"Real" Op-Amps:

<table>
<thead>
<tr>
<th></th>
<th>Ideal Op-Amp</th>
<th>'Real' Op-amp</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_{in}$</td>
<td>$\infty \Omega$</td>
<td>$\sim 10^5 \ldots 10^{12} \Omega$</td>
</tr>
<tr>
<td>$Z_{out}$</td>
<td>$0 \Omega$</td>
<td>$0.1 \ldots 100 \Omega$</td>
</tr>
<tr>
<td>$A_{\text{open-loop gain}}$</td>
<td>$\infty$</td>
<td>$\approx 10^5$ ($\approx 100 , \text{dB}$)</td>
</tr>
<tr>
<td>$G_{\text{non-invert}}$ (closed-loop)</td>
<td>$1 + \frac{R_f}{R}$</td>
<td>$\frac{A}{1+AB}$, $B = \frac{R}{R+R_f}$ for $R_f \ll Z_{in}$</td>
</tr>
<tr>
<td>$G_{\text{invert}}$ (closed-loop gain)</td>
<td>$-\frac{R_f}{R}$</td>
<td>$-\frac{A(1-B)}{1+AB}$, with $B = \frac{R}{R+R_f}$, $R_f \ll Z_{in}$</td>
</tr>
<tr>
<td>$f_T$ (Gain-Bandwith Product)</td>
<td>$\infty$ \dfrac{1}{2}</td>
<td>$\approx 1 \ldots 1500 \text{Hz}$</td>
</tr>
</tbody>
</table>

The open-loop gain $A(f)$ looks like an RC-low-pass but with $\approx 10^5$ gain at DC.

Note that $A_0 \cdot f_0 \approx 10 \cdot f_T$ gain-bandwidth product.
Frequency dependence of closed-loop gain $G$

Non-inverting amplifier:

$$G = \frac{A}{1 + AB}, \quad A = \frac{A_0}{1 + i \frac{f}{f_0}}$$

$$B = \frac{R}{R + R_f}$$

$$G = \frac{A_0}{1 + A_0 B} \frac{f}{1 + f_0 B} \frac{f_0}{1 + f_0 B}$$

Closed-loop gain at DC

3dB bandwidth

with:

$$G_0 = \frac{A_0}{1 + A_0 B} \quad f_3dB = \frac{f_0}{A_0 B + 1}$$

Note that $G_0 f_3dB = A_0 f_0 = f_T$, a constant, no matter what $G_0$ you choose.

"Gain-bandwidth product"

Graph:

- $G = A_0$ (open-loop gain)
- Closed-loop gain for $G_0 = 100$
Note: the "3dB-bandwidth" of an amplifier refers to the frequency at which the gain drops 3dB below the initial gain $G_0$ at DC. (i.e. it is not the frequency at which the gain is -3dB!)

Input–output impedance of "real" operational circuits (see lab #4)

Non-inverting amp:
\[ 2\text{in}' = 2\text{in} (1 + AB) \]
\[ 2\text{out}' = \frac{2\text{out}}{1 + AB} \]

Inverting amp:
\[ 2\text{in} = R_f + \frac{R_f}{1 + A} \]
\[ 2\text{out} = \frac{2\text{out}}{1 + AB} \]