About the layout / design of the

Differential Amplifier Experimentation Board

v2 - Multivibrator_v2_2026.07.29-1500

Document Rev. 1 - 2026.08.03-1500

https://ufelectronics.eu/product/differential-amplifier-experimentation-board-v1/

Version 1 of the PCB includes:

- Semi-schematic PCB layout for easier learning.
- Visible signal routing on the component side.
- Full bottom-side ground plane.
- Through-hole components throughout.
- Differential amplifier with space for two NPN transistors.
- Configurable emitter degeneration.
- Configurable emitter resistor matching.
- Supports both simple resistor and active current sources.
- Supports both simple resistor and active current sinks.
- Dedicated footprints for external Current Source and Current Sink boards.
- Multiple oscilloscope-friendly test points.
- Dual differential outputs (Vout+ and Vout-).
- Differential inputs (Vin+ and Vin-).
- Multiple power supply and ground connection points.
- Breadboard expansion connectors.
- Eight optional decoupling capacitor footprints.
- Designed for easy modification and experimentation.

Learning Objectives:

- Learn the operation of transistor differential amplifiers.
- Explore current sources, current sinks, and transistor matching.
- Study common-mode and differential signal behaviour.
- Prepare for understanding operational amplifier input stages.

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Foreword

The Differential Amplifier Experimentation Board was designed as a hands-on learning platform for exploring one of the most important transistor circuits in analog electronics.

The differential amplifier forms the input stage of countless analog circuits, including operational amplifiers, comparators, instrumentation amplifiers, and many communication systems. Understanding how this circuit works provides an excellent foundation for more advanced analog design.

Instead of repeatedly wiring differential amplifier circuits on a breadboard, this PCB provides a reusable platform where components can quickly be changed, measured, and compared while keeping the circuit easy to understand.

The board intentionally exposes many internal nodes through test points and configurable jumpers. Rather than presenting one fixed circuit, it encourages experimentation with different current sources, current sinks, emitter degeneration, transistor matching, and bias conditions.

The goal is not only to build a working differential amplifier, but to understand why it behaves the way it does.

Overall Concept

This board is intended as a reusable experimentation platform for transistor based differential amplifiers. Instead of repeatedly building circuits on a breadboard, users can quickly assemble, modify, and compare different multivibrator configurations while keeping a clear overview of the circuit.

Educational Design Philosophy

The footprints, routing, and component placement have been optimized to encourage experimentation, easy probing, and circuit modification while still maintaining good analog performance, rather than optimizing the PCB for one fixed application.

The board encourages learning by observation. Test points, visible routing, and semi-schematic component placement allow users to relate the electrical schematic directly to the physical circuit.

Overall Layout

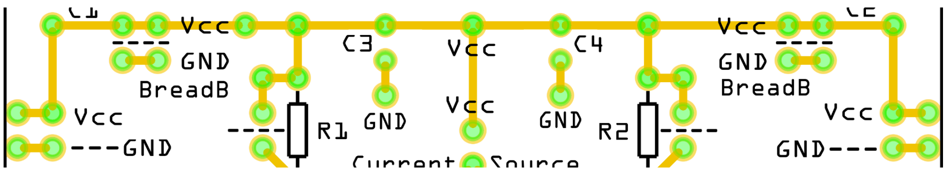
The components are placed semi-schematic to make the mental shift between schematic and PCB as easy as possible; Helping users relate schematics to their physical implementation.

Through-hole PCBs normally place most traces on the solder side. On this board, however, the traces are intentionally routed on the component side so they remain visible during experiments. The opposite side of the trace side, in this case the bottom side, is a full ground plane.

No ground plane is used on the top layer because the visible traces help users understand how the circuit is interconnected. A purple solder mask was intentionally selected because it provides good visual contrast with the copper traces, making them easier to follow during experiments.

Power Supply and Lab Equipment Connectors

VCC



There are VCC and ground connectors at the left-top and right-top. These are in pairs, and sitting close for connecting a single two-pin pin header, preferably male, as these make it easy to connect lab probes also. There are additional VCC connector options across the top VCC trace, so that the VCC from a lab power supply can be attached here, without getting too close to any ground pin.

Defining Ground

In a differential amplifier there is no absolute ground. Ground is simply the voltage reference chosen for the circuit.

In a dual-supply system (+V_Cc and -Vee), ground is normally defined as the point halfway between the two supplies. For example, with +9 V and -9 V, ground is defined as 0 V.

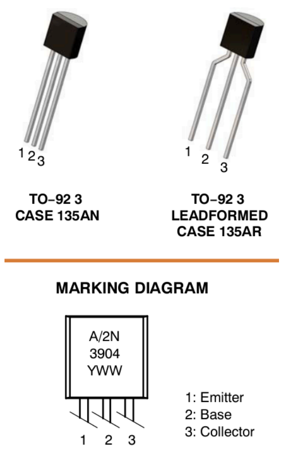
In a single-supply circuit, ground is usually connected to the negative terminal of the power supply, and all other voltages are measured relative to that point.

Although the differential amplifier mainly responds to the voltage difference between its two inputs, all laboratory equipment still requires a common reference point. Oscilloscopes, multimeters, function generators, and power supplies therefore need their ground connections tied to the circuit ground to produce meaningful measurements.

GND Traces on the PCB

At the left and right, as well as the bottom edge of the PCB you will find several options for ground connected female pin headers. As with the VCC, you also need the possibility to connect various lab equipment to ground. Even more so for ground than for VCC.

How to Orient the Transistors - 2N3904



You can potentially use other transistors than 2N3904. 2N3904 have the pin-out you see to the right. If you use other transistors, you will have to find their datasheet, and read there how to orient them for the specific part you use.

If the transistors aren't mounted correctly, the circuit normally won't work as intended. It might even break the transistors entirely.

In the circuits in this document, the 2N3904 transistors have to have **the flat side with the labeling to the right**. And hence, **the curved side to the left**.

Circuit Notation

Throughout this documentation, the notation follows the conventions used in many university analog electronics courses and standard textbooks, including Sedra/Smith, Horowitz & Hill, and Gray & Meyer.

Why Learn This Notation?
Although it may seem unfamiliar at first, becoming comfortable with this notation will make it much easier to read textbooks, datasheets, application notes and technical articles.

Throughout your studies, you will encounter symbols such as V_BE, I_C, R_E and r_e repeatedly. Learning to recognize them now will make it easier to understand more advanced circuits and communicate effectively with other engineers.

- **Reference designators** (R1, Q2, TP5, etc.) identify the physical components on the PCB.
- **Circuit variables** (R_C, I_C, V_BE, etc.) describe electrical quantities used in equations and circuit analysis.

Reference Designators

R1, R2, R3	Resistors
Q1, Q2	Transistors
C1, C2	Capacitors
D1	Diode
TP1	Test Point

Circuit Variables

VCC	Positive supply voltage
VEE	Negative supply voltage
V_C	Collector voltage
V_B	Base voltage
V_E	Emitter voltage
V_BE	Base-emitter voltage
V_CE	Collector-emitter voltage
V_IN	Input voltage
V_OUT	Output voltage

Currents

I_C	Collector current
I_B	Base current
I_E	Emitter current

Resistances

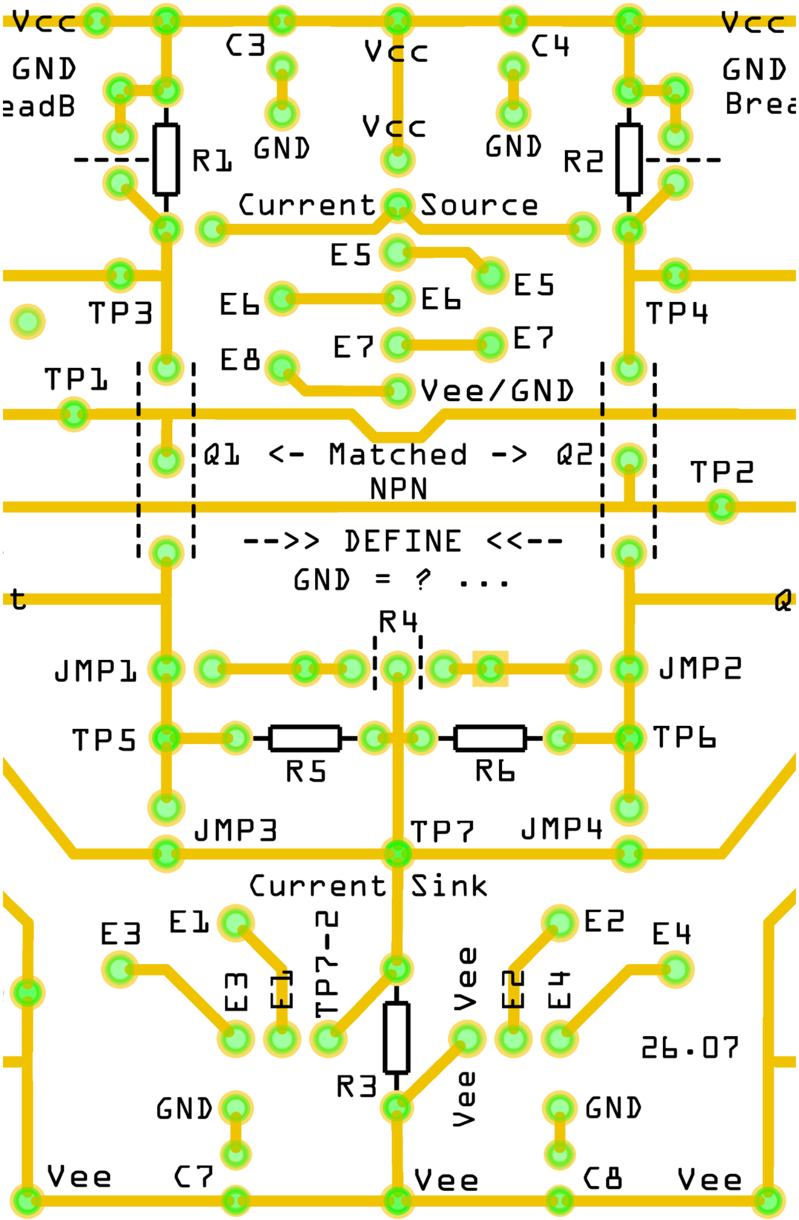
R_C	Collector resistor
R_E	External emitter resistor
R_B	Base resistor
r_e	Intrinsic (small-signal) emitter resistance
r_o	Small-signal output resistance

Note: Some textbooks denote the transistor's intrinsic emitter resistance as **r’e** (or **r'_e**). In this documentation the modern notation **r_e** is used.

Other Symbols

β	DC current gain
A_V	Voltage gain
CMRR	Common-Mode Rejection Ratio
PSRR	Power Supply Rejection Ratio

Simple Differential Amplifier Circuit



A differential amplifier amplifies the difference between two input voltages while rejecting signals that are common to both inputs.

If both inputs receive exactly the same voltage, the output ideally remains unchanged. Only when the voltages differ does the amplifier produce an output proportional to that difference.

This property makes differential amplifiers extremely useful for measuring very small signals in electrically noisy environments.

The circuit consists of two closely matched transistors sharing a common emitter current. As one transistor conducts more current, the other automatically conducts less. The total current remains nearly constant, causing the collector voltages to move in opposite directions.

This balancing behaviour is the defining characteristic of a differential amplifier.

Current Sources

A differential amplifier performs best when the collector current remains stable. The simplest way to obtain this current is by using ordinary resistors connected to VCC.

Although resistors are perfectly adequate for learning and many practical applications, the collector current still changes slightly with supply voltage and transistor operating conditions.

Replacing the resistors with active current sources greatly improves performance. A current source attempts to maintain a nearly constant current regardless of voltage variations, resulting in improved gain, better symmetry, and improved common-mode rejection.

This board supports both approaches so their differences can easily be compared experimentally.

The Obvious Current Source - R1, R2

The simplest way to provide collector current is by using ordinary resistors, R1 and R2. This is sufficient for most introductory experiments and clearly demonstrates the basic operation of a differential amplifier.

For improved symmetry, footprints are also provided for trimpots immediately to the left of R1 and to the right of R2. These allow the collector currents to be adjusted, making it easier to compensate for resistor tolerances and transistor mismatches during experiments.

The Advanced Current Source - E5 -> E8, V_Cc, 'Current Source'

For more advanced experiments, the board provides footprints E5, E6, E7, E8, V_Cc, and the trace labelled "Current Source". Together, these allow an external current source circuit to be connected in place of R1 and R2.

An active current source provides a much more constant collector current than a resistor, making the differential amplifier less sensitive to supply voltage variations and improving its overall performance.

The external board supplies current through the "Current Source" trace, which is then distributed to the collectors of Q1 and Q2. Remember to connect the "Current Source" trace to the collector nodes when using an external current source. - Do not populate R1 and R2 at the same time you use an external current source.

You may use the Current Source Board available from ufelectronics.eu, or design and build your own.

Q1, Q2

Although this documentation uses the 2N3904, the board is by no means limited to this transistor. Feel free to experiment with other small-signal NPN transistors, for example:

• 2N2222 • PN2222A • BC547 • BC548 • BC549	• BC550 • 2SC1815 • 2SC945 • BC337 (higher current capability)

Matching

Ideally, both transistors should have nearly identical electrical characteristics. But even transistors with the same part number may differ slightly in current gain, base-emitter voltage, and leakage current. These differences can introduce output offset voltages and reduce the symmetry of the amplifier.

Fortunately, perfect matching is not required for learning. In fact, using unmatched transistors often provides valuable insight into the practical limitations of real electronic components.

After becoming familiar with the circuit, try selecting better matched transistors and compare the resulting behaviour.

Emitter Side of Q1, Q2

The emitter side of the differential pair has been designed to support several different circuit configurations. Exploring these variations is an excellent way to understand not only how a differential amplifier works, but also how transistor circuits behave in general.

The PCB allows you to compare a basic differential pair with versions that use emitter degeneration and matched emitter resistors. By measuring the performance of each configuration, you can observe how these modifications affect gain, linearity, stability, and transistor matching.

Straight Down - JMP3, JMP4

Installing jumpers JMP3 and JMP4 connects the emitters of Q1 and Q2 directly to the tail current sink / R3 resistor. In this configuration, no emitter degeneration is used.

This is the simplest differential amplifier configuration and is a good starting point for initial experiments. It provides the highest voltage gain, but the circuit is also more sensitive to transistor parameter variations and temperature changes.

Emitter Degeneration - R5, R6

Emitter degeneration is created by inserting small resistors in series with the emitters. These resistors introduce local negative feedback. As the collector current increases, the voltage across the emitter resistor also increases, reducing the transistor's effective base-emitter voltage. This naturally limits further current increase.

Emitter degeneration offers several advantages:

- Improved linearity.
- Reduced distortion.
- Better thermal stability.
- Less sensitivity to transistor parameter variations.
- Improved predictable gain.

The price paid is reduced voltage gain. For many practical amplifier designs this trade-off is well worth making.

Matching Emitter Resistors - JMP1, JMP2, R4

R4 is intended as a single adjustable replacement for R5 and R6. By adjusting the trimpot or potentiometer, the emitter degeneration can be balanced so that both transistors operate under nearly identical conditions. This improves matching and makes it easier to achieve symmetrical operation of the differential amplifier.

When using a trimpot or potentiometer, remember to install JMP1 and JMP2 so the adjustable resistor is correctly connected into the circuit. - Do not use JMP3 and JMP4 at the same time.

Current Sink - R3

Both transistors share a common emitter current. Something therefore has to determine how much current flows through the pair. The simplest solution is a resistor connected to the negative supply (or ground in single-supply circuits). While simple, the current varies as transistor voltages change. A much better solution is an active current sink.

A current sink behaves almost like an ideal current source connected towards the negative supply. Instead of allowing the current to vary, it attempts to keep the emitter current constant. Using a current sink significantly improves differential amplifier performance by increasing gain, improving linearity, and improving common-mode rejection.

Since current sinks are themselves interesting transistor circuits, the board allows both simple resistor operation and external current sink modules.

The Basic Approach - R3, TP7, Vee

The simplest approach is to install a fixed resistor in the R3 position to establish the tail current. Alternatively, a trimpot or potentiometer may be installed, allowing the tail current to be adjusted during experimentation. This makes it easy to investigate how the tail current affects gain, linearity, operating point and Common-Mode Rejection Ratio (CMRR).

The Advanced Approach - E1, E2, E3, E4

For improved performance, the tail resistor may be replaced by an active current sink. The footprints E1, E2, E3 and E4 provide convenient connection points for extending the circuit to an external breadboard or additional PCB. An active current sink can be implemented using, for example, one or more NPN transistors.

See the **Current Sink Board** also available from UF Electronics, or design and build your own current sink circuit.

Use E1, E2, E3 and E4 to route the required signals via wires from the external PCB to needed sources on the local board. Additional connections, such as VCC and VEE, can be obtained from other test points or connectors on the local PCB. Maybe use the bottom side of the PCB for manual wiring.

Output

Vout+, Vout-

The differential amplifier provides two output signals.

- Vout+ is taken from the collector of Q1.
- Vout- is taken from the collector of Q2.

As one collector voltage rises, the other falls by approximately the same amount. The two outputs therefore contain equal but opposite signal variations. Either output may be used individually, or both outputs can be measured simultaneously to observe the full differential behaviour.

Q1- / Q2-Emitter

Q1 and Q2 emitter connections are routed to the potential breadboard connectors, allowing external components and experimental circuits to be inserted directly into the emitter paths. This provides an easy way to investigate emitter degeneration, current sharing, feedback techniques and other differential amplifier modifications without altering the PCB.

The emitter connections can be used for experiments such as:

- Alternative emitter-degeneration resistors.
- Bypassing emitter resistors with capacitors.
- Current sensing.
- External feedback networks.
- Active emitter circuits.

TP7

The tail node TP7 is also routed to the potential breadboard connectors. This allows the onboard current sink to be disconnected and replaced with experimental circuits such as resistor tails, JFET current sources, Wilson current mirrors, cascode current sinks or other current-source designs without altering the PCB.

TP7 lets you try things like:

- Tail resistor
- JFET current source
- Cascode current sink
- External current source
- External op-amp controlled current sink

...all from the same PCB.

Input

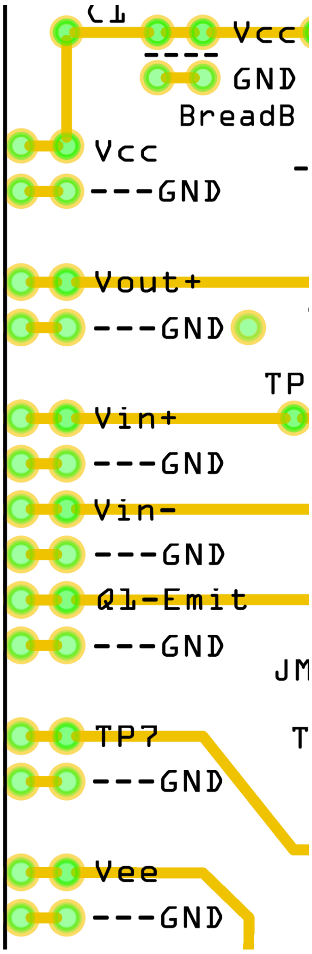
Vin+, Vin-

Vin+ and Vin- are the two differential inputs. The amplifier responds only to the voltage difference between these inputs.

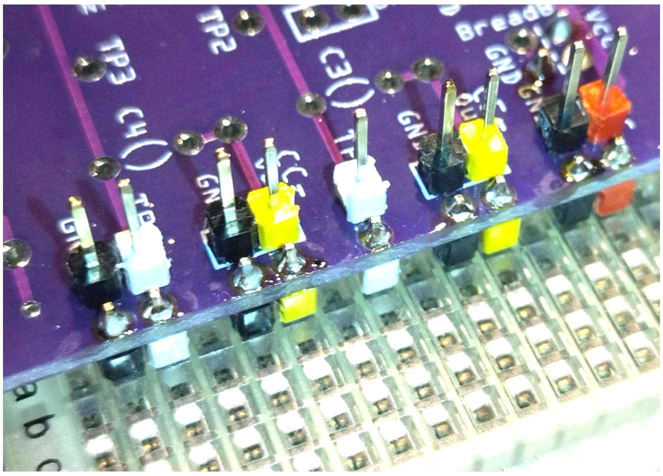
For initial experiments, keep one input (Vin-) at a fixed reference voltage (via a resistor of a few kΩ to GND, for example), while applying a slowly varying signal to the other input (Vin+).

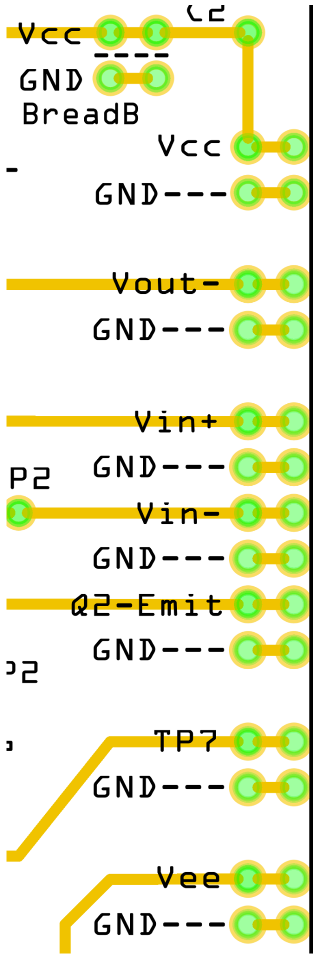
Once familiar with the basic operation, apply signals to both inputs and observe how the output depends only on their difference.

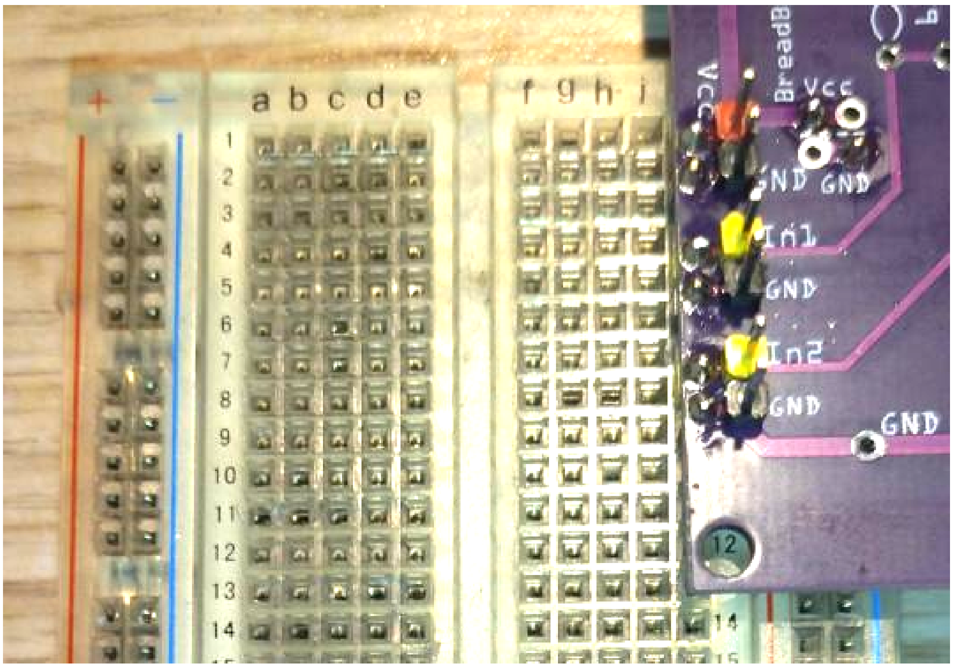
Breadboard Connectors



To be able to integrate the PCB into other experiments, both the left and right side of it facilitates the option for downwards male pin headers as shown in the following images (with another PCB design).





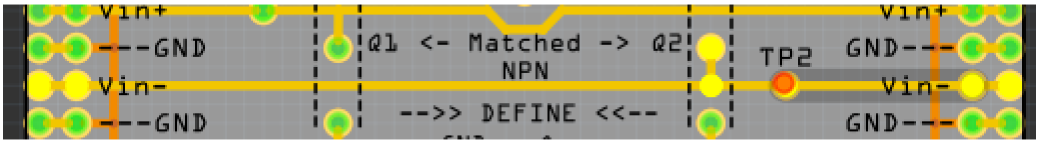


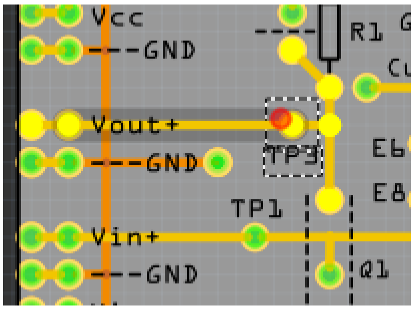
Test Points

The PCB includes numerous test points allowing convenient oscilloscope and multimeter measurements. Rather than probing directly on component leads, measurements can be taken at dedicated locations designed specifically for laboratory work. Following the signal through the various test points greatly improves understanding of how the differential amplifier operates internally.

TP1

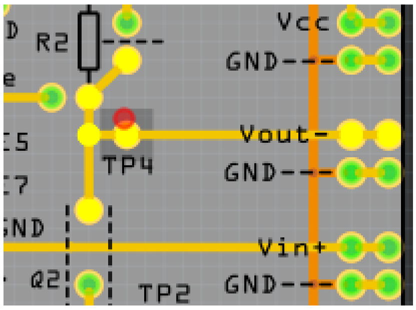
TP2

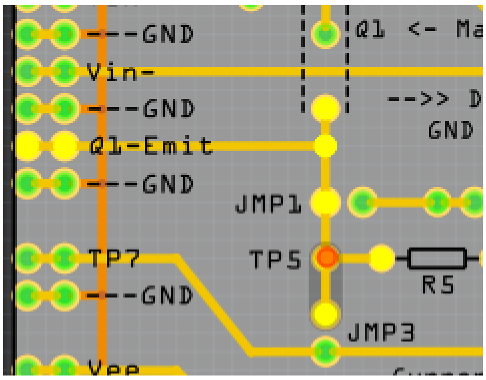




TP3

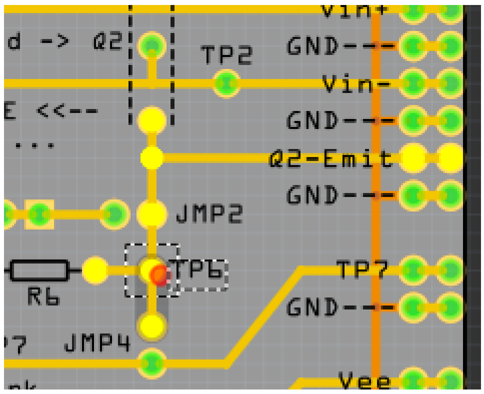
TP4

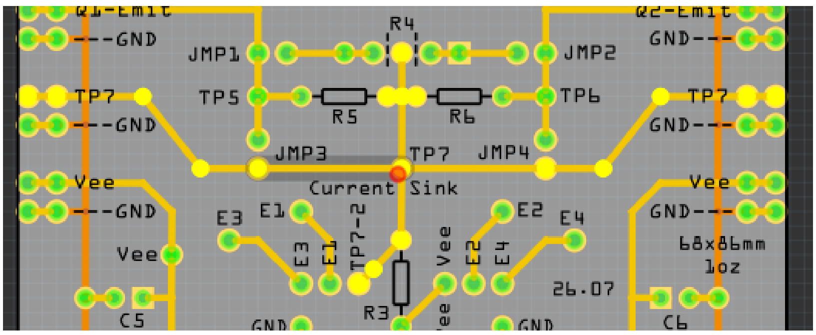




TP5

TP6





TP7

Decoupling Capacitors - C1 -> C8

Eight optional decoupling capacitor footprints are distributed around the PCB. Many simple experiments operate perfectly without them. However, as circuit complexity increases or when external current source and current sink boards are connected, supply decoupling may become important.

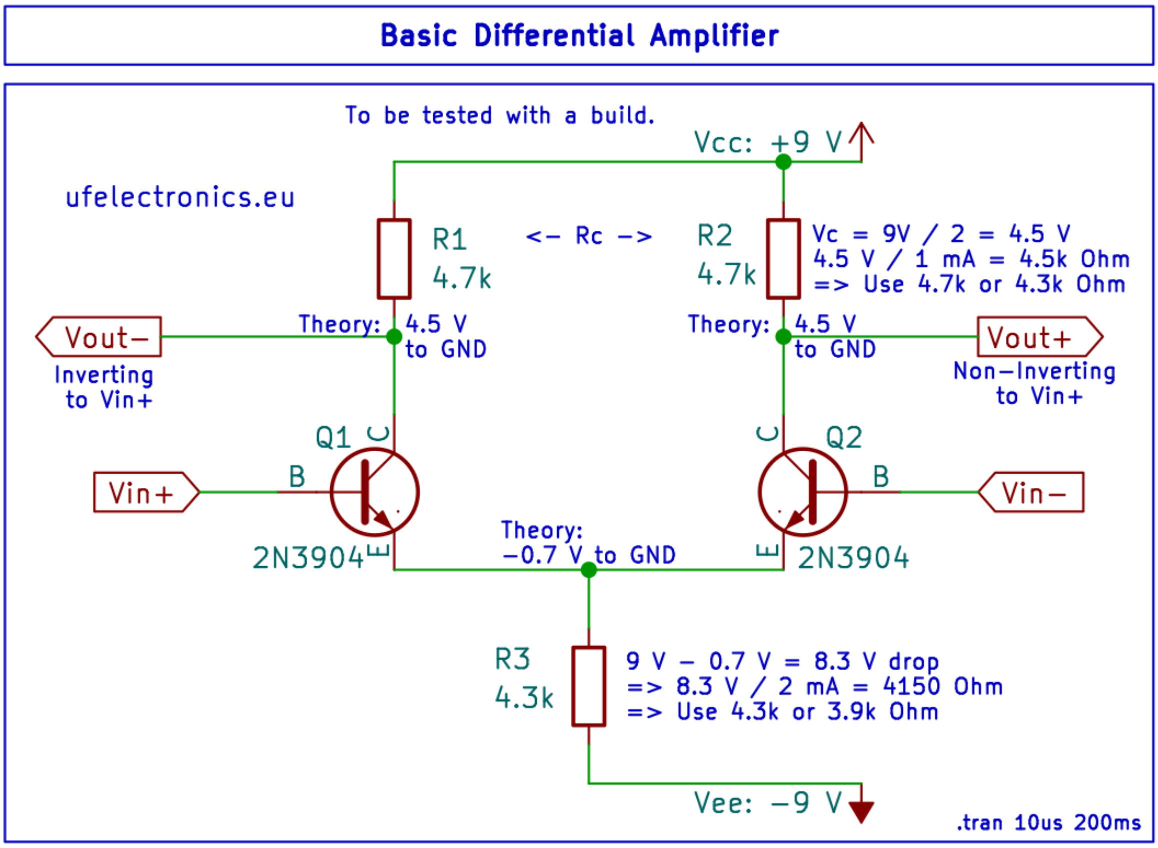
Decoupling capacitors provide a local energy reservoir and reduce unwanted supply voltage disturbances caused by rapidly changing currents. In most cases ceramic capacitors between 100 nF and 1 uF are suitable for high-frequency decoupling, while larger electrolytic capacitors can improve low-frequency supply stability.

Common Mode Rejection

One of the most useful properties of a differential amplifier is its ability to reject common-mode signals. A common-mode signal is any voltage that appears equally on both inputs. Examples include electrical interference, supply ripple, and electromagnetic noise picked up equally by both input wires.

Since both transistors experience the same change in a common-mode signal, the differential amplifier largely ignores the signal. The effectiveness of this rejection is described by the Common Mode Rejection Ratio (CMRR). A higher CMRR means better rejection of unwanted signals.

Basic Differential Amplifier - Schematic



This circuit is without degeneration resistors at the emitter side. More on them in a later circuit.

AC Analysis

The AC analysis is based on the small-signal behavior of the differential amplifier.

First, the tail current is selected. The current source R3 is designed for approximately 2 mA. In a balanced differential amplifier, this current is shared equally between the two transistors when there is no differential input signal.

Therefore:

R3 current = 2 mA

Q1 collector current ≈ 1 mA

Q2 collector current ≈ 1 mA

For DC analysis, the emitter current can be approximated as equal to the collector current:

$$I_E \approx I_C$$

The collector resistors are chosen so that the collector voltage can swing approximately halfway between the supply voltage and ground. With a 9 V supply, a collector voltage drop of approximately 4.5 V is desired.

Using Ohm's law:

$R_C = V_C / I_C$ (V_C: Voltage drop over the collector resistor)

$R_C = 4.5\ V / 1\ mA$ (I_C: Current running through the collector resistor)

$R_C = 4.5\ k\Omega$ (R_C: Resistor between VCC and collector)

The nearest standard resistor value is chosen: **$R_C \approx 4.7\ k\Omega$**

The transistor's internal emitter resistance (r_e) is calculated using the small-signal approximation:

$r_e = 26 \text{ mV} / I_E \text{ (mA)}$ (I_E: Current running out of the emitter)

$r_e = 26 / 1$ (r_e: Internal emitter resistance of the transistor)

$r_e = 26\ \Omega$

For a simple differential amplifier without external emitter resistors, the AC emitter resistance seen by each transistor can be approximated as:

$r_E \approx r_e$ (r_E: External emitter resistor)

This approximation is used for calculating the small-signal voltage gain.

Single-ended voltage gain

The input signal is applied to Vin+, while Vin- is connected to AC ground through a resistor. This causes one transistor to amplify the input signal while the other transistor produces an inverted output.

The voltage gain from the Q1 collector (Vout-) is:

$A_V = -R_C / (r_e + r_E)$ (A_V: Voltage gain)

Since:

$r_E \approx r_e$

the equation becomes:

$A_V \approx -R_C / (2 * r_e)$

$A_V = -4.7\ k\Omega / (2 * 26\ \Omega)$

$A_V = -4700 / 52$

$A_V \approx -90$

For the collector of Q2 (Vout+), the output is non-inverting:

$A_V = (R_C / r_e) * 0.5$

$A_V = (4.7\ k\Omega / 26\ \Omega) * 0.5$

$A_V = 181 * 0.5$

$A_V \approx 90$

The two collector outputs therefore have approximately equal gain but opposite polarity:

Q1 collector (Vout-) : $A_V \approx -90$

Q2 collector (Vout+) : $A_V \approx +90$

This is the expected behavior of a balanced differential amplifier, where the two outputs are complementary versions of the amplified input signal.

Observations / Conclusions

The gain is directly influenced by the collector current and the collector resistor.

If I_E doubles:

=> r_e is reduced by half
=> A_V approximately doubles

This is because the transistor's internal emitter resistance is inversely proportional to the emitter current.

If R_C doubles:

=> A_V doubles

This shows that higher collector resistance increases the voltage gain, but also affects the available output voltage swing.

Pro-Tip:
If you don't intend to use Vout-, you can practically remove R1 and short VCC directly to the collector of Q1. - This is why many circuits never show R1. They only use Vout+, and never Vout-. - In the following circuits, we will keep R1 as far as possible, to keep an optically consistent circuit.

The Position of GND is a Design Choice.

In a differential amplifier, the circuit can technically operate with a reference point located almost anywhere between VCC and VEE.

To simplify the design and make the signal swing symmetrical, GND is placed exactly halfway between VCC and VEE in this example. This can be achieved by using two 9 V batteries, creating a +9 V and -9 V supply with the center point as GND.

The circuit is powered from a dual supply:

VCC = +9 V
VEE = -9 V

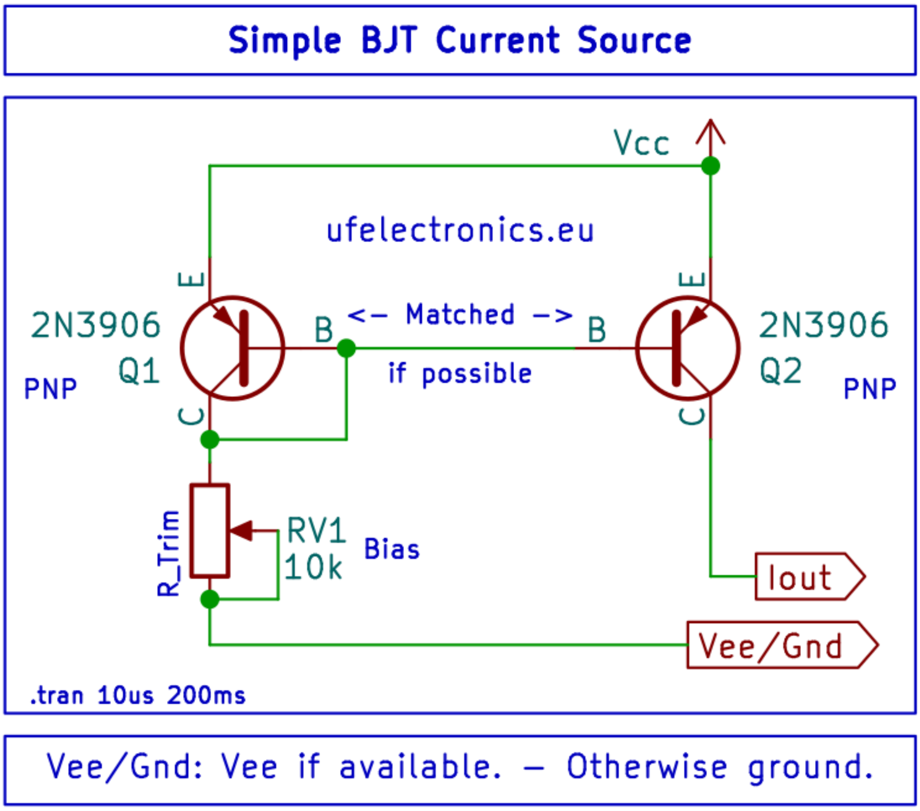
Total voltage difference = 18 V

Current Sources, Sinks and Mirrors

Before we can improve on the differential amplifier, we need to make a detour to current sources, sinks and mirrors. We will look at the three mentioned types, and four circuit examples of them.

Current sources, sinks and mirrors are widely used in analog electronics. They are found in transistor amplifiers, differential amplifiers, operational amplifiers and many integrated circuits, where stable bias currents are needed for predictable circuit operation.

Simple BJT Current Source - Schematic



Current Source

A current source is a circuit that provides a nearly constant current, regardless of changes in the load voltage. Instead of controlling the voltage across a load, a current source controls the amount of current flowing through it.

A simple example is an LED connected to a current source. The current source is placed in series with the LED and forces a fixed current through it. This is different from using a resistor, where the current depends on the supply voltage and the LED's forward voltage.

Current Sink

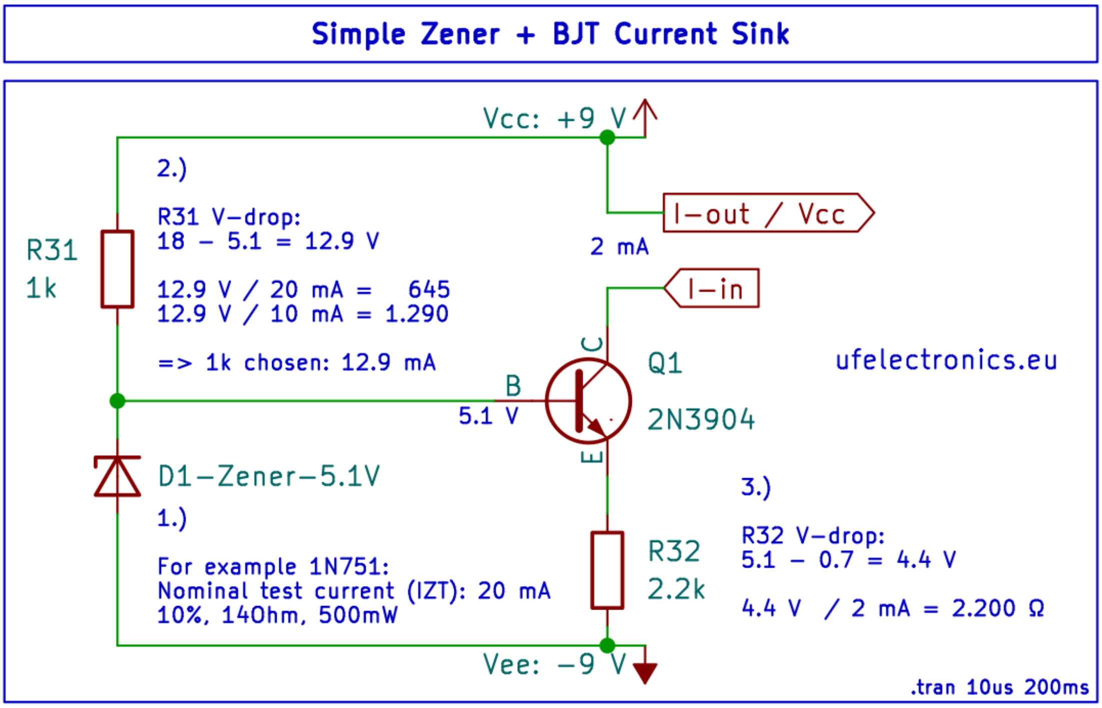
A current sink works in the opposite direction. Instead of supplying current from the positive supply rail, it pulls current towards ground or VEE. A typical connection is:

VCC -> Load -> Current Sink -> GND (or VEE)

The current sink controls how much current is allowed to flow through the load.

A current source is therefore normally connected between VCC and the load, while a current sink is normally connected between the load and GND. The function is the same: maintaining a controlled current through the circuit.

Simple Zener + BJT Current Sink - Schematic



In this circuit, the Zener diode provides a stable reference voltage to the base of the transistor. The transistor maintains an emitter voltage approximately one base-emitter voltage below the Zener voltage. Because the emitter resistor is fixed, the emitter current—and therefore nearly the collector current—remains almost constant. The emitter resistor R32 sets the current drawn from the load.

Compared with a simple resistor, an active current sink provides a much more stable operating current and is less sensitive to supply-voltage variations. Although the current is not perfectly constant, this circuit offers a simple and inexpensive introduction to active current regulation.

The sink current is approximately given by:

$$I\_SINK \approx (V\_Z - V\_BE) / R\_E$$

where:

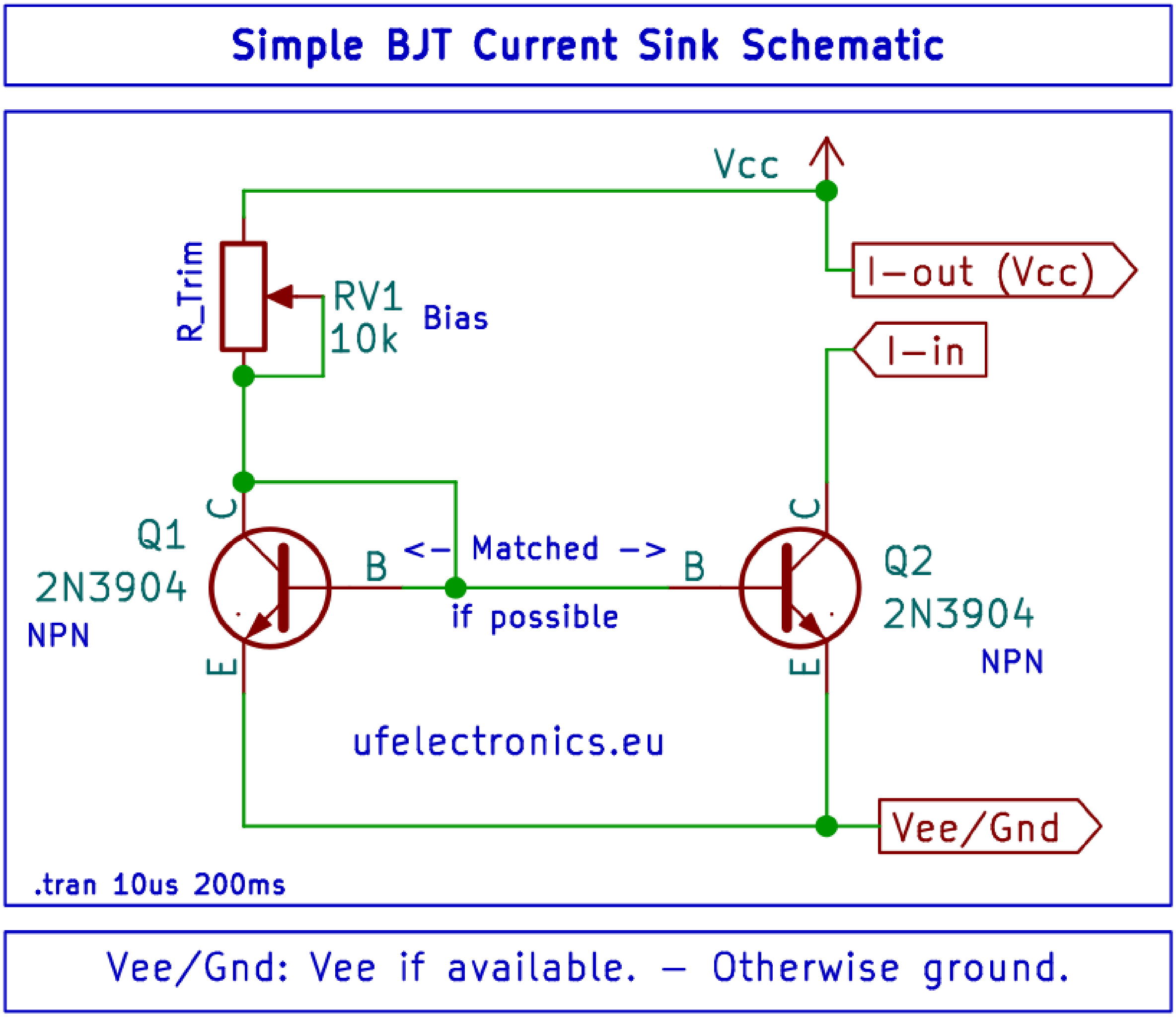
- V_Z = Zener voltage
- V_BE ≈ 0.65 V
- R_E = emitter resistor

Since I_C ≈ I_E the collector current is approximately equal to the calculated sink current.

The transistor must remain in its active region for the current sink to operate correctly. If the voltage across the transistor becomes too small, the circuit can no longer regulate the current, and the sink current will decrease.

Design Note: The Zener diode should be operated at its recommended current to maintain a stable reference voltage. If the Zener current becomes too low, the sink current will become less accurate.

Simple BJT Current Sink - Schematic



The first transistor is diode-connected and, together with the trimpot, establishes a reference current. The second transistor mirrors this current and provides the output current sink. Adjusting the trimpot changes the reference current and therefore the sink current supplied by the circuit.

The trimpot allows the sink current to be adjusted over a useful range, making the circuit suitable for experimentation and circuit biasing. Compared with a simple resistor, the current remains much more stable as the supply voltage and load conditions change.

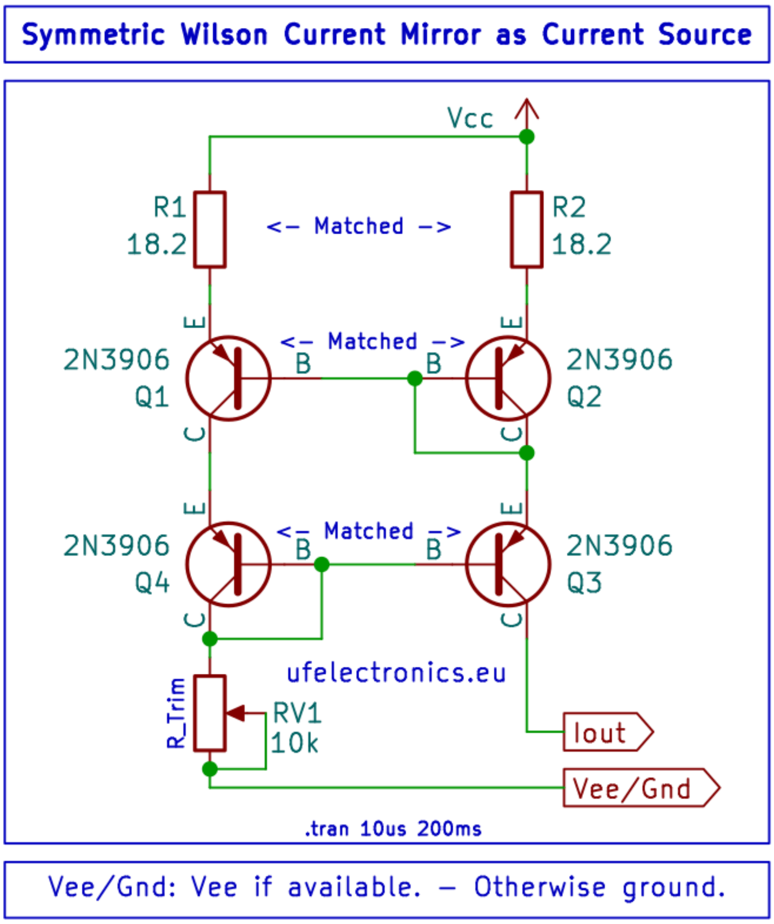
This circuit is an excellent introduction to transistor current mirrors, since many precision current-source circuits are based on the same operating principle.

Current Mirror

Current mirrors are a special type of current source or sink made using matched transistors. The purpose of a current mirror is to copy a reference current and reproduce it in another part of the circuit.

For example, a transistor current mirror can use one transistor with a known current flowing through it. A second transistor with the same characteristics will then produce approximately the same current. This allows a circuit to create stable bias currents without needing separate resistors for every stage.

Advanced Symmetric Wilson Current Mirror - Schematic



In the schematic to the left, R1 and R2 act as emitter-degeneration resistors. - These resistors improve current mirror performance by:

1) Making the V_BE - I_C relationship less transistor-dependent

Small emitter resistors convert variations in transistor β, V_BE, and device mismatch into small voltage drops across the resistors instead of directly affecting the transistor junctions.

2) Improving the matching of Q1 and Q2

Even if Q1 and Q2 have slightly different V_BE or β, the emitter resistors provide local negative feedback. If one transistor begins to conduct more current than the other, the increased voltage drop across its emitter resistor reduces its effective V_BE, helping to equalize the collector currents.

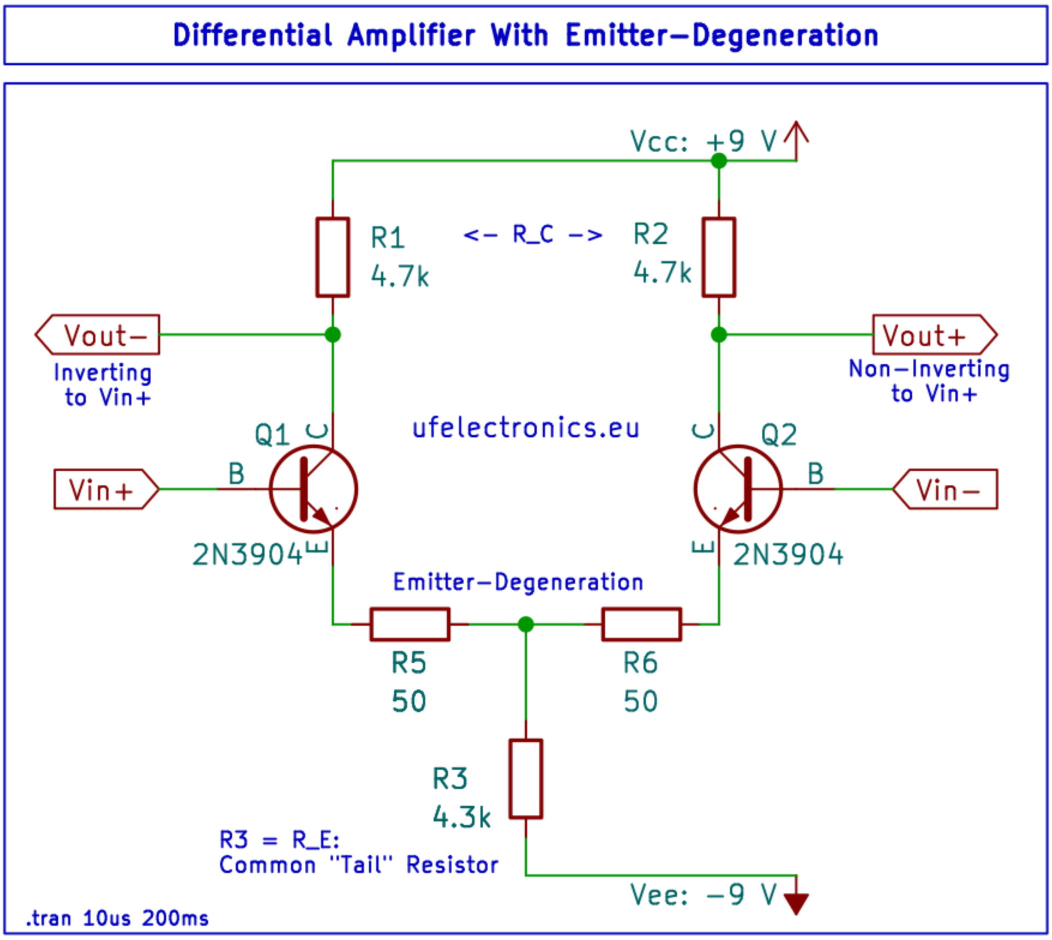
3) Reducing finite Early-voltage effects
Emitter degeneration increases the small-signal output resistance of the current mirror, making the output current less dependent on collector voltage.

Practical Design Guidelines

Typical V_BE mismatch for discrete BJTs: ΔV_BE = 1-5 mV To reduce the current mismatch to less than about 1%, choose: R1 = R2 >> ΔV_BE / I	Example If ΔV_BE ≈ 5 mV and the collector current is 1 mA: R >> (5 mV / 1 mA = 5 Ω) Common values in precision current mirrors: R1 = R2 = 10-22 Ω

('>>' means 'significantly higher')

Differential Amplifier - With Emitter-Degeneration



R5 and R6 act as emitter-degeneration resistors. They improve transistor matching, reduce distortion, make the differential amplifier less sensitive to transistor variations, increase the linear input range, and make the amplifier's gain more predictable.

Emitter-degeneration resistors provide several benefits, even in the simplest differential amplifier.

R3 (= R_E) is the common "tail" resistor.

Emitter-Degeneration Resistor Benefits Are:

1) Better Matching of the Two Transistors

Without R5 and R6, whichever transistor has the slightly lower V_BE tends to steal more current.

The emitter resistors provide negative feedback:

More collector current
-> larger voltage drop across the emitter resistor
-> emitter voltage rises
-> V_BE decreases
-> current is reduced again.

This naturally balances the currents in Q1 and Q2.

2) More Linear Operation

A differential pair without emitter degeneration has a very steep transfer characteristic. Adding emitter resistors spreads the transition over a larger input voltage range. Instead of switching abruptly from one transistor to the other, the current transfers much more gradually. - This reduces distortion.

3) Reduced Sensitivity to Transistor Parameters

The circuit becomes less dependent on

- β
- V_{BE}
- temperature
- transistor-to-transistor variation

The resistor voltage drops now determine part of the operating point instead of the transistor junctions alone.

4) Larger Differential Input Range

Without emitter resistors, only a few tens of millivolts of input difference are needed before one transistor carries nearly all the current.

With emitter degeneration, the amplifier remains in its linear region over a much larger input voltage difference.

5) Easier Gain Control

The small-signal voltage gain becomes approximately

$$A_V \approx R_C / (r_e + R_E)$$

where

- r_e is the transistor's intrinsic emitter resistance
- R_E is the emitter-degeneration resistor.

This makes the gain much more predictable.

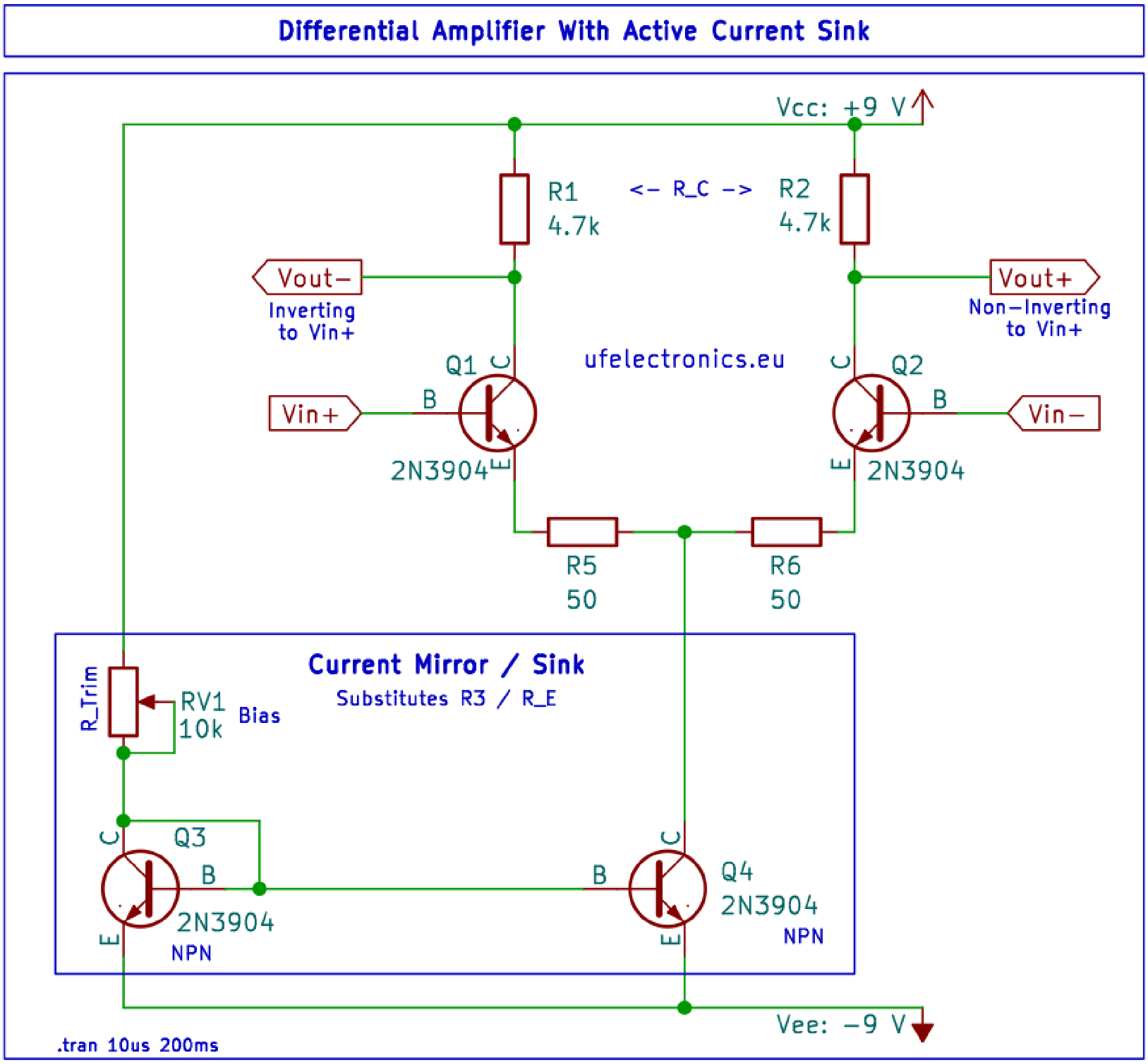
What They Do Not Do

The emitter resistors do not replace a proper current source. The common tail resistor R_E still allows the total emitter current to vary with supply voltage and common-mode input voltage.

A current sink or current mirror provides a much more constant tail current, resulting in:

- higher gain
- better common-mode rejection (CMRR)
- better PSRR, alias Power Supply Rejection Ratio
- improved symmetry

Differential Amplifier - With Active Current Sink



The tail resistor of the basic differential amplifier has in the following circuit been replaced by a transistor current sink.

An ideal tail current source maintains an almost constant current through the differential pair, independent of supply voltage and common-mode input voltage.

Compared to a simple tail resistor, this provides several advantages:

- Higher voltage gain
- Improved Common-Mode Rejection Ratio (CMRR)
- Better power-supply rejection
- More symmetrical operation
- More predictable operating point

The small emitter resistors R5 and R6 provide emitter degeneration, improving transistor matching, linearity and temperature stability.

Tail Current

Ignoring the small base current of Q4:

$$I\_TAIL \approx (VCC - VEE - V\_BE(Q3)) / RV1$$

Since

$V\_BE \approx 0.65$ V

the current can easily be adjusted with RV1.

Collector Current

With no differential input signal:

$$I\_C1 = I\_C2 \approx I\_TAIL / 2$$

Each transistor therefore carries half of the tail current.

Collector Voltage

$$V\_C = VCC - I\_C * R\_C$$

where

$R\_C = R1 = R2$

Differential Gain

Without emitter degeneration:

$$A\_D \approx R\_C / (2 * r\_e)$$

where

$r\_e \approx 26$ mV / I_E

With emitter degeneration:

$$A\_D \approx R\_C / (2 * (r\_e + R\_E))$$

where

$R\_E = R5 = R6$

This makes the gain slightly lower but considerably more linear.

Input Offset Voltage

Approximately

$$V\_OS \approx \Delta V\_BE$$

where

$\Delta V\_BE \approx 1...5$ mV (OS: OffSet)

for unmatched discrete transistors.

Common-Mode Gain

For a differential pair with a tail resistor:

$$A\_CM \approx R\_C / (2 * R\_TAIL)$$

where

$R\_TAIL = R3$

For a transistor current sink:

$$A\_CM \approx R\_C / (2 * r\_o)$$

where

r_o

is the output resistance of the current sink.

Since

$r\_o >> R3$

the common-mode gain becomes much smaller.

Common-Mode Rejection Ratio

$$CMRR = A\_D / A\_CM$$

or in decibels:

$$CMRR(dB) = 20 \log10(A\_D / A\_CM)$$

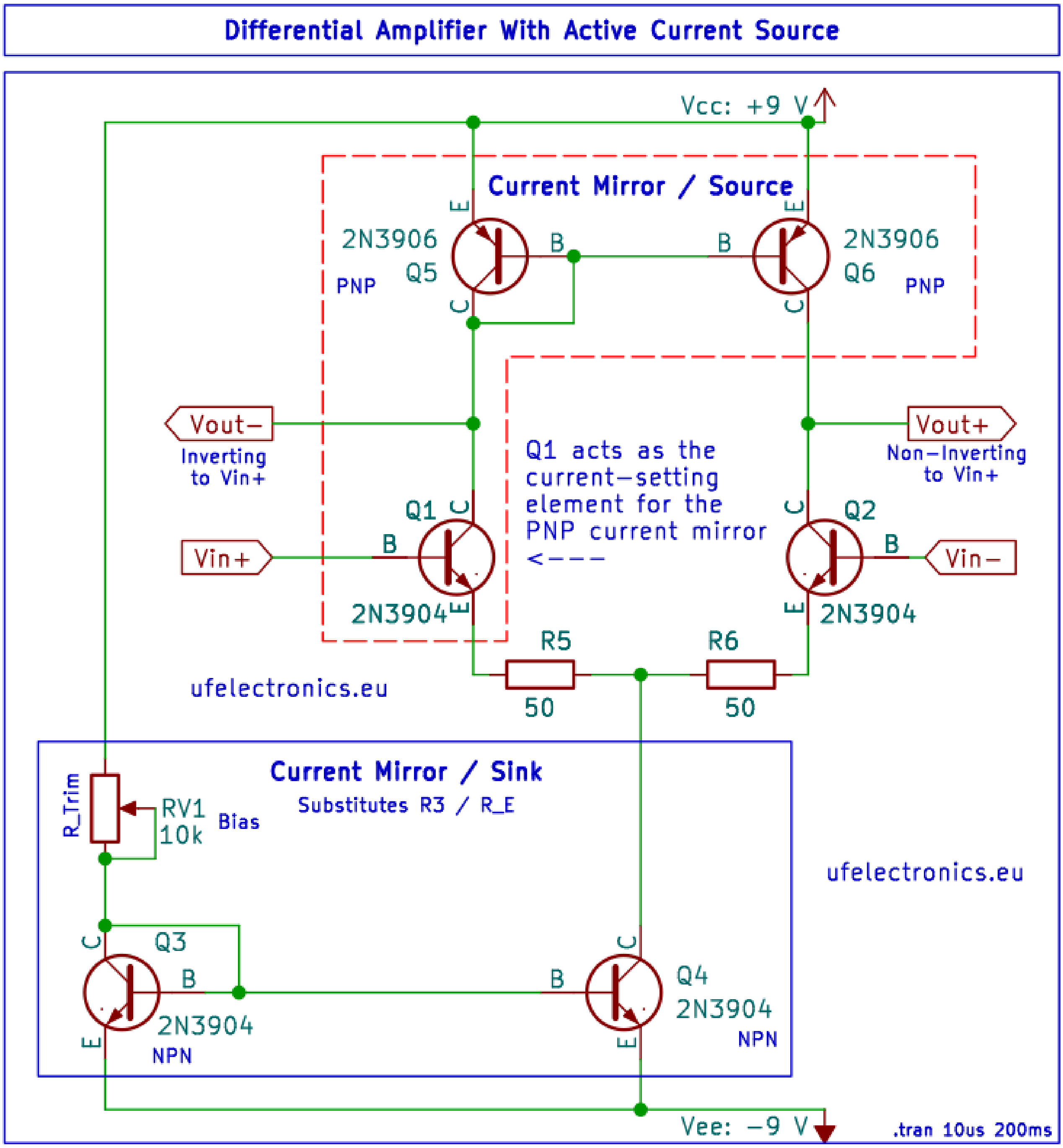
Higher CMRR means the amplifier responds mainly to the difference between Vin+ and Vin− while rejecting signals that appear equally on both inputs.

Example

Using the values shown: $R\_C = 4.7\ k\Omega$ $R\_E = 50\ \Omega$ $I\_TAIL = 2\ mA$ Each transistor conducts $I\_C \approx 1\ mA$ The intrinsic emitter resistance is $r\_e = 26\ mV / 1\ mA$ $r\_e \approx 26\ \Omega$	Therefore $r\_e + R\_E$ $= 26 + 50$ $= 76\ \Omega$ The differential voltage gain becomes approximately $A\_D \approx 4700 / (2 \times 76)$ $A\_D \approx 31$ or about 30 dB

Differential Amplifier - With Active Current Source

Replacing R1 and R2 with a current mirror, gives us the opportunity to let Q1 act as the current-setting element. - Just like we used a resistor earlier in the section 'Simple BJT Current Source - Schematic'.



Q1 effectively replaces the reference resistor found in a standalone current mirror. Instead of a resistor establishing the reference current, the collector current of Q1 becomes the reference current that the PNP current mirror reproduces in Q2's collector branch.

Why Replace the Collector Resistors?

In the previous differential amplifier, the collector resistors converted changes in collector current into output voltage.

Although simple and effective, they have several limitations.

The collector voltage changes according to

$$V_{OUT} = VCC - I_C * R_C$$

This means that the voltage gain is limited by the value of the collector resistors.

Increasing the resistor value increases the gain, but also increases the DC voltage drop across the resistor. Eventually there is not enough voltage left across the transistor for proper operation.

A different solution is therefore needed.

Active Collector Load

The two collector resistors are replaced by the PNP current mirror consisting of Q5 and Q6.

Unlike a resistor, a transistor current source behaves like a very large resistance while still supplying the required collector current.

This is known as an active load.

Because the active load has a much higher effective resistance than a normal resistor, the voltage gain of the differential amplifier increases significantly.

How the Current Mirror Works

Q5 is diode-connected.

Instead of using a resistor to establish the mirror current, the collector current of Q1 becomes the reference current.

Q6 copies this current into the collector branch of Q2.

As the collector current of Q1 changes, the current supplied by Q6 changes by nearly the same amount.

The current mirror therefore links the two collector branches together instead of allowing them to operate independently.

Why Does the Gain Increase?

Assume the current through Q1 increases slightly.

With collector resistors:

Q1 current increases
↓
Voltage across R1 increases
↓
Vout− decreases

Only the left output changes significantly.

With the active current mirror:

Q1 current increases
↓
Q5 reference current increases
↓
Q6 mirrored current increases
↓
Collector current of Q2 changes
↓
Both collector voltages change

Instead of only one collector responding, both collector branches participate in producing the output signal.

- The result is a much larger voltage swing.

Advantages

Replacing the collector resistors with an active current mirror provides:

- Much higher voltage gain.
- Higher effective collector load resistance.
- Better matching between the two collector branches.
- Improved differential operation.
- Larger output voltage swing.
- More efficient use of the available supply voltage.

Suggested Experiments

The following experiments are intended as suggestions rather than fixed laboratory exercises. They are arranged in a recommended order, gradually introducing more advanced differential amplifier concepts. Record your observations and compare the measured results with the theoretical values presented earlier in this documentation.

Experiment 1 – Basic Differential Amplifier

Build the basic differential amplifier using collector resistors (R1 and R2) and a common tail resistor (R3). Do not install emitter-degeneration resistors (R5 and R6) or any active current source or current sink.

Before applying an input signal, measure the DC operating point:

- Supply voltages (VCC and VEE)
- Collector voltages of Q1 and Q2
- Base voltages of Q1 and Q2
- Emitter voltage (TP7)

Verify that:

- Q1 and Q2 have approximately equal collector voltages.
- Both transistors share the tail current approximately equally.
- The collector voltages are close to the expected quiescent operating point.

Next, apply a small input signal to **Vin+** while keeping **Vin−** at a fixed reference voltage. Observe the collector voltages and verify that:

- An increase in collector current through one transistor results in a corresponding decrease in the other.
- The two collector outputs move in opposite directions.
- The amplifier responds to the difference between the two input voltages.

Record your measurements and compare them with the calculated values presented earlier in this documentation.

Questions to consider

- Why are the collector voltages approximately equal?
- What happens if one transistor is replaced with a different type?
- Why do the collector voltages move in opposite directions?
- What would happen if R3 were made much larger or much smaller?

Experiment 2 – Emitter Degeneration

Install the emitter-degeneration resistors **R5** and **R6**, then repeat the measurements performed in Experiment 1.

Compare the circuit's behavior with and without emitter degeneration. Measure the small-signal voltage gain and observe any changes in the DC operating point.

Verify that:

- The voltage gain decreases.
- The DC operating point remains approximately unchanged.
- The amplifier responds more gradually to changes in the input voltage.
- The collector voltages remain more symmetrical.

Record your measurements and compare them with the theoretical values presented earlier in this documentation.

Questions to Consider

- Why does adding emitter resistors reduce the voltage gain?
- How do R5 and R6 improve the linearity of the differential amplifier?
- Why does emitter degeneration make the amplifier less sensitive to transistor variations?
- What happens to the differential pair if the values of R5 and R6 are increased further?
- Is the reduction in gain worth the improvements in stability and linearity?

Experiment 3 – Active Current Sink

Replace the tail resistor **R3** with an active current sink. Leave all other circuit components unchanged.

Repeat the measurements performed in Experiments 1 and 2. Measure the DC operating point and compare the collector voltages with those obtained using the tail resistor.

If possible, vary the supply voltage over a small range (for example, ±1 V) and observe how the collector voltages and tail current change.

Verify that:

- The collector voltages remain more stable.
- The operating point is less sensitive to supply-voltage variations.
- The tail current remains nearly constant.
- The differential amplifier exhibits more symmetrical operation.

Record your measurements and compare them with the theoretical values presented earlier in this documentation.

Questions to Consider

- Why does an active current sink provide a more constant tail current than a resistor?
- How does a constant tail current improve the operation of the differential amplifier?
- Which amplifier characteristics are improved by replacing the tail resistor with an active current sink?
- How does the active current sink influence the Common-Mode Rejection Ratio (CMRR)?
- Why is an active current sink commonly used in operational amplifier input stages?

Experiment 4 – Active Current Source

Replace the collector resistors **R1** and **R2** with an active current source (current mirror). Keep the active current sink from Experiment 3 in place.

Repeat the measurements performed in the previous experiments. Measure the DC operating point and compare the collector voltages and output signal with those obtained using resistor collector loads.

Apply a small differential input signal and observe how the output voltage changes.

Verify that:

- The collector currents are established by the active current source.
- The collector voltages remain at a suitable operating point.
- The output voltage swing increases.
- The differential voltage gain increases compared with the resistor-loaded version.
- Both collector branches participate in producing the output signal.

Record your measurements and compare them with the theoretical values presented earlier in this documentation.

Questions to Consider

- Why does an active current source behave like a much larger collector resistance than a resistor?
- Why does replacing the collector resistors increase the voltage gain?
- How does the current mirror link the two collector branches together?
- Why do many operational amplifier input stages use an active current source instead of collector resistors?
- Which improvement has the greatest effect on amplifier performance: the active current sink (Experiment 3) or the active current source (this experiment)? Explain your reasoning.

Experiment 5 – Voltage Gain

Apply a small sinusoidal input signal to **Vin+** while keeping **Vin−** at a fixed reference voltage. Adjust the input amplitude so that the differential amplifier operates within its linear region.

Measure the input and output signal amplitudes using an oscilloscope, then calculate the small-signal voltage gain using:

$A_V = V_{OUT} / V_{IN}$

Repeat the measurements for several circuit configurations, such as:

- Basic differential amplifier.
- Differential amplifier with emitter degeneration.
- Differential amplifier with an active current sink.
- Differential amplifier with both an active current sink and an active current source.

Compare the measured voltage gains with the calculated values presented earlier in this documentation.

Verify that:

- The measured gain is reasonably close to the calculated value.
- Emitter degeneration reduces the voltage gain.
- The active current sink improves the stability of the operating point.
- The active current source (active collector load) provides the highest voltage gain.

Record your measurements and compare the different circuit configurations.

Questions to Consider

- Why is the measured voltage gain different from the calculated value?
- Which assumptions were made in the small-signal analysis?
- How does transistor mismatch influence the measured gain?
- Why does emitter degeneration reduce the voltage gain while improving linearity?
- Which circuit modification provides the greatest increase in voltage gain?
- At what input signal amplitude does the amplifier begin to leave its linear operating region?

Experiment 6 – Common-Mode Rejection Ratio (CMRR)

Apply the same sinusoidal signal, with the same amplitude and phase, to both **Vin+** and **Vin−**.

Measure the output signal using an oscilloscope. Ideally, the output should remain unchanged because the amplifier responds only to the difference between the two input voltages.

Next, apply the signal to only one input (or apply equal but opposite signals to the two inputs) and compare the output amplitude with the common-mode measurement.

Estimate the Common-Mode Rejection Ratio (CMRR) by comparing the differential gain with the common-mode gain.

Verify that:

- The output signal is much smaller when identical signals are applied to both inputs.
- The amplifier responds primarily to the voltage difference between the inputs.
- Common-mode signals are largely rejected.
- The measured CMRR improves when using an active current sink.

Record your measurements and compare them with the theoretical discussion presented earlier in this documentation.

Questions to Consider

- Why does a differential amplifier reject signals that appear equally on both inputs?
- Why is the measured output not exactly zero during common-mode operation?
- Which circuit components have the greatest influence on the CMRR?
- How does replacing the tail resistor with an active current sink improve the CMRR?
- How would transistor mismatch affect the measured CMRR?
- Why is a high CMRR important in practical applications such as sensor amplifiers and operational amplifiers?

Experiment 7 – Transistor Matching

Replace one of the transistors with another device of the same type, but with different electrical characteristics. Repeat the measurements performed in the previous experiments.

Measure the DC operating point, the collector voltages, and the input offset voltage. Compare the circuit's behavior with that obtained using a well-matched transistor pair.

If several transistors are available, try different combinations and observe how the circuit performance changes.

Verify that:

- The collector voltages are no longer identical.
- A measurable input offset voltage is introduced.
- The current is no longer shared equally between the two transistors.
- The symmetry of the differential amplifier is reduced.

Record your measurements and compare them with those obtained using a better-matched transistor pair.

Questions to Consider

- Why do two transistors with the same part number not behave exactly the same?
- Which transistor parameters have the greatest influence on matching (for example, **V_BE**, **β**, and leakage current)?
- How does transistor mismatch affect the input offset voltage?
- How does emitter degeneration help reduce the effects of transistor mismatch?
- Would an active current sink eliminate the effects of transistor mismatch? Why or why not?
- Why are matched transistor pairs often used in precision analog circuits and operational amplifiers?

Experiment 8 – JFET Current Sink

Replace the transistor current sink with a JFET current sink of similar current rating. Keep the remainder of the differential amplifier unchanged.

Repeat the measurements performed in the previous experiments. Measure the DC operating point, collector voltages and small-signal voltage gain. If possible, also estimate the Common-Mode Rejection Ratio (CMRR).

Compare the performance of the JFET current sink with that of the transistor current sink.

Verify that:

- The differential amplifier operates correctly with the JFET current sink.
- The tail current remains nearly constant.
- The operating point is stable over a range of supply voltages.
- The measured voltage gain is similar to that obtained with the transistor current sink.
- The Common-Mode Rejection Ratio remains high.

Record your measurements and compare them with those obtained using the transistor current sink.

Questions to Consider

- How does a JFET current sink differ from a transistor current sink?
- What are the advantages of using a JFET as a current sink?
- What are the limitations of a JFET current sink compared with a transistor current sink?
- Which current sink is easier to construct and adjust?
- Which current sink provides the most stable operating point?
- In which applications would you choose a JFET current sink instead of a transistor current sink?

After completing all eight experiments, which current-sink implementation would you choose for a practical differential amplifier, and why?

Experiment 9 – Differential vs. Common-Mode Signals

Configure the differential amplifier using the circuit version that provides the best overall performance (for example, with an active current sink, emitter degeneration and, if available, an active current source).

First, apply the same sinusoidal signal, with identical amplitude and phase, to both **Vin+** and **Vin−**. Observe and measure the output signal.

Next, apply equal-amplitude signals that are **180° out of phase** (or apply the signal to only one input while keeping the other at a fixed reference voltage). Again, observe and measure the output signal.

Compare the output amplitudes obtained under common-mode and differential operation, and relate your observations to the concepts of differential gain and Common-Mode Rejection Ratio (CMRR).

Verify that:

- Common-mode signals produce little or no output.
- Differential signals produce a much larger output.
- The amplifier responds primarily to the voltage difference between the two inputs.
- The measured results agree with the expected differential amplifier behavior.

Record your measurements and compare them with the theoretical discussion presented earlier in this documentation.

Questions to Consider

- Why does the differential amplifier reject common-mode signals?
- Why are differential signals amplified while common-mode signals are suppressed?
- Which circuit modifications made during the previous experiments contributed most to improving the CMRR?
- What practical sources of common-mode signals exist in real electronic systems?
- Why are differential amplifiers widely used for sensor interfaces, communication systems and operational amplifier input stages?
- If the common-mode output is larger than expected, what circuit imperfections or measurement errors might be responsible?

Suggestions?

Have suggestions for improvements, or need a personalized PCB design? - Feel free to get in touch:

Contact

https://ufelectronics.eu/about/contact/

Social

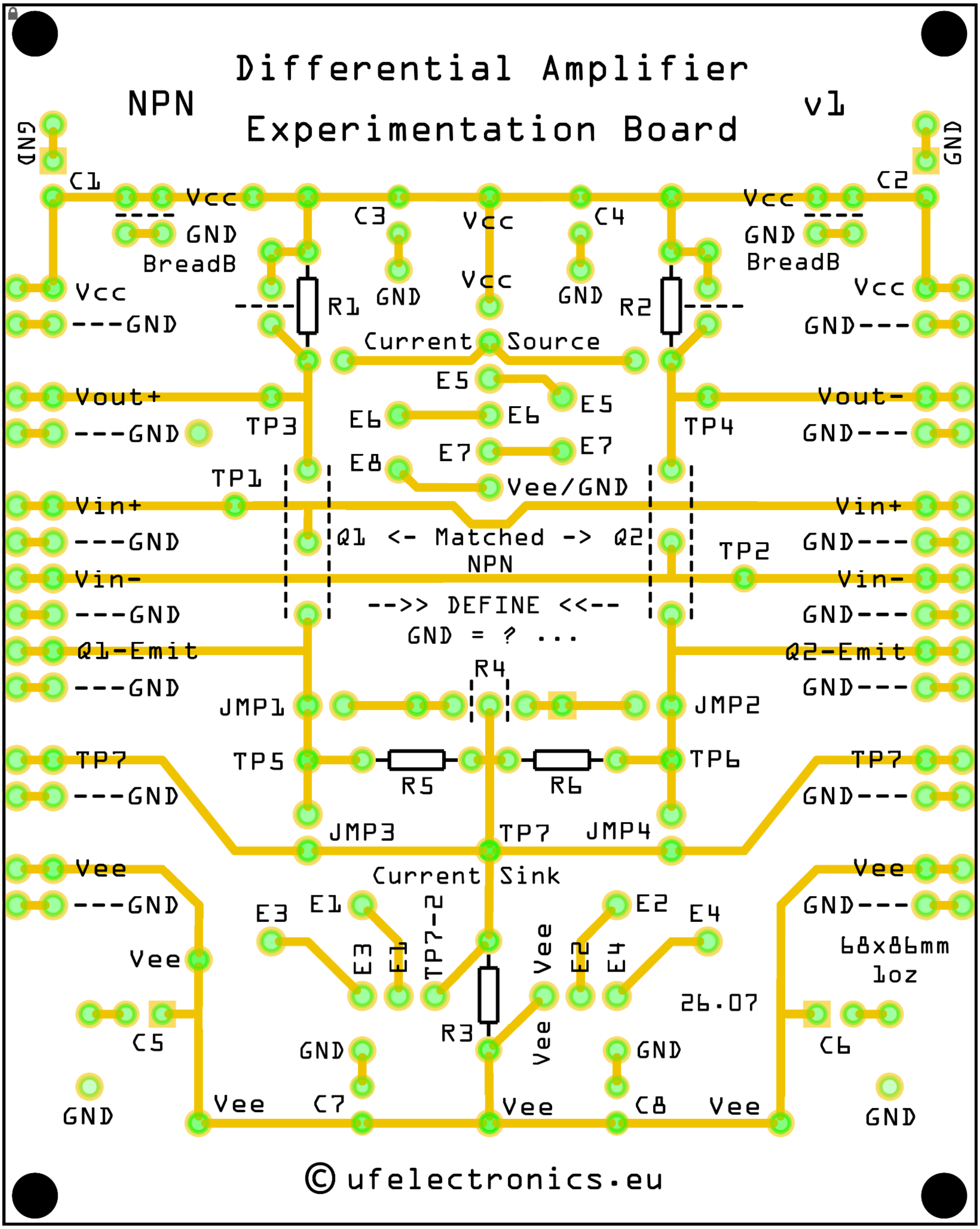
YouTube: https://www.youtube.com/@ufelectronics

Discord: https://discord.com/channels/1373552306817339535/1373552307467325542

Facebook: https://www.facebook.com/profile.php?id=61577320711532

LinkedIn: https://www.linkedin.com/company/ufelectronics/posts/?feedView=all

Semi-Schematic PCB Layout



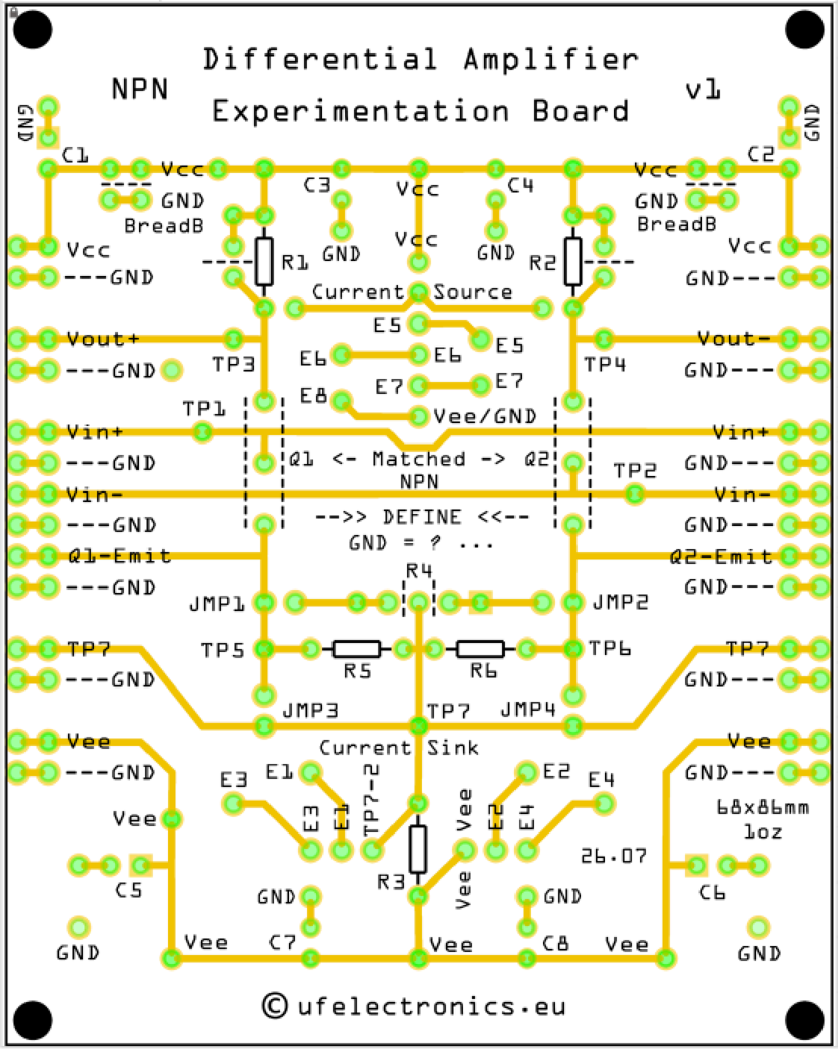
The figure above shows the routing on the top layer of the PCB. - Ground is routed on the bottom side of the PCB. The bottom layer with the ground plane is not visible in the figure above.

Assembly Sheet

Differential Amplifier - v1 - Assembly Sheet

Circuit .... :

Vers. / Date :



Resistors	Value	Capacitors	Value
R1		C1	
R2		C2	
R3		C3	
R4		C4	
R5		C5	
R6		C6	
		C7	
		C8	
Q1			
Q2			

Notes Vcc: