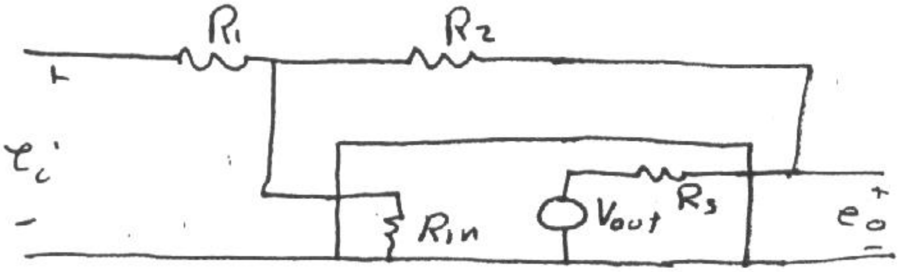
Assumption here was that adding the amplifier did not "load" the point $\epsilon$ nor having to supply current did not change the amplifier's output. In terms of the VCVS model:




$R_{in} \to \infty$
$R_s \to 0$

From preceding the characteristics which make an amplifier an "operational" amplifier are:

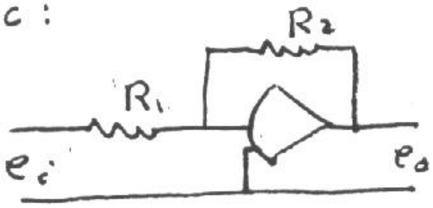
| Feature | Ideal | Practical values |
|---|---|---|
| "Raw" Gain G | $\infty$ | $10^4 \to 10^7$ |
| Input resistance $R_{in}$ | $\infty$ | $10^5 \to 10^9$ |
| Input current implied by $R_{in}$ | 0 | .1 ma $\to 10^{-9}$ |
| Output resistance $R_s$ | 0 | 100 $\to$ 1000 |
| Other features not apparent from preceding: | | |
| Bandwidth | $\infty$ | large enough for job |
| DC drift | 0/°C | 1 mv/°C $\to$ .001 mv/°C |

Cost of the amplifiers range from 50¢ to $50 depending on special features such as high power output capability.

Golden rules { 1. Amplifier draws no curent
2. " input is at 0 potential

Typical instrumentation applications:

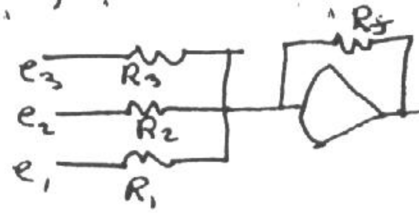
1. Basic:




$$e_o = -\frac{R_2}{R_1} e_i$$

$R_2 > R_1$ amplifier
$R_2 = R_1$ inverter
$R_2 < R_1$ active attenuator

2. Weighted summer (basic idea behind D/A converters)

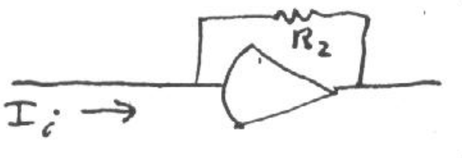



$$e_o = -\left[\frac{R_f}{R_1} e_1 + \frac{R_f}{R_2} e_2 + \cdots\right]$$

each channel can have separate scale factor

One of the inputs can be used for offset control.

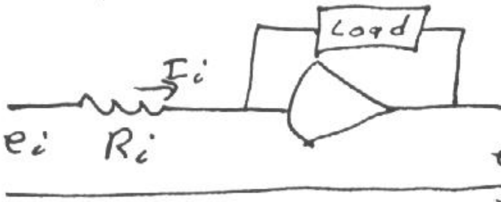
3. Current measuring (current to voltage transduction)




$$e_o = -R_2(I_i)$$ ideal ammeter

measures $I_i$

4. Current controlling (measure V-I characteristic of non-linear device, e.g. diodes)

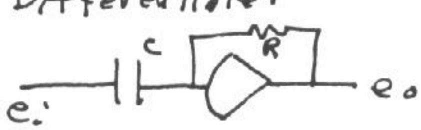



force $I_i = \frac{e_i}{R_i}$ through the load

$$e_o = -V_{device} \ f(I_{device})$$

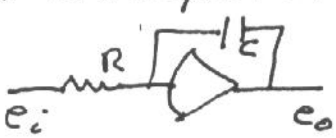
Basic idea of Tektronik curve tracer

5. Differentiator

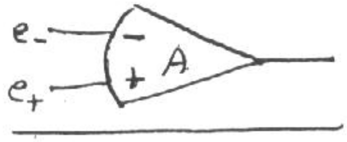



$$e_o = -RC\frac{de_i(t)}{dt}$$

6. Integrator



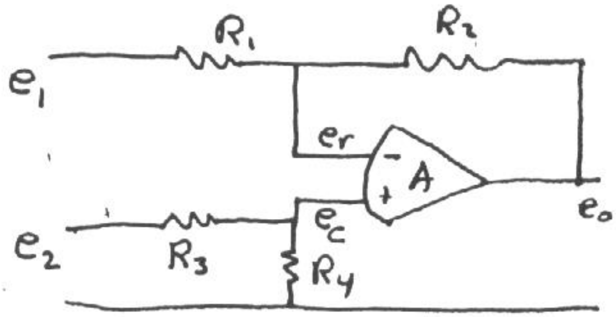

$$e_o = -\frac{1}{RC}\int e_i(t)\,dt$$

Differential amplifier: OPA actuall have two inputs with output given by: 



$e_o = A(e_+ - e_-)$

In preceding the "+" input was assumed grounded.





$$e_o = A(e_r - e_c)$$

$$e_c = \frac{R_4}{R_3 + R_4} \cdot e_2$$

$$e_r = \frac{R_1}{R_1 + R_2} e_o + \frac{R_2}{R_1 + R_2} e_1$$

$$e_o = A\left[\frac{R_4}{R_3 + R_4} e_2 - \frac{R_1}{R_1 + R_2} e_o - \frac{R_2}{R_1 + R_2} e_1\right]$$

solve for $e_o$: can put in form when take $A \to$ large

$$e_o = -\frac{R_2}{R_1} e_1 + \frac{R_2}{R_1} \frac{1 + \frac{R_1}{R_2}}{1 + \frac{R_3}{R_4}} e_2$$

set $\frac{R_1}{R_2} = \frac{R_3}{R_4}$ (condition for a "differential" amplifier

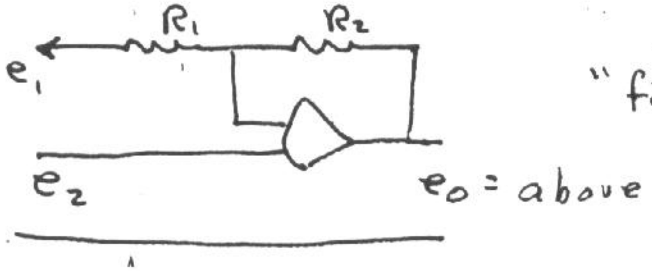
to get $e_o = \frac{R_2}{R_1}(e_2 - e_1)$ (useful for balanced to unbalanced conversion such as when inputs are from a bridge.

If solve for $e_r$ find it $= e_c$ = generalized virtual ground concept i.e. differential input to amp $= 0$ (ie $e_r = e_c$ in ideal case of large A]

Special cases:

1) Let $R_3 \to 0$ output reduces to $e_o = -\frac{R_2}{R_1} e_1 + \left(1 + \frac{R_2}{R_1}\right) e_2$

Note that then $R_4$ is incidental so have




"follower with gain and offset control"

(Very useful ckt)

$e_1$ can of course be set to 0 if not needed

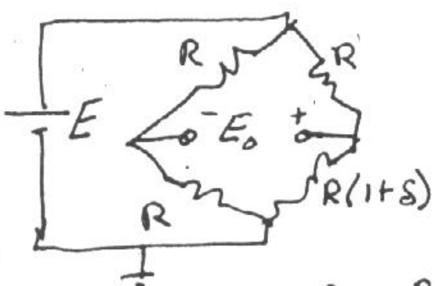
source of $e_2$ sees no loading i.e. is "buffered"

2) If now set $R_2 = 0$, $e_1 = 0$ (then $R_1$ is incidental) get "unity gain buffer) stage


(simplest ckt since no R's involved)

3, Linearized bridge:

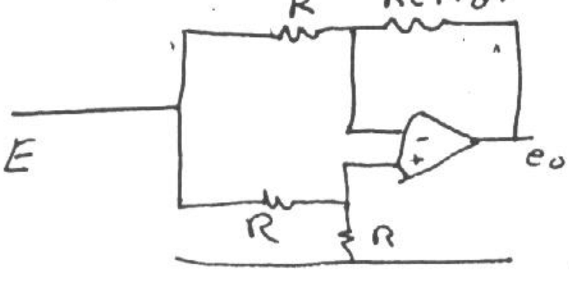
Say have element whose resistance is $R(1+\delta)$ where $\delta$ is deviation from reference (eg a temp dependent device) Used in a bridge




$$E_o = \left[\frac{R(1+\delta)}{R + R(1+\delta)} - \frac{1}{2}\right] E_{in} = \frac{\delta}{2(2+\delta)} E_{in}$$

= nonlinear in $\delta$

instead use:



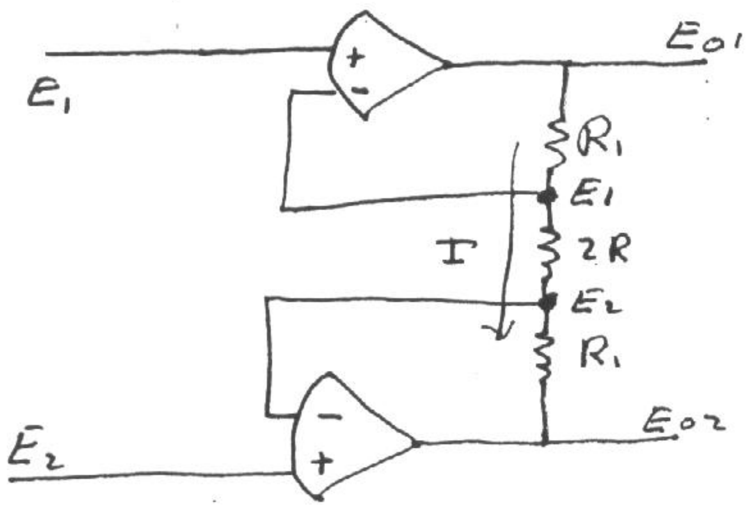

$$e_o = E\left(\tfrac{1}{2}\right)\left(1 + \frac{R(1+\delta)}{R}\right) - \frac{R(1+\delta)}{R} E$$

$$= \left[\tfrac{1}{2}(1+\delta) - (1+\delta)\right] E$$

$$= E \cdot \frac{\delta}{2} = \text{linear in } \delta$$

Instrumentation amplifier: readily available now and at reasonable cost (\#6 – \#20)

Combines buffering with differential action:




$$I = \frac{E_1 - E_2}{2R}$$

$$E_{o1} = E_1 + I_1 R_1 = E_1 + \frac{R_1}{2R}(E_1 - E_2)$$

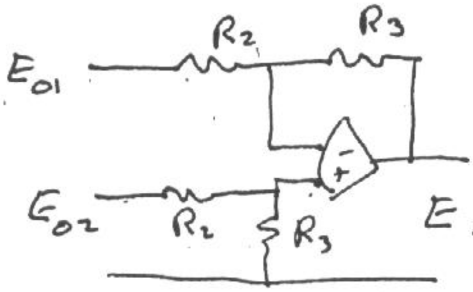
$$E_{o1} = E_1\left(1 + \frac{R_1}{2R}\right) - \frac{R_1}{2R} E_2$$

similarly get

$E_{o2} = E_2 - I R_1$ which give

$$E_{o2} = E_2\left(1 + \frac{R_1}{2R}\right) - \frac{R_1}{2R} E_1$$

put $E_{o1}, E_{o2}$ into a standard dif. amp stage




$$E_o = \cdot \frac{R_3}{R_2}\left(1 + \frac{R_1}{R}\right)\left(E_2 - E_1\right)$$

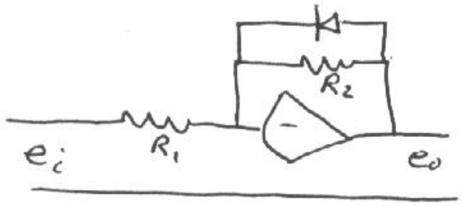
All above put in one package with R brought out to set gain.

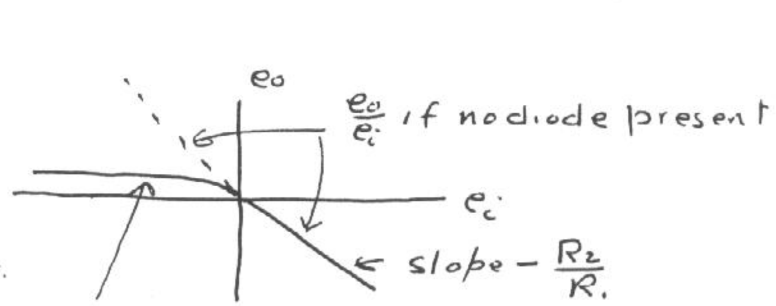
(Very useful ckt)

Note both inputs buffered, gain set with one R.

# Some non-linear OA applications

## Diode limiter - soft



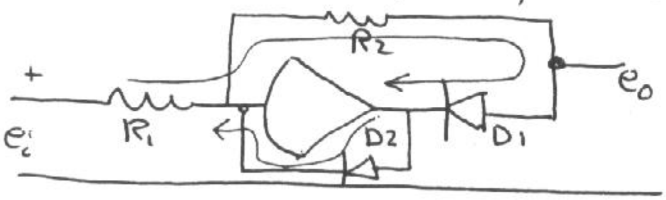




as output tries to go +ve diode conducts, slope then $\sim \frac{r_d \| R_2}{R_1}$

reverse diode to get limiting in other direction.

## Diode limiter - hard

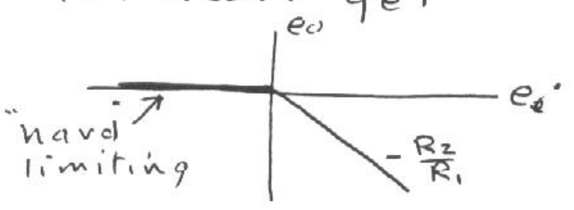
Improve characteristic by putting diode inside the f.b. loop and taking output as shown:




$e_o = -\frac{R_2}{R_1} e_i = -R_2 \left( \frac{e_i}{R_1} \right)$ as long as D1 is conducting (current direction as show).

$D_2$ needed to provide path for current in opposite direction to avoid amplifier going into saturation.

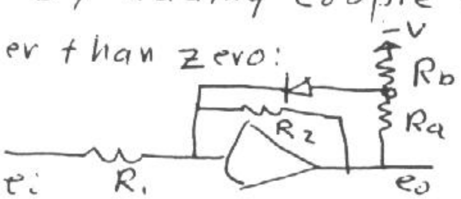
for above get




if reverse both diodes get

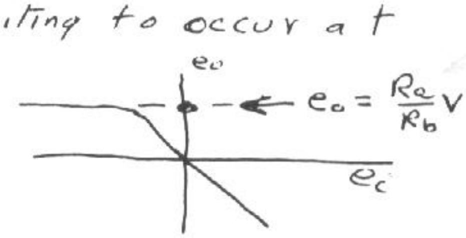
## Variable level limiting

By adding couple resistors can get limiting to occur at other than zero:

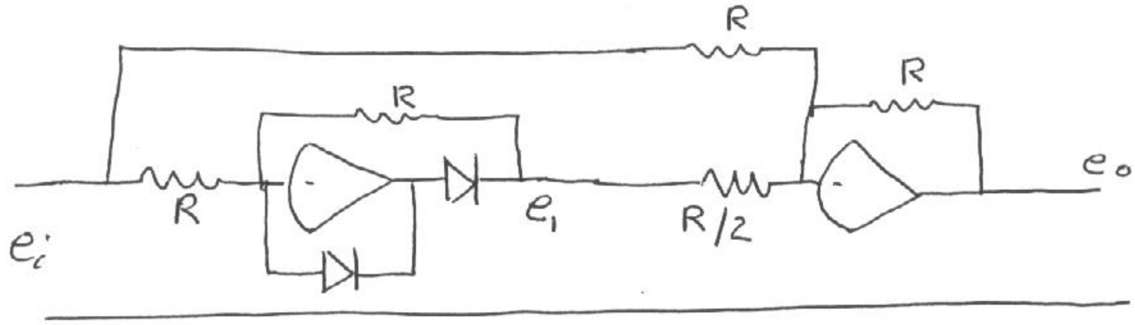



home exercise

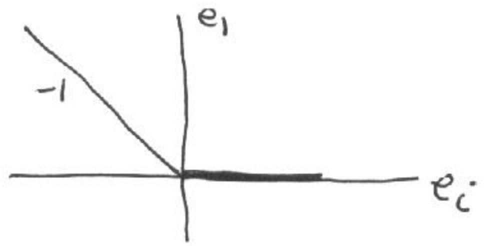
show that get



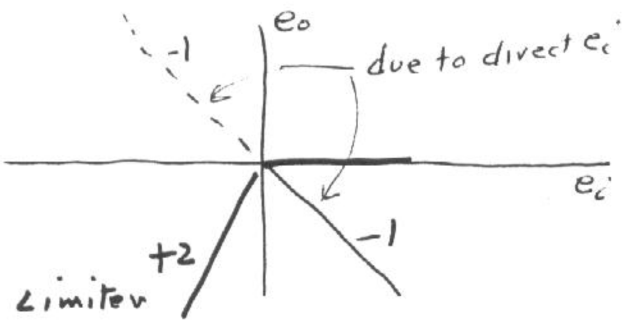
## The || circuit:



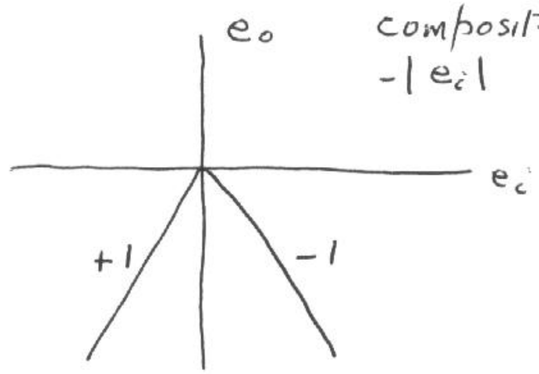

Note that output amplifier sums $-1 \cdot e_i - 2 \cdot e_1$ and that $e_1$ is a hard limiter, i.e.




+ direct input yields



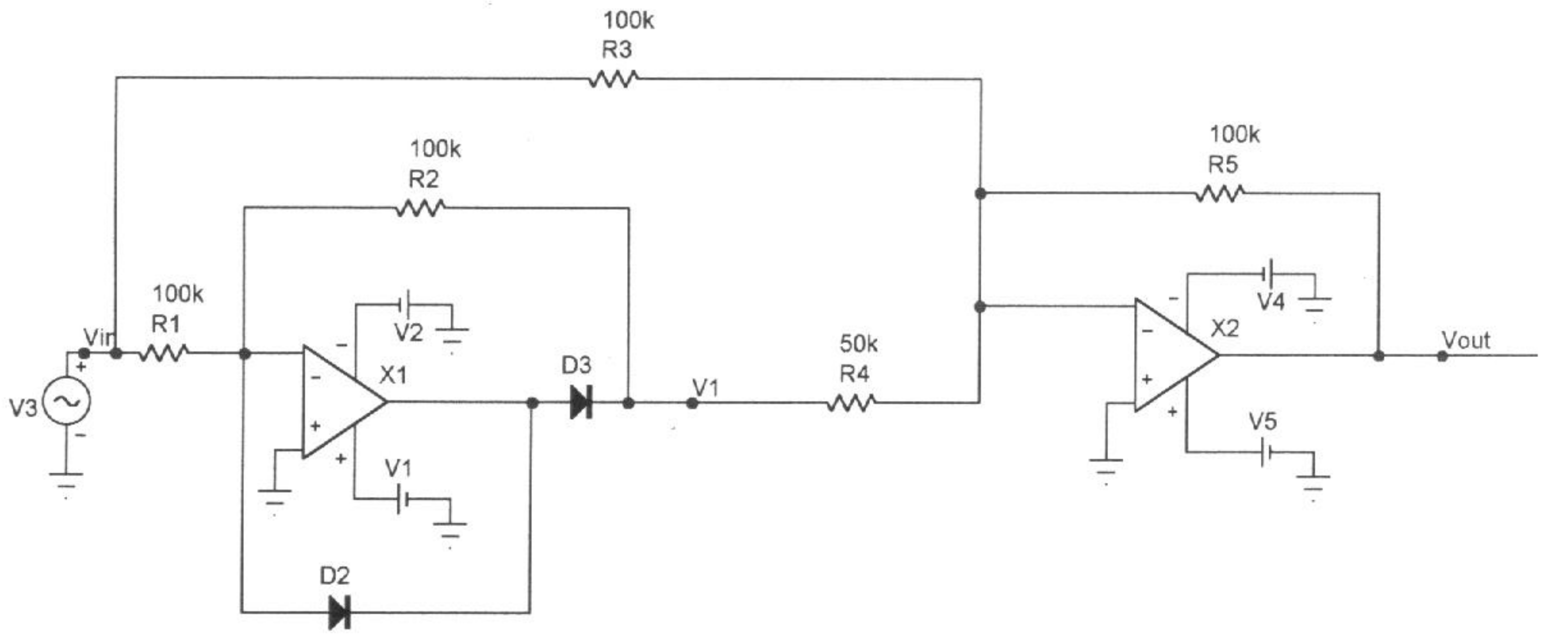

=

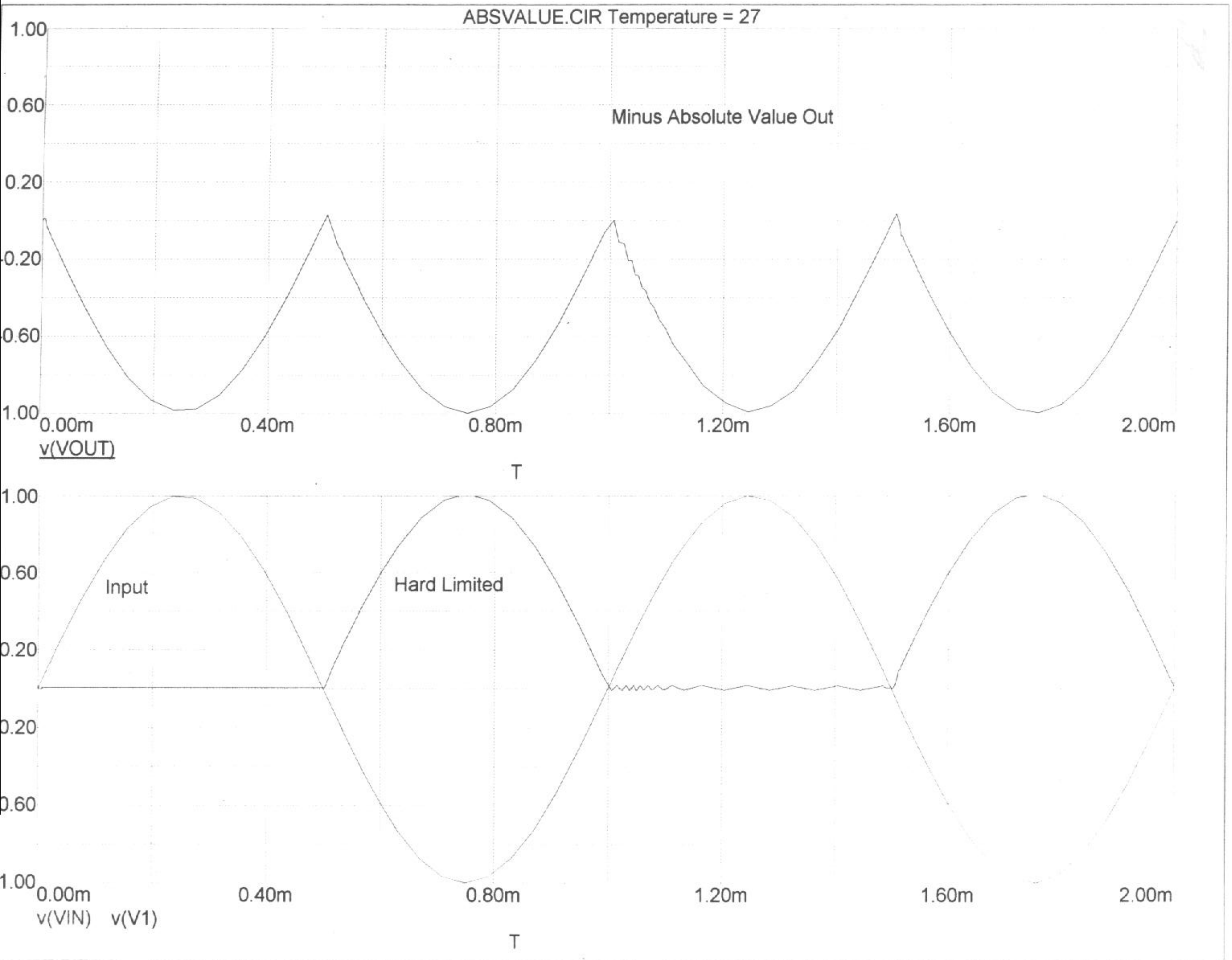



composite = $-|e_i|$

Circuit is also called a precision rectifier. Can add an inverter to get $+||$. Can be used as front end to A/D converter or DMM which want unipolar inputs.

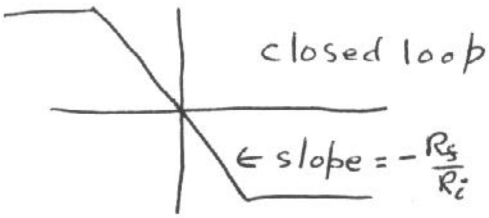
Precision Rectifier



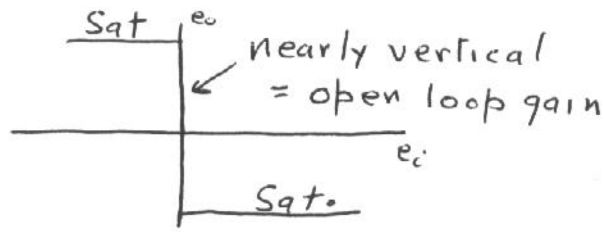

ABSVALUE.CIR Temperature = 27
Minus Absolute Value Out
1.00
0.60
0.20
-0.20
-0.60
-1.00
0.00m
0.40m
0.80m
1.20m
1.60m
2.00m
v(VOUT)
T
Input
Hard Limited
v(VIN) v(V1)

## Comparators (AKA zero crossing detectors, level detector)

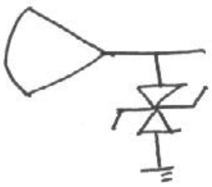
for  as $R_f \to \infty$, $\frac{e_o}{e_i}$ goes from




to

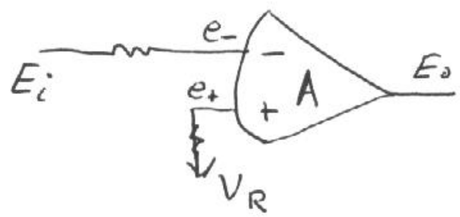



Saturation level could be left to amplifier to decide or set by back-to-back Zener diodes

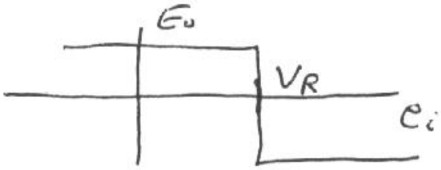


Zener diodes use well defined reverse breakdown →

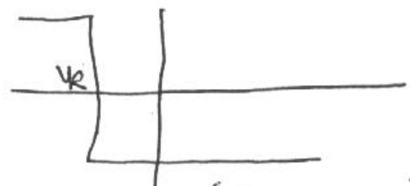
Using open loop OA and reference voltages get following types of operation:




$$E_o = A\,(e_+ - e_-)$$
$$= A\,(V_R - E_i)$$

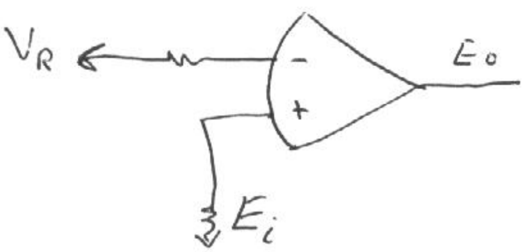



$(V_r = +ve)$

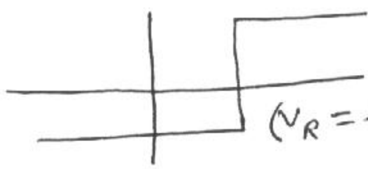



$(V_R = -ve)$

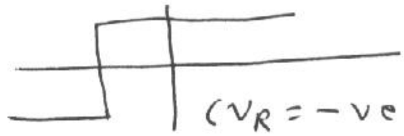
or




$$E_o = A\left(E_i - V_R\right)$$



$(V_R = +ve)$



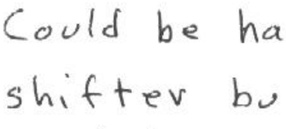
$(V_R = -ve)$

Comparator as indicated above have two issues to be addressed in practice:

1. Ordinary OA's would use ±15 V power supplies giving saturation values that are bipolar, i.e. + and − values, either set by the OA itself or by clamping diodes. Not suitable if output is to drive digital logic ckts, Could be handled by another OA used as a level shifter but in practice manufacturers design from begining to use single, +5V, supplies with internal clamping so that output sat values are ~0, +5V.

   Hence there are many IC's designated as comparators accepting analog inputs and outputting standard logic levels.

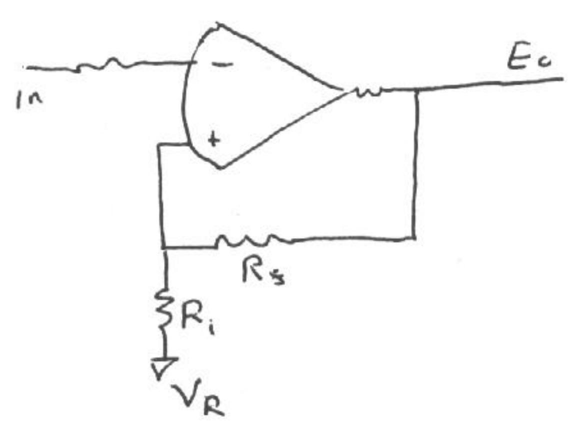
2. Chatter (AKA squegging or jitter): If the input has noise spikes on it will get multiple, unwanted, state transitions.

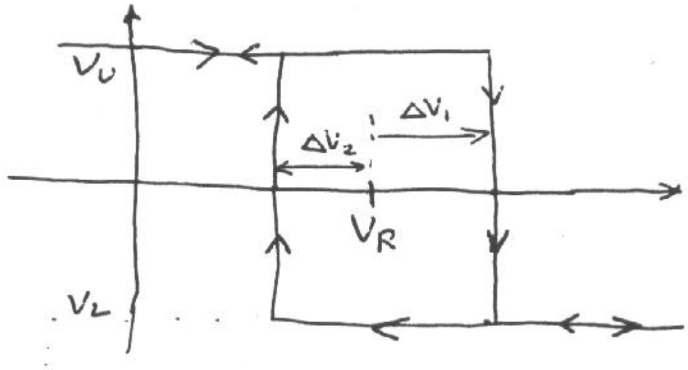



Depending on the application may or may not be serious: e.g. turning on sump pump when water level rises – not a problem probably.

Counting process events – probably a problem.

Common way out is to insert hysteresis (= automatic modification of the threshold (i.e $V_r$) level) via a little feedback. i.e small increment is added to the reference when the output is "high" and subtracted from the reference when the output is "low".




When output is positive the fixed reference $V_R$ is modified to $V_R + \Delta V_1$ with $\Delta V_1 \doteq \frac{R_1}{R_1 + R_s} V_U$

When output is negative, fixed reference modified to $V_R - \Delta V_2$ where $\Delta V_2 \doteq \frac{R_1}{R_1 + R_s} V_L$

Note: approximation used that $R_s >> R_1$ as is usually the case. Actual values of hysterisis in practice range from mV to fractions of a volt.

Packaged units available (eg 7413) and usually have symbol like

7413 has built in hysteris of ~0.4V.