Basic Electronics
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Lecture – 35
Op-amp circuits (continued)

Welcome back to Basic Electronics. In the previous lecture, we looked at the op-amp buffer as a special case of the non-inverting amplifier. In this lecture, we will see the meaning of the term loading effects and see how an op-amp buffer can be used to eliminate these loading effects. We will then look at another useful op-amp circuit, the summer, which can be used to add two or more input voltages. We will illustrate the operation of the summer with the help of simulation results. We will then comment on the range of resistance values that are commonly used in an op-amp circuits. Finally, we will present an op-amp circuit, an amplifier circuit, which allows a relatively large gain without using large resistance values. So, let us begin.

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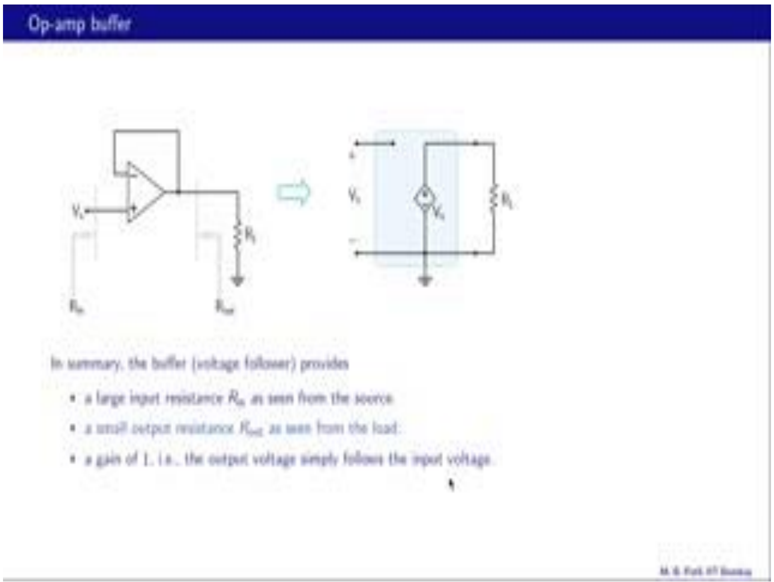

So, here is summary of the op-amp buffer. This is the circuit. We have a source on one side and we have a load register on the other side. The input resistance of the op-amp buffer is the resistance we see from here and the output resistance is the resistance we see from here. And, we have seen that the input resistance is very large, almost infinite. And therefore, in the equivalent circuit of the buffer we can show an infinite resistance here, which is an open circuit. We have also seen that the output resistance of the op-amp buffer is very small, almost zero. And therefore, we have shown a 0 ohm resistance here, which is a short circuit. We have also seen that the gain of the buffer is just 1. And therefore, if this voltage is V s, this A v times V i is simply V s. So, that is the equivalent circuit of the op-amp buffer. And, to summarize it provides a large input resistance as seen from the source, a small output resistance R out as seen from the load and a gain of 1. That is, the output voltage simply follows the input voltage.

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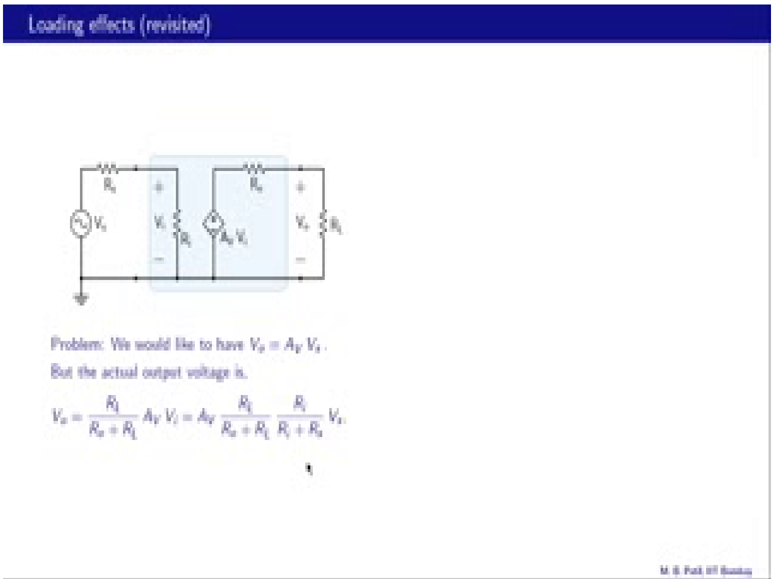

We now return to our original problem. We have a source with source voltage V s, source resistance R s, our load resistance is R L. We want to apply an amplified V s across R L. And, this is the amplifier we want to use which has the voltage given of A v. So, what we would like is V o to be equal to A v times V s. Now, if you recall with this configuration, the output voltage is not A v times V s, but something smaller; A v times R L divided by R o plus R L. And, this factor arises because of the voltage division happening here on the load side times R i divided by R i plus R s, where this factor is because of voltage division happening on the source side that multiplied by V s. So, it is not quite what we want. What we want is V o equal to A v times V s. And, now let us see how we can use an op-amp buffer to achieve this target.

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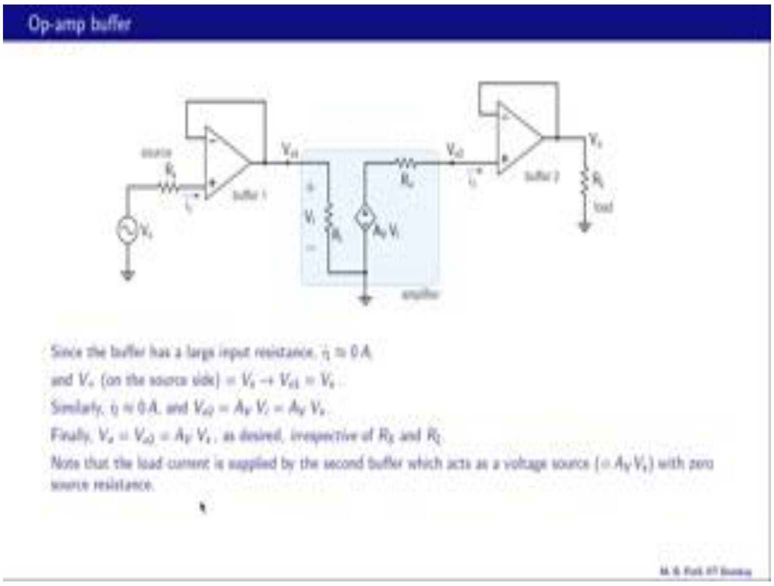

So, this is how we can use an op-amp buffer. One on the source side and one on the load side to obtain V o equal to A v times V s and eliminate the loading effects on the load side as well as on the source side. So, this part is our source as before. This is the amplifier and this is the load. What we have done is on the source side between the source and the amplifier; we have inserted one buffer circuit. Similarly, on the output side between the amplifier and the load we have inserted another op-amp buffer. And, let us see what this does. Since, the buffer has a large input resistance i 1 is 0, this current, therefore no voltage drop here. And, V plus is the same as V s. Now for the buffer, the output voltage is the same as the input voltage. So, therefore V o 1 is equal to this voltage here, which is V s.

Now, let us come to the load side, i 2, this current is also 0 because the buffer has a large input resistance. Therefore, no voltage drops here. And, V o 2 is equal to A v times V i. V i here is this voltage, which is V o 1 equal to V s; that gives us V o 2 equal to A v times V s. And, V o is the same as V o 2. And therefore, we get V o is equal to A v times V s, as we wanted. And that is irrespective of R s and R L; because we did not have a voltage division on the source side or on the load side.

Let us note that the load current is supplied by the second buffer. So, the load current is really coming like this, and that acts as a voltage source equal to A v times V s with 0 source resistance. Why 0 source resistance because that is a buffer, and as we have seen the buffer has a very very small output resistance. So, this is how buffer can be used. Whenever we are concerned about loading effects, we can insert a buffer and that essentially eliminates the loading effects.

So, when we started off we got V o equal to V i for the buffer. And, it was not clear whether that is at all the useful relationship because we are simply getting V o equal to V i. But, now it should be clear that a buffer really has a very important role to play in electronics, when we want to isolate the source from the load.

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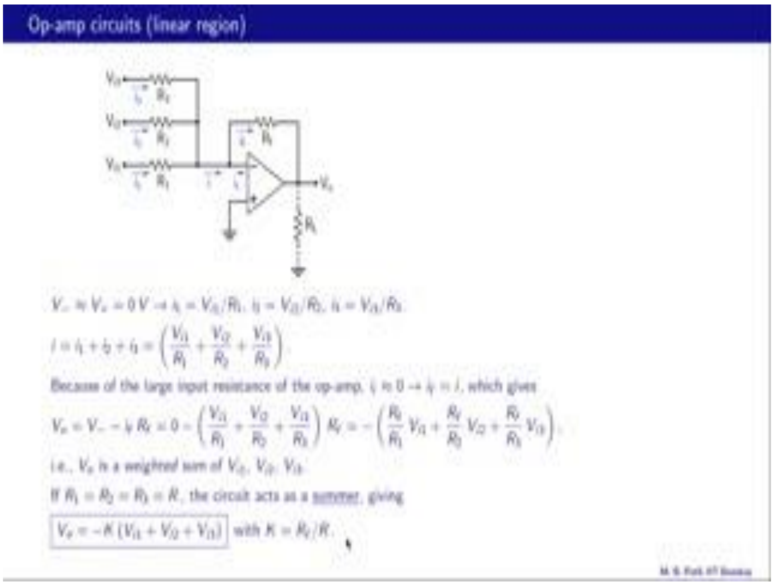

Here is another commonly used op-amp circuit. And, in fact we are already somewhat familiar with this circuit. Imagine that we do not have this R 2 and R 3. And, in that case the circuit reduces to the inverting amplifier. That we have seen earlier.

Now coming back to this circuit, there are three inputs here; V i 1, V i 2 and V i 3, that of course is the output. And, now let us see how the circuit works. We will assume that the op-amp is operating in the linear region, and therefore V minus and V plus are nearly equal. So, we have V minus equal to 0. What would this current be then? i 1, it would be V i 1 minus 0 divided by R 1. What about i 2? It would be V i 2 minus 0 divided by R 2 and so on. So, we have these three currents. Now, i 1 equal to V i 1 by R 1, i 2 equal to V i 2 by R 2 and i 3 equal to V i 3 by R 3.

Next because of the large input resistance of the op-amp, i i, this current is 0. And therefore, we can say that i f is equal to i. And once we know i f, we can obtain the output voltage V o, which is V minus minus this voltage drop. V minus is 0 and i f is the same as i, this expression here. So, then putting it together we get V o equal to minus R f by R 1 times V i 1 plus R f by R 2 times V i 2 plus R f by R 3 times V i 3.

Now, this we can think of as K 1 times V i 1 plus k 2 times V i 2 plus K 3 times V i 3, where we can adjust K 1, K 2, K 3, by simply choosing the values of R 1, R 2 and R 3. So, this circuit is in fact doing a weighted sum of V i 1 V i 2 and V i 3 and the weights K 1, K 2, K 3 can be adjusted using the resistances. And, if we make R 1, R 2 and R 3 all equal, denoted by R, then we have minus R f over R V i 1 plus R f over R V i 2 plus R f over R V i 3, so that R f over R is a common factor. We can take that out, and then get minus K times V i 1 plus V i 2 plus V i 3.

So, this is simply summer circuit. It is simply adding three voltages. In fact, we can extend it to four voltages, if you like by adding another resistance or we can have just two voltages V i 1 and V i 2. So, there is some flexibility in configuring it appropriately.

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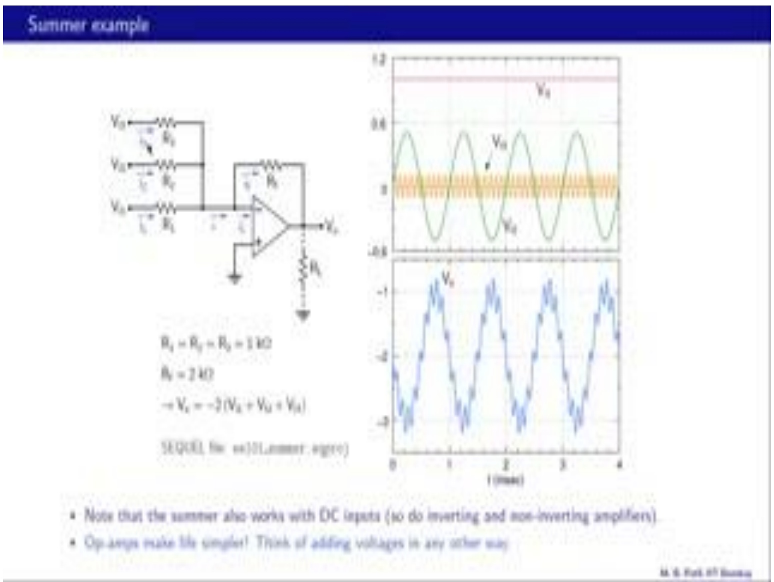

Here is an example. The sequel file is also available. So, you can check out this simulation and change the input voltages or resistance values and so on. What we have here is three voltages; V i 1, which is a constant DC voltage, 1 volt, V i 2 with the sinusoid, V i 3 also a sinusoid with the lower amplitude and higher frequency as compared to V i 2. The resistance values R 1, R 2, R 3 are chosen to be equal 1 k and R f is chosen to be 2 k. So, if we substitute these values in our previous expression, we end up with V o equal to minus two times V i 1 plus V i 2 plus V i 3.

Let us look at the output voltage waveform now. This one we see that there is this low frequency component, and that comes from V i 2. And super imposed on that, we have this high frequency component, and that comes from V i 3. And, notice that this entire waveform has been shifted first that it has an average value of about minus 2 volts. And that comes from V i 1. And, it is easy to see where this minus 2 volts is coming from. We have V i 1 equal to 1 volt, and that 1 volt gets multiplied by minus two here and that gives us minus 2 volts.

Now, let us make a few important points. Note that the summer also works with DC inputs. This is a D C input, for example. And that comment applies also to the inverting, non-inverting amplifiers. These circuits do also work with a DC input. And, compare that with the common emitter amplifier. We have seen before in the common emitter amplifier, if you recall we had a coupling capacitor which connected the input voltage to the amplifier.

And, if the input voltage is DC voltage, then this coupling capacitor would block that input voltage because the entire DC input voltages would appear cross the coupling capacitor and the amplifier will not even see that DC voltage. And therefore, it will have no impact on the output of the amplifier. So, in that sense these op-amp circuits are definitely better because they can be used for DC voltages or slowly varying voltages, whereas the common emitter amplifier cannot be used for those conditions.

Second point, op-amps make life simpler. And, this is something that should be obvious by now. For example, if we think of adding voltages in any other way, we will find that it is not at all trivial; whereas this circuit, the summer, makes it very easy. And, not only that it even allow us to vary the weights for these three input voltages by simply changing this resistance values.

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Let us now talk about the choice of resistance values in op-amp circuits. And, this is a very important question from a practical perspective. If you want to build an op-amp circuit, we will definitely need to know whether any arbitrary resistance value is good enough or there is some restriction turns out that there are some restrictions. And, let us see why.

If the resistance values are too small, for example, then they draw larger currents. And, where do these currents come from? They eventually come from the power supply, that is, V CC and minus V E. And that leads to an increase in the power dissipation. And that of course is in general, undesirable. What if the resistance values are too large? Let us see what happens in that case. One, the effect of offset voltage and input bias current becomes more pronounced. And, this is something we are not yet discussed; we will look at its own. In short, what happens is the circuit performance is then not what we would accept, and that of course is not desirable.

Second, combined with parasitic or wiring capacitances, large resistance can affect the frequency response and stability of the circuit. Two, given example say we connect an op-amp amplifier circuit and give certain input voltage and expect a certain output voltage. Now, we connect our output to the oscilloscope and find that there are some oscillations at the output, which are nothing to do with the input voltage. Now, this kind of situation can arise if the circuit is unstable. And that can happen if the resistances are very large. And therefore, those should be avoided.

Third, there is something called thermal noise. What is a meaning of noise? Noise is a kind of disturbance that rides on our signal voltages. And, it is something that we do not want because that corrupts our signal. Now, this thermal noise increases as the resistance value increases. And, it may not be desirable in some applications. So, because of all of these considerations, very small resistance values and very large resistance values are avoided in practice. And, the typical resistance values which we use in op-amp circuits are in the range 0.1 k to 100 k. So, if we are designing an op-amp circuit we should make sure, in general that our resistance values fall in this range.

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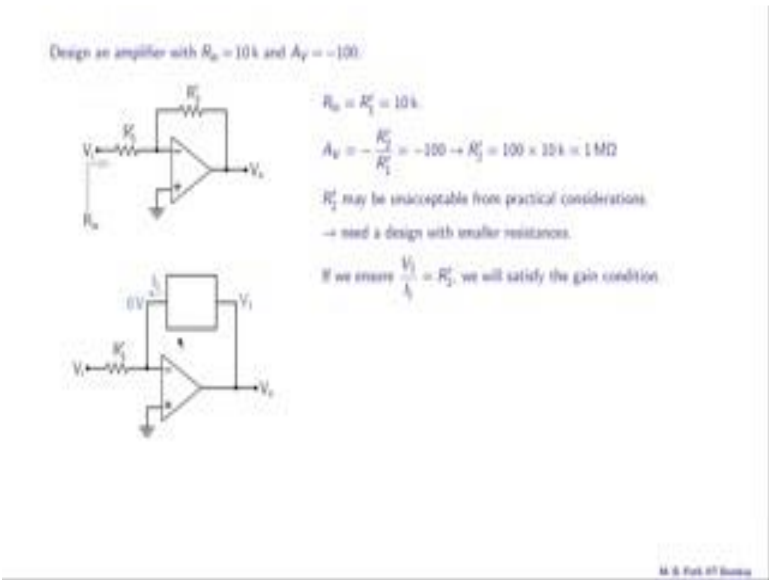

Let us do this design problem. We want to design an amplifier with R in equal to 10 k, the input resistance of the amplifier and a voltage gain of minus 100. We have already seen an op-amp circuit, the inverting amplifier, which gives us negative gains. So, we can choose that. The input resistance should be 10 k of this amplifier. So, let us see what that gives us. What is R in? It is the same as R 1 prime, as we have seen earlier. And that happens because the inverting terminal is at virtual ground. And, this current is V i by R 1 prime. So, that gives us an input resistance of R 1 prime.

Since R in is supposed to be 10 k, we have to have R 1 prime equal to 10 k. What about R 2 prime? That is given by the gain now. Since, the voltage gain of the inverting amplifier is minus R 2 prime by R 1 prime. And that we want to be minus 100; that gives us R 2 prime. So, R 2 prime should be 100 times R 1 prime, which is 10 k. So, that comes to 1 mega ohm. And, as we saw in the last slide this value is somewhat large and it may be unacceptable from practical considerations.

So, therefore this solution is certainly not the best. So, let us see if you can improve on that. So, we need a design which has smaller resistance values. Fortunately, for us electronics is full of clever tricks. And, here is one of them. So, we modify the circuit. We put a black box here, instead of R 2 prime. And what should that black box do? The same thing as what R 2 prime does here. What does R 2 prime do? If I call this voltage V 1, this is of course the virtual ground and this current as i 1, then V 1 divided by i 1 should be R 2 prime, which is 1 mega ohm.

So, in this black box we should ensure that V 1 divided by i 1 is the same value; that is 1 mega ohm. But, the network inside should be designed, so that it does not use large resistance values.

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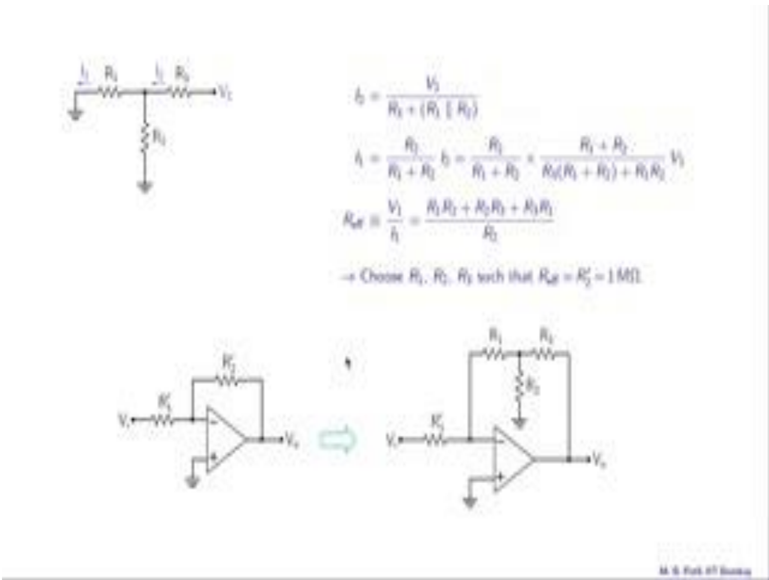

So, let us see how that can be done. Let us consider this 'T' network; as called T because it looks like the letter 'T'. It consists of three resistances R 1, R 2 and R 3. So, this is going to be our black box. That we saw in the last slide. And, what we want from this black box is V 1 divided by i 1 is 1 mega ohm. So, let us first see what V 1 over i 1 is in terms of R 1, R 2 and R 3.

Let us look at i 2 first. Now, in this circuit R 1 and R 2 are actually in parallel because this node is common and that other node is also common. Therefore, the net resistance seen from here is R 3 plus R 1 parallel R 2. So therefore, i 2 is V 1 divided by R 3 plus R 1 parallel R 2. Let us now look at i 1, that current. Once we know i 2, we can obtain i 1 by using the current division formula. So, i 1 is going to be R 2 divided by R 1 plus R 2 times i 2. And that gives us this expression for i 1.

Let us define R effective to be V 1 by i 1. And, since we already have i 1 in terms of V 1, here we can find V 1 over i 1. And, we can see that this R 1 plus R 2 is going to cancel out and we get V 1 by i 1 as R 1 R 2 plus R 2 R 3 plus R 3 R 1 divided by R 2. And, now our job is to choose R 1, R 2, R 3, such that R effective which corresponds to R 2 prime in our previous slide should be 1 mega ohm. If we can do this without using large resistance values, then our design is done.

So, what we are going to do is replace our original inverting amplifier with this circuit. And, the job of R 2 prime is now being done by this T network. And, our next step is to find R 1, R 2, R 3, which will give us the same R effective as R 2 prime, which is one mega.

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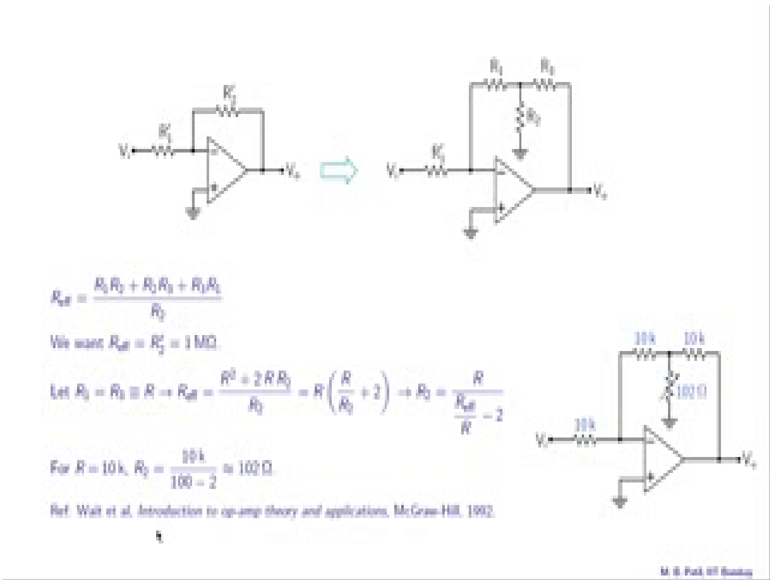

Here is our expression for R effective. And, we want R effective to be 1 mega ohm. So, what we will do is take R 1 and R 3 to be equal, and we will call that R. Then in terms of R, R effective turns out to be this expression here. And, we can now solve for R 2 as R divided by R effective by R minus 2. For R equal to 10 k, for example, R 2 turns out to be 102 ohms.

So, in this manner our objective of gain of minus 100 is now achieved. And, we have done that without using large resistances. And therefore, our design is good one. Now, 102 ohms is not something that is readily available. So, we would generally put a part here and then adjust its value. By the way, this circuit is taken from this book here by Wait and others. And, there are many other interesting op-amp circuits in that book. And, you may take a look.

In conclusion, we have seen how an op-amp buffer can be used to avoid loading effects. We also looked at the op-amp summer and illustrated its functioning with the help of an example. We commented on the range of resistance values, which are typically used in op-amp circuits. Finally, we looked at an interesting amplifier circuit, which gives a relatively large gain without using very large resistance values. So, that is all for now, see you next time.