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

Lecture – 38
Instrumentation amplifier (continued)

Welcome back to Basic Electronics. In the last lecture we have started looking at the Instrumentation Amplifier. We will continue with that discussion we will see how the instrumentation amplifier is better both in terms of input resistance and common more rejection. We will look at two additional op-amp circuits, in this lecture the current to voltage convertor and the integrator. So, let us start.

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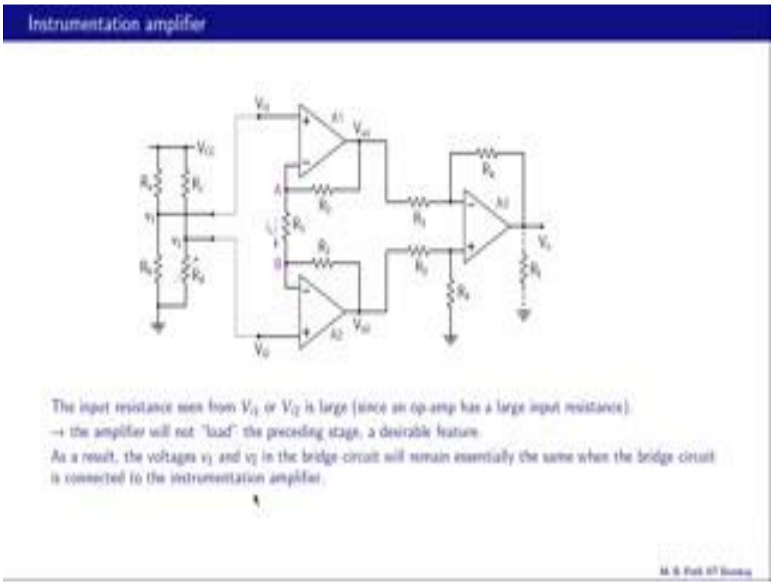

The input resistance as seen from V i 1 or V i 2 is obviously large, because we are looking into the op-amp directly and the op-amp as a large input resistance. And therefore, this instrumentation amplifier will not load the preceding stage and that of course is a very desirable feature.

In other words it will not draw any current when we connect it to for example, the bridge circuit that we have seen earlier, like that. So, now, when we connect the amplifier to the bridge circuit this current is almost 0, and therefore v 1 will not get disturbed this current is also 0 so therefore v 2 also will not get disturbed. And now when we make the measurement we can expect our v o to be what it really should be.

So, the voltages v 1 and v 2 in the bridge circuit will remain essentially the same when the bridge circuit is connected to the instrumentation amplifier.

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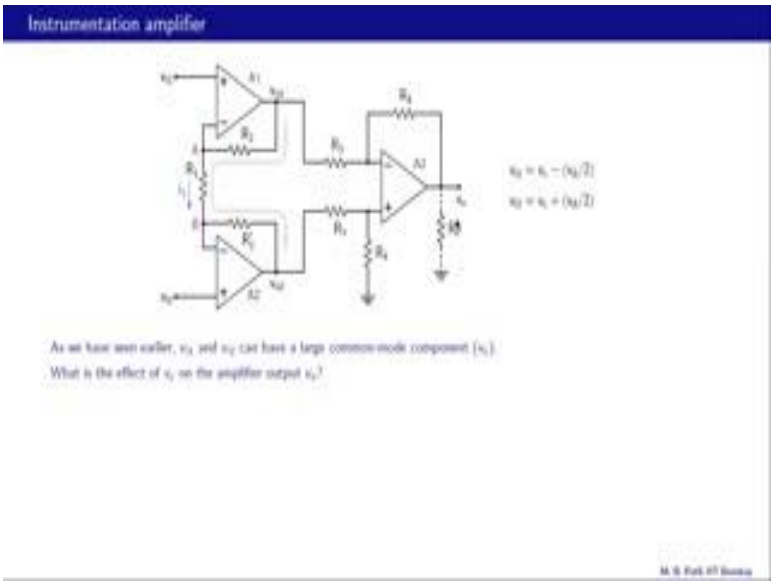

So, the instrumentation amplifier is definitely superior to the difference amplifier, because it offers so much larger input resistance. And therefore, when we connect this to the bridge circuit for example these voltages V i 1 and V i 2 will not get disturbed, and therefore our measure output would be a two reflection of what we are trying to quantify.

Now, let us look at the other important issue that is the performance of the instrumentation amplifier with respect to common mode input voltages. As we have seen before V i 1 and V i 2 can have a large common mode component. V i 1 is given by v c minus v d by 2 V i 2 is given by v c plus v d by 2. And we have seen earlier in the bridge circuit is ampere that we see can be quite larger for example 7.5 volts there and v d was only 37.5 millivolts in that example.

And now we want to know; what is the effect of this common mode input voltages on the amplifier output v o there.

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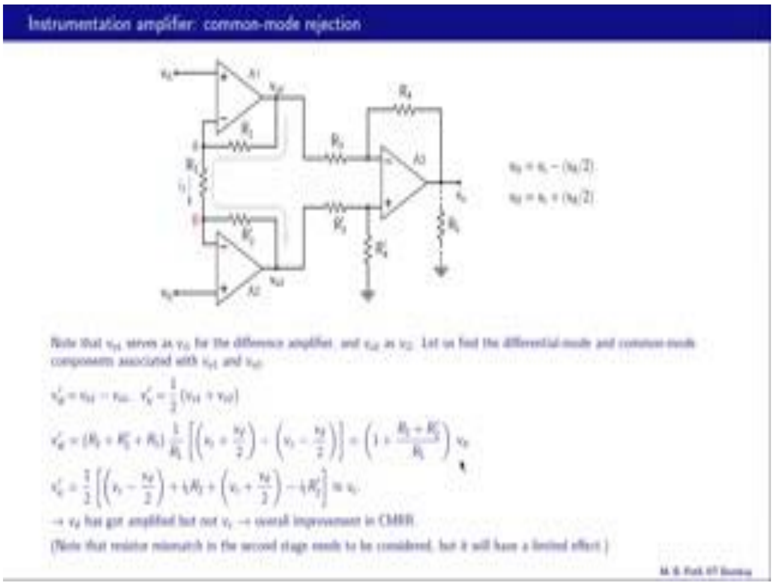

When we look at the common mode rejection performance of the instrumentation amplifier we will assume that the op-amps themselves are perfect; that means they have very high CMRR infinity. So, the finite CMRR of the instrumentation amplifier as a role will arise only because of resistance mismatch. So, this R 2 and R 2 prime are supposed to be same, but they would not exactly the same because of tolerance values. Similarly, this R 3 and R 3 prime would be slightly different. And R 4 and R 4 prime would be slightly different. So, as a result of that the instrumentation amplifier will have a finite CMRR and that is what we want to find.

Let us note that V o 1 this voltage serves as the input V i 1 of this difference amplifier and similarly V o 2 serves as the input V i 2 of the difference amplifier. And now we will find the differential mode and common mode components of this input voltage. What is the differential model input voltage? We will denote that by V i d prime so that is equal to V o 2 minus V o 1, V o 2 minus V o 1, and the common mode component V i c prime is half V o 1 plus V o 2.

What is V i d prime is V o 2 minus V o 1, so it is this voltage plus that plus that. So, its R 2 prime plus R 1 plus R 2 times i 1 with a negative sign because we are looking at V o 2 minus V o 1. What is i 1? it is v a minus v b divided by R 1 and v a itself is V i 1 which is the same as v c minus v d by 2. V b is the same as V i 2 which is v c by v d by 2. So, when we put all that together we get this expression here. And v c cancels out and we are left with 1 plus R 2 plus R 2 prime divided by R 1 times v d.

So, that is our differential mode input voltage as seen by the difference amplifier. Let us now look at the common mode voltage seen by the difference amplifier and that is half V o 1 plus V o 2. So, that is half this is V o 1, what is V o 1? It is v a plus this voltage drop that is i 1 times R 2 and v a is V i 1 which is v c minus v d by 2. So, v c minus v d by 2 plus this voltage drop i 1 R 2.

What about V o 2? It is v b which is the same as V i 2 which is v c plus v d by 2 minus i 1 R 2 prime, so that is V o 2. And now we see that this v d by 2 of course get cancelled v c plus v c is 2 v c. And this i 1 times R 2 minus R 2 prime is a very small quantity, because R 2 and R 2 prime are actually are actually supposed to be matched and their difference would be negligible compare to v c. So therefore, overall we have the i c prime nearly equal to v c; the common mode voltage at the input of the instrumentation amplifier.

So, something very significant as happened let us see what that is. At this stage our common mode voltage was v c and the differential mode voltage was v d and that is why V i 1 was given by v c minus v d by 2 V i 2 by v c plus v d by 2. When we come here our differential mode input voltage has got amplified 1 plus R 2 plus R 2 prime divided by R 1. And this gain could be substantial could be 20 could be 50, whereas our common mode input voltage as remained equal to v c. And of course is a very big advantage. In short v d as got amplified but not v c, and therefore that leads to an overall improvement in the CMRR.

So, we have come up to this point and now we want to see what the output voltage of the instrumentation amplifier is. Let us take the simple case first in which there is no resister mismatch, so R 4 and R 4 prime are equal R 3 and R 3 prime are equal. In that case this is a perfect difference amplifier and its gain is R 4 by R 3, so therefore the output voltage would be R 4 by R 3 times V o 2 minus V o 1. And the common mode component of V o 1 and V o 2 which is v c will get cancelled out and we will get an amplified version of this quantity at the output.

So, at the output we will have no common mode voltage at all, and therefore the CMRR of the entire instrumentation amplifier would be infinite. In real life of course the resister mismatch in the second stage needs to be considered, but it will surely have a limited effect, and let us see why. Let us compare two: cases 1 in which this difference amplifier gets V i 1 and V i 2 as inputs directly without this stage, and in that case what is the common mode voltage it sees it is v c; what is the differential mode input voltage it sees, it is v d: that is case 1.

Case 2: the instrumentation amplifier. Now what is the common mode voltage it sees? It is v c, and what is the differential mode input voltage it sees? It is an amplified form of v d and that is a difference. So therefore, the overall gain that the common mode voltage goes through is much much smaller relative to the gain that the differential mode voltage goes through and gives us much better performance than the plane difference amplifier that we have seen before.

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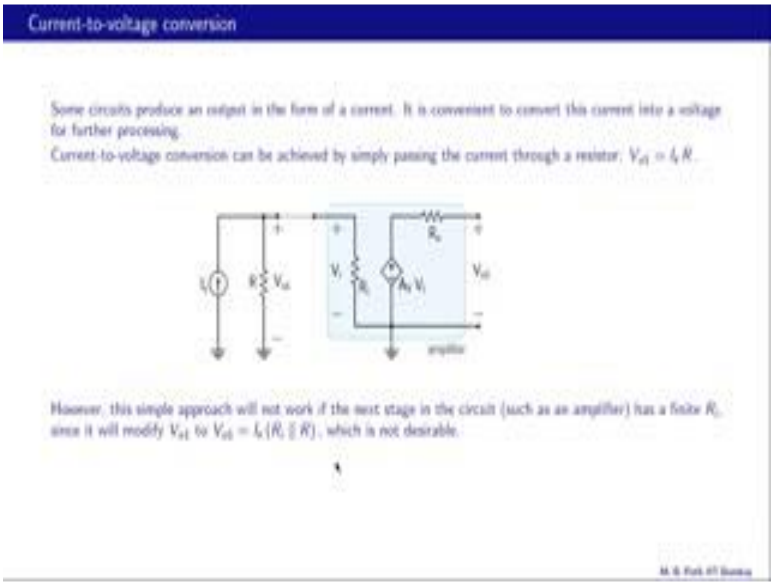

Let us now look at current to voltage conversion and that is relevant because some circuits produce an output in the form of a current, and it is then convenient to convert this current into a voltage for further processing. For example, we might want to display that voltage or we might want to amplified further and so on. Now what is the simplest way of converting a current to a voltage? Just pass it through a resister. So, this is our signal current I s we pass it through a resistance R and that produces an output voltage I s times R. And that is exactly what we want; we have got a voltage which is proportional to our signal current.

Fair enough, but there is a problem with that approach. Let us say we want to now amplify or measure this V o 1 by connecting an amplifier between this node and down, like that. This is our amplifier with the voltage gain of A v. So, we would expect this V o 2 to be A v times V o 1 which is A v times I s times R. Now that is not what happens because this amplifier has an input resistance R i which comes in parallel with R and therefore this V o 1 would now change to I s times R parallel R i, like that. And that of course, is not desirable and why did not this happen because this amplifier as loaded our source circuit.

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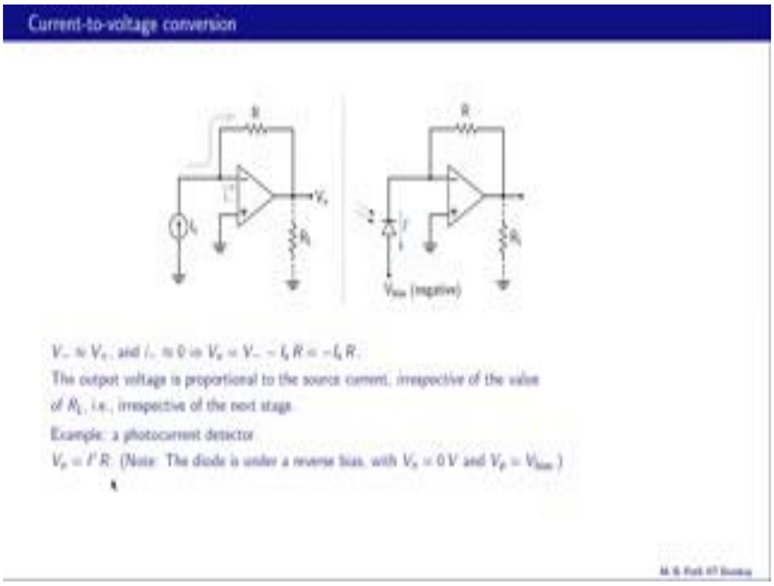

So, let us now look at an op-amp circuit which avoids this problem. Here is an op-amp circuits which can be used to convert a current to a voltage. How does it work it is very easy to understand. This current is 0 because that is an input current for the op-amp and therefore our signal current I s would go through this resistance R, and v o would then be v minus minus this voltage drop. And since v minus and v plus are nearly equal assuming the op-amp to be operating in the linear region. This node is at virtual ground, so therefore v o would be 0 minus I s times R, like that. And node particularly that the load resistance simply does not enter this equation. So, this relationship is independent of what we connect as the load, and that of course is what we wanted.

Let us take a look at an example; that is a photocurrent detector. What is a photocurrent? Photocurrent is a current that we generate by shining light on a semiconductor device;

typically a diode. These diodes of course are specially made, but they are basically the same as a p-n junction.

So, let us look at the circuit; here is the circuit. This v bias is negative let us say minus 5 volts, this node is at virtual ground. So, the n terminal of the diode is at 0 volts and the p is at minus 5 volts for example. So therefore, the diode is under reverse bias. In this situation if we shine light on this diode this reverse current can change significantly and that is our signal current. So, what is the output voltage in this case? This i prime would also go through this R like that and therefore v o is 0 volts plus this voltage drop that is i prime times R.

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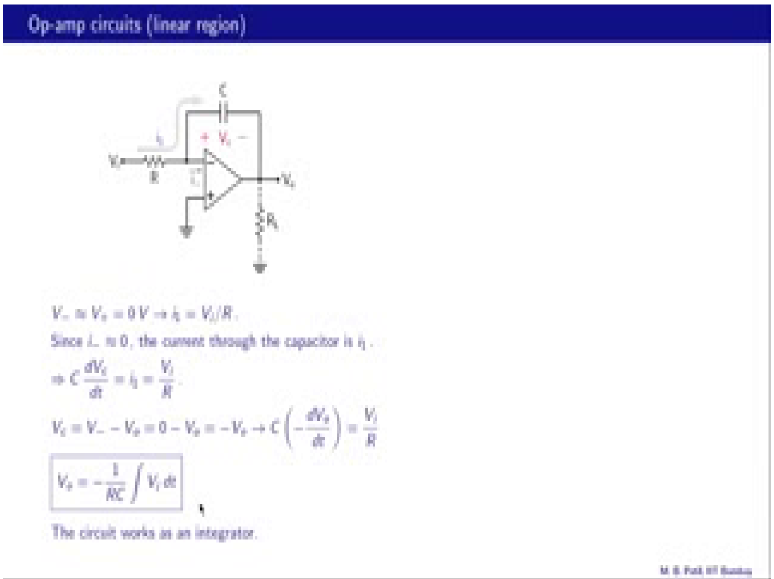

So, that is a common application of this current voltage converter. Here is another useful op-amp circuit; let us see what it is doing. We will assume that the op-amp is operating in the linear region. So, v minus and v plus are nearly equal therefore this is at virtual ground that gives us i 1 v i minus 0 divided by R or v i by R. Since i minus is 0 that is in input current for the op-amp the current through the capacitor it is also i 1 like that. And what is the current through capacitor it is C d V c dt. So, therefore, we have C d V c dt equal to i 1 equal to v i by r.

Now, we want to relate v c and v o; what is v c? Its v minus minus v o and we know that v minus is 0 volts, so therefore v c is 0 minus v o that is simply minus v o. So, instead of v c here we can put minus v o so that gives us this equation c times minus d v o dt equal to v i by R. In other words v o is minus 1 over R c integral V i dt, and v c that this circuit is working as an integrator. So, it integrates the applied input voltage.

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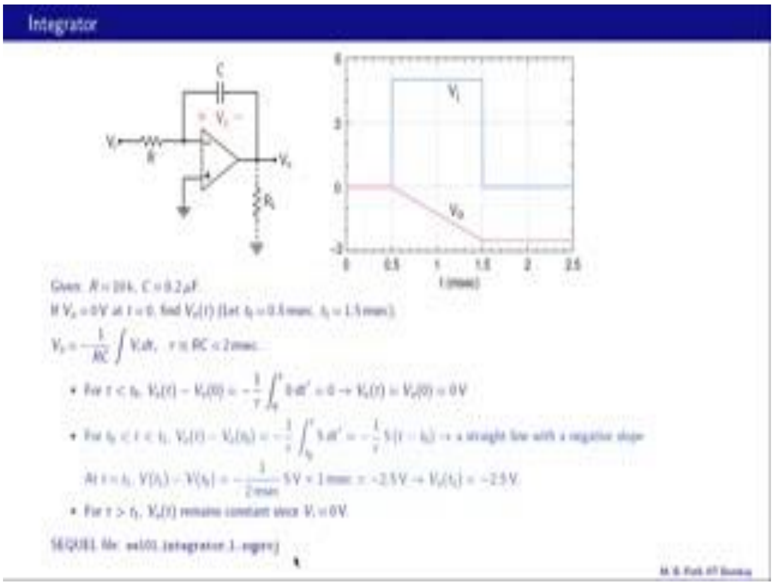

Let us look at an example of the integrator circuit given R is equal to 10 k, c equal to 0.2 micro farads. And the input voltage waveform is given it is 0 up to this point up to point 5 millisecond, then it raises appropriately to 5 volts then it remains at 5 volts up to 1.5 milliseconds and then it comes down to 0 states at 0 thereafter. That is our input voltage, we have also given that the output voltage this is 0 at t equal to 0. And given these conditions given these component values we want to find v o as a function of time.

Let us use t 0 to denote this time at which v i is going from low to high, so t 0 is 0.5 milliseconds and let us use t 1 to denote this time at which v i is going from high to low so t 1 is 1.5 milliseconds. Now what do we know about the integrator; we know that v o is given by minus 1 over R c integral V i dt this R c we will denote by tau. And what is the value of tau? R is 10 k c is 0.2 micro farads, so 10 times 0.2 is 2 kilo times micro is milli; so tau is 2 milliseconds.

What we will do now is to consider three different intervals this one that is 0 to t 0 this one from t 0 to t 1 and this one that is t greater than t 1. And in each of these intervals we will find v o of t and then finally we will put it all together. So, let us start with this first interval that is t less than t 0. So, what we can do now is to evaluate this integral from 0 to t where t is somewhere in this intervals. On the left hand side we will get v 0 of t minus v 0 at 0 and on the right hand side we will get minus 1 over tau integral 0 to t v i dt and v i is 0 here. So therefore, this whole right hand side becomes simply 0 and therefore v o of t becomes equal to v o of 0 that is 0 volts; as shown here by the red line.

Next let us consider the interval from t 0 to t 1 that is 0.5 milliseconds to 1.5 milliseconds. Throughout this interval v i is constant 5 volts, so let us find the output voltage now. Again we integrate v i from t 0 to t and on the left hand side we will get v 0 at t minus v 0 at t 0 and on the right hand side we will get minus 1 over tau t 0 to t integral V i d t and v i is 5 volts. So therefore, this turns to be minus 1 over tau 5 times t minus t 0. And this is simply a straight line, this is our y, this is a constant and this is our x. So, it as the form y equal to m x plus c. So, that is a straight line, and as we can see it as a negative slope minus 5 divided by tau.

So, we expect v o to go down at this point a straight line with negative slope, so something like this and now let us calculate what v o should be at t 1 that is 1.5 milliseconds. At t equal to t 1 all we need to do now is substitute t equal to t 1 in this expression. So, v o at t 1 minus v o at t 0 is equal to minus 1 over tau, tau is 2 milliseconds times 5 volts times t minus t 0; that is t 1 minus t 0, t 1 is here t 0 is here. So, t 1 minus t 0 is 1 millisecond so that is 1 millisecond. So, this turns out to be 5 divided by 2 or 2.5 volts, these milliseconds will cancel with these milliseconds and we are left with minus 2.5 volts. So, that gives us the output voltage at t 1, and that is what v o of t looks like up to t equal to t 1.

After this point the input voltage is 0 and therefore this integral will be 0, and therefore v o will not change. So, for t greater than t 1 v o remains constant since v i is equal to 0 volts, like that. So, that is our overall v o of t. There is circuits file available for this example and you can check out the simulation you can try to increase this capacitance. For example from 0.2 micro farads to 0.5 micro farads work out what you except for v o and then simulate and check whether your prediction is correct. You can also try to change this v i from 5 volts to let say 3 volts again workout v o of t and check if it is according to your prediction.

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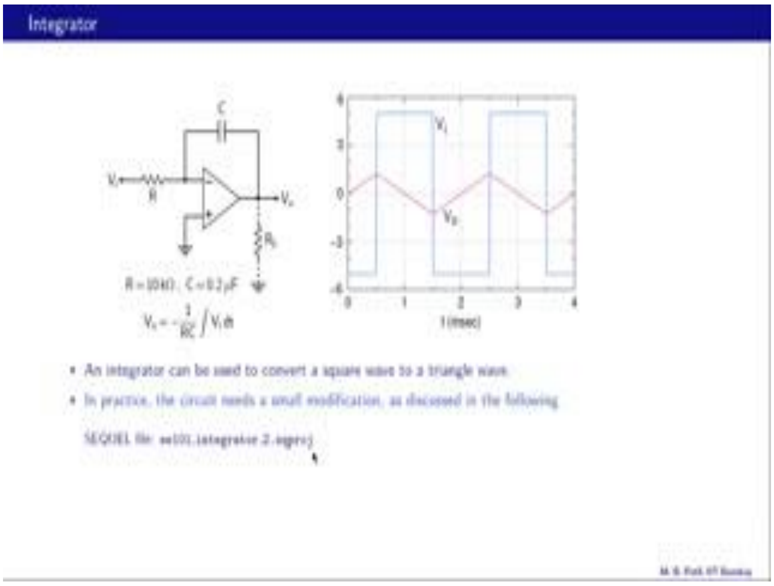

What we saw previously was a simple example just to get used to the numbers and the action of the integrator, but an integrator can actually be used for doing something very useful and that is to convert a square wave to a triangle wave. So, here is our input square wave going from minus 5 volts to plus 5 volts with a period of 2 milliseconds and that is our output triangle wave. And with these numbers you should really work out what v o of t is going to be and check that this plot is indeed correct.

Now, in practice this circuit will not work in its present form and we will see what the reason is, it will require a small modification and we will also discuss that modification. But the basic idea is bring out very clearly in this graph, square wave input and triangle output. Again the sequel circuit file is available for the circuits and you can check out the results.

To conclude we have seen that the instrumentation amplifier offers a high input resistance and a high CMRR and that makes it well suited for sensed applications. We have looked at two additional op-amp circuits; the current two voltage converter and the integrator. In the next lecture we will look at some non idealities associated with an op-amp and how they can affect the circuits we have considered earlier. So see you next time.