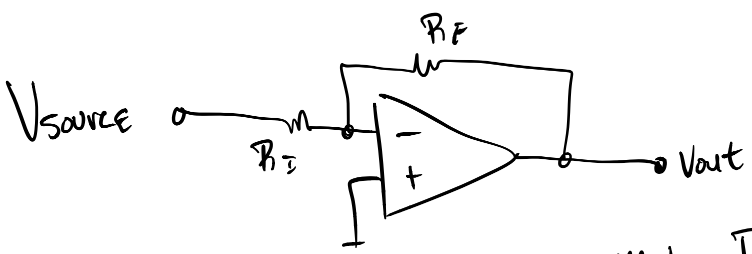
homework: design a circuit using ideal op-amps that acheives

$$\boxed{V_{out} = 3V_A + 2V_B - 5V_C}$$

negative!

- use as few op-amps as possible
- sketch V_{out} if $V_A = 1\,V$ [D.C.]
  $V_B = 10\,mV$ [D.C.]
  $V_C = 50\,mV_{p\text{-}p}$ [sine, 1 kHz]

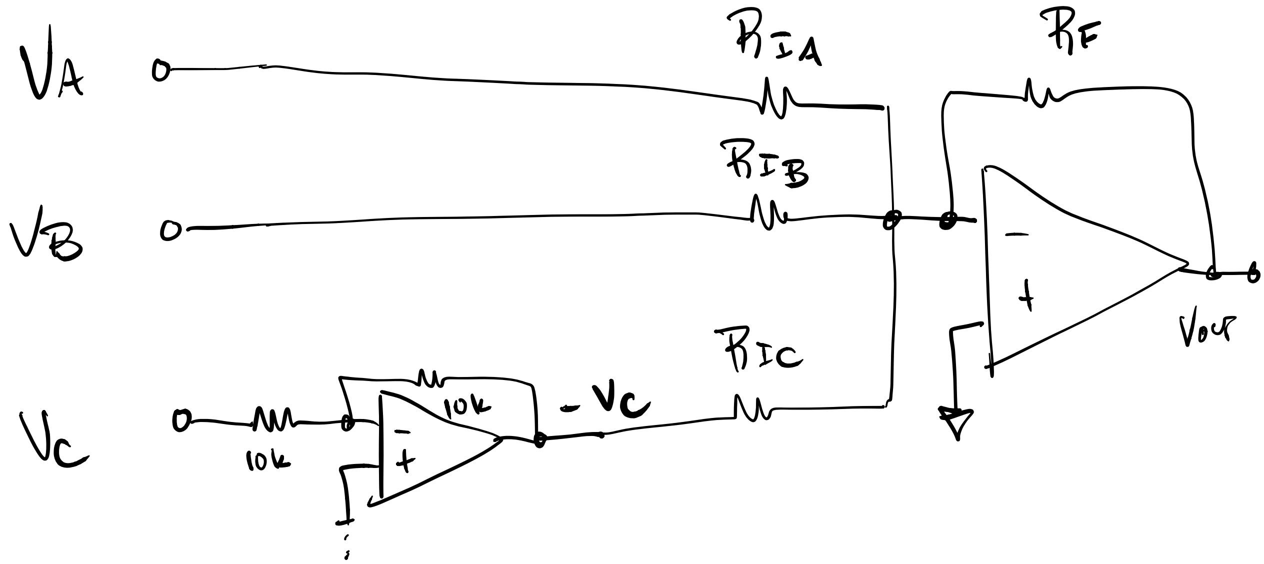
- need to get polarities right!
- one way to "fix" polarity is with unity-gain inverting amplifier



10kΩ is fine!

$$\frac{V_{out}}{V_{source}} = A_V = \frac{-R_F}{R_I}$$

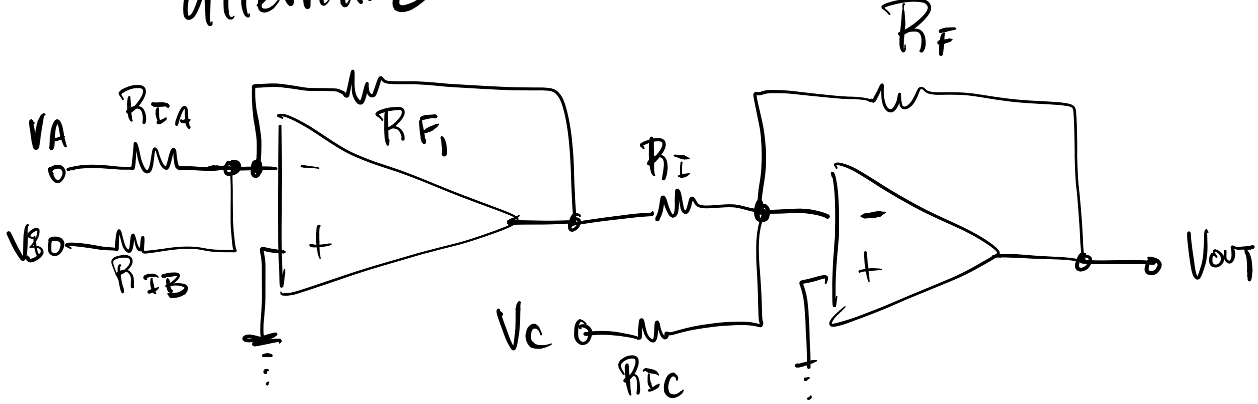
- make $R_F = R_I$, then $V_{out} = -V_{source}$



∴ since summing amp is <u>inverting</u>,
V_{OUT} <u>must</u> be function of $-V_A$, $-V_B$, and $+V_C$.

∴ will need <u>another</u> unity-gain inverting amplifier after Vout!

alternative :



1st summing amp:

$$V_{OUT_1} = VA\left(\frac{-R_{F_1}}{R_{IA}}\right) + VB\left(\frac{-R_{F_1}}{R_{IB}}\right)$$

pick $R_{F_1} = 30\,k\Omega$; then $R_{IA} = 10k\Omega$

$R_{IB} = 15\,k\Omega$

$$V_{OUT} = -VA\left(\frac{30k}{10k}\right) - VB\left(\frac{30k}{15k}\right)$$

$$V_{OUT} = -3VA - 2VB$$ (closer!)

2nd summing amp:

$$V_{OUT} = (-3VA - 2VB)\left(\frac{-R_F}{R_I}\right) + V_C\left(\frac{-R_F}{R_{IC}}\right)$$

pick $R_F = 100k\Omega$, then $R_I = 100k$

$\therefore R_{IC} = 20k$

then $$V_{OUT} = (-3VA - 2VB)\left(\frac{-100k}{100k}\right) + V_C\left(\frac{-100k}{20k}\right)$$

$$V_{OUT} = 3VA + 2VB - 5V_C$$

10k
15k
30k
100k

Note: all resistors are already E24 / 5%!

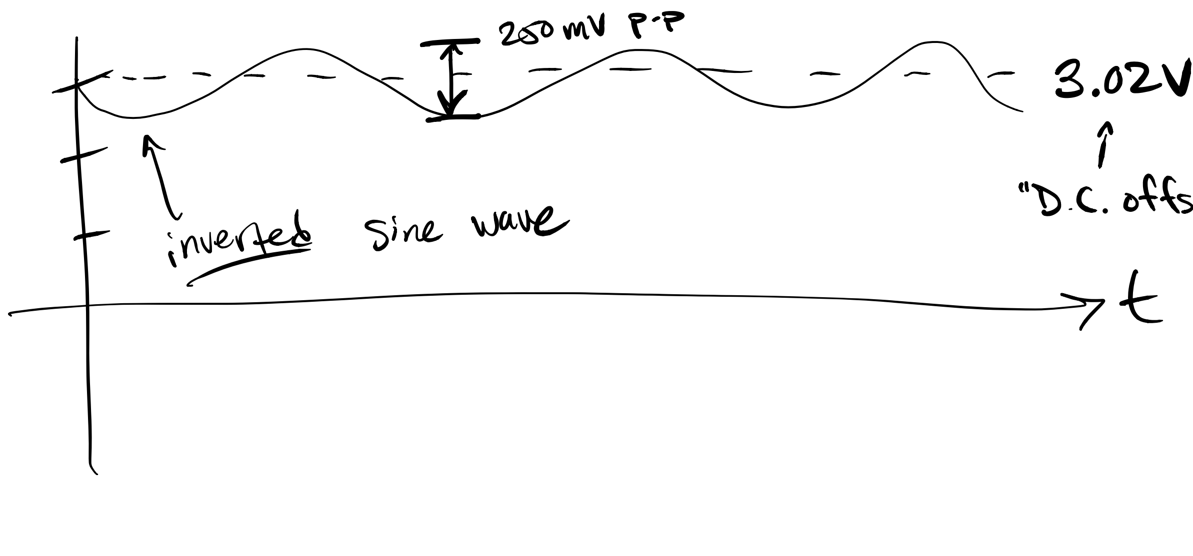
$\therefore$ if $\underbrace{V_A = 1V,\ V_B = 10mV}_{\text{D.C. voltages}}$, $V_C = \underbrace{50mV\ p\text{-}p}_{\text{A.C.}}$

$$V_{OUT\,(D.C.)} = 3 \cdot 1 + 2 \cdot 10m = \underline{3.02\ V}$$

$$V_{OUT\,(A.C.)} = -5 \cdot 50 = \underline{-250\ mV\ p\text{-}p}$$

or 250 mV p-p
<u>inverted</u> sine wave!

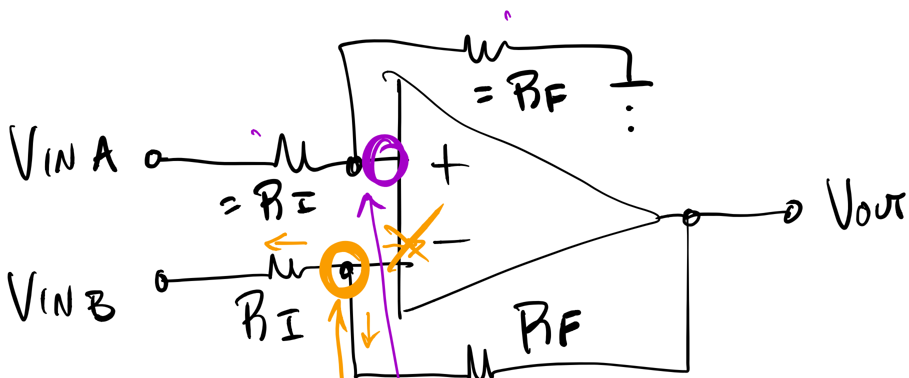
$\therefore$ final waveform will be 250 mV p-p sine wave, inverted, <u>shifted upward</u> 3.02 V



Balanced Differential Amplifier

- crucial concept in electronic measurement!
- amplifies difference between two voltages, not referenced to ground

(instrumentation)



- note equality of resistor values in balanced differential amplifier case!

- let's look at V_{in}^+
- ideal op-amp has zero input current (rule # 2)

$$\therefore V_{in}^+ = V_{IN\,A}\left(\frac{R_F}{R_F + R_I}\right)$$

$$\therefore V_{in}^- = V_{INA}\left(\frac{R_F}{R_F+R_I}\right)$$ (rule # 1)

$V_{in}^+ = V_{in}^-$

KCL @ V_{in}^- :

$$\frac{V_{in}^- - V_{INB}}{R_I} + \frac{V_{in}^- - V_{OUT}}{R_F} = 0$$

$$\frac{V_{in}^-}{R_I} - \frac{V_{INB}}{R_I} + \frac{V_{in}^-}{R_F} = \frac{V_{OUT}}{R_F}$$

$$V_{OUT} = V_{in}^-\left(\frac{R_F}{R_I}\right) - V_{INB}\left(\frac{R_F}{R_I}\right) + V_{in}^-$$

$$V_{OUT} = V_{in}^-\left(\frac{R_F+R_I}{R_I}\right) - V_{INB}\left(\frac{R_F}{R_I}\right)$$

$$V_{OUT} = V_{INA}\left(\frac{R_F}{\cancel{R_F+R_I}}\right)\left(\frac{\cancel{R_F+R_I}}{R_I}\right) - V_{INB}\left(\frac{R_F}{R_I}\right)$$

$$V_{OUT} = \underbrace{\left(V_{INA} - V_{INB}\right)}_{\text{difference !!!}}\left(\frac{R_F}{R_I}\right)$$

Gain-Bandwidth Product

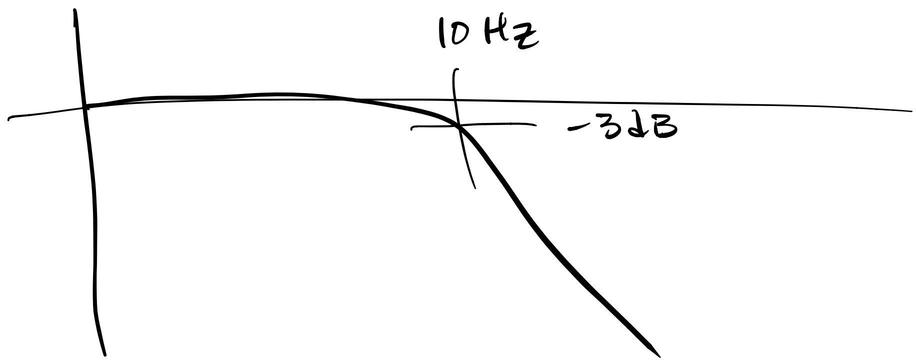
- ideal op-amps: perfect frequency response, no high- or low-pass filtering
- real op-amps: low-pass
- $\mu A741$, for example:

$$A_{v(o.l.)} = 100{,}000$$

$$20 \log_{10}(100{,}000) = 100 \text{ dB}$$

very high!

- built-in low-pass filter w/ cutoff frequency of $f_c = 10$ Hz (what?)



.. negative feedback proportionally raises the bandwidth!

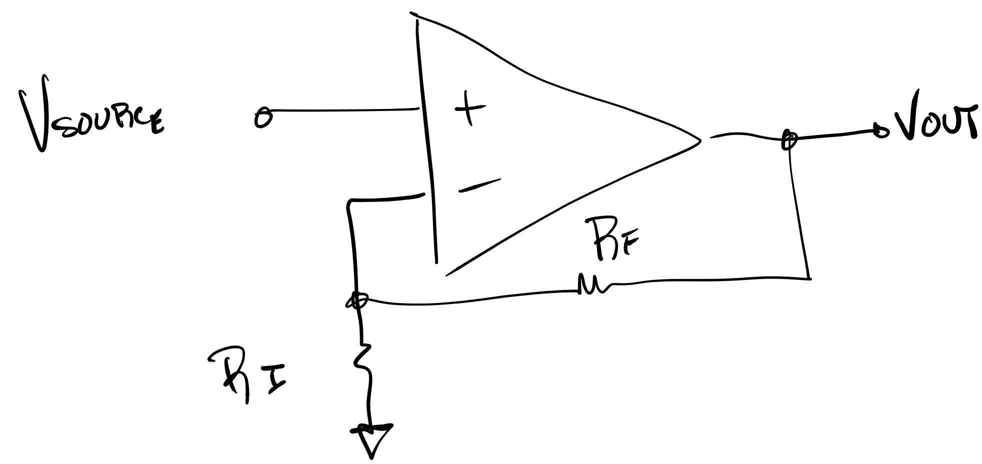
.. negative feedback also lowers gain.

.. product of gain and bandwidth is a constant, called the gain-bandwidth product

.. μA741 has GBP of 1 MHz

.. how do you use this concept?

example: non-inverting amplifier w/ gain of 36



$$GBP = A_v \cdot BW$$

↑ gain (under A_v)

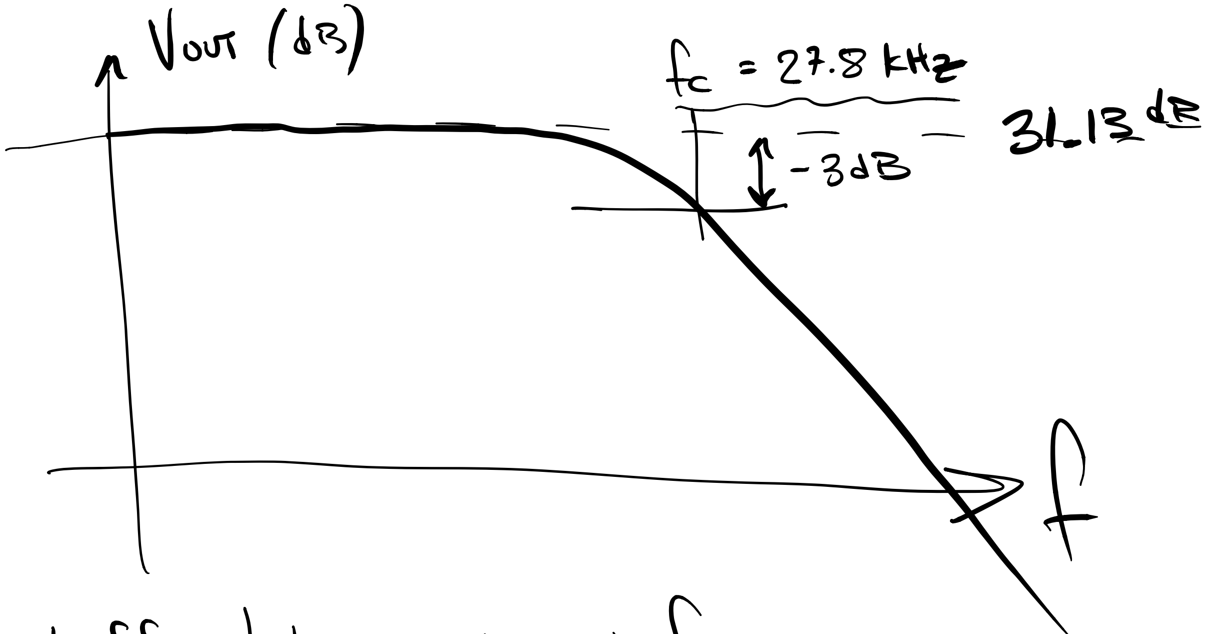
↑ bandwidth (under BW)

then $BW = \dfrac{GBP}{A_v} = \dfrac{1\,MHz}{36}$

$= 27777.8$

or 27.8 kHz

side note: gain of 36 is $20 \log_{10} 36 = 31.13\,dB$



∴ tradeoff between gain and frequency response!

∴ higher gain → lower bandwidth

∴ if you need wider bandwidth at higher gain, select op-amp w/ higher GBP.