The BJT Differential Amplifier

Basic Circuit

Figure 1 shows the circuit diagram of a differential amplifier. The tail supply is modeled as a current source $I_Q$. The object is to solve for the small-signal output voltages and output resistances. It will be assumed that the transistors are identical.

![Circuit diagram of the differential amplifier.](image)

DC Solution

Zero both base inputs. For identical transistors, the current $I_Q$ divides equally between the two emitters.

(a) The dc currents are given by

$$I_{E1} = I_{E2} = \frac{I_Q}{2} \quad I_{C1} = I_{C2} = \frac{\alpha I_Q}{2}$$

(b) Verify that $V_{CB} > 0$ for the active mode.

$$V_{CB} = V_C - V_B = (V^+ - \alpha I_E R_C) - \left( -\frac{I_E}{1+\beta} R_B \right) = V^+ - \alpha I_E R_C + \frac{I_E}{1+\beta} R_B$$

(c) Calculate the collector-emitter voltage.

$$V_{CE} = V_C - V_E = V_C - (V_B - V_{BE}) = V_{CB} + V_{BE}$$
Small-Signal AC Solution using the Emitter Equivalent Circuit

This solution uses the $r_0$ approximations.

(a) Calculate $g_m$, $r_\pi$, $r_e$, and $r'_e$.

\[
g_m = \frac{\alpha I_E}{V_T} \quad r_\pi = \frac{(1 + \beta) V_T}{I_E} \quad r_e = \frac{V_T}{I_E} \quad r'_e = \frac{R_B + (1 + \beta + r_e) r_e}{\alpha I_E}
\]

(b) Redraw the circuit with $V^+ = V^- = 0$. Replace the two BJTs with the emitter equivalent circuit. The emitter part of the circuit obtained is shown in Fig. 2.

![Emitter equivalent circuit using the $r_0$ approximations.](image)

(c) Using Ohm’s Law, solve for $i'_{e1}$ and $i'_{e2}$.

\[
i'_{e1} = \frac{v_{i1} - v_{i2}}{2(r'_e + R_E)} \quad i'_{e2} = -i'_{e1}
\]

(d) The circuit for $v_{o1}$, $v_{o2}$, $r_{out1}$, and $r_{out2}$ is shown in Fig. 3.

![Circuits for calculating $v_{o1}$, $v_{o2}$, $r_{out1}$, and $r_{out2}$.](image)

\[
v_{o1} = -i'_{c1} r_{ic} R_C = -\alpha i'_e r_{ic} R_C = \frac{-\alpha r_{ic} R_C}{2(r'_e + R_E)} (v_{i1} - v_{i2})
\]

\[
v_{o2} = -i'_{c2} r_{ic} R_C = -\alpha i'_e r_{ic} R_C = \frac{-\alpha r_{ic} R_C}{2(r'_e + R_E)} (v_{i2} - v_{i1})
\]

\[
r_{out1} = r_{out2} = r_{ic} R_C
\]

\[
r_{ic} = \frac{r_0 + r'_e R_{te}}{1 - \frac{r'_e}{r'_{e} + R_{te}}} \quad R_{te} = 2R_E + r'_e
\]
(e) The resistance seen looking into the $v_{i1}$ ($v_{i2}$) input with $v_{i2} = 0$ ($v_{i1} = 0$) is

$$r_{in} = R_B + r_x + r_\pi + (1 + \beta) R_{te}$$
$$= R_B + r_x + (1 + \beta) \left(2R_E + \frac{R_B + r_x}{1 + \beta} + r_e\right)$$
$$= 2 \left[R_B + r_x + r_\pi + (1 + \beta) R_E\right]$$
$$= 2 \left(R_B + r'_x\right)$$

where $r_\pi = (1 + \beta) r_e$ has been used and

$$r'_x = r_x + r_\pi + (1 + \beta) R_E$$

The differential input resistance $r_{id}$ is the resistance seen between the two inputs when $v_{i1} = v_{id}/2$ and $v_{i2} = -v_{id}/2$, where $v_{id}$ is the differential input voltage. It can be seen from the figure that it is given by $r_{id} = 2 (R_B + r'_x)$.

**The Diff Amp with an Active Load**

Figure 5 shows a BJT diff amp with an active load formed by a current mirror with base current compensation. The object is to solve for the open-circuit output voltage $v_{oc}$, the short-circuit output current $i_{sc}$, and the output resistance $r_{out}$. By Thévenin’s theorem, these are related by the equation $v_{oc} = i_{sc} r_{out}$. It will be assumed that the current mirror consisting of transistors $Q_3 - Q_5$ is perfect so that its output current is equal to its input current, i.e. $i_{c4} = i_{c1}$. In addition, the $r_0$ approximations will be used in solving for the currents. That is, the Early effect will be neglected except in solving for $r_{out}$. For the bias solution, it will be assumed that the tail current $I_Q$ splits equally between $Q_1$ and $Q_2$ so that $I_{E1} = I_{E2} = I_Q/2$.

Because the tail supply is assumed to be a current source, the common-mode gain of the circuit is zero when the $r_0$ approximations are used. In this case, it can be assumed that the two input signals are pure differential signals that can be written $v_{i1} = v_{id}/2$ and $v_{i2} = -v_{id}/2$. For differential input signals, it follows by symmetry that the signal voltage is zero at the node above the tail current supply $I_Q$. Following the analysis above, the small-signal collector currents in $Q_1$ and $Q_2$ are given by

$$i'_{c1} = \frac{\alpha}{r'_e + R_E} \frac{v_{id}}{2}$$
$$i'_{c2} = -\frac{\alpha}{r'_e + R_E} \frac{v_{id}}{2}$$

where

$$r'_e = \frac{R_B + r_x}{1 + \beta} + r_e$$

The short-circuit output current is given by

$$i_{sc} = i'_{c4} - i'_{c2}$$
With $i_{c4}' = i_{c3}' = i_{c1}'$ and $i_{c2}' = -i_{c1}'$, this becomes

$$i_{sc} = 2i_{c1}' = \frac{\alpha}{r_e' + R_E} v_{id} = \frac{\alpha}{r_e' + R_E} (v_{i1} - v_{i2})$$

The output resistance is given by

$$r_{out} = r_{04}||r_{ic2}$$

where $r_{ic2}$ is given by

$$r_{ic2} = \frac{r_0 + r_e' || R_{te2}}{1 - \frac{\alpha R_{te2}}{r_e' + R_{te2}}} \quad R_{te2} = 2R_E + r_{ie1} = 2R_E + r_e'$$

By Thévenin’s theorem, the small-signal open-circuit output voltage is given by

$$v_{oc} = i_{sc} r_{out} = \frac{\alpha \times r_{04}||r_{ic2}}{r_e' + R_E} (v_{i1} - v_{i2})$$

**Example 1** For $I_Q = 2 \text{ mA}$, $R_B = 100 \Omega$, $R_E = 51 \Omega$, $V^+ = 15 \text{ V}$, $V^- = -15 \text{ V}$, $V_T = 0.025 \text{ V}$, $r_x = 50 \Omega$, $\beta = 99$, $\alpha = 0.99$ $V_{BE1} = V_{BE2} = 0.65 \text{ V}$, $V_{EB3} = V_{EB4} = V_{EB5} = 0.65 \text{ V}$, $V_C2 = V_C4 = 13.7 \text{ V}$, and $V_A = 50 \text{ V}$, calculate $i_{sc}$, $r_{out}$, and $v_{oc}$.

**Solution.**

$$r_{e1} = r_{e2} = \frac{2V_T}{I_Q} = 25 \Omega \quad r_{e1}' = r_{e2}' = \frac{R_B + r_x}{1 + \beta} + r_e = 26.5 \Omega$$

$$R_{te2} = 2R_E + r_{ie1} = 2R_E + r_e' = 128.5 \Omega \quad i_{sc} = \frac{\alpha}{r_e' + R_E} (v_{i1} - v_{i2}) = 0.0128 (v_{i1} - v_{i2})$$

Figure 5: Diff amp with active current-mirror load.
\[ r_{02} = \frac{V_A + (V_C + V_{BE})}{\alpha I_Q/2} = 65 \Omega \quad r_{ic2} = \frac{r_{02} + r_{ic}' || R_{te2}}{1 - \alpha R_{te2}} = 362.7 \Omega \]

\[ r_{04} = \frac{V_A + (V^+ - V_{C4})}{I_Q} = 51.82 \Omega \quad r_{out} = r_{04} || r_{ic2} = 45.34 \Omega \]

\[ v_{oc} = i_{sc} r_{out} = 579.2 (v_{i1} - v_{i2}) \]

This is a dB gain of 55.3 dB.

**Diff Amp with Non-Perfect Tail Supply**

Fig. 6 shows the circuit diagram of a differential amplifier. The tail supply is modeled as a current source \( I'_Q \) having a parallel resistance \( R_Q \). In the case of an ideal current source, \( R_Q \) is an open circuit. Often a diff amp is designed with a resistive tail supply. In this case, \( I'_Q = 0 \). The solutions below are valid for each of these connections. The object is to solve for the small-signal output voltages and output resistances.

![Figure 6: BJT Differential amplifier.](image)

**DC Solutions**

This solution assumes that \( I'_Q \) is known. If \( I_Q \) is known, the solutions are the same as above.

(a) Zero both inputs. Divide the tail supply into two equal parallel current sources having a current \( I'_Q/2 \) in parallel with a resistor \( 2R_Q \). The circuit obtained for \( Q_1 \) is shown on the left in Fig. 7. The circuit for \( Q_2 \) is identical. Now make a Thévenin equivalent as shown in on the right in Fig. 7. This is the basic bias circuit.
(b) Make an "educated guess" for $V_{BE}$. Write the loop equation between the ground node to the left of $R_B$ and $V^-$. To solve for $I_E$, this equation is

$$0 - (V^- - I'_Q R_Q) = \frac{I_E}{1 + \beta} R_B + V_{BE} + I_E (R_E + 2 R_Q)$$

(c) Solve the loop equation for the currents.

$$I_E = \frac{I_C}{\alpha} = (1 + \beta) I_B = \frac{-V^- + I'_Q R_Q - V_{BE}}{R_b/ (1 + \beta) + R_E + 2 R_Q}$$

(d) Verify that $V_{CB} > 0$ for the active mode.

$$V_{CB} = V_C - V_B = (V^+ - \alpha I_E R_C) - \left(-\frac{I_E}{1 + \beta} R_B\right) = V^+ - \alpha I_E R_C + \frac{I_E}{1 + \beta} R_B$$

(e) Calculate the collector-emitter voltage.

$$V_{CE} = V_C - V_E = V_C - (V_B - V_{BE}) = V_{CB} + V_{BE}$$

(f) If $R_Q = \infty$, it follows that $I_{E1} = I_{E2} = I'_Q/2$. If $I'_Q = 0$, the currents are given by

$$I_E = \frac{I_C}{\alpha} = (1 + \beta) I_B = \frac{-V^- - V_{BE}}{R_b/ (1 + \beta) + R_E + 2 R_Q}$$

Small-Signal or AC Solutions

Emitter Equivalent Circuit

This solution uses the $r_0$ approximations.
(a) Calculate \( g_m, r_\pi, r_e, \) and \( r'_e \).

\[
g_m = \frac{\alpha I_E}{V_T} \quad r_\pi = \frac{(1 + \beta) V_T}{I_E} \quad r_e = \frac{V_T}{I_E} \quad r'_e = \frac{R_B + r_x}{1 + \beta} + r_e \quad r_0 = \frac{V_A + V_{CE}}{\alpha I_E}
\]

(b) Redraw the circuit with \( V^+ = V^- = 0 \) and \( I'_Q = 0 \). Replace the two BJTs with the emitter equivalent circuit. The emitter part of the circuit obtained is shown in 8.

(c) Using superposition, Ohm’s Law, and current division, solve for \( i'_e_1 \) and \( i'_e_2 \).

\[
i'_e_1 = \frac{v_{i1}}{r'_e + R_E + R_Q \| (r'_e + R_E)} - \frac{v_{i2}}{R_Q} \quad i'_e_2 = \frac{v_{i2}}{r'_e + R_E + R_Q \| (r'_e + R_E)} - \frac{v_{i1}}{R_Q}
\]

For \( R_Q = \infty \), these become

\[
i'_e_1 = \frac{v_{i1} - v_{i2}}{2(r'_e + R_E)} \quad i'_e_2 = \frac{v_{i2} - v_{i1}}{2(r'_e + R_E)}
\]

(d) The circuit for \( v_{o1}, v_{o2}, r_{out1}, \) and \( r_{out2} \) is shown in Fig. 9.

![Emitter equivalent circuit for the simplified T model.](image)

![Circuits for calculating \( v_{o1}, v_{o2}, r_{out1}, \) and \( r_{out2} \).](image)

\[
v_{o1} = -i'_c r_{ic} \| R_C = -\alpha r_{ic} \| R_C = \frac{-\alpha r_{ic} \| R_C}{r'_e + R_E + R_Q \| (r'_e + R_E)} \left( \frac{v_{i1} - v_{i2}}{R_Q} \right) \quad R_Q + r'_e + R_E)
\]

\[
v_{o2} = -i'_c r_{ic} \| R_C = -\alpha r_{ic} \| R_C = \frac{-\alpha r_{ic} \| R_C}{r'_e + R_E + R_Q \| (r'_e + R_E)} \left( \frac{v_{i2} - v_{i1}}{R_Q} \right) \quad R_Q + r'_e + R_E)
\]
\[ r_{out1} = r_{out2} = r_{ic}\|R_C \]

\[ r_{ic} = \frac{r_0 + r'_e\|R_{te}}{1 - \frac{\alpha R_{te}}{r'_e + R_{te}}} \]

\[ R_{te} = R_E + R_Q\|(r'_e + R_E) \]

(e) The resistance seen looking into the \(v_i1\) \((v_i2)\) input with \(v_i2 = 0\) \((v_i1 = 0)\) is

\[ r_{ib} = R_B + r_x + r_{\pi} + (1 + \beta) R_{te} \]

(f) Special case for \(R_Q = \infty\).

\[ v_{o1} = -\frac{\alpha r_{ic}\|R_C}{2 (r'_e + R_E)} (v_i1 - v_i2) \quad v_{o2} = -\frac{\alpha r_{ic}\|R_C}{2 (r'_e + R_E)} (v_i2 - v_i1) \]

(g) The equivalent circuit seen looking into the two inputs is similar to that in Fig. 4 with the exception that a resistor representing the effect of \(R_Q\) must be added. It is shown in Fig. 10. The resistors labeled \(r'_{\pi}\) have the same value as the ones in Fig. 4. They are given by

\[ r'_{\pi} = r_x + r_{\pi} + (1 + \beta) R_E \]

![Figure 10: Equivalent circuits for calculating \(i_{b1}\) and \(i_{b2}\).](image)

The differential input resistance \(r_{id}\) is defined the same way that it is defined for Fig. 4. That is, it is the resistance seen between the two inputs when \(v_i1 = v_{id}/2\) and \(v_i2 = -v_{id}/2\), where \(v_{id}\) is the differential input voltage. In this case, the small-signal voltage at the upper node of the resistor \((1 + \beta) R_Q\) is zero so that no current flows it. It follows that \(r_{id}\) is given by \(r_{id} = 2 (R_B + r'_x)\).

**Hybrid-π Model**

This solution assumes that \(r_0 = \infty\). Replace the two transistors with the hybrid-π model as shown in Fig. 11.

(a) Write the loop equations for the two input loops. Use the relations \(v_{r1} = \frac{i'_{c1}}{g_m}\) and \(v_{r2} = \frac{i'_{c2}}{g_m}\).

\[ v_{i1} = \frac{i'_{c1}}{\beta} (R_B + r_x) + \frac{i'_{c1}}{g_m} + \frac{i'_{c1}}{\alpha} R_E + \left(\frac{i'_{c1}}{\alpha} + \frac{i'_{c2}}{\alpha}\right) R_Q \]

\[ v_{i2} = \frac{i'_{c2}}{\beta} (R_B + r_x) + \frac{i'_{c2}}{g_m} + \frac{i'_{c2}}{\alpha} R_E + \left(\frac{i'_{c1}}{\alpha} + \frac{i'_{c2}}{\alpha}\right) R_Q \]

These equations are in the form

\[ v_{i1} = (A + B) i'_{c1} + B i'_{c2} \]
Figure 11: Hybrid-π model ($r_0 = \infty$).

$$v_i = B i_c' + (A + B) i_e'$$

where

$$A = \frac{R_B + r_x}{\beta} + \frac{1}{g_m} + \frac{R_E}{\alpha} \quad B = \frac{R_Q}{\alpha}$$

(b) Use determinants to solve the two equations simultaneously for $i_{c1}'$ and $i_{c2}'$.

$$i_{c1}' = \frac{(A + B) v_{i1} - B v_{i2}}{(A + B)^2 - B^2} = \frac{(A + B) v_{i1} - B v_{i2}}{A (A + 2B)}$$

$$i_{c2}' = \frac{(A + B) v_{i2} - B v_{i1}}{(A + B)^2 - B^2} = \frac{(A + B) v_{i2} - B v_{i1}}{A (A + 2B)}$$

Thus the solutions are

$$i_{c1}' = \frac{\left(\frac{R_B + r_x}{\beta} + \frac{1}{g_m} + \frac{R_E}{\alpha}\right) v_{i1} - \frac{R_Q}{\alpha} v_{i2}}{\left(\frac{R_B + r_x}{\beta} + \frac{1}{g_m} + \frac{R_E}{\alpha}\right) - \frac{R_Q}{\alpha}}$$

$$i_{c2}' = \frac{\left(\frac{R_B + r_x}{\beta} + \frac{1}{g_m} + \frac{R_E}{\alpha}\right) v_{i2} - \frac{R_Q}{\alpha} v_{i1}}{\left(\frac{R_B + r_x}{\beta} + \frac{1}{g_m} + \frac{R_E}{\alpha}\right) - \frac{R_Q}{\alpha}}$$

After some algebra, the solutions reduce to those obtained with the emitter equivalent circuit.

The output voltages are given by

$$v_{o1} = -i_{c1}' R_C \quad v_{o2} = -i_{c2}' R_C$$

For the case of a finite $r_0$, the $r_0$ approximation replaces $R_C$ with $r_{ic}||R_C$. 


Differential and Common-Mode Gains

This solution uses the $r_0$ approximations.

(a) Define the common-mode and differential input voltages as follows:

$$v_{id} = v_{i1} - v_{i2} \quad v_{icm} = \frac{v_{i1} + v_{i2}}{2}$$

With these definitions, $v_{i1}$ and $v_{i2}$ can be written

$$v_{i1} = v_{icm} + \frac{v_{id}}{2} \quad v_{i2} = v_{icm} - \frac{v_{id}}{2}$$

By linearity, it follows that superposition of $v_{icm}$ and $v_{id}$ can be used to solve for the currents and voltages.

(b) Redraw the emitter equivalent circuit as shown in Fig. 12.

(c) For $v_{i1} = v_{id}/2$ and $v_{i2} = -v_{id}/2$, it follows by superposition that $v_a = 0$ and

$$i_{e1}' = \frac{v_{id}/2}{r_e' + R_E} \quad i_{e2}' = \frac{-v_{id}/2}{r_e' + R_E}$$

$$v_{o1} = -\alpha_{i1}' r_{iec} \| R_C = -\frac{\alpha_{i1}' R_{e1} R_{Q} v_{id}}{r_e' + R_E} = -\frac{\alpha_{i1}' R_{e1} R_{Q} v_{id}}{r_e' + R_E} \left( \frac{v_{i1} - v_{i2}}{2} \right)$$

$$v_{o2} = -\alpha_{i2}' r_{iec} \| R_C = +\frac{\alpha_{i2}' R_{e2} R_{Q} v_{id}}{r_e' + R_E} = +\frac{\alpha_{i2}' R_{e2} R_{Q} v_{id}}{r_e' + R_E} \left( \frac{v_{i1} - v_{i2}}{2} \right)$$

The differential voltage gain is given by

$$A_d = \frac{v_{o1}}{v_{id}} = -\frac{v_{o2}}{v_{id}} = \frac{1}{2} \frac{\alpha_{i1}' R_{e1} R_{Q}}{r_e' + R_E}$$

(d) For $v_{i1} = v_{i2} = v_{icm}$, it follows by superposition that $i_a = 0$ and

$$i_{e1}' = \frac{v_{icm}}{r_e' + R_E + 2 R_Q} \quad i_{e2}' = \frac{v_{icm}}{r_e' + R_E + 2 R_Q}$$

$$v_{o1} = -\alpha_{i1}' r_{iec} \| R_C = \frac{\alpha_{i1}' R_{e1} R_{Q} v_{icm}}{r_e' + R_E + 2 R_Q} = \frac{\alpha_{i1}' R_{e1} R_{Q} v_{icm}}{r_e' + R_E + 2 R_Q} \left( \frac{v_{i1} + v_{i2}}{2} \right)$$

$$v_{o2} = -\alpha_{i2}' r_{iec} \| R_C = \frac{\alpha_{i2}' R_{e2} R_{Q} v_{icm}}{r_e' + R_E + 2 R_Q} = \frac{\alpha_{i2}' R_{e2} R_{Q} v_{icm}}{r_e' + R_E + 2 R_Q} \left( \frac{v_{i1} + v_{i2}}{2} \right)$$
The common-mode voltage gain is given by
\[ A_{cm} = \frac{v_{o1}}{v_{icm}} = \frac{v_{o2}}{v_{icm}} = -\frac{\alpha r_{ie} R_C}{r_e' + R_E + 2R_Q} \]

(e) If the output is taken from the collector of \( Q_1 \) or \( Q_2 \), the common-mode rejection ratio is given by
\[ CMRR = \frac{|v_{o1}/v_{id}|}{|v_{o2}/v_{id}|} = \frac{1}{\frac{r_e' + R_E + 2R_Q}{2}} = \frac{1}{2} + \frac{R_Q}{r_e' + R_E} \]
This can be expressed in \( dB \).
\[ CMRR_{dB} = 20 \log \left( \frac{1}{2} + \frac{R_Q}{r_e' + R_E} \right) \]

**Example 2** For \( I_Q' = 2 \text{ mA}, \ R_Q = 50 \text{k}\Omega, \ R_B = 1 \text{k}\Omega, \ R_E = 100 \text{ \Omega}, \ R_C = 10 \text{k}\Omega, \ V^+ = 20 \text{ V}, \ V^- = -20 \text{ V}, \ V_T = 0.025 \text{ V}, \ r_x = 20 \text{ \Omega}, \ \beta = 99, \ V_{BE} = 0.65 \text{ V}, \ \text{and} \ V_A = 50 \text{ V}, \ \text{calculate} \ v_{o1}, \ v_{o2}, \ v_{od}, \ r_{out}, \ \text{and} \ CMRR.\]

**Solution.**
\[ I_E = 0 - \left( V^- - I_Q'R_Q \right) - V_{BE} \]
\[ = \frac{R_B}{(1 + \beta)} + \frac{R_E + 2R_Q}{R_E} = 1.192 \text{ mA} \]
\[ V_{CB} = V_C - V_B = (V^+ - \alpha I_E R_C) - \left( -\frac{I_E}{1 + \beta} R_B \right) = 8.209 \text{ V} \]
\[ g_m = \frac{\alpha I_E}{V_T} = 0.0472 \text{ S} \quad r_\pi = \frac{(1 + \beta) V_T}{I_E} = 2.097 \text{ k}\Omega \]
\[ r_e = V_T/I_E = 20.97 \text{ \Omega} \quad r_e' = \frac{R_B + r_x}{1 + \beta} + r_e = 31.17 \text{ \Omega} \]
\[ r_0 = \frac{V_A + V_{CE}}{I_C} = 49.869 \text{ k}\Omega \quad R_{te} = R_E + R_Q \parallel \left( r_e' + R_E \right) = 230.83 \text{ \Omega} \]
\[ r_{ic} = -\frac{r_0 + r_e'}{\alpha R_{te}} = 390.5 \text{ k}\Omega \]
\[ v_{o1} = \frac{-\alpha r_{ie} R_C}{r_e' + R_E + R_Q \parallel (r_e' + R_E)} \left( \frac{v_{i1} - v_{i2}}{R_Q + r_e' + R_E} \right) = -36.84v_{i1} + 36.75v_{i2} \]
\[ v_{o2} = -36.84v_{i1} + 36.75v_{i2} \]
\[ r_{out} = \frac{1}{A_{vd} R_C} = 9.75 \text{ k}\Omega \]
\[ A_{vd} = -\frac{1}{2} \frac{r_e' + R_E}{r_e' + R_E + R_Q} = -36.80 \]
\[ A_{vcm} = \frac{-\alpha r_{ie} R_C}{r_e' + R_E + 2R_Q} = -0.0964 \]
\[ CMRR_{dB} = 20 \log \left| \frac{A_{vd}}{A_{vcm}} \right| = 51.63 \text{ dB} \]