Andy's Analog Quiz 1 – Basic Op Amp Circuits: Correct Answers & Explanations

1. Something Else

Don't get discouraged — this question was to see if you're awake and paying attention — the rest will be straightforward.

Though this circuit may look very familiar, the feedback path going to the positive input makes it a completely different beast than what you may have thought it was at a casual glance.

This circuit is a non-inverting Schmitt trigger.

Schmitt triggers are similar to comparators, but their reference voltage changes, depending on the state of the op amp's output, which goes to the rails when the magnitude of the input signal exceeds the magnitude of the threshold voltage. Because of the dynamic change in the reference voltage, Schmitt triggers have hysteresis for when the output will switch to the positive rail vs. the negative rail, which is very useful for low frequency, slow rise/fall, or noisy input signals.

2. Either an amplifier or attenuator, depending on R1 and R2

This circuit is the classic inverting amplifier that can have:

1) gain if R2 > R1

2) attenuation if R2 < R1

The relationship of Vout/Vin is simply R2/R1.

In practice, a resistor equaling the value of R1 in parallel with R2, versus the direct connection, to ground from the negative input can be used to reduce errors in the output due to input bias currents.

3. An integrator

This is another classical topology that performs the mathematical integral of the input. For example, a square wave in Vin will produce a ramp from zero while the square wave is positive, then will change direction to an opposite slope ramp when the input square-wave amplitude is negative. It is a sort of low-pass filter, if you ignore the textbooks.

The formula to predict the output voltage, Vout, for the op amp integrator is: Vout(t) = – (1 / (R1 * C1)) * ∫Vin(t) dt

4. A differentiator

This is another classical topology that performs the mathematical differentiation of the input.

For example a triangle wave of Vin will produce a constant output square wave if the input keeps a constant slope while the triangle wave is ramping, then will switch to an opposite polarity of the square wave when the input triangle wave slope goes in the opposite polarity.

The formula to predict the output voltage, Vout, for the op amp differentiator is: Vout = -R1 * C1 * (dVin/dt)

The differentiator is not typically implemented as the textbook topology shown here due to high noise sensitivity, though.

Real-world circuits will place a capacitor, an order of magnitude smaller, across the feedback resistor R1 and a resistor in the input signal path to stabilize the circuit and prevent oscillation.**

So, don't let that compensation for noise sensitivity throw you off. Look at the magnitudes of the capacitors to see which one is dominant in the circuit to generalize its behavior. For those with OCD, yes there are equations that can predict the resulting non-ideality, but for most engineers, close enough.

In practice, a resistor equaling the value of R2, versus the direct connection, to ground from the negative input can be used to reduce errors in the output due to input bias currents.

***"In theory, you can make a differentiator — a rate-of-change computer — by taking op amp A3 and just connecting an input capacitor Cin and a feedback resistor Rf. But in practice, with real op amps, this will cause a local* *oscillation of the amplifier, due to the lag in the feedback loop. The fix is fairly simple: For most cases, to prevent local oscillations, add a small resistor R111 in series with Cin, and add a small capacitor (Cf) in parallel with Rf. In practice, if you make R111 about 1/10 or 1/100 of Rf, and Cf about 1/20 or 1/200 of Cin, that works pretty well. In other cases, it may be a bit more critical which value you choose, either to prevent local oscillation or avoid degradation of loop stability"* - Bob Pease

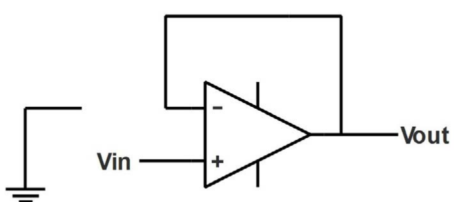
5. Schmitt trigger

This circuit is another Schmitt Trigger. This time, it's inverting.

Schmitt triggers are similar to comparators, but their reference voltage changes, depending on the state of the op amp's output, which goes to the rails when the magnitude of the input signal exceeds the magnitude of the threshold voltage. Because of the dynamic change in the reference voltage, Schmitt triggers have hysteresis on when the output will switch to the positive rail versus the negative rail, which is very useful for low frequency, or slow rise/fall, or noisy input signals.

6. A voltage follower

First thing we do is look at the relative magnitudes of the components. R1 at 100 MΩ is pretty much an open circuit, whereas R2 being 0 Ω is just a piece of wire. So, we can redraw the circuit to confirm to our biases:



Applying the golden rule where the op amp tries to make its inputs the same, i.e., an effective short, and with Vout the same voltage as Vin, the output Vout will follow Vin...a voltage follower. The redrawn circuit here agrees with what's in your textbooks, whereas the drawing in the question was unfamiliar, despite being given resistor values that equate the two diagrams. Don't pattern match — understand what you are looking at.

Note that, in practice, R2 is not set necessarily set to zero, as found in textbooks, but can match the source resistance of the signal on Vin. What that does is minimize output error due to input bias currents that are significant in some op amps.

7. Va + Vb

We can apply the golden rules where the inputs try to have the same voltage and that the inputs do not have any current flow in or out of their pins.

So, we can write that as Va/R1 + Vb/R1 = −Vout/R2

or

1/R1 (Va+Vb) = -Vout/R2 or Vout/R2 = −(Va + Vb)/R1

arriving at

Vout = −(Va + Vb)* R2/R1

This op amp circuit sums the two inputs to produce an output that has a gain/attenuation factor of the sum.

So, this is what's known as a summer, or summing op amp circuit.

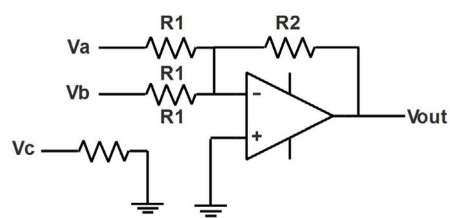
In practice, a resistor equaling the value of all R1 input resistors in parallel with each other, versus the direct connection, to ground from the negative input can be used to reduce errors in the output due to input bias currents.

If you want a real whiz-bang summing amp topology, check out this article.

8. Va + Vb

For some of you, this one may be a headscratcher.

Is there any difference between the circuit as drawn, and this one?



No. The resistor can be anywhere on your circuit board. It is not part of the op amp circuit gymnastics. So, this circuit is identical to the previous summing op amp circuit, except that there's a resistor on a Vc signal/supply to ground somewhere for some reason that has nothing to do with the op amp circuit.

In practice, a resistor equaling the value of all R1 input resistors in parallel with each other (other than the resistor on Vc, of course), versus the direct connection, to ground from the negative input can be used to reduce errors in the output due to input bias currents.

9. Amplifier, Differentiator, Integrator

A2 is in the "proportional" path of the PID where its amplifier output is proportional to its input by the factor of 2M/100k or a factor of 20. It is an amplifier with gain, in other words.

A3 has the 1M feedback resistor and a 1-μF capacitor on its negative input, with positive input grounded. It also has a resistor in the input path and a 0.1-μF capacitor in the feedback path, but since it's 10X smaller, we can write those two pieces off the schematic as improving stability against oscillation.** The result is your textbook differentiator circuit.

A4 has a 1-µF capacitor in the feedback loop and a 21M resistor in the input signal path to the negative op amp input with the positive input grounded. This is a textbook integrator op amp circuit.

So, it's easy to see how PID is just the signal path split three ways, coming from the error output of A1 (setpoint minus weighted PID feedback that's modulated by the temperature sensor in Bob's circuit), into proportional (amplifier), integrating, and differentiating paths. Those are then weighted and combined to form the feedback for the error amp A1.

Note that Bob does not use input bias current balancing resistors to ground on his op amps. You can get away with this on low input bias current devices.

**"In theory, you can make a differentiator — a rate-of-change computer — by taking op amp A3 and just connecting an input capacitor Cin and a feedback resistor Rf. But in practice, with real op-amps, this will cause a local oscillation of the amplifier, due to the lag in the feedback loop. The fix is fairly simple — for most cases, to prevent local oscillations, add a small resistor R111 in series with Cin, and add a small capacitor (Cf) in parallel with Rf. In practice, if you make R111 about 1/10 or 1/100 of Rf, and Cf about 1/20 or 1/200 of Cin, that works pretty well. In other cases, it may be a bit more critical which value you choose, either to prevent local oscillation or avoid degradation of loop stability." —Bob Pease*

10. Increase the resistance of P4 with respect to ground; decrease the resistance of P3 with respect to ground; decrease the resistance of P2 with respect to ground.

The integral term is the output of the integrator A4 which is connected to pot P4.

The outputs of the differentiator A3 and proportional A2 op amps are also connected to pots P3 and P2, respectively.

Think of it this way. The wiper of a pot turned to 0 Ω (closest to its grounded terminal) is grounded and has to produce zero, nada, nothing out, and conversely, crank the pot furthest from ground (increase its resistance to ground) and you get the signal on its non-grounded terminal in its full amplitude glory.

So, to increase the weight of the integration term, you can turn pot P4 the furthest from ground, i.e., increase its resistance.

But weight, er...wait...there's more...

Because PID are relative weights at the summer, the integration term can be given more weight by decreasing the weight of either, or both, of the differentiation and proportional terms...turning their pots, P2 and P3, toward ground, decreasing their resistance to ground.

Note that Bob does not use input bias current balancing resistors to ground on his op amps. You can get away with this on low input bias current devices.

11. Yes.

The point of this entire exercise is to be able to recognize topologies in analog circuits, not to humiliate or to inflate egos.

If you know what an amplifier, an integrator, a differentiator, and a summer looks like now, you have about half of analog licked as far as control loops and analog computing goes. The devil of course is in the equations and tuning, but at least you can look at a schematic to follow what an analog designer has done as far as the circuit architecture goes. The hardcore folks will derive the differential equations from the schematics.

For the bit twiddlers, this stuff can be directly translated to a computer program. And some people actually do PID control using the very same equations we implement in op amps.

Run through the quiz again if you want to burn it into your brain, and to be comfortable in amazing the ones and zeroes crowd next time you go out for lunch or drinks.

Feel free to leave comments, grumblings, observations, and to correct me, in the comments section, below. Hope you had fun with these...

-andyT
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