2.5 Effect of finite open-loop gain and bandwidth on circuit performance

Reading **Assignment**: 89-93

Bad News! → Real Op-Amps are **not** ideal!

In the "real world", op-amp have a slew (pun intended) of **problems** that limit their performance and application.

It is vital that we electrical engineers **understand** these limitations.

HO: THE GAIN OF REAL OP AMPS

An approximation of can simplify the transfer function.

HO: A USEFUL APPROXIMATION OF THE OP-AMP TRANSFER FUNCTION

We find the gain-bandwidth product to be a very useful value!

EXAMPLE: THE GAIN-BANDWIDTH PRODUCT

An amplifier built with an op-amp must have a gain (i.e., the closed-loop gain) **less** than that of the op amp. We find that the resulting amplifier **bandwidth** is easily determined!

HO: The Closed-Loop Bandwidth

Example: Amplifier Bandwidth

National Semiconductor

August 2000

LM741
Operational Amplifier

General Description

The LM741 series are general purpose operational amplifiers which feature improved performance over industry standards like the LM709. They are direct, plug-in replacements for the 709C, LM201, MC1439 and 748 in most applications.

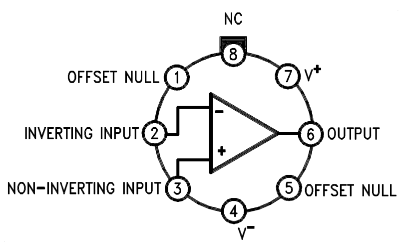
The amplifiers offer many features which make their application nearly foolproof: overload protection on the input and output, no latch-up when the common mode range is exceeded, as well as freedom from oscillations.

The LM741C is identical to the LM741/LM741A except that the LM741C has their performance guaranteed over a 0˚C to +70˚C temperature range, instead of −55˚C to +125˚C.

Features

Connection Diagrams

Metal Can Package



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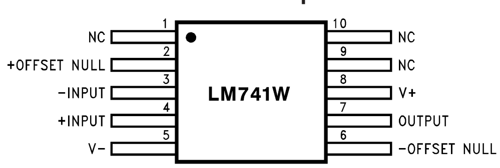
Note 1: LM741H is available per JM38510/10101

Order Number LM741H, LM741H/883 (Note 1), **LM741AH/883 or LM741CH**
See NS Package Number H08C

Ceramic Flatpak



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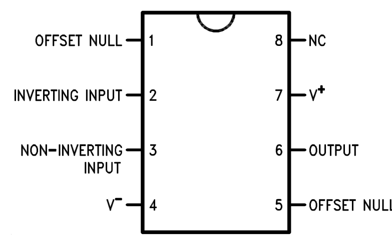
Order Number LM741W/883
See NS Package Number W10A

Dual-In-Line or S.O. Package



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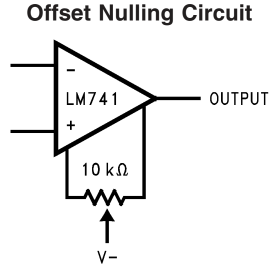
Order Number LM741J, LM741J/883, LM741CN
See NS Package Number J08A, M08A or N08E

Typical Application

Offset Nulling Circuit



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Absolute Maximum Ratings (Note 2)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/ Distributors for availability and specifications.

(Note 7)

	LM741A	LM741	LM741C
Supply Voltage	±22V	±22V	±18V
Power Dissipation (Note 3)	500 mW	500 mW	500 mW
Differential Input Voltage	±30V	±30V	±30V
Input Voltage (Note 4)	±15V	±15V	±15V
Output Short Circuit Duration	Continuous	Continuous	Continuous
Operating Temperature Range	−55˚C to +125˚C	−55˚C to +125˚C	0˚C to +70˚C
Storage Temperature Range	−65˚C to +150˚C	−65˚C to +150˚C	−65˚C to +150˚C
Junction Temperature	150˚C	150˚C	100˚C
Soldering Information			
N-Package (10 seconds)	260˚C	260˚C	260˚C
J- or H-Package (10 seconds)	300˚C	300˚C	300˚C
M-Package			
Vapor Phase (60 seconds)	215˚C	215˚C	215˚C
Infrared (15 seconds)	215˚C	215˚C	215˚C

See AN-450 "Surface Mounting Methods and Their Effect on Product Reliability" for other methods of soldering

surface mount devices.

ESD Tolerance (Note 8)	400V	400V	400V

Electrical Characteristics (Note 5)

Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage	T_A = 25˚C										
	$R_S \leq$ 10 kΩ					1.0	5.0		2.0	6.0	mV
	$R_S \leq$ 50Ω		0.8	3.0							mV
	$T_{AMIN} \leq T_A \leq T_{AMAX}$										
	$R_S \leq$ 50Ω			4.0							mV
	$R_S \leq$ 10 kΩ						6.0			7.5	mV
Average Input Offset Voltage Drift				15							μV/˚C
Input Offset Voltage Adjustment Range	T_A = 25˚C, V_S = ±20V	±10				±15			±15		mV
Input Offset Current	T_A = 25˚C		3.0	30		20	200		20	200	nA
	$T_{AMIN} \leq T_A \leq T_{AMAX}$			70		85	500			300	nA
Average Input Offset Current Drift				0.5							nA/˚C
Input Bias Current	T_A = 25˚C		30	80		80	500		80	500	nA
	$T_{AMIN} \leq T_A \leq T_{AMAX}$			0.210			1.5			0.8	μA
Input Resistance	T_A = 25˚C, V_S = ±20V	1.0	6.0		0.3	2.0		0.3	2.0		MΩ
	$T_{AMIN} \leq T_A \leq T_{AMAX}$, V_S = ±20V	0.5									MΩ
Input Voltage Range	T_A = 25˚C							±12	±13		V
	$T_{AMIN} \leq T_A \leq T_{AMAX}$				±12	±13					V

Electrical Characteristics (Note 5) (Continued)

Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Large Signal Voltage Gain	T_A = 25˚C, $R_L \geq 2$ kΩ										
	V_S = ±20V, V_O = ±15V	50									V/mV
	V_S = ±15V, V_O = ±10V				50	200		20	200		V/mV
	$T_{AMIN} \leq T_A \leq T_{AMAX}$,										
	$R_L \geq 2$ kΩ,										
	V_S = ±20V, V_O = ±15V	32									V/mV
	V_S = ±15V, V_O = ±10V				25			15			V/mV
	V_S = ±5V, V_O = ±2V	10									V/mV
Output Voltage Swing	V_S = ±20V										
	$R_L \geq 10$ kΩ	±16									V
	$R_L \geq 2$ kΩ	±15									V
	V_S = ±15V										
	$R_L \geq 10$ kΩ				±12	±14		±12	±14		V
	$R_L \geq 2$ kΩ				±10	±13		±10	±13		V
Output Short Circuit Current	T_A = 25˚C	10	25	35		25			25		mA
	$T_{AMIN} \leq T_A \leq T_{AMAX}$	10		40							mA
Common-Mode Rejection Ratio	$T_{AMIN} \leq T_A \leq T_{AMAX}$										
	$R_S \leq 10$ kΩ, V_{CM} = ±12V				70	90		70	90		dB
	$R_S \leq 50Ω$, V_{CM} = ±12V	80	95								dB
Supply Voltage Rejection Ratio	$T_{AMIN} \leq T_A \leq T_{AMAX}$,										
	V_S = ±20V to V_S = ±5V										
	$R_S \leq 50Ω$	86	96								dB
	$R_S \leq 10$ kΩ				77	96		77	96		dB
Transient Response	T_A = 25˚C, Unity Gain										
Rise Time			0.25	0.8		0.3			0.3		µs
Overshoot			6.0	20		5			5		%
Bandwidth (Note 6)	T_A = 25˚C	0.437	1.5								MHz
Slew Rate	T_A = 25˚C, Unity Gain	0.3	0.7			0.5			0.5		V/µs
Supply Current	T_A = 25˚C					1.7	2.8		1.7	2.8	mA
Power Consumption	T_A = 25˚C										
	V_S = ±20V		80	150							mW
	V_S = ±15V					50	85		50	85	mW
LM741A	V_S = ±20V										
	$T_A = T_{AMIN}$			165							mW
	$T_A = T_{AMAX}$			135							mW
LM741	V_S = ±15V										
	$T_A = T_{AMIN}$					60	100				mW
	$T_A = T_{AMAX}$					45	75				mW

Note 2: "Absolute Maximum Ratings" indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is functional, but do not guarantee specific performance limits.

Electrical Characteristics (Note 5) (Continued)

Note 3: For operation at elevated temperatures, these devices must be derated based on thermal resistance, and T_j max. (listed under "Absolute Maximum Ratings"). $T_j = T_A + (\theta_{jA} P_D)$.

Thermal Resistance	Cerdip (J)	DIP (N)	HO8 (H)	SO-8 (M)
θ_{jA} (Junction to Ambient)	100˚C/W	100˚C/W	170˚C/W	195˚C/W
θ_{jC} (Junction to Case)	N/A	N/A	25˚C/W	N/A

Note 4: For supply voltages less than ±15V, the absolute maximum input voltage is equal to the supply voltage.

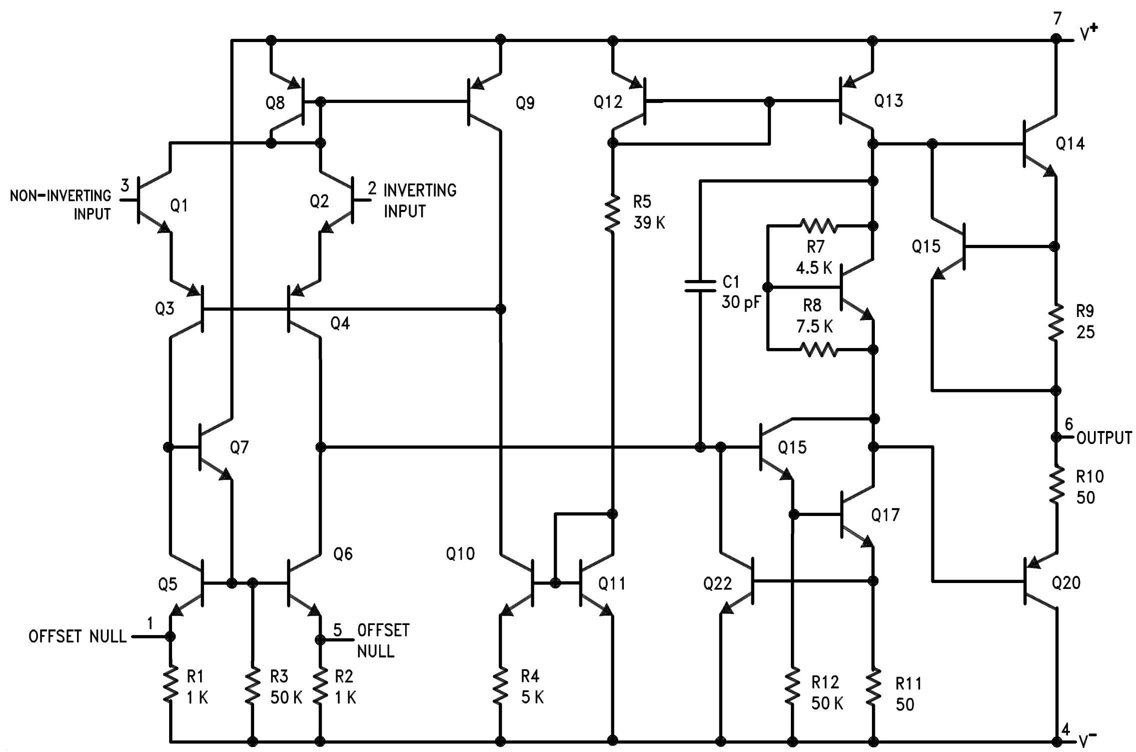
Note 5: Unless otherwise specified, these specifications apply for V_S = ±15V, −55˚C ≤ T_A ≤ +125˚C (LM741/LM741A). For the LM741C/LM741E, these specifications are limited to 0˚C ≤ T_A ≤ +70˚C.

Note 6: Calculated value from: BW (MHz) = 0.35/Rise Time(µs).

Note 7: For military specifications see RETS741X for LM741 and RETS741AX for LM741A.

Note 8: Human body model, 1.5 kΩ in series with 100 pF.

Schematic Diagram



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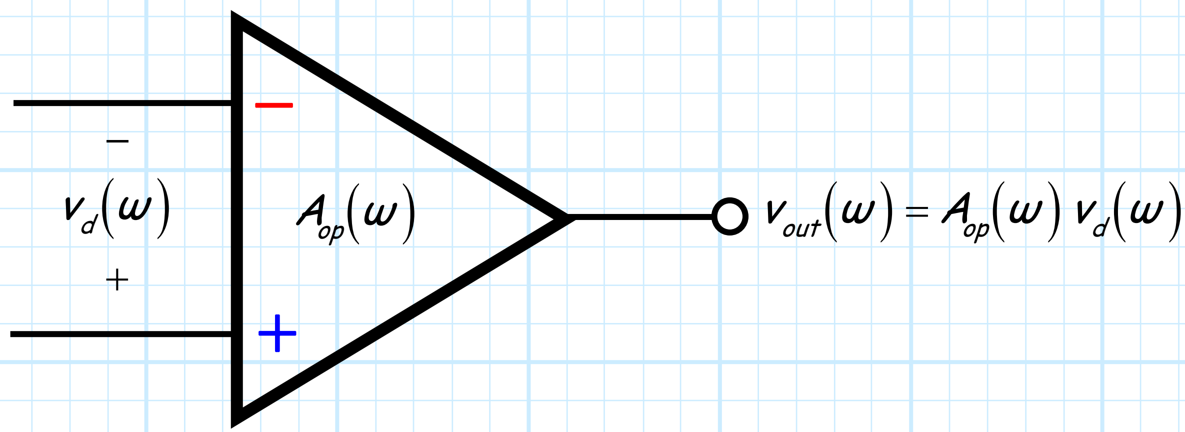
The Gain of Real Op-Amps

The **open-circuit** voltage gain A_{op} (a **differential** gain!) of a **real (i.e., non-ideal)** operational amplifier is **very** large at D.C. (i.e., $\omega = 0$), but gets **smaller** as the signal frequency ω **increases**!

In other words, the **differential** gain of an op-amp (i.e., the **open-loop** gain of a feedback amplifier) is a function of frequency ω.

We will thus express this gain as a **complex** function in the **frequency domain** (i.e., $A_{op}(\omega)$).



Gain is a complex function frequency

Typically, this op-amp behavior can be described mathematically with the **complex** function:

$$A_{op}(\omega) = \frac{A_0}{1 + j\left(\omega/\omega_b\right)}$$

or, using the frequency definition $\omega = 2\pi f$, we can write:

$$A_{op}(f) = \frac{A_0}{1 + j\left(f/f_b\right)}$$

where ω is frequency expressed in units of **radians/sec**, and f is signal frequency expressed in units of **cycles/sec**.

DC is when the signal frequency is zero

Note the squared **magnitude** of the op-amp gain is therefore the **real** function:

$$\begin{aligned} |A_{op}(\omega)|^2 &= \frac{A_0}{1+j\left(\omega/\omega_b\right)} \frac{A_0}{1-j\left(\omega/\omega_b\right)} \\ &= \frac{A_0^2}{1+\left(\omega/\omega_b\right)^2} \end{aligned}$$

Therefore at **D.C.** ($\omega = 0$) the op-amp gain is:

$$A_{op}(\omega=0) = \frac{A_0}{1+j\left(0/\omega_b\right)} = A_0$$

and thus:

$$|A_{op}(\omega=0)|^2 = A_0^2$$

Where:

A_0 = op-amp D.C. gain

The break frequency

Again, note that the D.C. gain A_0 is:

1) an **open-circuit** voltage gain
2) a **differential** gain
3) also referred to as the **open-loop** D.C. gain

The open-loop gain of real op-amps is **very large,** but fathomable —typically between **10^5 and 10^8**.

Q: *So just what **does** the value ω_b indicate ?*

A: The value ω_b is the op-amp's **break frequency**.

Typically, this value is very **small** (e.g. $f_b = 10Hz$).

The 3dB bandwidth

To see **why** this value is **important**, consider the op-amp gain at $\omega = \omega_b$:

$$A_{op}\left(\omega = \omega_b\right) = \frac{A_0}{1 + j\left(\omega/\omega_b\right)} = \frac{A_0}{1+j} = \frac{A_0}{2} - j\,\frac{A_0}{2} = \frac{\left|A_0\right|}{\sqrt{2}}\, e^{-j\pi/4}$$

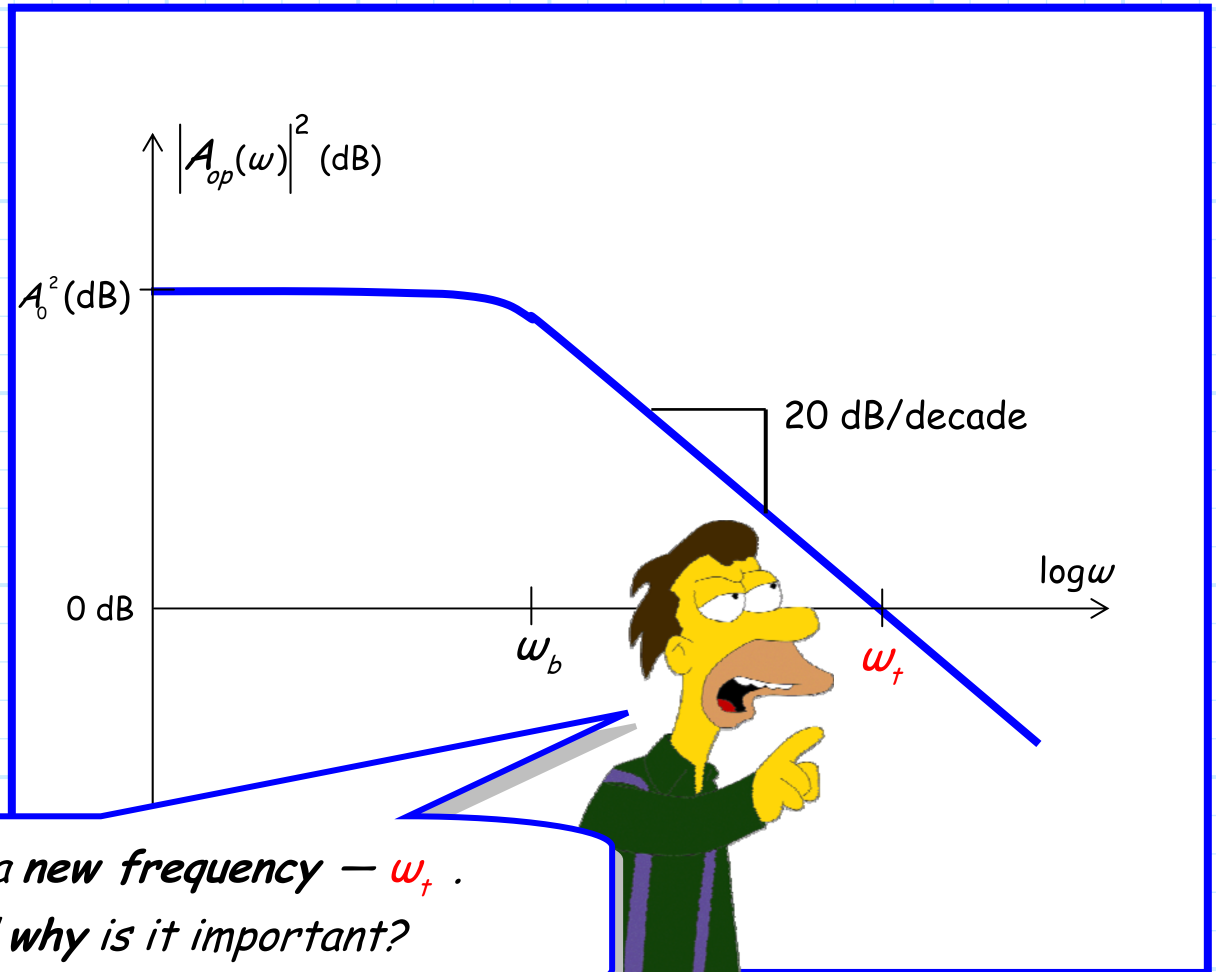
The **squared magnitude** of this gain is therefore:

$$\left|A_{op}(\omega = \omega_b)\right|^2 = \frac{A_0}{1+j}\,\frac{A_0}{1-j} = \frac{A_0^2}{1-j^2} = \frac{A_0^2}{2}$$

As a result, the **break** frequency ω_b is also referred to as the "**half-power**" frequency, or the "**3 dB**" frequency.

This value is very important!

If we **plot** $\left|A_{op}(\omega)\right|^2$ on a "**log-log**" scale, we get something like this:



Q: *Hey! You have defined a* ***new frequency*** *—* ω_t *.*
What *is this frequency and* ***why*** *is it important?*

The unity gain frequency

A: Note that ω_t is the frequency where the magnitude of the gain is "**unity**" (i.e., where the gain is **1**). I.E.,

$$\left|A_{op}(\omega=\omega_t)\right|^2=1$$

Note that when expressed in dB, **unity** gain is:

$$10\ \log_{10}\left|A_{op}(\omega=\omega_t)\right|^2=10\ \log_{10}\left(1\right)=0\text{ dB}$$

Therefore, on a "log-log" plot, the gain curve crosses the **horizontal axis** at frequency ω_t.

We thus refer to the frequency ω_t as the "**unity-gain frequency**" of the operational amplifier.

It's the product of the gain and the bandwidth!

Note that we can **solve** for this frequency in terms of **break frequency** ω_b and **D.C. gain** A_o:

$$1 = \left|A_{op}(\omega = \omega_t)\right|^2 = \frac{A_0^2}{1 + \left(\omega_t / \omega_b\right)^2}$$

meaning that:

$$\omega_t^2 = \omega_b^2 \left(A_0^2 - 1\right)$$

But recall that $A_0 \gg 1$, therefore $A_0^2 - 1 \approx A_0^2$ and:

$$\boxed{\omega_t = \omega_b \left|A_0\right|}$$

Note since the frequency ω_b defines the 3 dB **bandwidth** of the op-amp, the unity gain frequency ω_t is simply the **product** of the op-amp's D.C. **gain** $\left|A_0\right|$ and its **bandwidth** ω_b.

It's not rocket science!

As a result, ω_t is **alternatively** referred to as the **gain-bandwidth product**!

$$\omega_t \doteq \textbf{Unity Gain Frequency}$$

and

$$\omega_t \doteq \textbf{Gain - Bandwidth Product}$$

*This is so **simple** perhaps even I can remember it:*

*The **gain-bandwidth-product** is the **product** of the **gain** and the **bandwidth**!*

An Approximation of the Op-Amp Transfer Function

Recall the complex transfer function describing the **differential** gain of an op-amp is:

$$A_{op}(\omega) = \frac{v_{out}(\omega)}{v_d(\omega)} = \frac{A_0}{1 + j\left(\omega/\omega_b\right)}$$

For frequencies **much less** than the break frequency, we find that $\omega/\omega_b \ll 1$ and thus this gain is approximately equal to A_0:

$$A_{op}(\omega \ll \omega_b) \approx A_0$$

For "large" frequencies, the math gets simple

Likewise, for frequencies **much greater** than the break frequency, we find that $\omega/\omega_b \gg 1$ and thus this gain is approximately equal to:

$$A_{op}(\omega \gg \omega_b) = \frac{A_0}{1 + j\left(\omega/\omega_b\right)} \approx \frac{A_0}{j\left(\omega/\omega_b\right)} = -j\,\frac{A_0 \omega_b}{\omega}$$

But, we recall that the **product** of the op-amp D.C. **gain** A_0 and the op-amp **bandwidth** ω_b is the **gain-bandwidth product** ω_t (aka the unity gain frequency).

Thus, we can likewise write the previous approximation as:

$$A_{op}(\omega \gg \omega_b) \approx -j\,\frac{A_0 \omega_b}{\omega} = -j\,\frac{\omega_t}{\omega}$$

A useful approx. of the transfer function

Recall also that when the signal frequency is **equal** to the op-amp break frequency (i.e., $\omega = \omega_b$), the transfer function is:

$$A_{op}(\omega = \omega_b) = \frac{A_0}{1 + j\left(\omega/\omega_b\right)} = \frac{A_0}{1 + j}$$

such that $\left|A_{op}(\omega = \omega_b)\right| = A_0/\sqrt{2}$.

Expressed in terms of the **magnitude** of this complex transfer function, we can express these **approximations** as:

$$\left|A_{op}(f)\right| \approx \begin{cases} A_0 & \text{if } f \ll f_b \\ A_0/\sqrt{2} & \text{if } f \approx f_b \\ \dfrac{f_t}{f} & \text{if } f \gg f_b \end{cases}$$

Example: The Gain -Bandwidth Product

An op-amp has a **D.C.** differential gain of $A_0 = 10^5$.

At a frequency of **1MHz** (f=10^6), the differential op-amp gain **drops to 10** (i.e., $\left|A_{op}(f=10^6)\right| = 10$).

Q: *What is the **break** frequency and **unity-gain** frequency of this op-amp?*

A: We know that if $f > f_b$:

$$\left|A_{op}(f)\right| = \frac{A_0 f_b}{f}$$

and thus at a frequency of **1MHz**, we find for the parameters of this problem:

$$\left|A_{op}(f = 10^6)\right| = 10 = \frac{10^5 f_b}{10^6}$$

It's 10 MHz

It is apparent then that the **break frequency** of this op-amp must be:

$$f_b = \frac{(10)(10^6)}{10^5} = 100 \text{ Hz}$$

and since the **unity-gain bandwidth** f_t is related to the break frequency and D.C. gain as:

$$f_t = A_0 \, f_b$$

we find that:

$$\begin{aligned} f_t &= A_0 \, f_b \\ &= 10^5 (100) \\ &= 10^7 \end{aligned}$$

Thus, the **unity-gain frequency** (i.e., the **gain-bandwidth product**) for this problem is **10 MHz.**

The gain depends on frequency

Q: *What is the differential gain of this op-amp at a frequency of 10 kHz (i.e., $\left|A_{op}(f=10^4)\right|$)?*

A: We know that:

$$\left|A_{op}(f)\right| = \frac{A_0 f_b}{f} = \frac{f_t}{f}$$

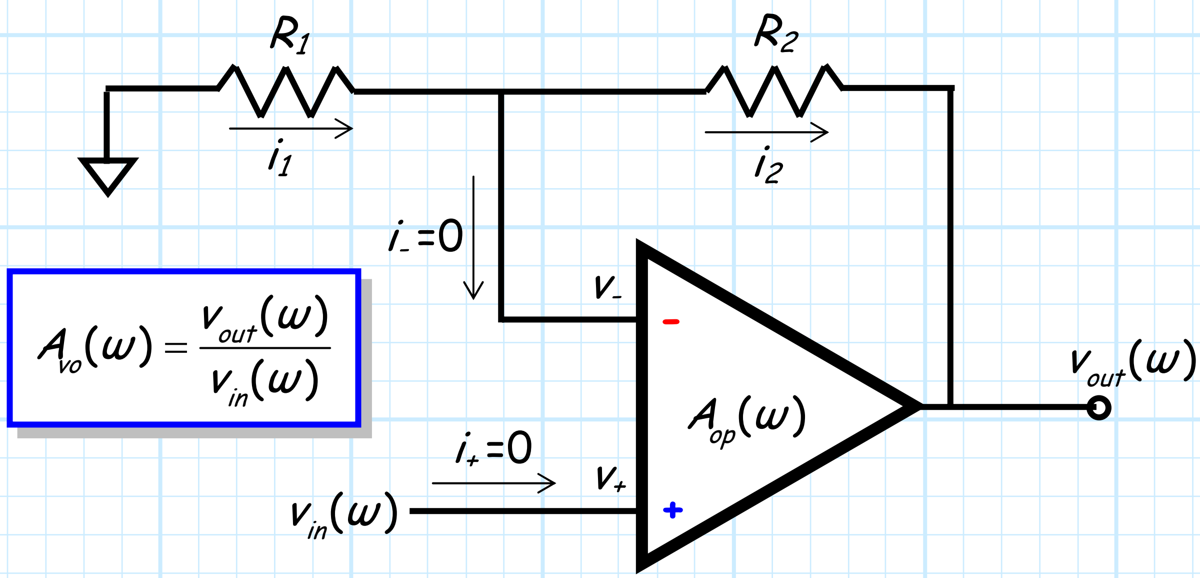
therefore, using the values of this example:

$$\begin{aligned}\left|A_{op}(f=10^4)\right| &= \frac{f_t}{f} \\ &= \frac{10^7}{10^4} \\ &= 10^3\end{aligned}$$

Hence, the differential **op-amp gain at 10 kHz** is **1000**.

Closed-Loop Bandwidth

Say we build in the **lab** (i.e., the op-amp is not ideal) **this** amplifier:



We know that the open-circuit voltage gain (i.e., the closed-loop gain) of this amplifier **should** be:

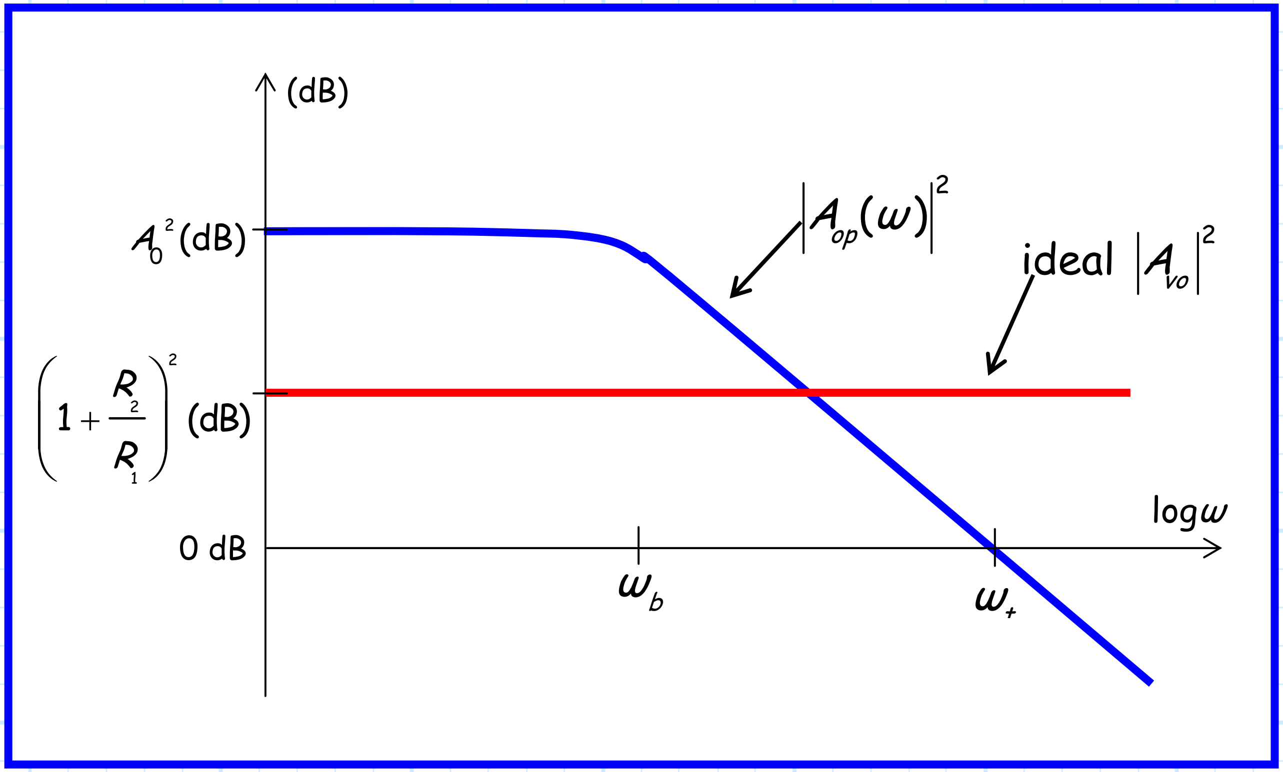
$$A_{vo}(\omega) = \frac{v_{out}(\omega)}{v_{in}(\omega)} = 1 + \frac{R_2}{R_1} \quad ???$$

This gain **will** certainly be accurate for input signals $v_{in}(\omega)$ **at low frequencies** ω.

As the signal frequency increases

But remember, the Op-amp (i.e., open-loop gain) gain $A_{op}(\omega)$ **decreases with frequency**.

If the signal frequency ω becomes **too large**, the **open-loop** gain $A_{op}(\omega)$ will become **less** than the **ideal closed-loop gain**!



The amp gain cannot exceed the op-amp gain

Note as some sufficiently high frequency (ω' say), the open-loop (op-amp) gain will become **equal** to the ideal closed-loop (non-inverting amplifier) gain:

$$\left|A_{op}(\omega = \omega')\right| = 1 + \frac{R_2}{R_1}$$

Moreover, if the input signal frequency is greater than frequency ω', the op-amp (**open-loop**) gain will in fact be smaller that the **ideal** non-inverting (**closed-loop**) amplifier gain:

$$\left|A_{op}(\omega > \omega')\right| \quad < \quad 1 + \frac{R_2}{R_1}$$

Q: *If the signal frequency is greater than ω', will the non-inverting amplifier still exhibit an open-circuit voltage (closed-loop) gain of $A_{vo}(\omega) = 1 + R_2/R_1$?*

A: Allow my response to be both direct and succinct—**NEVER!**

Closed-loop gain < or = open-loop gain

The gain $A_{vo}(\omega)$ of **any** amplifier constructed with an op-amp can **never** exceed the gain $A_{op}(\omega)$ of the op-amp itself.

In other words, the closed-loop gain of any amplifier can **never** exceed its open-loop gain.

* We find that if the input signal frequency **exceeds** ω', then the amplifier (closed-loop) gain $A_{vo}(\omega)$ will **equal** the **op-amp** (open-loop) gain $A_{op}(\omega)$.

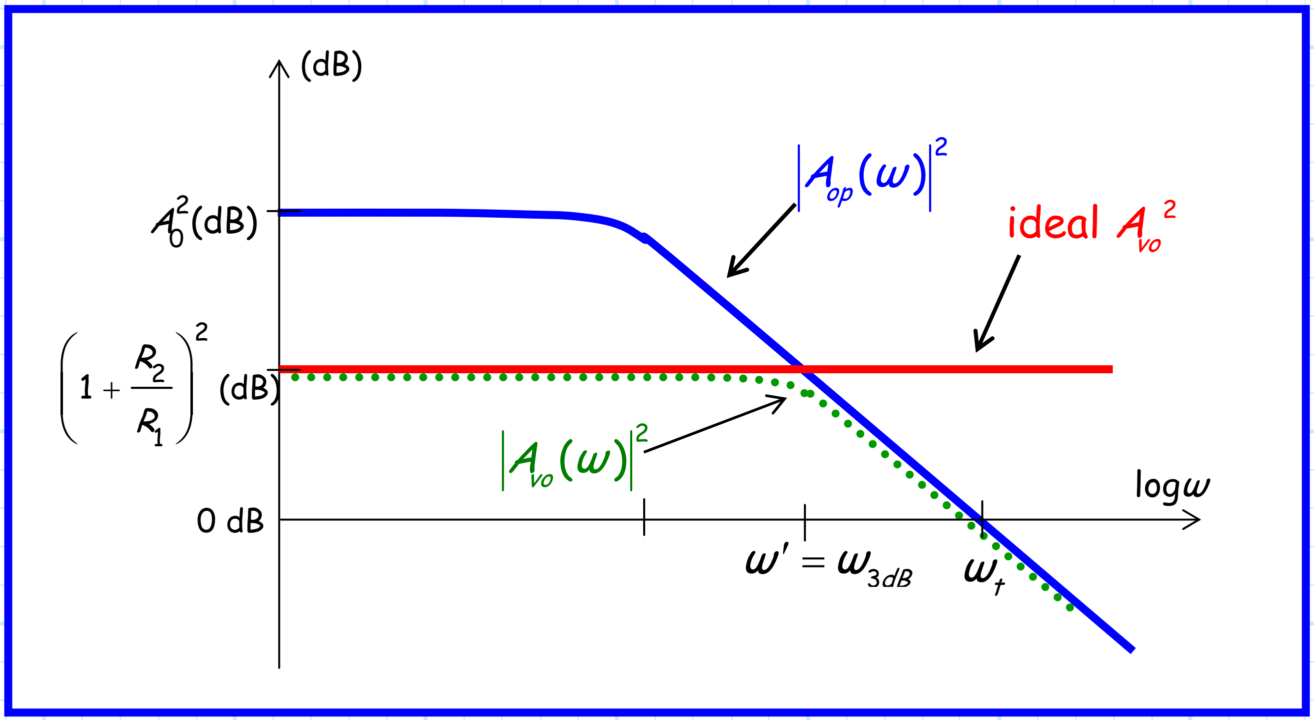
* Of course, if the signal frequency is **less** than ω', the closed-loop gain will be **equal** to its **ideal** value $A_{vo}(\omega) = 1 + R_2/R_1$, since the op-amp (open-loop) gain is much **larger** than this **ideal** value ($|A_{op}(\omega < \omega')| \gg 1 + R_2/R_1$).

* We now refer to the value $1 + R_2/R_1$ as the **mid-band gain** of the amplifier.

1+R2/R1 is the midband gain

Therefore, we find for **this** non-inverting amplifier that:

$$|A_{vo}(\omega)| \approx \begin{cases} 1+\dfrac{R_2}{R_1} & \omega < \omega' \\ |A_{op}(\omega)| & \omega > \omega' \end{cases}$$



Can we determine this bandwidth?

Now for **one** very **important** fact: the transition frequency ω' is the **break** frequency of the amplifier **closed-loop** gain $|A_{vo}(\omega)|$.

Thus, we come to conclusion that ω' is the **3dB bandwidth** of this non-inverting amplifier (i.e., $\omega' = \omega_{3dB}$)!

Q: *Is there some way to numerically determine this value ?*

A: Of course!

Recall we defined frequency ω' as the value where the open-loop (op-amp) gain and the **ideal** closed-loop (non-inverting amplifier) gains were equal:

$$|A_{op}(\omega = \omega')| = 1 + \frac{R_2}{R_1}$$

Recall also that for $\omega > \omega_b$, we can approximate the op-amp (open-loop) gain as:

$$|A_{op}(\omega)| \approx \frac{A_0 \omega_b}{\omega}$$

Divide the gain-bandwidth product by gain, and you have determined the bandwidth!

Combining these results, we find:

$$\left|A_{op}(\omega = \omega')\right| = 1 + \frac{R_2}{R_1} \simeq \frac{A_0 \omega_b}{\omega'}$$

and thus:

$$\omega' = \left(1 + \frac{R_2}{R_1}\right)^{-1} \left(A_0 \omega_b\right)$$

But remember, we found that this frequency is equal to the **breakpoint** of the non-inverting amplifier (closed-loop) gain $A_{vo}(\omega)$.

Therefore, the 3dB, closed-loop **bandwidth** of this amplifier is:

$$\omega_{3dB} \simeq \left(1 + \frac{R_2}{R_1}\right)^{-1} \left(A_0 \omega_b\right)$$

This is not rocket science

Recall also that $A_0 \omega_b = \omega_t$, so that:

$$\omega_{3dB} \simeq \left(1+\frac{R_2}{R_1}\right)^{-1} \omega_t$$

If we rewrite this equation, we find something interesting:

$$\omega_{3dB}\left(1+\frac{R_2}{R_1}\right) \simeq \omega_t$$

Look what this says: the **PRODUCT** of the amplifier (mid-band) ***GAIN*** and the amplifier **BANDWIDTH** is equal to the **GAIN-BANDWIDTH PRODUCT**.

→ This result should **not** be difficult to remember !

The gain-bandwidth product is an op-amp parameter

The above approximation is valid for virtually **all** amplifiers built using operational amplifiers, i.e.:

$$\left|A_{vo}(\omega_m)\right| \omega_{3dB} = \omega_t$$

where:

$$\left|A_{vo}(\omega_m)\right| \doteq \text{mid-band gain}$$

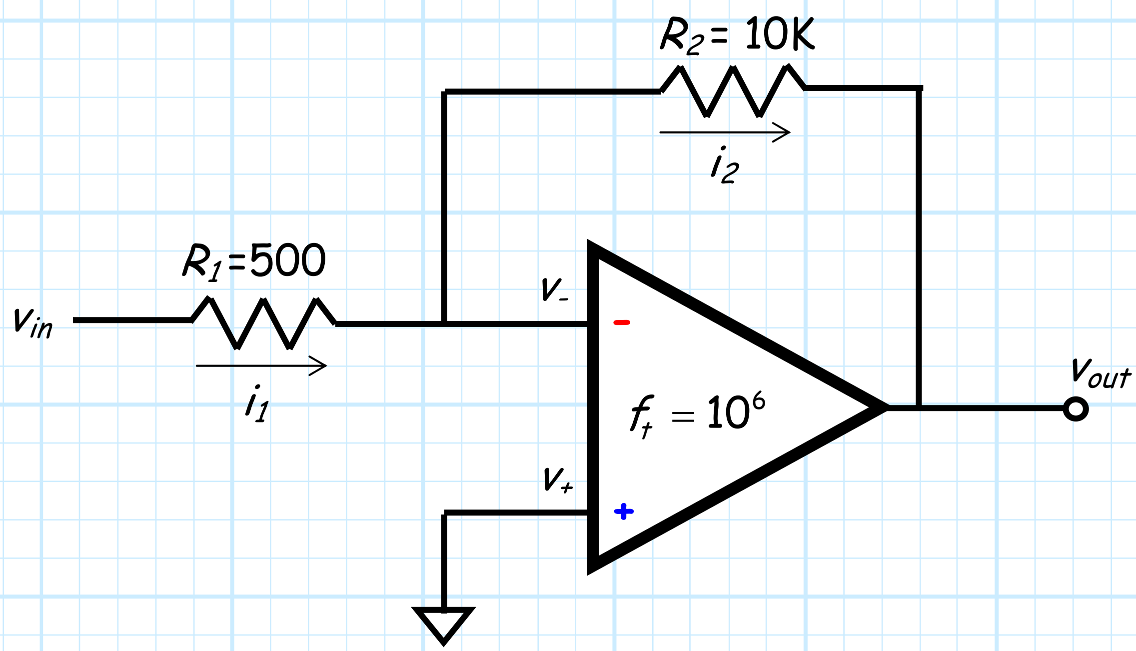
In other words, ω_m is some frequency **within the bandwidth** of the amplifier (e.g., $0 < \omega_m < \omega_{3dB}$). We of course can equivalently say:

$$\left|A_{vo}(f_m)\right| f_{3dB} = f_t$$

The product of the **amplifier** gain and the amplifier **bandwidth** is equal to the **op-amp** gain-bandwidth product!

Example: Amplifier Bandwidth

Say we build the following amplifier in the **lab**:



The **op-amp** in this circuit happens to have a unity-gain bandwidth of **1MHz**.

Q: *What is the **3 dB bandwidth** of this amplifier?*

xy=10^6 and x=20; you figure it out

A: We know that the mid-band **gain** of this amplifier is:

$$\left|A_{vo}(\omega_m)\right| = \left|\frac{-R_2}{R_1}\right| = \frac{R_2}{R_1} = \frac{10}{0.5} = \mathbf{20} \qquad (26\text{dB})$$

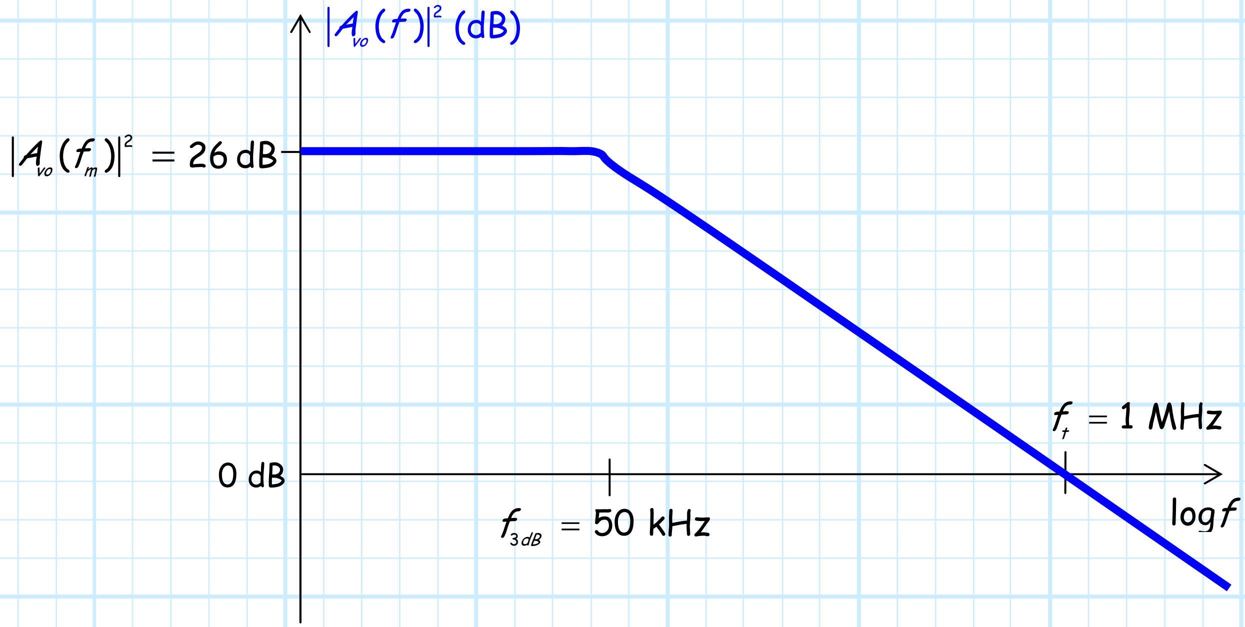
Since we know that $f_t = 10^6$, we can directly determine the amplifier **bandwidth**:

$$f_{3dB} = \frac{f_t}{\left|A_{vo}(f_m)\right|} = \frac{10^6}{20} = 5\text{x}10^4$$

Since the **product** of the amplifier **gain** and **bandwidth** is equal to the **gain-bandwidth product**, we find that the gain-bandwidth product f_t **divided** by the mid-band **gain** equals the amplifier **bandwidth** f_{3dB}!

If I want more bandwidth…

In this case, the amplifier **bandwidth** is $f_{3dB} = 50\,\text{kHz}$.



Q: *Is there any way to* ***increase*** *the bandwidth of this amplifier to 500 kHz?*

A: Sure! But we must **decrease** its mid-band gain.

...I must accept less gain

The gain-bandwidth product $f_t = 10^6$ is a constant—if we **increase** the bandwidth, we must **decrease** the gain.

Therefore, if we want the amplifier bandwidth to equal 500 kHz, we must **decrease** the mid-band gain to:

$$\left|A_{vo}(f_m)\right| = \frac{f_t}{f_{3dB}} = \frac{10^6}{5\text{x}10^5} = 2 \quad (6\text{dB})$$

A gain of 2—**quite** a decrease!

But this of course **makes sense**.

To **increase** the bandwidth **10 times**, we must **decrease** the gain by a factor of **10**.

There's no free lunch

Note we **could** accomplish this by simply changing the **feedback resistor** from $R_2 = 10K$ to $R_2 = 1K$.