Basic Electronics
Prof. Mahesh Patil
Department of Electrical Engineering
Indian Institute of Technology, Bombay

Lecture - 34
Op-amp circuits (continued)

Welcome back to Basic Electronics. In this lecture, we will look at the input and output resistances of the non-inverting amplifier. We will also look at a special case of the non-inverting amplifier that is the op-amp buffer. So, let us begin.

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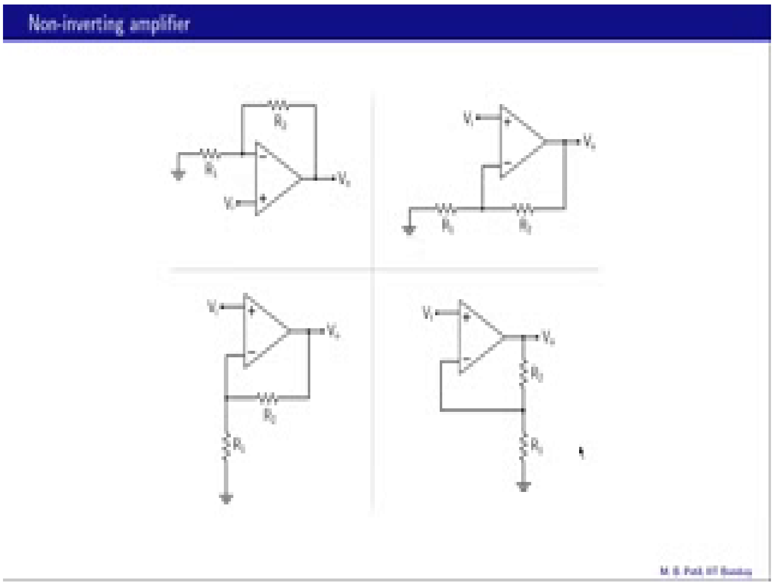

Let us look at the non-inverting amplifier once again. Here is the circuit. The input voltage goes to the non-inverting input of the op-amp. From the inverting input of the op-amp, we have R 1 going to ground and R 2 going to the output node of the op-amp. And the load resistance is not shown here, because that is not really a part of the amplifier circuit. Let us redraw this non-inverting amplifier circuit as shown here; it looks different, but it is the same circuits same connections. So, V i connected to the non-inverting input once again. From the inverting input of the op-amp, we have R 1 going to ground and R 2 going to the output node of the op-amp.

Here is another way of drawing a circuit. Again V i connected to the non-inverting input; and from the inverting input we have R 1 going to ground, R 2 going to the output node. Yet another way V i going to the non-inverting input again; and from the inverting input, we have R 1 going to ground and R 2 connected between the inverting input of the op-amp and a output node of the op-amp. So, there are the seemingly different ways of trying the same circuit and we might come across these in some real examples. So, we should familiar with in this different ways of trying the same circuit.

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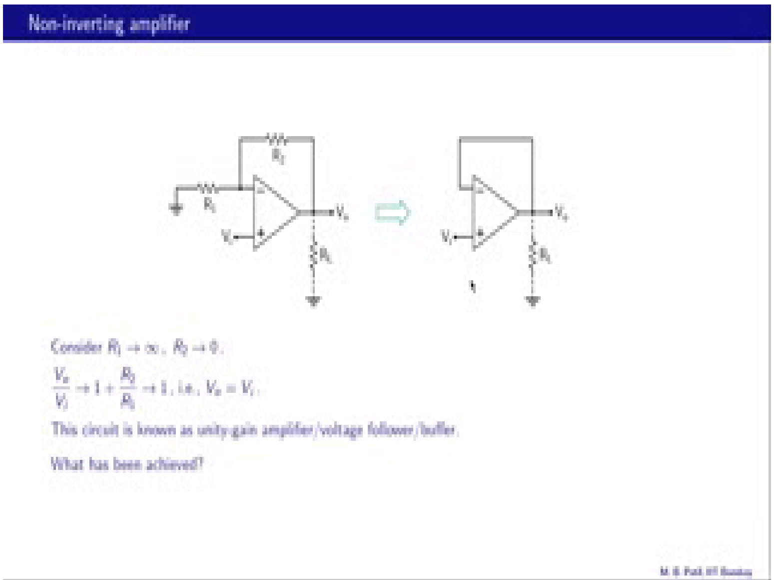

We now consider a special case of the non-inverting amplifier with R 1 very large and R 2 very small. If R 1 is very large say infinite, we can remove this resister; if R 2 is very small say 0 ohms, this becomes a short circuit, and we get the circuit shown here on the right side. Now, let us see what V o is in terms of V i. For the non-inverting amplifier as we have already seen V o divided by V i is 1 plus R 2 by R 1. R 2 is 0, R 1 is very large, so this quantity is simply becomes one so that means, V o is equal to V i because the gain is 1. And we can also observe this directly from this circuit, since the op-amp is operating in the linear region V minus and V plus are nearly equal. So, V minus is also equal to V i and since that is connected directly to the output V o is also equal to V i.

And this circuit the one on the right is known as unity gain amplifier, because the gain is 1 or voltage follower because the output voltage simply follows the input voltage or buffer. And why it is known as buffer, we should see very soon. The question is what has been achieved by doing this; we have got an output voltage which is just equal to the input voltage no gain. So, is this circuit useful at all, it turns out that it is very useful and we will see how it can be used.

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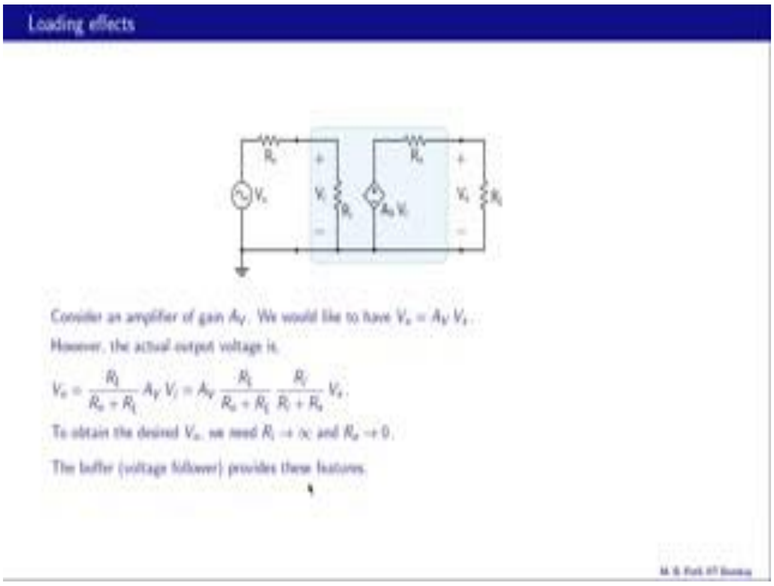

Before we look at the buffer circuit, let us discuss something called loading effects. Here is the signal source, which is represented by a voltage source in series with resistance R s. And we want to amplify this signal voltage and apply the amplified voltage across the load resister R L. And we do that using this amplifier, the equivalent circuit of the amplifier is represented by the input resistance R i the voltage gain A V and the output resistance R o. So, what we would really like to have is V o to be equal to A V times V s. Let us say we have V s equal to 1 millivolt, and the gain of the amplifier is 100 then we would like to have an output voltage of 100 times 1 or 100 millivolts.

Now, in reality the actual output voltages are slightly different, and let us see how. This V o is not quite a V times V i, because there is a voltage division here. So, it is a V times V i multiplied by R L divided by R L plus R o that is this expression here. Also this V i the voltage across the amplifier input terminals is not quite V s, and again there is a voltage division here, so it is V s times R i divided by R s plus R i. So, the net V o is given by this expression here. This is less than one this is also less than one. So, this whole gain is not A v, but something less than A V and that is not desirable what we would really like is V o equals to A V times V s.

This reduction in gain from A V to this number is referred to as the loading effects. It represents the loading of the amplifier by the load resister R L, and also loading of the voltage source by the amplifier that is this input resistance of the amplifier. Is there a way to minimize or eliminate these loading effects let us see. Suppose, we make R i very large then R i plus R s is about R i, and this factor becomes equal to 1. Similarly, if we make R o very small then R o plus R L is nearly equal to R L this factor also becomes one and then we have the gain equal to A V times one times one and that is just A V as we would like. And the buffer circuit that we have seen in the last slide or also called the voltage follower provides exactly these features and that is why it is very useful.

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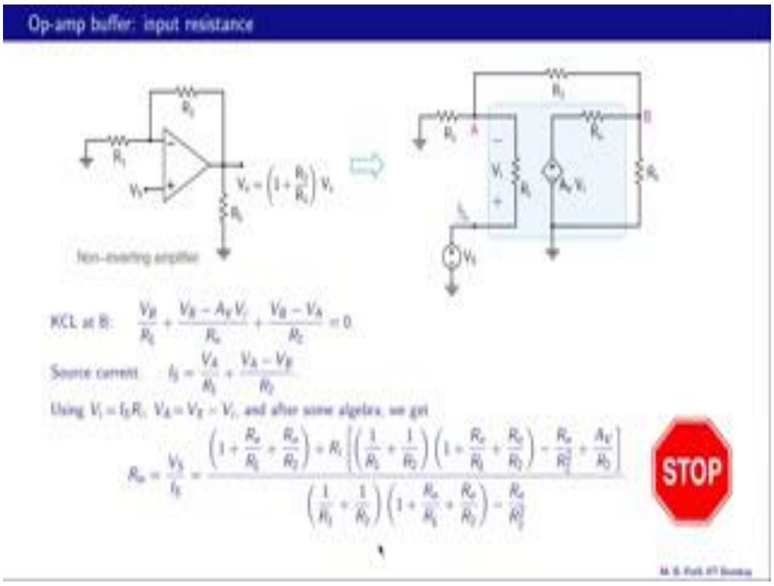

We now want to look at the op-amp buffer. Find its input resistance and output resistance. To begin with let us look at the non-inverting amplifier, because the buffer is special case of this circuit with R 1 equal to infinity, and R 2 equal to 0 as we have seen before. Now, for this circuit let us replace the op-amp with its equivalent circuit consisting of the input resistance, gain element and output resistance. And to obtain the input resistance, what we do is apply voltage source V s here, find this current I s and then the input resistance of the non-inverting amplifier as seen from here will be V s divided by I s.

To get V s over I s, there may be different ways of doing is what we will do is to treat V A the node voltage at A with respective to ground, V B, V i - the voltage that appears across the input terminals of the op-amp that one and I s. So, we will treat these four quantities V A, V B V i and I s as our unknowns. We will treat this V s as known number and then we will obtain equations which will enable us to solve for I s in terms of V s.

Let us begin with KCL at node B. What do we have at node B, we have this current plus this current plus this current. And these three current must add up to 0; this one is V b divided by R l this one is V B minus the node voltage here which is a V times V i with respect to ground. So, V B minus A V times V i divided by R o, and this current is V B minus V A divided by R 2. So, these three must add up to 0 that gives us to KCL at node B. What about the source current the source current is the same as the current through this R i and that is the sum of two currents - this current here and that current. This current is V A by divided by R 1 and that one is V A minus V B divided by R 2. So, that is what this equations says I s is equal to V A by R 1 plus V A minus V B by R 2.

In addition to these two equations, we have two more conditions one is V i equal to I s times R i; this V i is I s times R i, and V A is V s minus V i. This node voltage is equal to V s minus this voltage drop, so it is V s minus V i. So, we have four equations 1, 2, 3, 4. And we have four unknowns what are the unknowns V A, V B, I s and V i. And remember we are treating V s as unknown quantity, so we have four equations and four unknowns we can solve these and obtain I s. Once we obtain I s, we can find the input resistance as seen from there as V s over I s and that turns out to be this expression here. It is a bit messy.

And you are of course, encourage to do all the algebra and arrive at this result, but let us look at least the dimensions of this R in whether it is indeed ohms or not. What about the numerator dimensionless, dimensionless; dimensionless R i and this whole quantity as units of 1 over ohms, so ohms by ohms. So, this entire numerator is dimensionless. What about the denominator 1 over ohms, this is dimensionless, and this also is 1 over ohms ohms by ohms square, so 1 over ohms. So, the denominator has dimensions of 1 over ohms. And therefore, this entire expression is in ohms. The stop sign has come, and it is telling you that you have to work out this relationship and then proceed further. It is a bit of algebra where we have page or so, but it is definitely worth doing.

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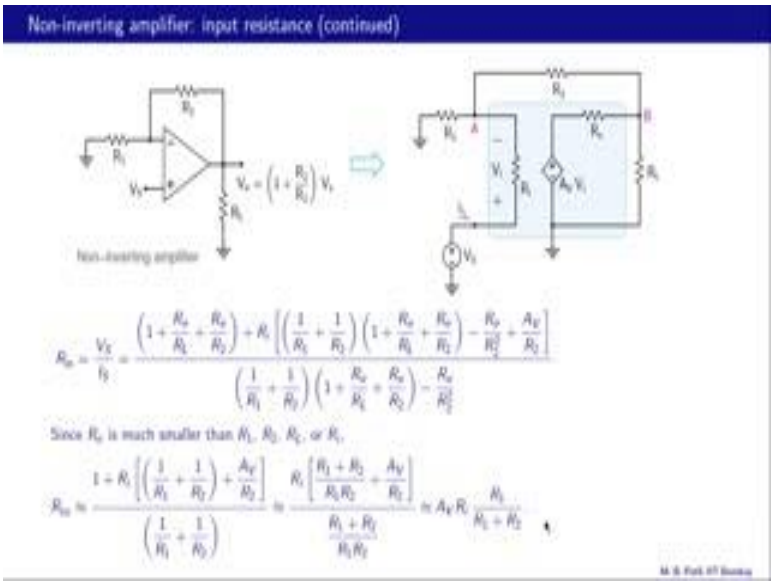

Let us try to simplify this expression for the input resistance. We know that R o is much smaller than all of these resistances R 1, R 2, R L would be in the kilo ohms range whereas, R i would be in the mega ohms range; and R o is much smaller than all of those, it would be something like 50 ohms. So, therefore, these ratios R o by R 1 or R o by R 2 etcetera would be much smaller than 1 and we can ignore those. So, we can ignore all of these terms containing R o in this expression, and get a simplified expression given here.

Now, in this expression, this one is much smaller than the second term. This represents R 1 parallel R 2. So, the first term here is R i divided by R 1 parallel R 2 definitely would be much larger than 1, so therefore, we can ignore this one and then simplify these expression to this quantity, and then after a bit of we get our algebra we get our final result. This R 1 divided by R 1 plus R 2 is smaller than 1, let say 1 by 10, 1 by 20, 1 by 50 something of that order. Now, A V times R i is a very huge resistance A V is 10 raise to 5 or the 741, R i is 2 mega ohms. So, altogether this input resistance is very, very large; and therefore, for all practical purposes we see an open circuit from this terminal. And this very large input resistance is definitely a big advantage of using the non-inverting configuration.

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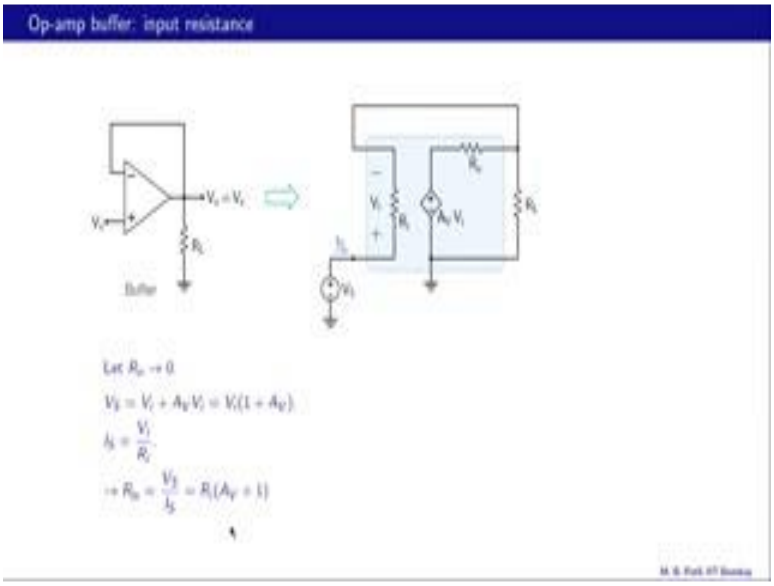

Let us get back to the op-amp buffer circuit, and we are interested in finding its input resistance as seen from here. First, we replace the op-amp with its equivalent circuit shown here consisting of the input resistance, the gain element and the output resistance. We apply a voltage source V s and find this current, and then the ratio of V s and I s gives us the input resistance as seen from the non-inverting terminal of the buffer. As before, we will assume that R o is very small with respect to other resistances and we will treat it as 0.

First let us look at V s this voltage. So, what we will do is we will start with 0, we will go like that, we come across the rise of A V times V i then go like that R o is 0. So, there is no voltage drop there, and then go like this, so that is a voltage rise of V i. So, altogether we come across a voltage rise of a V times V i plus V i. So, that is a V times V i plus V i or V i times 1 plus A V that is V s. What about I s, this voltage drop is V i and that is simply I s times R I, so that gives us I s V i divided b R i. And now all we need to do is to take the ratio V s divided by I s. So, R in as seen from here is then V s divided by I s which is R i times A V plus 1. And this of course, is a very large input resistance R i is a few mega ohms and A V is 10 raise to 5. So, it is really very huge, so that means, looking from here we see a very, very large input resistance for the op-amp buffer.

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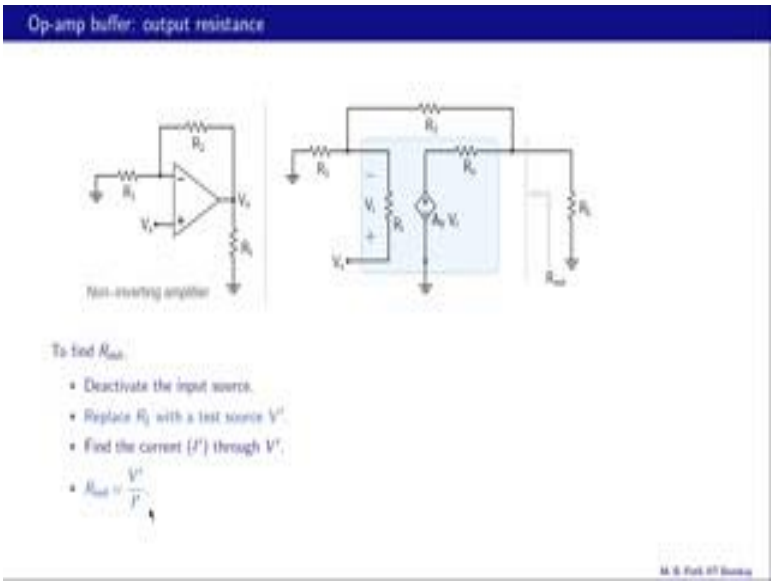

Let us now look at the output resistance of the op-amp buffer. And let us start with the non-inverting amplifier, because buffer is a special case of this circuit. What do we mean by the output resistance? What we mean is the resistance as seen by the load resistor here? And first what we do is replace this op-amp with its equivalent circuit as shown over here. The rest of the connections of course, are the same, we have R 1 going to ground from the inverting terminal in both cases, and R 2 between the inverting terminal and the output terminal.

Here is our R L, and R out is defined as the resistance as seen from R l like that. And how can we find R out, we deactivate the input source first that means connect this node to ground replace R L with a test source V prime. So, we remove R L and put a voltage source V prime over there. Find the current I prime through V prime that current and then R out is given by V prime divided by I prime. So, let us do that.

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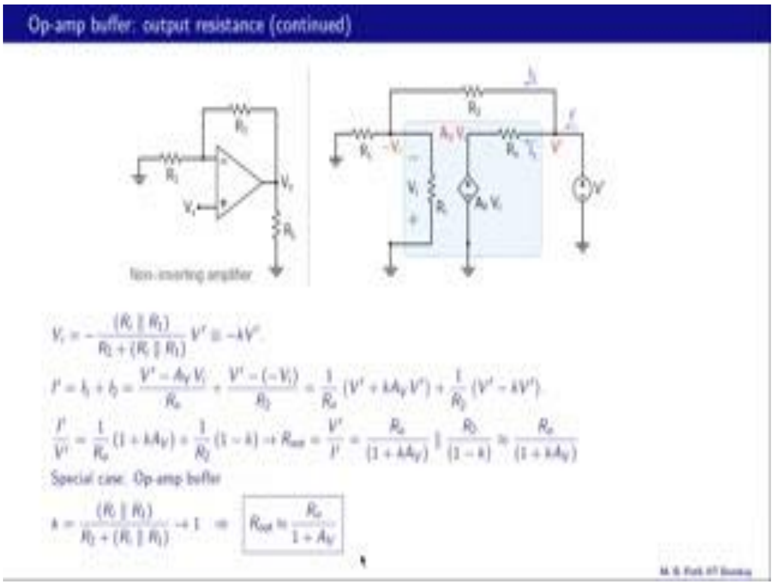

So, this is what we do, we deactivate the input voltage; that means, connect this node to ground we replace R L with voltage source as shown over here. And now we find the ratio V prime divided by I prime and that will give us the output resistance. To begin with let us mark the node voltages. This node is at V prime with respect to ground; this node is at a V times V i with respect to ground again; and this node is at minus V i with respect to ground. Now, this voltage minus V i can be related to V prime when we realize that this R 1 and R i are actually in parallel.

So, from this node, we have two resistances going to ground R 1 and R i, so they are actually in parallel. So, we have a single resistance R 1 parallel R i going to ground from this node. And once we figure that out we can obtain this node voltage, so minus V i would be this R 1 parallel R i divided by R 2 plus R 1 parallel R i times V prime and that is simply voltage division. So, this is what we get for V i in terms of V prime. And notice that R i is a large resistance is the input resistance of the op-amp. And therefore, R i parallel R 1 is nearly equal to R 1. So, what we have over here is essentially R 1 by R 1 plus R 2 and that fraction has been defined as K over here. As an example let us say R 2 is 9 k, and R 1 is 1 k then this fraction would be 1 k divided by 10 k or 1 by 10.

Let us now look at this current I prime. What is I prime? it is I 1 plus I 2. And let us now get I 1 and I 2 individually. What is I 1 V prime minus A V times V i divided by R o the first term. What is I 2 V prime minus minus V i divided by R 2 - the second term here.

And this V i we can replace with minus k V prime, so that gives us I prime equal to 1 over R o times V prime plus k A V V prime this term here comes from here plus 1 over R 2 times V prime plus V i and V i is minus k V prime. So, 1 over R 2 times V prime minus k V prime, so that is our I prime.

So, we now have I prime in terms of V prime all of these are in terms of V prime and we can now obtain I prime divided by V prime what we want is V prime divided by i prime the output resistance. So, let us do that. So, I prime by V prime is 1 over R o 1 plus k times a V the first term here plus 1 over R 2 1 minus k the second term here. So, this is like the conductance and it is a sum of two conductances. So, the resistance which is the reciprocal of this quantity which is the output resistance we are looking for is basically two resistors in parallel one of them is R o divided by 1 plus k A V, and the other is R 2 divided by 1 minus k. So, that is what we get for the output resistance as seen from R L.

Now, of these two this resistance is clearly very small because we have R o here and R o of an op-amp is a small resistance and therefore, a small resistance in parallel with a larger resistance is essentially that smaller resistance itself. So, then we have R out approximately equal to R o divided by 1 plus k times A v. Now, A V is a large number 100 thousand for the 741 op-amp. So, therefore, this quantity is actually a very small resistance.

Let us now take the special case of the op-amp buffer. How do we obtain the buffer from the non-inverting amplifier, we make R 1 infinite and R 2 equal to 0. Now this k, which is this fraction here, will become 1 when R 2 is 0. And therefore, this expression for R out will now become R o divided by 1 plus 1 times A V or R o divided by 1 plus A V. A V of course, is the voltage gain of the op-amp; the open loop gain which is a large number 100 thousand R o is already very small something like 50 ohms for the 741, 50 or 75. So, this quantity is really, really tiny. So, for all practical proposes we can treat R out as the 0 ohm resistance. So, the op-amp buffer not only provides a very high input resistance, it also provides a very low output resistance. So, let us keep these desirable features of the op-amp buffer in mind.

To summarize, we have found expressions for R in - the input resistance and R o - the output resistance of the non-inverting amplifier. We found that R in is very large and R o is very small and that makes this circuits very useful in certain applications. We also looked at the op-amp buffer, which is a special case of the non-inverting amplifier. In the next class, we will look at how a buffer can be used to avoid loading effects, until then goodbye.