

## The Four Basic Building Blocks of an Op Amp

Operational amplifiers are the main building block of analog systems. They can provide gain, buffering, filtering, mixing and multiple mathematic functions. In system diagrams, they are represented by a triangle with 5 connections: positive supply, negative supply, positive input, negative input and output (Figure 1). The supply pins are used for powering the device. They might be connected to  $\pm 5V$ , for example, or with special consideration, be connected to  $+10V$  and ground. The relationship between the outputs and the inputs is straightforward:

$$V_{out} = A (V_{in+} - V_{in-}) \quad (EQ. 1)$$

Which means that the output voltage is equal to the gain (A) of the amplifier times the difference of the input voltages.

Many engineers never need to know what happens inside this magical triangle. Have you ever been curious? There are four basic sections: bias, 2:1, gain and buffer (Figure 2). These four stages can be combined in some op amp devices, but the four functions are fundamental.

### Bias Section

The bias section provides all of the voltages and currents needed by the other 3 sections. When you dive into this section, you find circuits like bandgaps and current mirrors. Bandgaps are small circuits that provide a constant voltage. Although that may seem like an easy task, the voltage must be constant even if the supply voltage changes or if the temperature changes. These effects can be larger than you expect, so they must be planned for and canceled out.

Current mirrors take a given current and create copies of it for other circuits. By sizing the transistors or placing multiple mirrors in parallel, these currents can be properly sized as well. This powerful technique allows the op amp designer to scale the amount of current into each stage. The bias section often consumes a very small fraction of the total current while the buffer stage consumes the most on-demand current to drive an output load.

### 2:1 Section

Given that an op amp has two inputs and one output, there has to be a 2:1 stage somewhere inside. This may be very close to the input or later in the signal path. In the simplest form, the circuit that performs this action is called a differential pair. A differential pair is two transistors hooked to a common current source, as in Figure 3. The operation of this circuit is much like a seesaw. On a seesaw, either side can adjust the balance. If I'm on one side and you are on the other, I can raise, which causes your side to lower. If instead I drop my side, then your side raises. If we correlate height of each side of the seesaw with the amount of current that flows through each side of the differential pair, you've got it! In this way, the non-inverting input controls one side of the circuit and the inverting input controls the other side of the circuit. Whichever side has a larger input voltage will have larger current.

Let's think about what happens when both sides have the same voltage. Remember the seesaw? If you and I exert the same amount of pressure (weight) on both sides of the seesaw, who's side will be higher? Neither! They will be the same height. What happens if we both apply more pressure? If we both apply the same amount of pressure, then the seesaw stays balanced. The only way the seesaw will move is if one of us applies more pressure than the other. Another way of looking at this is to say that the seesaw will only respond to differences in pressure. That is exactly the way the inputs of the differential pair (and the inputs of the op amp) work.

Achieving the 2:1 function is easier than you might expect. In the differential circuit shown in Figure 3, there are two inputs and two outputs. A 2:1 circuit would only have one output. Ok, then let's ignore one of the outputs. That may seem crude, but it's been done many times. There are extra transistors you can add to the unused side if you want to fold and sum the currents back together, but they aren't necessary. It all depends on what you are optimizing for. For example, if you are optimizing for space or simplicity, then there is no need for the extra circuitry.

The critical parameter of this section is offset voltage. Back to the seesaw; what if I installed a comfy chair on my side? You would have to add pressure/weight to your side (without the comfy chair) just to balance the seesaw. The same can occur with the transistors. Offset appears if the two transistors composing the differential pair aren't exactly the same size or shape. Designers do their best to create exactly duplicate transistors, but their efforts can be limited by available space or even the structure of the equipment used to fabricate the integrated circuit.

### Gain Section

Gain means the output is bigger than the input. If your investments gain, you have more money. If your investments go down, you lose money. Since an op amp's primary role is to provide gain, this is the flagship section of the device. In an ideal op amp, the gain is infinite. That means that the smallest difference in the input voltages causes the output to slam up or slam down. Luckily, the power supplies limit how far the output can travel, so the output doesn't have to reach thousands or millions of volts in the positive or negative direction. In the simplest form, the gain function can be provided by a single transistor. If a single transistor can provide gain, why do we need to collect many of them to create an op amp? A single transistor has one input and one output. The op amp needs two balanced inputs and more gain than a single transistor can provide.

Since this section has the largest amount of gain, it is also the section where we would include compensation. Compensation in an op amp has nothing to do with your paycheck. Compensation means creating stability. Let me offer a bit of intuition.

With lots of gain, a small input signal will cause a very large output signal. Similarly, if the input voltage changes from zero to small, the output would have to change from zero to large. The larger the gain or the faster the input changes, the faster we need the output to respond. Fast circuits need more control. Think about all the feedback and support that goes into driving a race car at 200mph. There's an entire pit crew needed. Now think about what is needed to drive a golf cart. It's much easier and takes much less skill to drive a golf cart. Going back to the circuit from this analogy, the race car would need a lot of compensation to keep it stable (keep it from crashing) while the golf cart would need very little, if any compensation. Compensation in op amps takes the form of a capacitance, shown in Figure 2 connected between the input and output of the gain stage.

### Buffer Stage

The buffer stage serves two critical functions. First, it protects the gain circuit from anything that can be connected to the output. Secondly, it drives the load. That means it can provide the current needed to take the load to the correct output voltage. This stage provides no gain, which means that the input voltage and the output voltage are the same size. Instead, it provides more current, which translates into more power. Think of it like training in the U.S. Army. A colonel could go and fight with all of his skills, but if he teaches those skills to an entire battalion, the force of the group is far stronger. This is very similar to the action of a buffer. The output tracks the input to the best of its ability with the force of a larger current, making its Army strong.

When examining output stages, you will find different classes: A, AB, B, C and more down the alphabet. Class A is the simplest stage with the most linearity, but also burns the most power.

Class B and C are related, each slicing away different parts of the output signal to adjust for offsets needed to turn on transistors. There are many other output stage circuits. Some include transformers, some use transmission lines and some use clocked signals. All have been optimized for specific applications. There is a plethora of information available if you want to learn more.

### Bringing It All Together

What is an op amp? It's a seesaw on a race car followed by an army battalion fueled by the nourishment of the bias section (I wouldn't suggest putting that on a T-shirt or sharing this with one of your company's technical fellows). Truly, it is a unique device that provides so many wonderful functions. The balanced input creates the perfect opportunity to allow for feedback. Feedback will allow us to control gain, to trade it for bandwidth and performance and to stability systems.

For now, let us celebrate the four main blocks that make the op amp a pillar of the analog community. Whether you use 5 transistors or 500, an appreciation and understanding of those internal circuits empowers you to find new ways to use the greatest analog building block, the op amp. To find a useful parametric search tool for different kind of op amps, go to <http://www.intersil.com/amps/>.

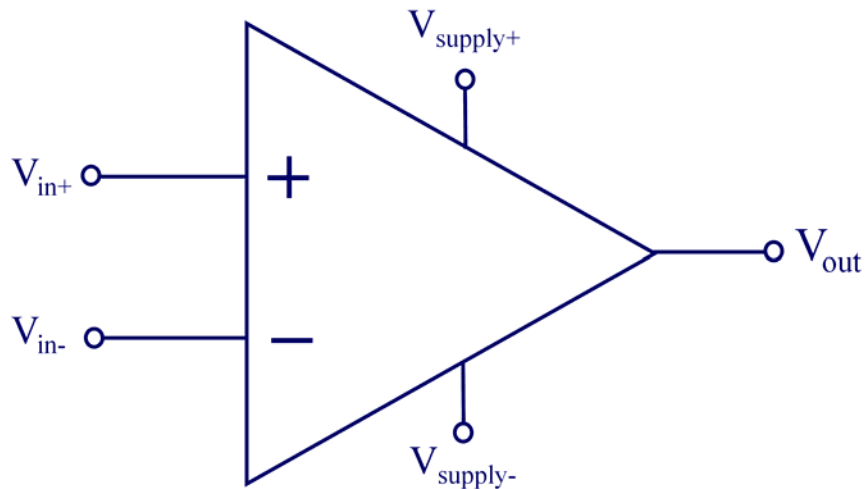


FIGURE 1. THE COMMON INPUT AND OUTPUT PINS OF AN OP AMP

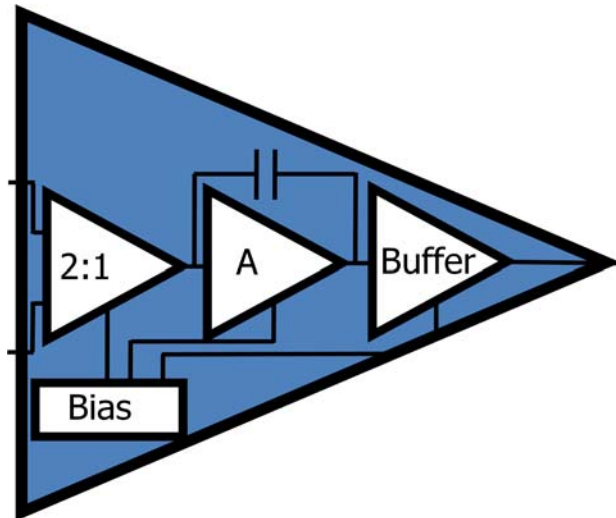


FIGURE 2. THE FOUR INTERNAL BLOCKS OF AN OP AMP

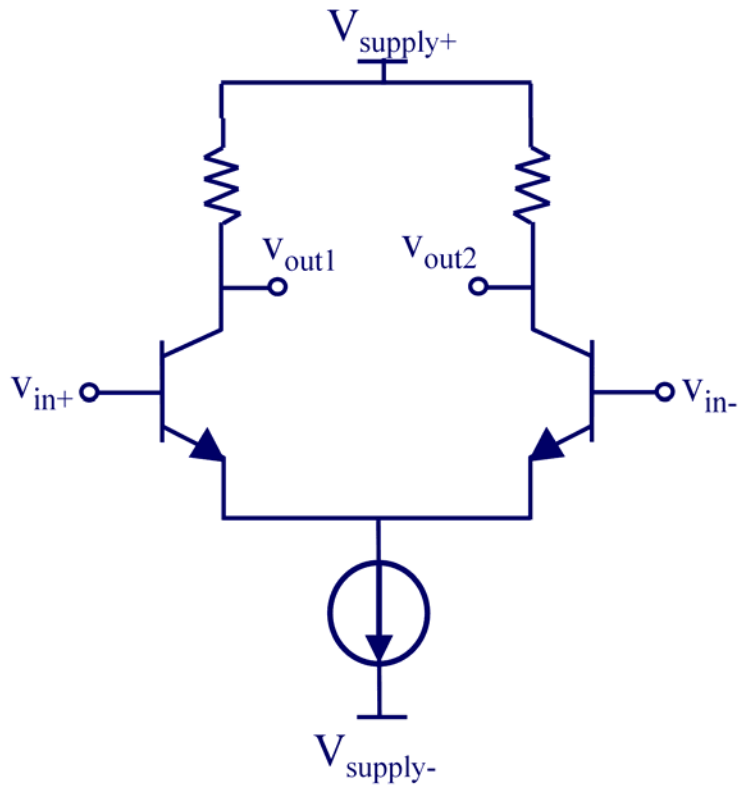


FIGURE 3. SIMPLE 2:1 STAGE

## Notice

1. Descriptions of circuits, software and other related information in this document are provided only to illustrate the operation of semiconductor products and application examples. You are fully responsible for the incorporation or any other use of the circuits, software, and information in the design of your product or system. Renesas Electronics disclaims any and all liability for any losses and damages incurred by you or third parties arising from the use of these circuits, software, or information.
  2. Renesas Electronics hereby expressly disclaims any warranties against and liability for infringement or any other claims involving patents, copyrights, or other intellectual property rights of third parties, by or arising from the use of Renesas Electronics products or technical information described in this document, including but not limited to, the product data, drawings, charts, programs, algorithms, and application examples.
  3. No license, express, implied or otherwise, is granted hereby under any patents, copyrights or other intellectual property rights of Renesas Electronics or others.
  4. You shall not alter, modify, copy, or reverse engineer any Renesas Electronics product, whether in whole or in part. Renesas Electronics disclaims any and all liability for any losses or damages incurred by you or third parties arising from such alteration, modification, copying or reverse engineering.
  5. Renesas Electronics products are classified according to the following two quality grades: "Standard" and "High Quality". The intended applications for each Renesas Electronics product depends on the product's quality grade, as indicated below.  
"Standard": Computers; office equipment; communications equipment; test and measurement equipment; audio and visual equipment; home electronic appliances; machine tools; personal electronic equipment; industrial robots; etc.  
"High Quality": Transportation equipment (automobiles, trains, ships, etc.); traffic control (traffic lights); large-scale communication equipment; key financial terminal systems; safety control equipment; etc.  
Unless expressly designated as a high reliability product or a product for harsh environments in a Renesas Electronics data sheet or other Renesas Electronics document, Renesas Electronics products are not intended or authorized for use in products or systems that may pose a direct threat to human life or bodily injury (artificial life support devices or systems; surgical implantations; etc.), or may cause serious property damage (space system; undersea repeaters; nuclear power control systems; aircraft control systems; key plant systems; military equipment; etc.). Renesas Electronics disclaims any and all liability for any damages or losses incurred by you or any third parties arising from the use of any Renesas Electronics product that is inconsistent with any Renesas Electronics data sheet, user's manual or other Renesas Electronics document.
  6. When using Renesas Electronics products, refer to the latest product information (data sheets, user's manuals, application notes, "General Notes for Handling and Using Semiconductor Devices" in the reliability handbook, etc.), and ensure that usage conditions are within the ranges specified by Renesas Electronics with respect to maximum ratings, operating power supply voltage range, heat dissipation characteristics, installation, etc. Renesas Electronics disclaims any and all liability for any malfunctions, failure or accident arising out of the use of Renesas Electronics products outside of such specified ranges.
  7. Although Renesas Electronics endeavors to improve the quality and reliability of Renesas Electronics products, semiconductor products have specific characteristics, such as the occurrence of failure at a certain rate and malfunctions under certain use conditions. Unless designated as a high reliability product or a product for harsh environments in a Renesas Electronics data sheet or other Renesas Electronics document, Renesas Electronics products are not subject to radiation resistance design. You are responsible for implementing safety measures to guard against the possibility of bodily injury, injury or damage caused by fire, and/or danger to the public in the event of a failure or malfunction of Renesas Electronics products, such as safety design for hardware and software, including but not limited to redundancy, fire control and malfunction prevention, appropriate treatment for aging degradation or any other appropriate measures. Because the evaluation of microcomputer software alone is very difficult and impractical, you are responsible for evaluating the safety of the final products or systems manufactured by you.
  8. Please contact a Renesas Electronics sales office for details as to environmental matters such as the environmental compatibility of each Renesas Electronics product. You are responsible for carefully and sufficiently investigating applicable laws and regulations that regulate the inclusion or use of controlled substances, including without limitation, the EU RoHS Directive, and using Renesas Electronics products in compliance with all these applicable laws and regulations. Renesas Electronics disclaims any and all liability for damages or losses occurring as a result of your noncompliance with applicable laws and regulations.
  9. Renesas Electronics products and technologies shall not be used for or incorporated into any products or systems whose manufacture, use, or sale is prohibited under any applicable domestic or foreign laws or regulations. You shall comply with any applicable export control laws and regulations promulgated and administered by the governments of any countries asserting jurisdiction over the parties or transactions.
  10. It is the responsibility of the buyer or distributor of Renesas Electronics products, or any other party who distributes, disposes of, or otherwise sells or transfers the product to a third party, to notify such third party in advance of the contents and conditions set forth in this document.
  11. This document shall not be reprinted, reproduced or duplicated in any form, in whole or in part, without prior written consent of Renesas Electronics.
  12. Please contact a Renesas Electronics sales office if you have any questions regarding the information contained in this document or Renesas Electronics products.
- (Note 1) "Renesas Electronics" as used in this document means Renesas Electronics Corporation and also includes its directly or indirectly controlled subsidiaries.  
(Note 2) "Renesas Electronics product(s)" means any product developed or manufactured by or for Renesas Electronics.

(Rev.4.0-1 November 2017)



### SALES OFFICES

Renesas Electronics Corporation

<http://www.renesas.com>

Refer to "<http://www.renesas.com/>" for the latest and detailed information.

**Renesas Electronics America Inc.**  
1001 Murphy Ranch Road, Milpitas, CA 95035, U.S.A.  
Tel: +1-408-432-8888, Fax: +1-408-434-5351

**Renesas Electronics Canada Limited**  
9251 Yonge Street, Suite 8309 Richmond Hill, Ontario Canada L4C 9T3  
Tel: +1-905-237-2004

**Renesas Electronics Europe Limited**  
Dukes Meadow, Millboard Road, Bourne End, Buckinghamshire, SL8 5FH, U.K  
Tel: +44-1628-651-700, Fax: +44-1628-651-804

**Renesas Electronics Europe GmbH**  
Arcadiastrasse 10, 40472 Düsseldorf, Germany  
Tel: +49-211-6503-0, Fax: +49-211-6503-1327

**Renesas Electronics (China) Co., Ltd.**  
Room 1709 Quantum Plaza, No.27 ZhichunLu, Haidian District, Beijing, 100191 P. R. China  
Tel: +86-10-8235-1155, Fax: +86-10-8235-7679

**Renesas Electronics (Shanghai) Co., Ltd.**  
Unit 301, Tower A, Central Towers, 555 Langao Road, Putuo District, Shanghai, 200333 P. R. China  
Tel: +86-21-2226-0888, Fax: +86-21-2226-0999

**Renesas Electronics Hong Kong Limited**  
Unit 1601-1611, 16/F., Tower 2, Grand Century Place, 193 Prince Edward Road West, Mongkok, Kowloon, Hong Kong  
Tel: +852-2265-6688, Fax: +852-2886-9022

**Renesas Electronics Taiwan Co., Ltd.**  
13F, No. 363, Fu Shing North Road, Taipei 10543, Taiwan  
Tel: +886-2-8175-9600, Fax: +886-2-8175-9670

**Renesas Electronics Singapore Pte. Ltd.**  
80 Bendemeer Road, Unit #06-02 Hyflux Innovation Centre, Singapore 339949  
Tel: +65-6213-0200, Fax: +65-6213-0300

**Renesas Electronics Malaysia Sdn.Bhd.**  
Unit 1207, Block B, Menara Amcorp, Amcorp Trade Centre, No. 18, Jln Persiaran Barat, 46050 Petaling Jaya, Selangor Darul Ehsan, Malaysia  
Tel: +60-3-7955-9390, Fax: +60-3-7955-9510

**Renesas Electronics India Pvt. Ltd.**  
No.777C, 100 Feet Road, HAL 2nd Stage, Indiranagar, Bangalore 560 038, India  
Tel: +91-80-67208700, Fax: +91-80-67208777

**Renesas Electronics Korea Co., Ltd.**  
17F, KAMCO Yangjae Tower, 262, Gangnam-daero, Gangnam-gu, Seoul, 06265 Korea  
Tel: +82-2-558-3737, Fax: +82-2-558-5338