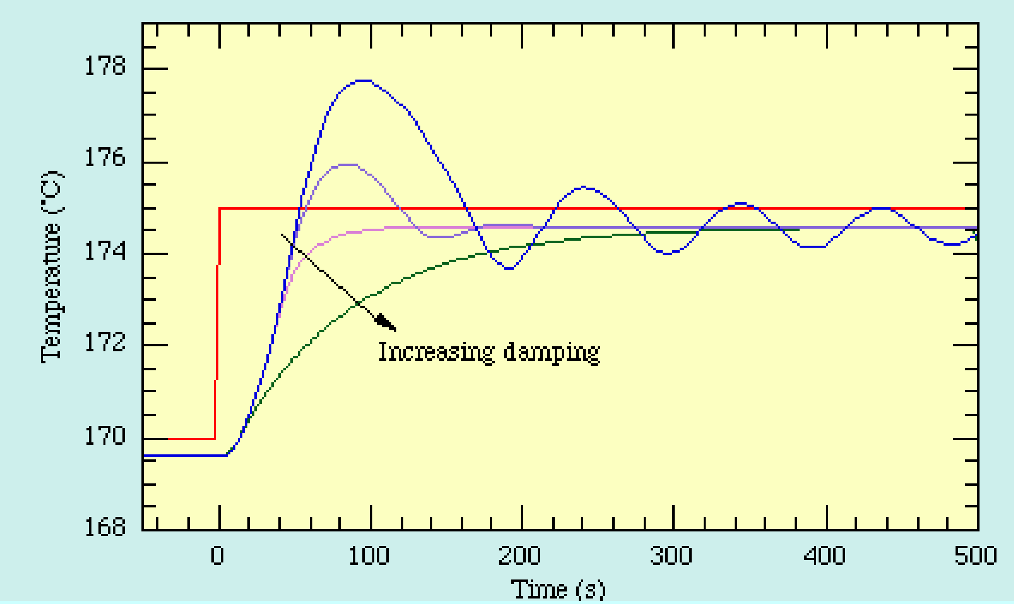


•Add control term proportional to rate of change (PD)

$W = P[(T_{meas} - T_0) + Dd(T_{meas} - T_0)/dt]$

D too large: overshoot & ringing

D too small: slow response



PID Temperature control

- PD can eliminate ringing & overshoot but undershoot error remains

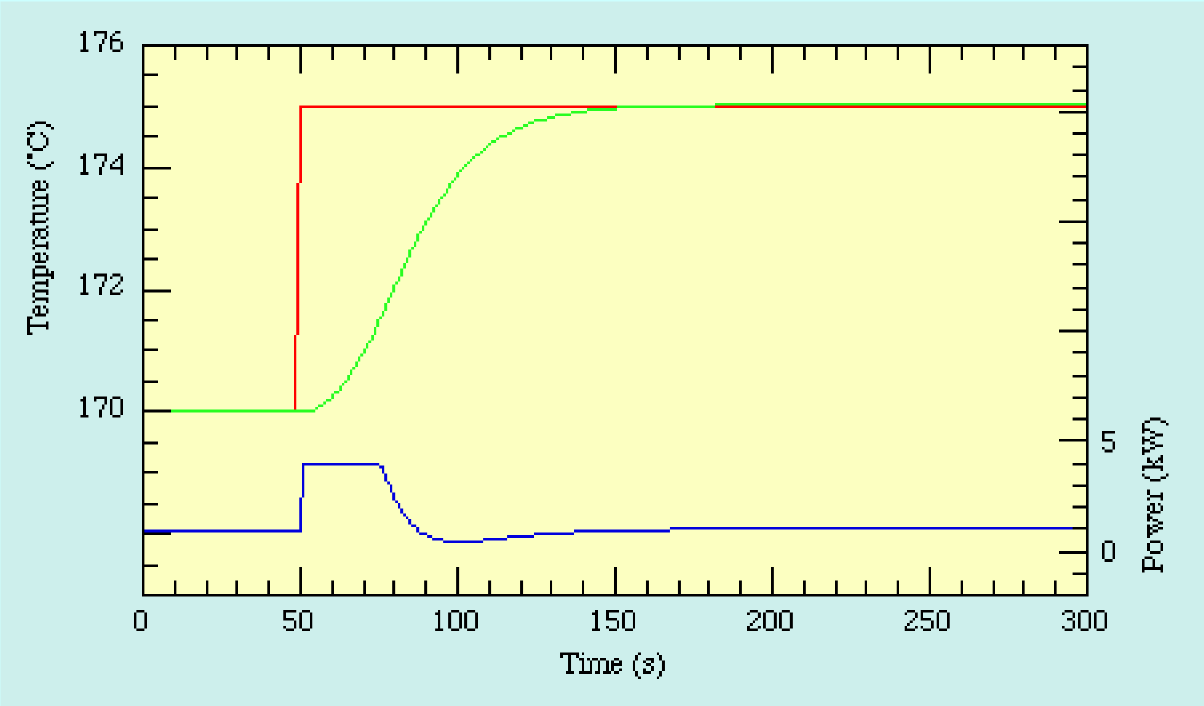
  add integral term

- PID control

  $$W = P[(T_{meas}-T_0) + D\,d(T_{meas}-T_0)/dt + I\int(T_{meas}-T_0)\,dt]$$

good results but
need to choose coefficients
P, D, I empirically to ensure
stability

we'll later look at methods
to solve such system
equations using transforms



Temperature control circuit

- Notes
- $R_1 \gg R_2$ to avoid loading
- still need heating circuit

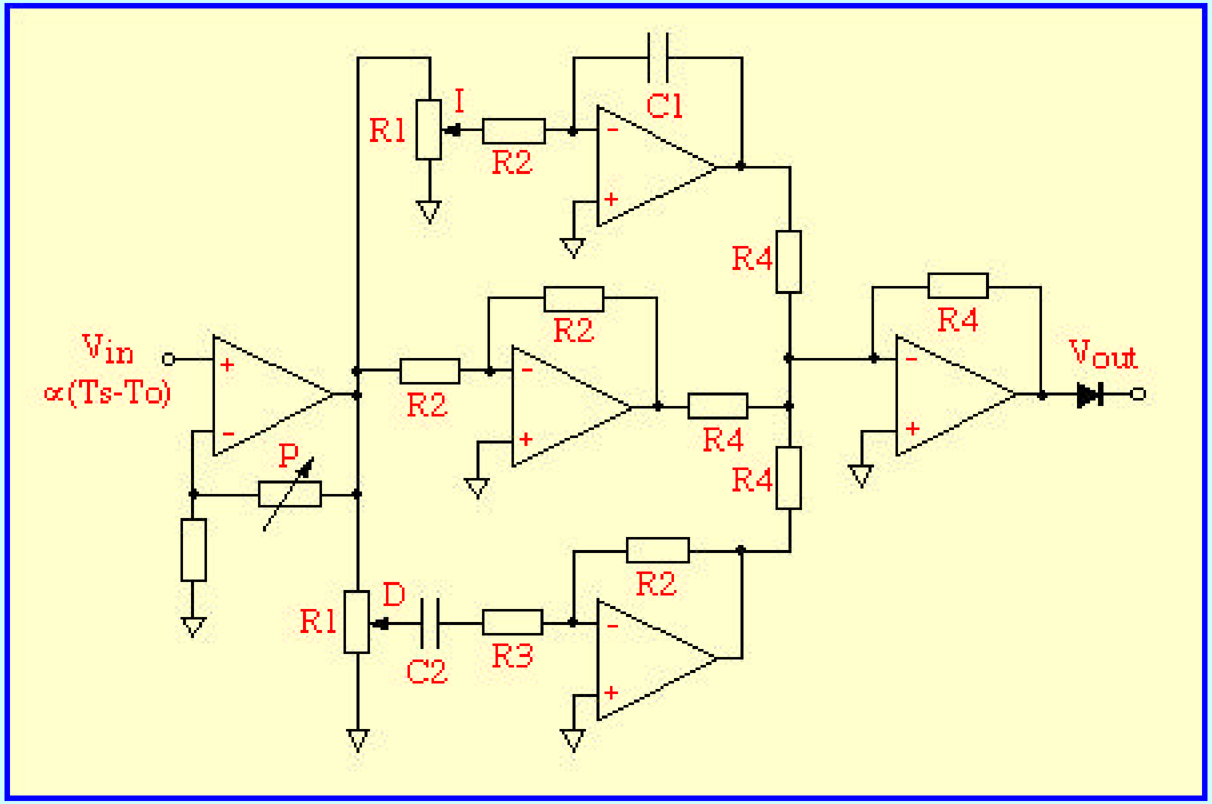
  want W α V_{out}
- Diode ensures W≥ 0

  V_{diode}?
- Time constants to be selected

  depend on appliance chosen

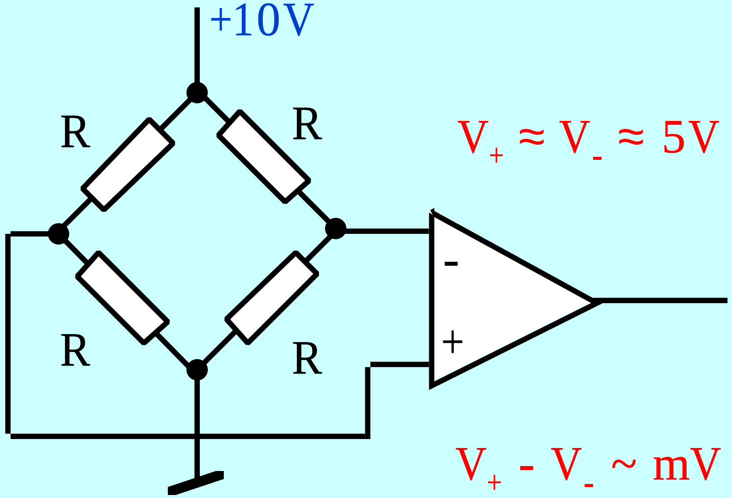
  commercial devices will recommend values
- Need to consider offset currents and voltages

  null, or consider more complex circuit design



Instrumentation amplifier

- High gain, dc-coupled differential amplifier
  - single ended output
  - high input impedance
  - high CMRR
  - use to amplify small differential signals where large CM signal may be present but small normal mode
    - eg strain gauge, other bridge circuits
    - "weak" voltage source



$V_+ \approx V_- \approx 5V$

$V_+ - V_- \sim mV$

To measure 5mV signal with 1% error

CMRR = 0.05/5000 = 100dB

- Drawback of differential amplifier
  - relatively low input impedance
  - CMRR relies on excellent resistor matching
  - cheap op-amps may have CMRR ~80dB

Improved differential amplifier

- Add voltage buffers and choose precise resistors

  improves input impedance

  0.1% resistors available

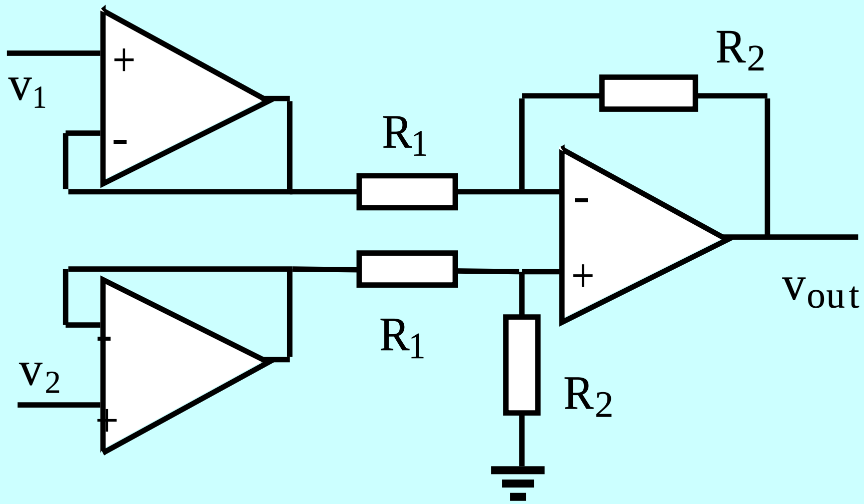
  careful nulling of circuits

  still need high CMRR from output amplifier

  big demands on R precision

  often find restrictions on driving circuit

  ie source



Classic instrumentation amplifier

- Input stage differential gain

$v_{10} - v_1 = iR_2 = v_2 - v_{20}$ (1)

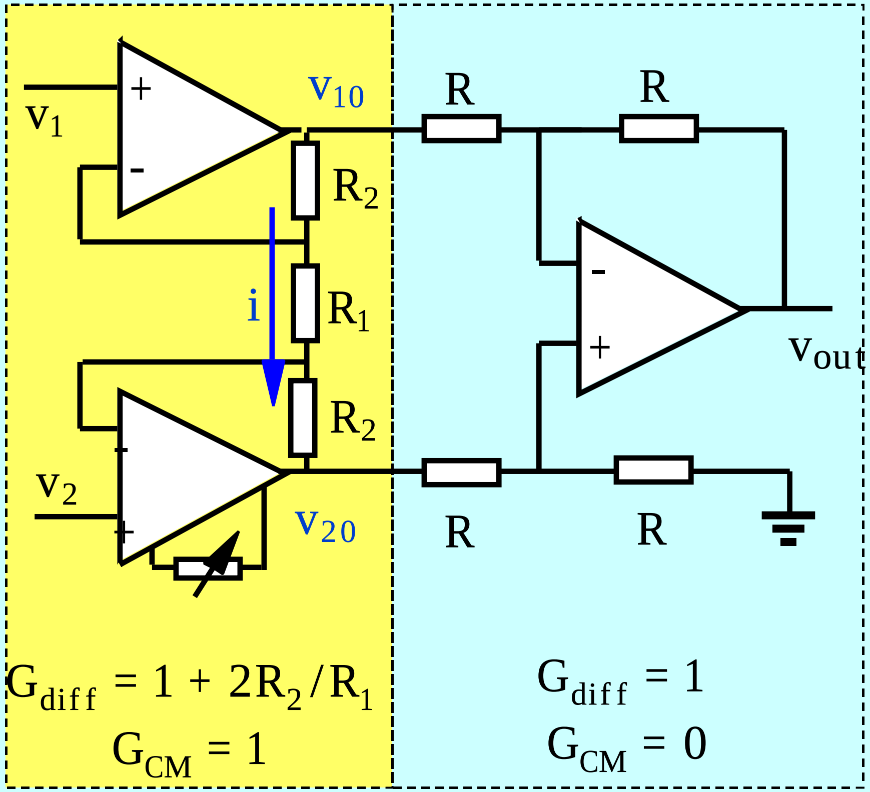
$iR_1 = v_1 - v_2$

$(v_{10} - v_{20}) - (v_1 - v_2) = 2iR_2$

$(v_{10} - v_{20}) = 2iR_2 + iR_1$

$= (v_1 - v_2)(2R_2 + R_1)/R_1$

$G_{diff} = 1 + 2R_2/R_1$



- Input stage common mode gain

$v_1 = v_{CM} + u_1$

$v_2 = v_{CM} + u_2$

$2v_{CM} = v_1 + v_2$ with signal $u_1 = u_2 = 0$

From (1) $v_{10} + v_{20} = v_1 + v_2$

$G_{CM} = 1$

Reduce requirements on second stage
still choose input amps for good CMRR
and null carefully

- Remainder is normal differential amplifier, (G = 1 in this case)

Instrumentation ICs available

The Instrumentation Amplifier in practice

- Can add some more useful features

  feed common mode level back as guard

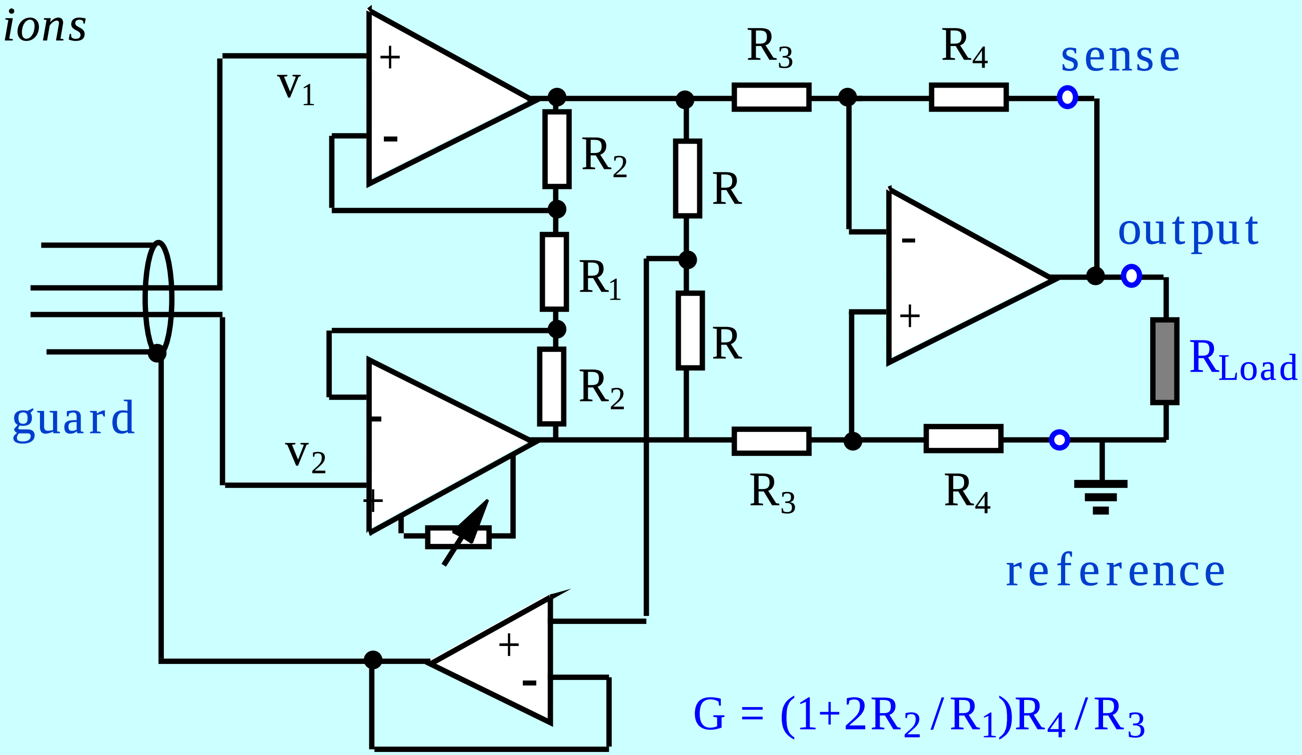
  connect to cable shield

  reduce effects of cable capacitance, leakage currents

  sense voltage at load

  allows feedback to correct for losses in wiring

  or offset of DC conditions



$$G = (1+2R_2/R_1)R_4/R_3$$