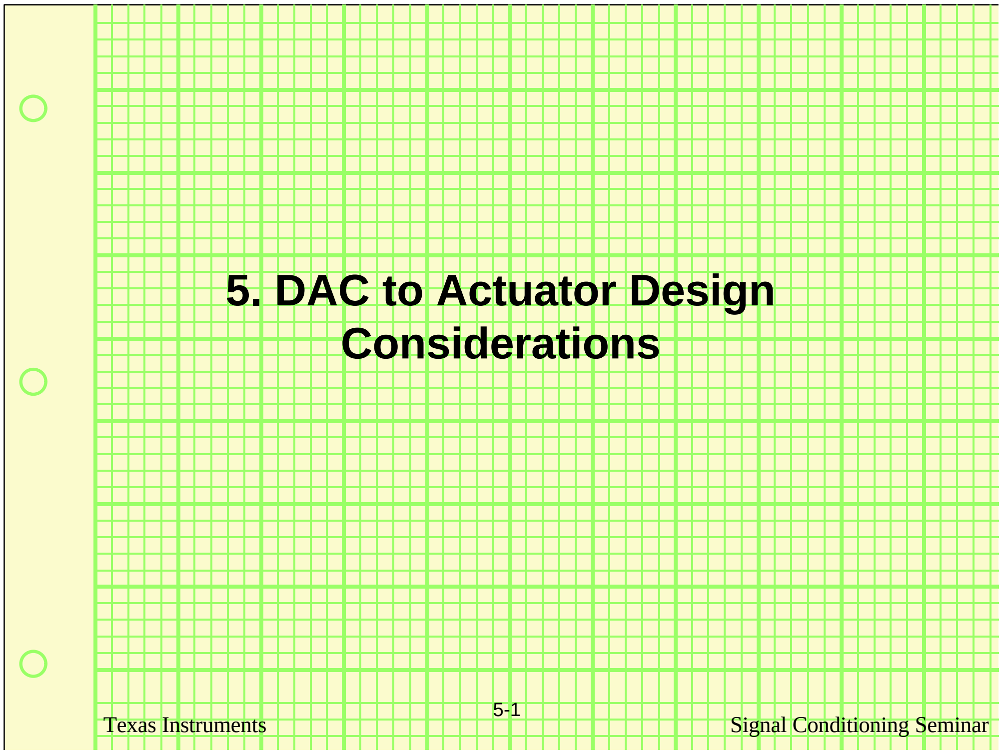
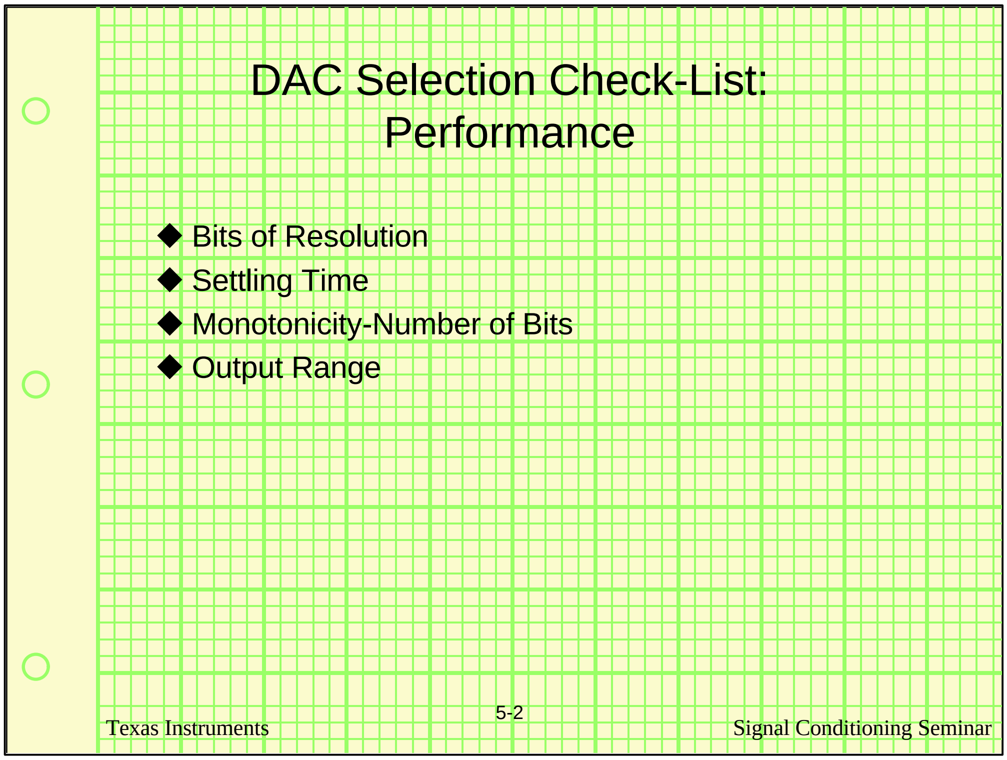


5. DAC to Actuator Design Considerations

DAC to Actuator Design Considerations. Taking a signal from the sensor through a processor and converting it to produce results in the real world.

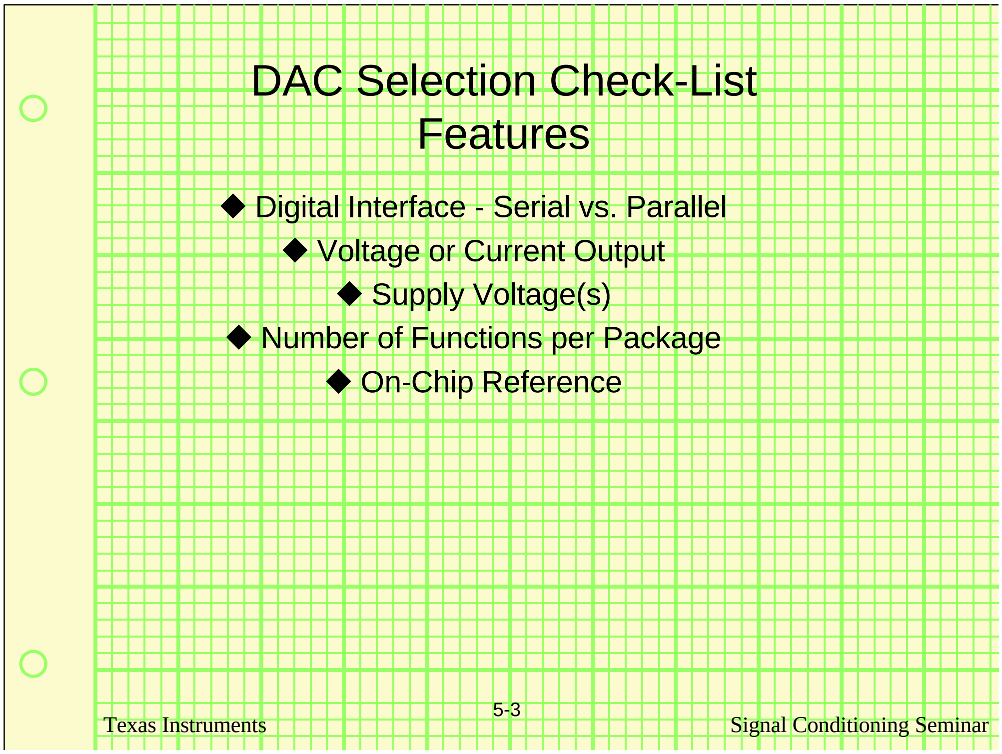


DAC Selection Check-List: Performance

- ◆ Bits of Resolution
- ◆ Settling Time
- ◆ Monotonicity-Number of Bits
- ◆ Output Range

There are four primary areas of performance that are of concern:

1. How much resolution is required for the application, how fine of a step is needed
2. The settling time, how quick do things have to be done
3. Monotonicity, or increasing change in applied digital word; the output must either stay the same or increase - this is very important for servo applications where we're closing the loop, adjusting the output of our DAC, measuring the results through another system and then deciding whether to increase or decrease our word to the DAC, to position a part in the right location
4. Output range, select from a 0-5V, ±5V, ±10V signal range. This section is going to take that limited output range signal and convert it into a useful high-voltage, high-current signal, precision current signal, to actually get the work done.



DAC Selection Check-List
Features

◆ Digital Interface - Serial vs. Parallel

◆ Voltage or Current Output

◆ Supply Voltage(s)

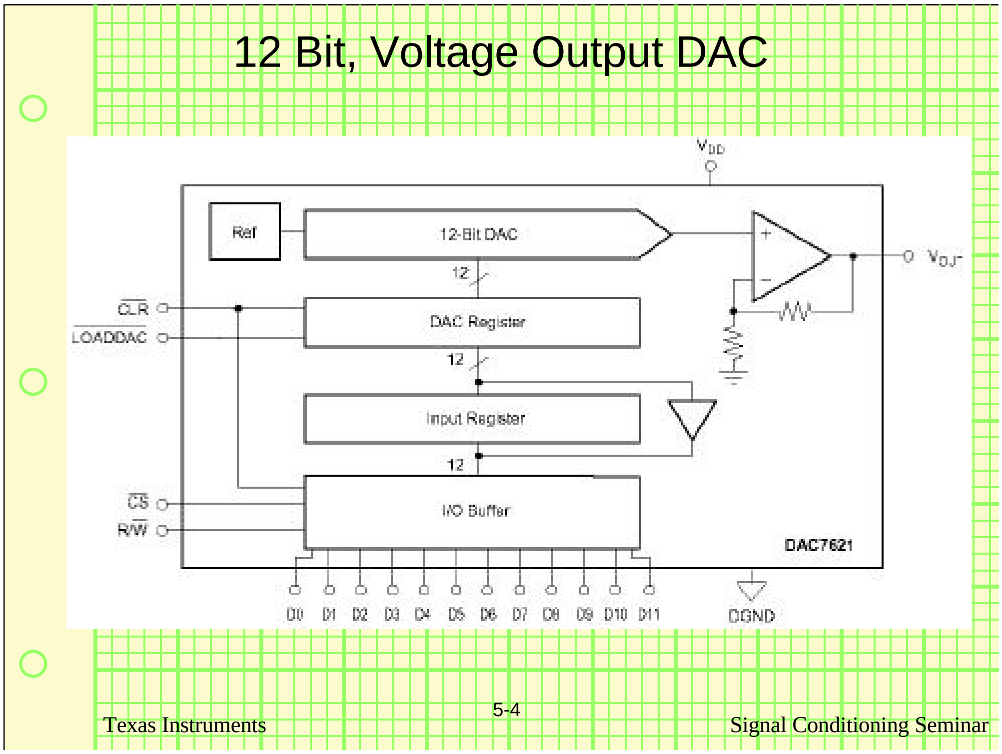
◆ Number of Functions per Package

◆ On-Chip Reference

This is a list of the DAC features that are considered in selecting a DAC.

- Serial ports are usually in short supply on embedded controllers.
- Almost all DAC are voltage out now. Older designs and very high speed DACs may still be current out devices but that is rare.
- Supply voltage is always a concern
- DACs are available in singles, duals, quads and octals.
- Some DACs have on chip reference.
- From the analog signal conditioning the major concern is the output voltage.

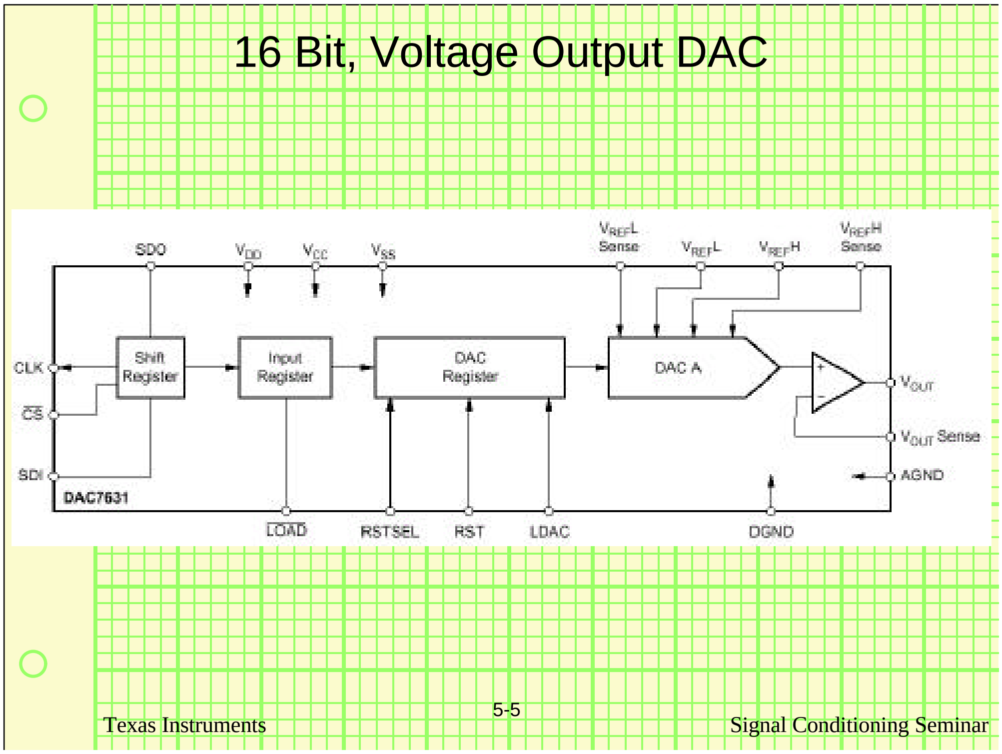
5. DAC to Actuator Design



12 Bit, Voltage Output DAC

Texas Instruments 5-4 Signal Conditioning Seminar

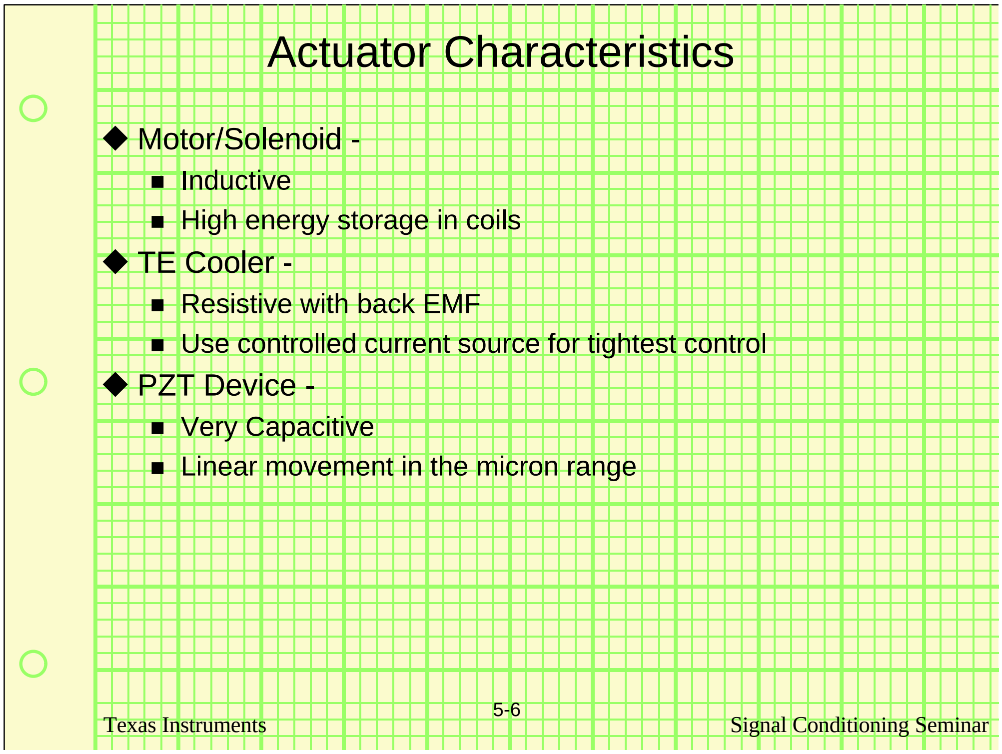
A 12 bit, parallel input DAC with voltage output. This has the feedback resistors included around the output op amp. With this circuit the feedback resistor are matched and will track with temperature. A voltage reference is on chip.



16 Bit, Voltage Output DAC

Texas Instruments 5-5 Signal Conditioning Seminar

This is a 16 bit, serial input DAC. The output op amp inverting input node is brought to a pin so that it can be included in the application circuit and compensate for board losses if needed. A voltage reference is not included.



Actuator Characteristics

- Motor/Solenoid -
  - Inductive
  - High energy storage in coils
- TE Cooler -
  - Resistive with back EMF
  - Use controlled current source for tightest control
- PZT Device -
  - Very Capacitive
  - Linear movement in the micron range

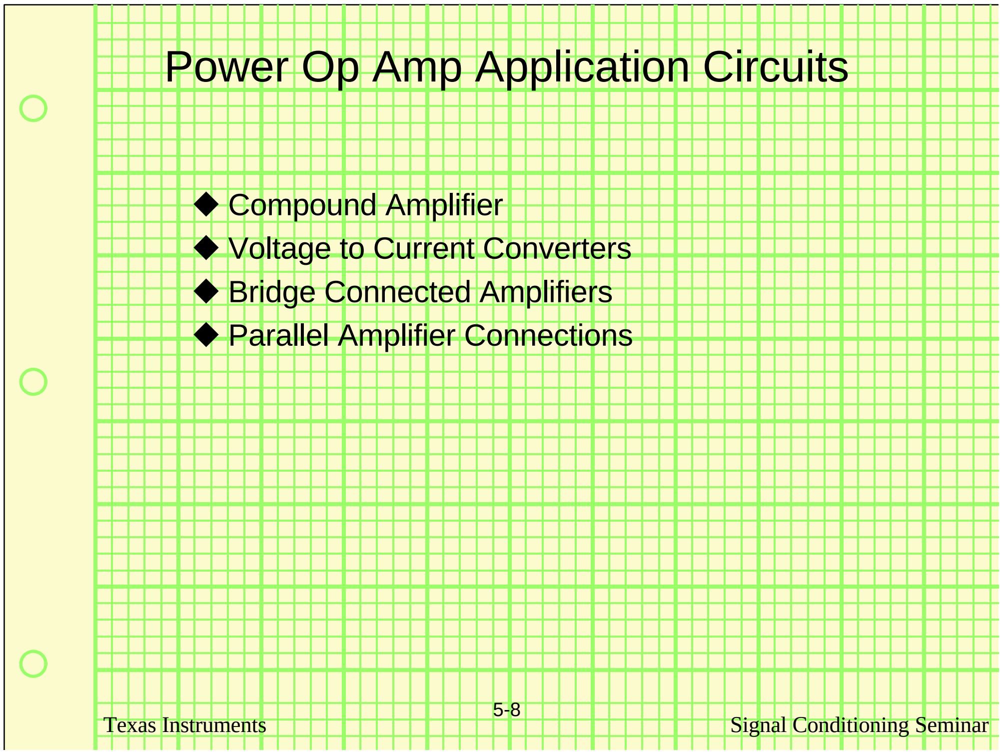
Looking at the other end of the system; what is to be done with this signal? Are we going to move something, maybe a motor; drive a motor or move a solenoid, adjust a valve with a solenoid for partial closing of the valve? Solenoids and motors are inductive and can have a energy stored in the coils. This becomes significant when calculating the stress on the output transistor of the op amp that's driving the motor. A motor has constant torque with constant current. To control the torque drive it with a current source.

The TE cooler, thermoelectric cooler is finding wide application in DWDM, Dense Wave Division Multiplexing, keeping the lasers at a constant temperature. TE coolers rely on the Peltier effect, which perhaps is more familiar in terms of the Seabeck effect. That is the phenomenon seen in thermocouples. Two dissimilar metals at different temperatures will develop a current flow through the circuit. Conversely if a current is driven through a circuit of dissimilar metals it will cause heat flow or energy flow. It can use this as a heater/cooler to maintain a constant temperature.

5. DAC to Actuator Design

These parts look like resistors with a back EMF; because I've got the junction to different temperatures, I'm going to be generating a slight voltage there. The tightest control or the most accurate control can be accomplished when these are driven with a current source, and we'll do some considerable current source analysis here in a moment.

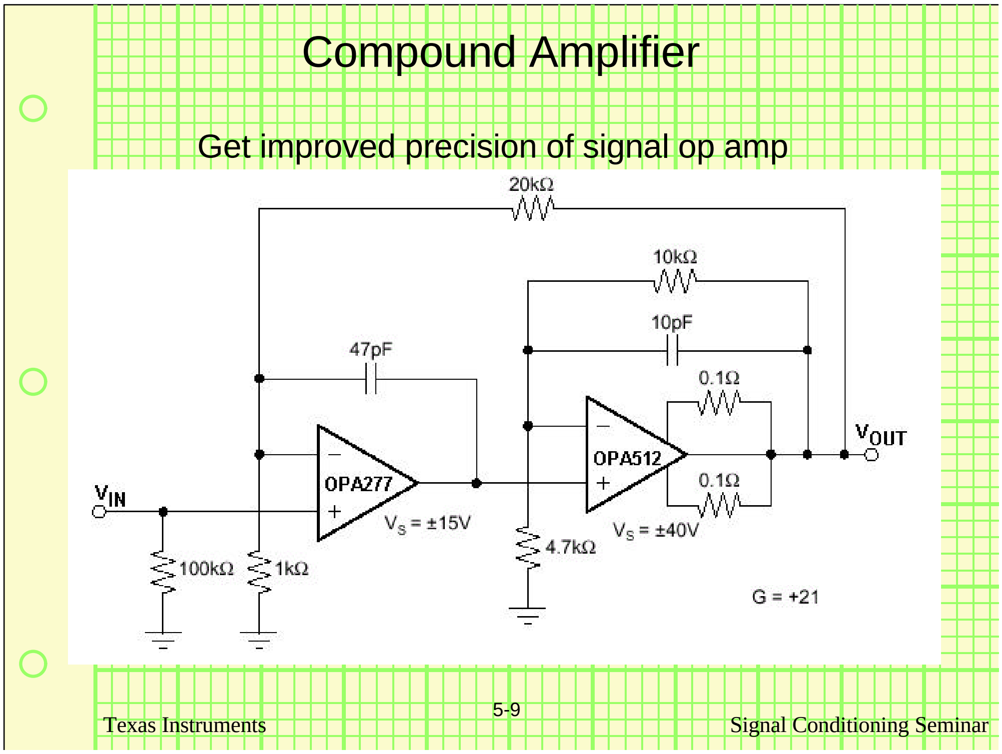
And finally we'll mention a piezoelectric device. A piezoelectric device is really a very big capacitor, so the DC current is actually zero. If DC current flows through the piezoelectric device the device is probably destroyed. It can, however, require high current out of the op amp to operate at high frequency. In order to change the voltage across the capacitor quickly requires current. Recall the expression that $I=C\,dV/dt$. The faster a voltage across a capacitor is changed, the more current it will take. These devices are used to obtain linear movement in the micron range, such as positioning mirrors and moving small elements.



Power Op Amp Application Circuits

- Compound Amplifier
- Voltage to Current Converters
- Bridge Connected Amplifiers
- Parallel Amplifier Connections

Power op amp application circuits will make the bridge between the low-voltage, low-current output from a DAC and the required accurate high current, high voltage required by the output devices. Circuits include compound amplifiers, voltage-to-current converters, bridge-connected amplifiers and the parallel amplifier connection.

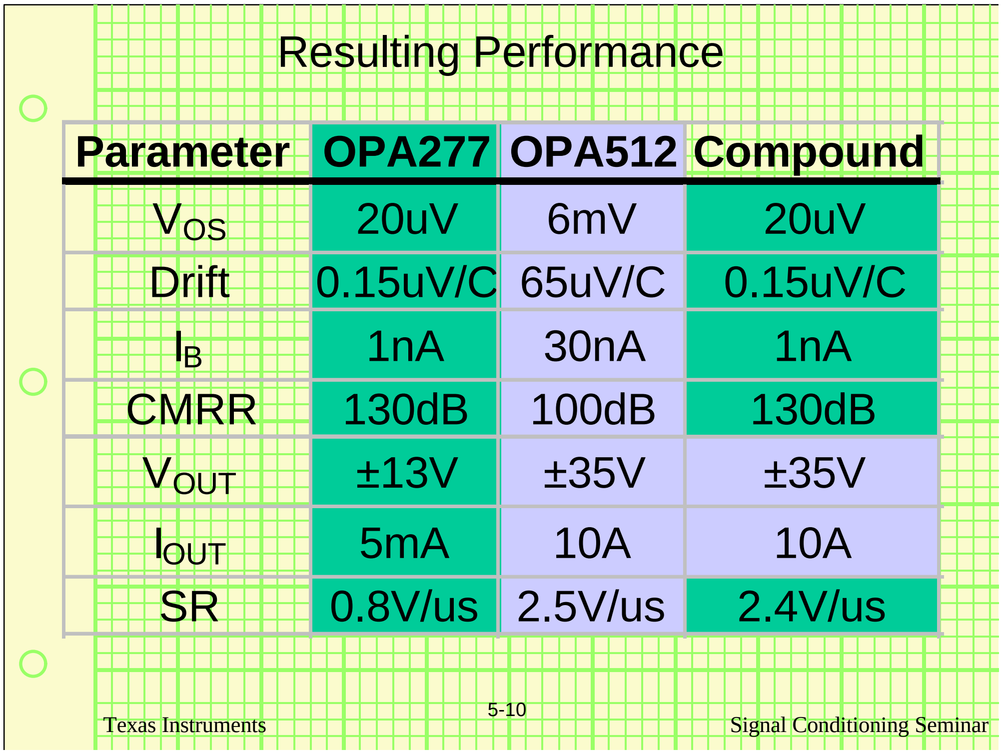


Compound Amplifier

Get improved precision of signal op amp

This circuit address the need for a power output stage with a precision input circuit. The combination is not available in one device. It is possible to combine the power capabilities of the OPA512 with the precision of the OPA277.

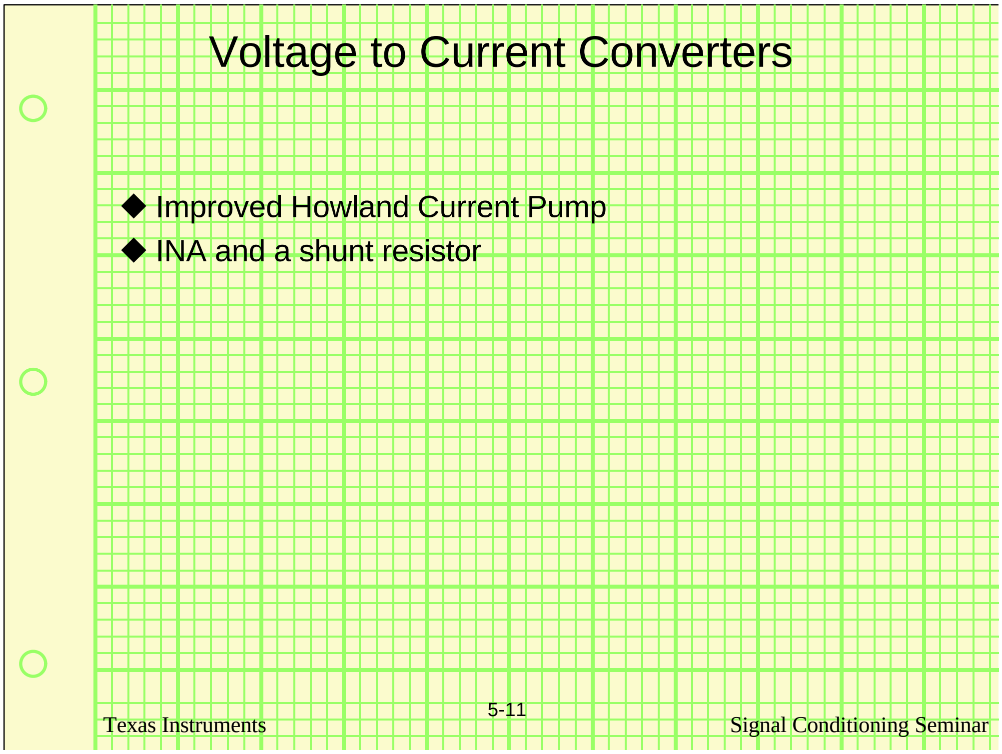
The OPA512 has the highest slew rate and therefore is operated within a local closed loop. The slower OPA277 is operated within the outer loop. The 47pF capacitor provides a small amount of phase shift to help stabilize the system.



Resulting Performance

Parameter	OPA277	OPA512	Compound
V_{OS}	20uV	6mV	20uV
Drift	0.15uV/C	65uV/C	0.15uV/C
I_B	1nA	30nA	1nA
CMRR	130dB	100dB	130dB
V_{OUT}	±13V	±35V	±35V
I_{OUT}	5mA	10A	10A
SR	0.8V/us	2.5V/us	2.4V/us

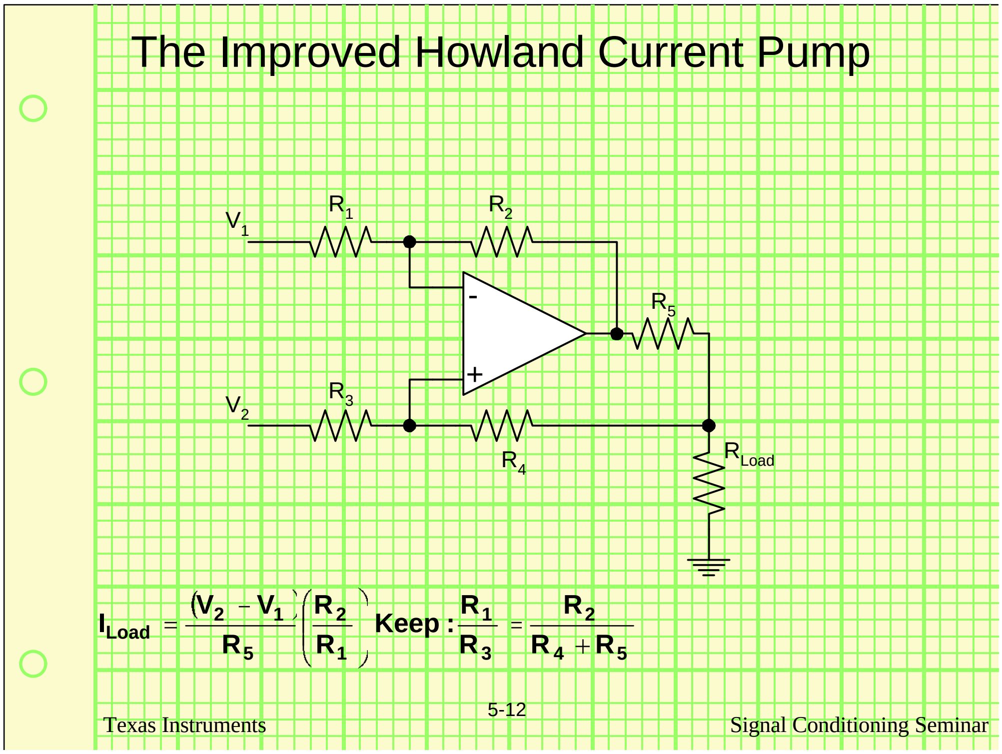
The resulting performance of the compound amplifier shows that the front-end characteristics of the OPA277 are joined with the ±35V at 10A drive current capabilities out of the OPA512. The slew rate of the OPA277 is 0.8V/µs. That slew rate is gained up times three in the OPA512 so that there is an effective slew rate for the compound amplifier of 2.4V/µs.



Voltage to Current Converters

- Improved Howland Current Pump
- INA and a shunt resistor

In voltage-to-current converters there are two options: The improved Howland current pump, and using an INA with a shunt resistor.



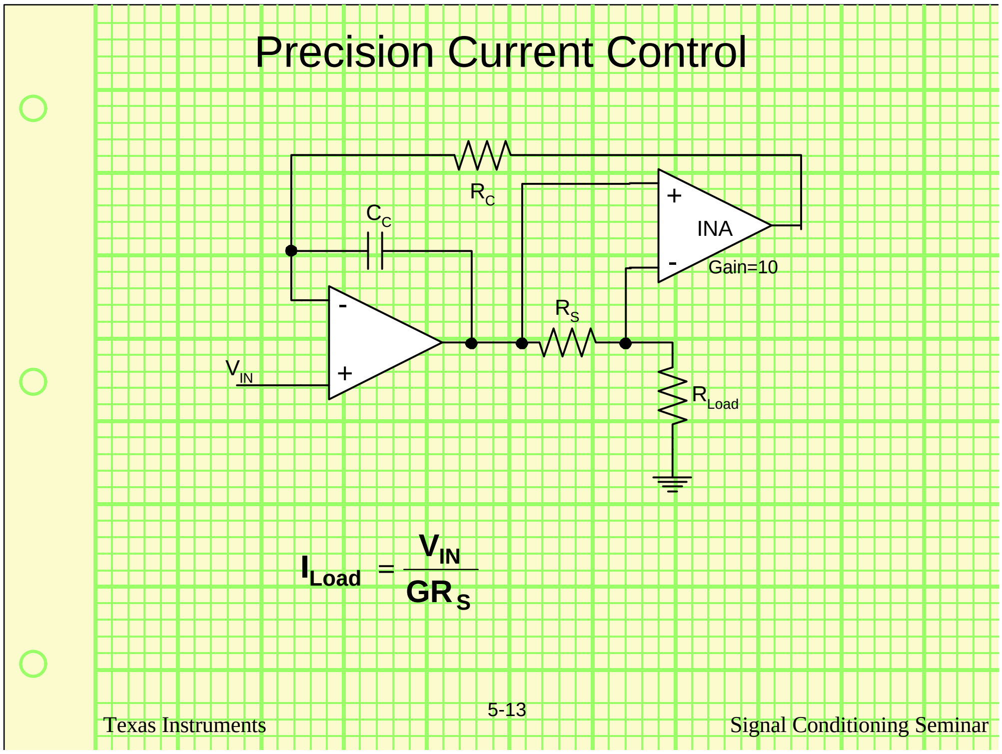
The Improved Howland Current Pump

$$I_{Load} = \frac{(V_2 - V_1)}{R_5}\left(\frac{R_2}{R_1}\right) \quad \textbf{Keep}: \frac{R_1}{R_3} = \frac{R_2}{R_4 + R_5}$$

Texas Instruments 5-12 Signal Conditioning Seminar

The improved Howland current pump uses the differential capabilities of the op amp to detect the voltage across R_5, the sense resistor, and use that to control the current flow through the load. The Howland current pump is a good compromise on getting controlled current into a grounded load. However, there are a couple of drawbacks here. Number one, the resistor ratios, R_1/ R_3 ratio, must equal the $R_2/(R_4+R_5)$ ratio to give us this transfer function. Even if build with 1% resistors accuracy will be on the order of 10 to 20 percent.

The accuracy issue is because of circuit interactions. The resultant circuit is still adequate for most motor drive applications.

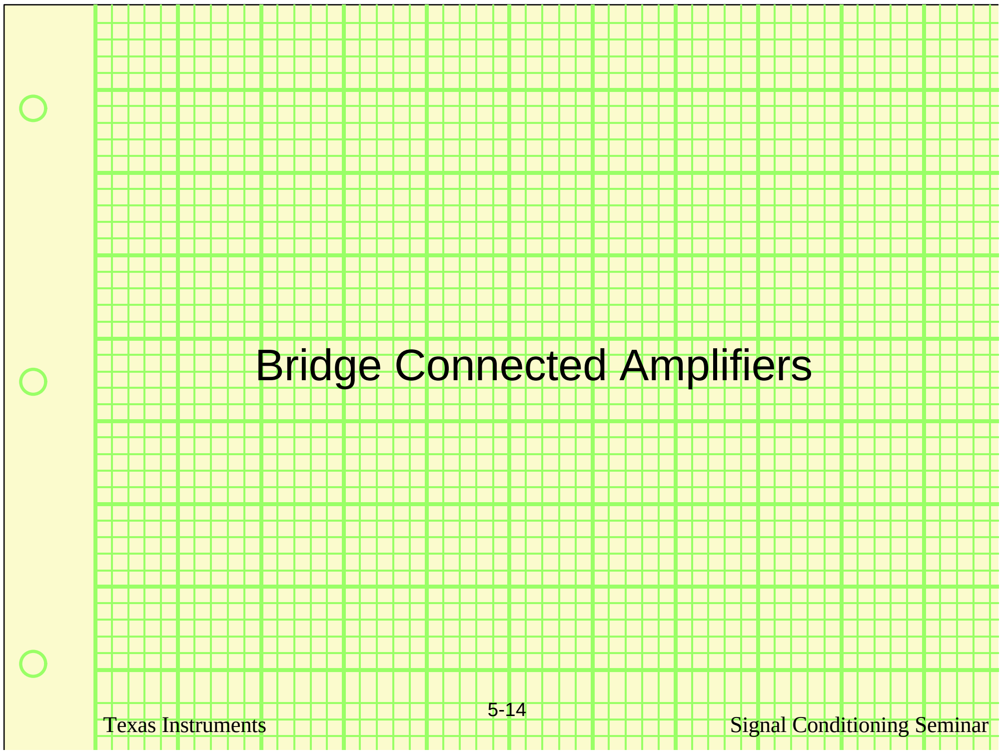


Precision Current Control

$$I_{Load} = \frac{V_{IN}}{GR_S}$$

For a high precision current control take an instrumentation amplifier that has been talked about earlier today, connect it across the sense resistor as shown here, put in a gain to increase the effective value of the sense resistor and then feed that signal back to drive the op amp. It is required that the instrumentation amplifier have a higher bandwidth than the op amp.

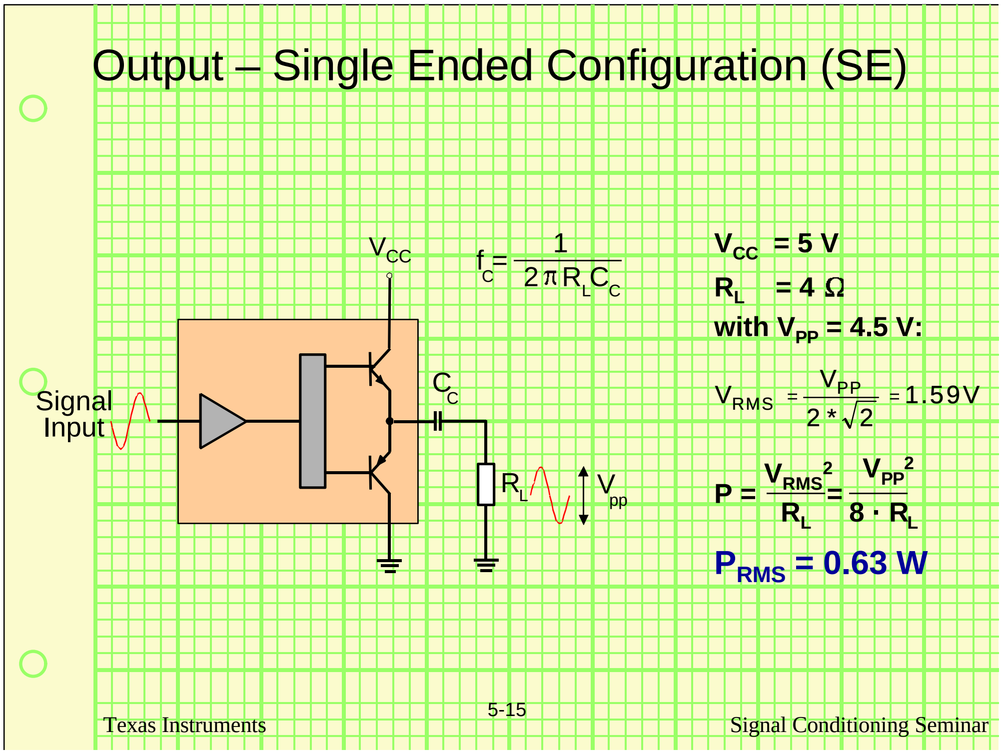
In some applications it may be necessary to put in a phase comp network as shown here with R_C and C_C to slow down the op amp.



Bridge Connected Amplifiers

Texas Instruments 5-14 Signal Conditioning Seminar

Bridge connected op amps; very powerful - mind the pun - a very powerful operation here.



Output – Single Ended Configuration (SE)

$$f_C = \frac{1}{2\pi R_L C_C}$$

V_{CC} = 5 V

R_L = 4 Ω

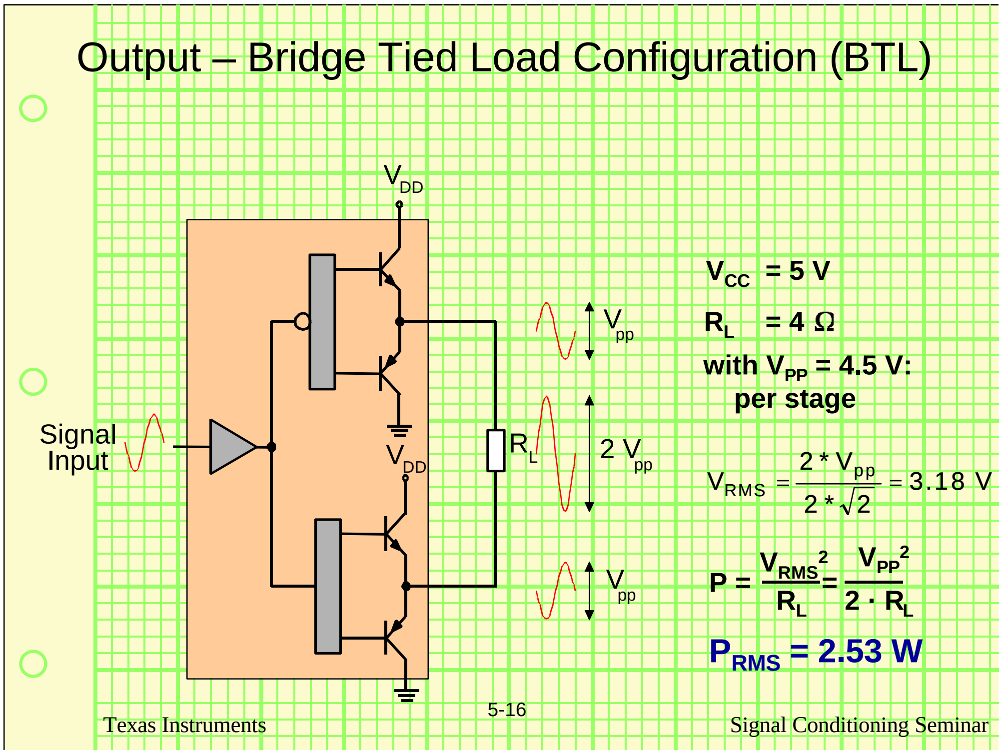
with V_{PP} = 4.5 V:

$$V_{RMS} = \frac{V_{PP}}{2 * \sqrt{2}} = 1.59V$$

$$P = \frac{V_{RMS}^2}{R_L} = \frac{V_{PP}^2}{8 \cdot R_L}$$

P_{RMS} = 0.63 W

Consider the single-ended configuration. Given a 5V supply and a 4Ù load the amplifier can swing 4.5V_{PP} out. This results in a RMS power to the load of 5/8 of a watt.



Output – Bridge Tied Load Configuration (BTL)

V_{CC} = 5 V

R_L = 4 Ω

with V_{PP} = 4.5 V: per stage

$$V_{RMS} = \frac{2 * V_{pp}}{2 * \sqrt{2}} = 3.18\ V$$

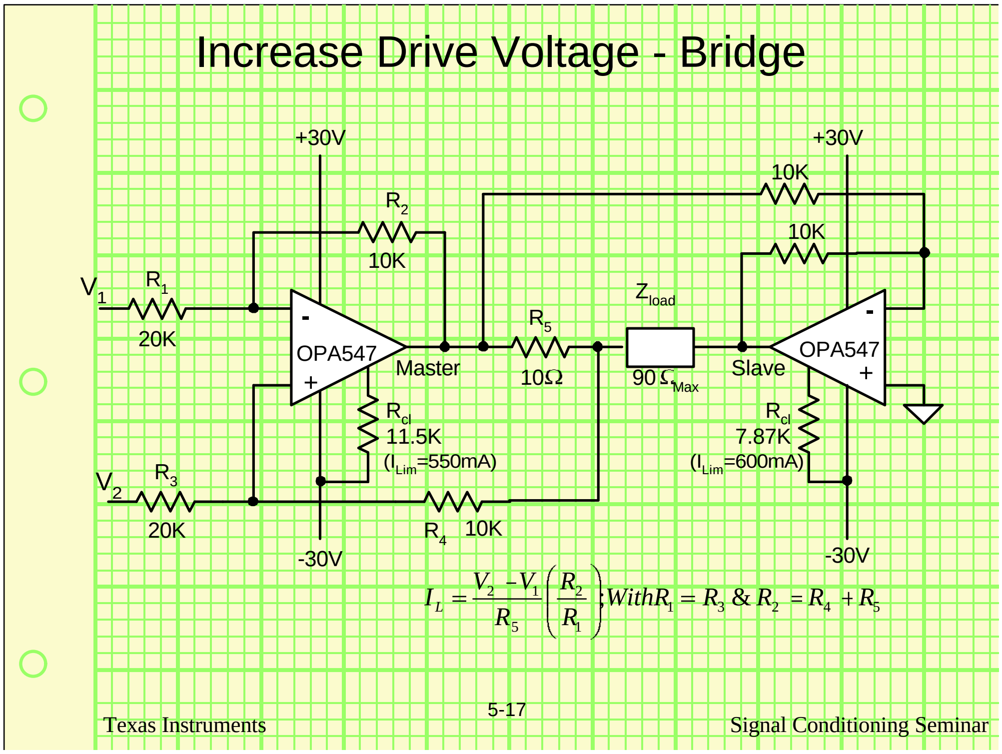
$$P = \frac{V_{RMS}^2}{R_L} = \frac{V_{PP}^2}{2 \cdot R_L}$$

P_{RMS} = 2.53 W

Texas Instruments 5-16 Signal Conditioning Seminar

If both ends of the load are available then put in a second stage to greatly increase the power to the load. The signal to the top stage is inverted from the bottom stage. The 5V, 4Ù, 4.5V_{PP} per stage parameters still apply. Because power goes with the square of the voltage, double the voltage and get four times the power. Now the RMS power, instead of being 5/8 of a watt, is going to be over 2.5W.

5. DAC to Actuator Design



Increase Drive Voltage - Bridge

$$I_L = \frac{V_2 - V_1}{R_5}\left(\frac{R_2}{R_1}\right); With R_1 = R_3 \ \& \ R_2 = R_4 + R_5$$

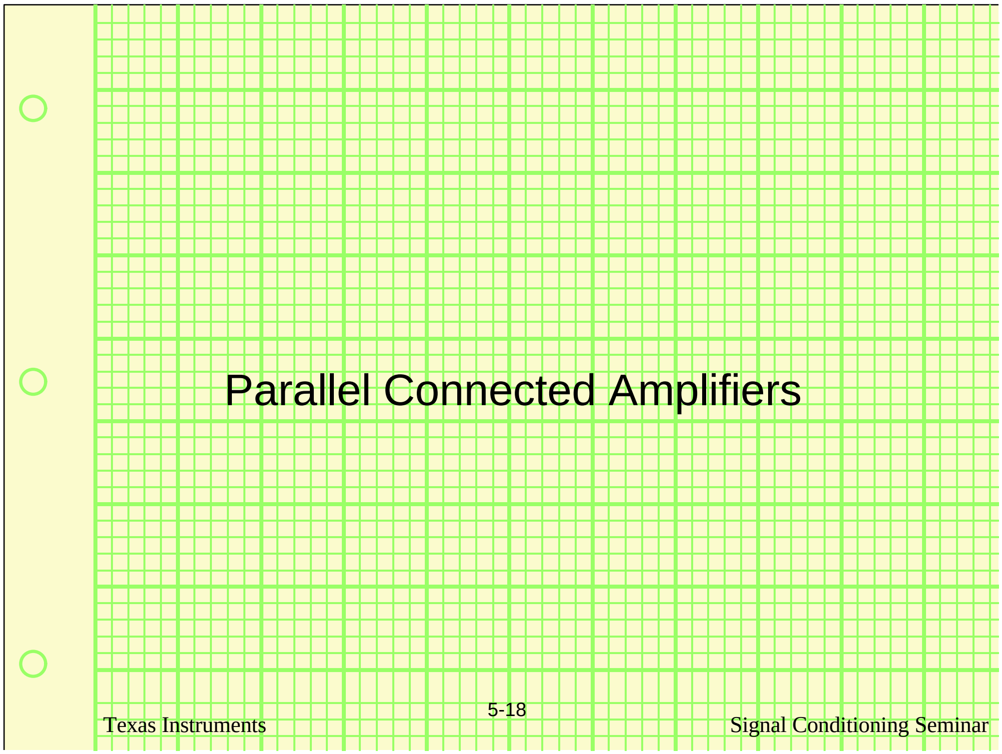
Texas Instruments 5-17 Signal Conditioning Seminar

For more powerful bridge applications such as improved drive on a motor or a piezoelectric cell. This circuit is using the improved Howland current pump but any circuit on the master side can be done. It could be an active filter, a current source a plain gain stage. The master will establish an output voltage which will then be inverted with the slave amplifier. With voltage at the bridge of the center of the load does not move. Therefore, for power dissipation calculations and stability concerns operate the master side into half the normal load which is connected to ground. Any stability issues with the master side must be resolved before the slave side is added.

The OPA547 used here allows an external current limit set. This is an advantage because now the current limit on the slave can be set slightly higher than the limit current on the master.

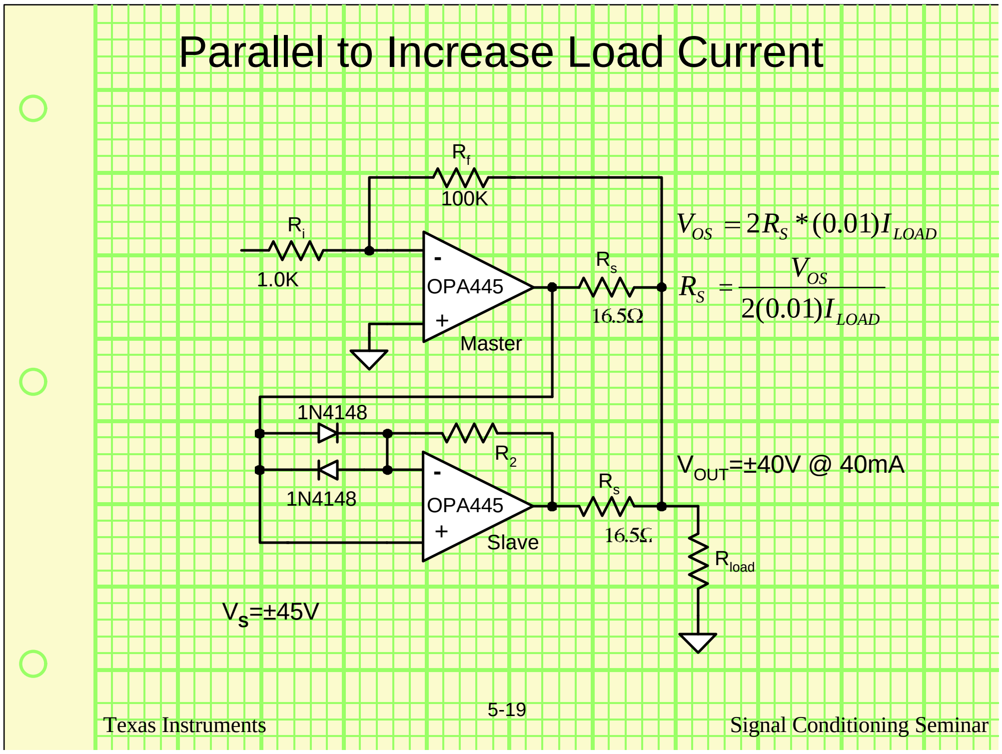
In a fault condition such as a stalled motor or shorted load which produces an over-current condition - the master will go into current limit first. As the master shuts down, the slave will follow, limiting the current output from both devices. If the slave is allowed to go into current limit first, the master would continue to drive and that will put considerable stress on the slave output stage. By staggering the current limit points as is done here, the amplifier drive circuit is protected.

A second advantage is that the slew rate of the circuit is twice that of the individual amplifier. As one side is going up at max slew rate the other side is going down at the same rate.



Parallel Connected Amplifiers

Increase current drive with parallel connected amplifiers.



Parallel to Increase Load Current

$$V_{OS} = 2R_S*(0.01)I_{LOAD}$$

$$R_S = \frac{V_{OS}}{2(0.01)I_{LOAD}}$$

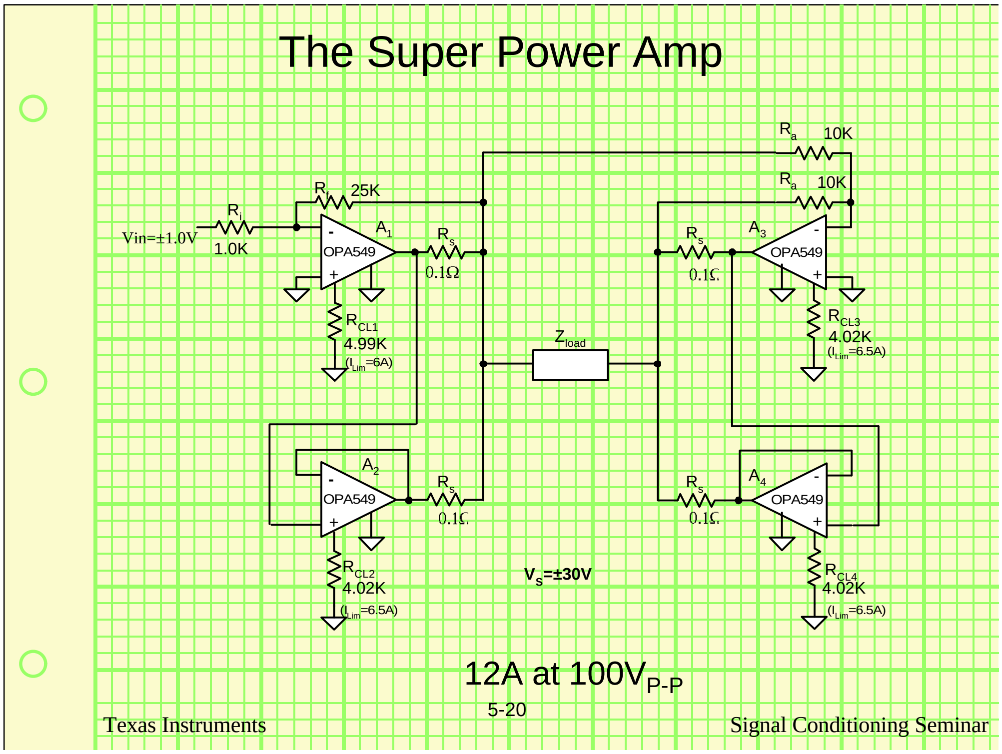
V_{OUT}=±40V @ 40mA

V_S=±45V

To increase load current, connect two amplifiers in parallel. There is no real limit to the number of amplifiers that can be connect in parallel. In this example the master op amp is operated in a gain of 100. The output of the master amplifier is applied to the slave, which is running in a non-inverted gain of 1.

With the two outputs connected together it is necessary to provide R_S to force the amplifiers to share the load. The output of the slave is going to be equal to the output of the master plus the voltage offset of the slave. That voltage is going to be impressed across both R_S resistors. Any current that flows in that loop is not flowing through the load. The nominal goal is limit that current to 1 percent of the load current. This gives the relationship shown on the slide.

The resistor, R_2, and the diodes are there because the OPA445 suffers from phase inversion; that is if the input is over driven to the negative rail, the output will flip to the positive rail. In this fault condition the amplifiers fighting against each other. The diodes and resistor prevent the overdrive.



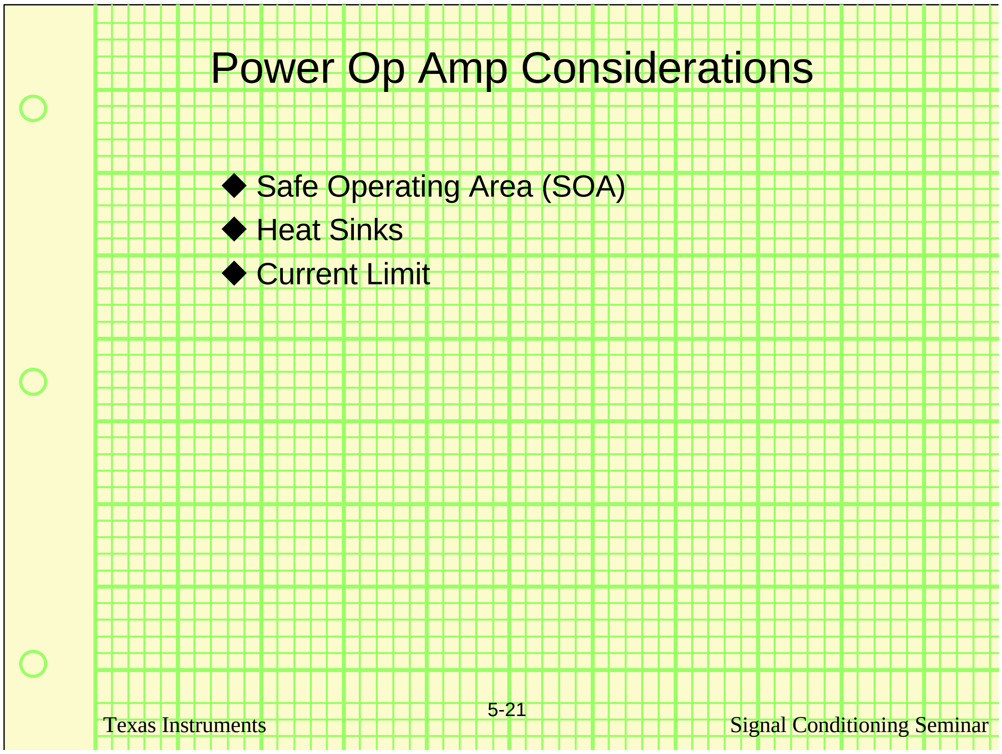
The Super Power Amp

12A at $100V_{P-P}$

For the super amplifier use four OPA549s, an 8A output op amp. Place two of them in parallel - A_1, A_2 on the left-hand side. A_1 is the master, running in a gain of 25. It is sharing the load with A_2 with each putting out 6A. That output voltage is connected to A_3, which is running as a bridge slave. The A_3 output is applied to A_4 which is run as a parallel slave. Total capability is 12A at $100V_{PP}$

The master is current-limited at 6A, all of the slaves at 6.5A.

Circuits like this with six amplifiers on each side of the bridge are not out of the question. That could result in a 50A-output device to be used to drive a stepper motor on a wafer-scanning station. This system will require a significant heat sink as there will be a significant quantity of heat generated in these op amps.



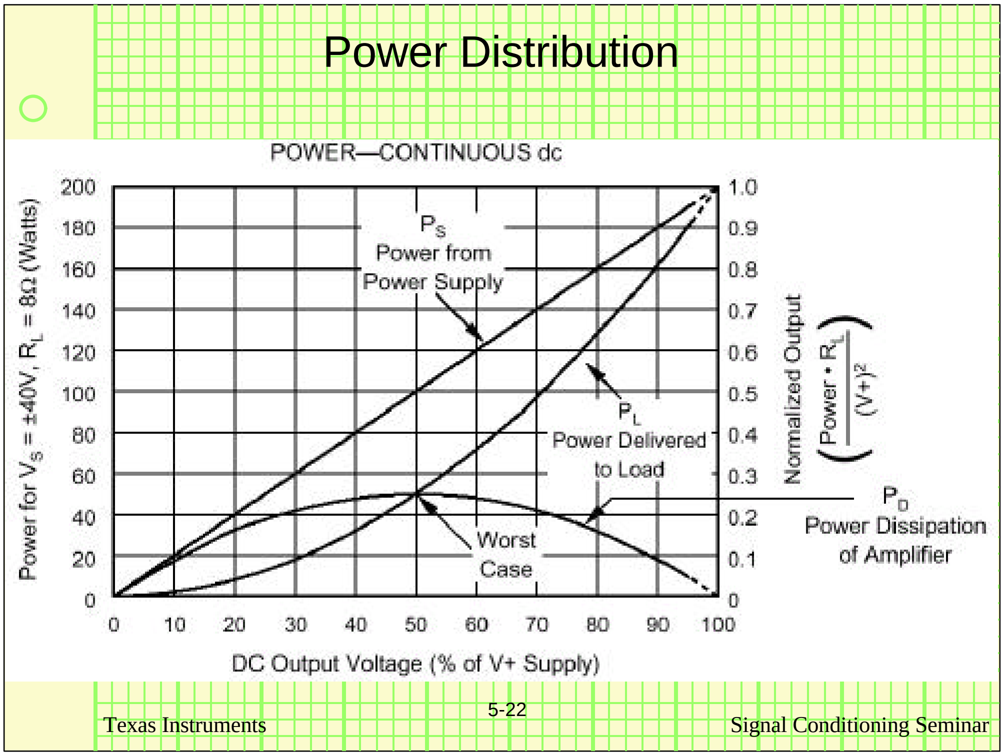
Power Op Amp Considerations

- ◆ Safe Operating Area (SOA)
- ◆ Heat Sinks
- ◆ Current Limit

Power op amp considerations: Safe operating area, heat sinks, and limiting the current.

Application bulletins of interest:

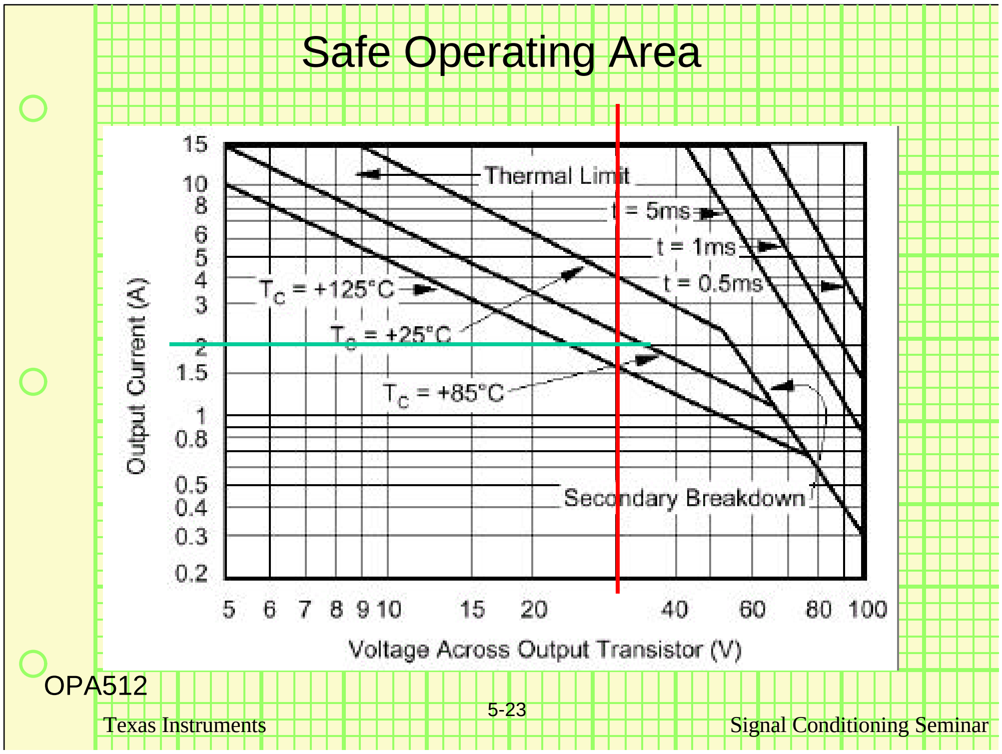
MOUNTING CONSIDERATIONS FOR TO-3 PACKAGES - SBOA020
HEAT SINKING — TO-3 THERMAL MODEL - SBOA021
POWER AMPLIFIER STRESS AND POWER HANDLING LIMITATIONS - SBOA022



Power Distribution

This is a plot of the power dissipation in the load and in the op amp as the load voltage goes from zero to maximum. Notice that the peak power in the amplifier is when the output voltage is at 50% of the supply rail. For heat sink requirements and Safe Operating Area (SOA) concerns this is the power to considered.

This is for a pure resistive load. As the load becomes more reactive this curve is going to shift. The power dissipated in the amplifier will go up at the higher outputs, and the peak will actually move closer to 60 or 70% of supply.



Safe Operating Area

OPA512

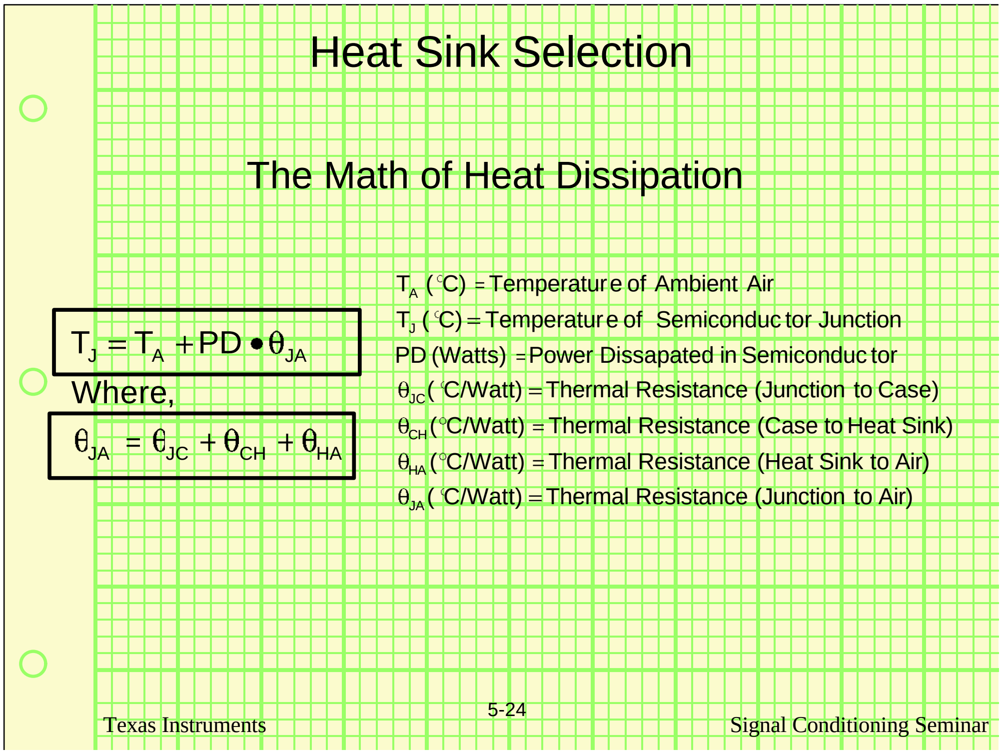
Texas Instruments 5-23 Signal Conditioning Seminar

There is an upper limit to the stress that can be supported by the output devices of the amplifier. In this case the curves are for case temperatures of 25°C, 85°C and 125°C for the OPA512. These are lines of constant power. The EI product along any line is going to be a constant.

Notice the slope on the right-hand side marked secondary breakdown. This is zone of operation that is unique to bi-polar transistors where the device goes into thermal run away.

As an example, consider a situation with 30V developed across the output transistor at 2A into the load. To remain within the SOA it is necessary to maintain a case temperature of approximately 100°C. This means there will be a need for a pretty good-sized heat sink.

This op amp is a 15A device if the temperature at the case is 25°C or less and the voltage across the output transistor at 9V or less. Keeping 25°C at 9V times 15A or 135W dissipation in the amplifier. Notice the only concerned is with the power being dissipated in the amplifier; there is no concern with the power being dissipated in the load.



Heat Sink Selection

The Math of Heat Dissipation

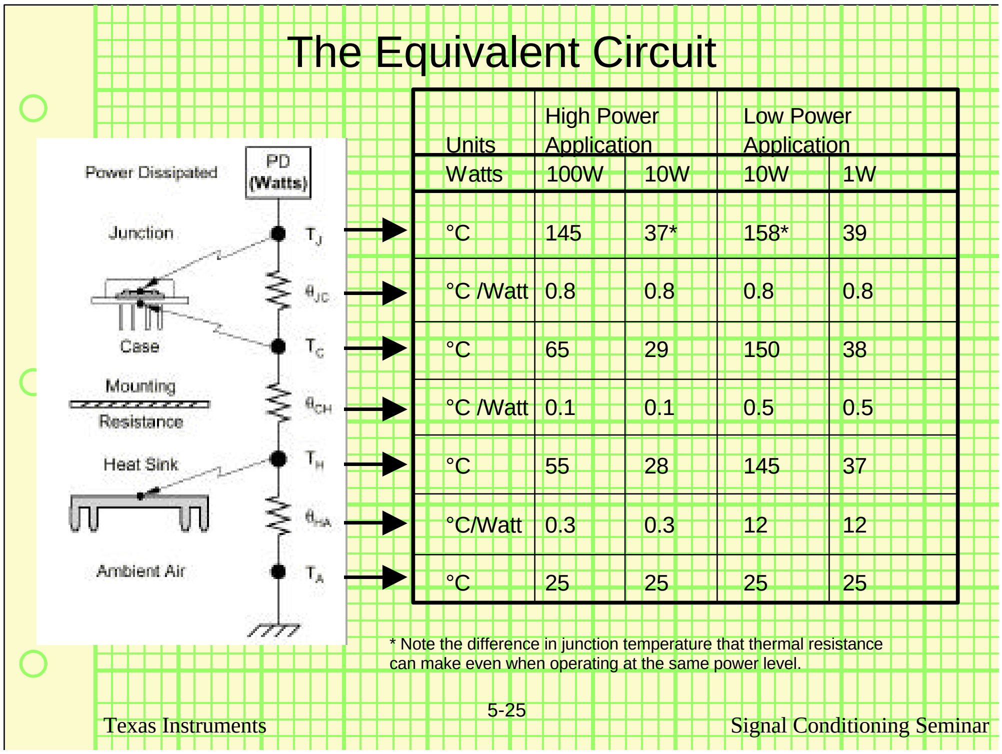
$$\boxed{T_J = T_A + PD \bullet \theta_{JA}}$$

Where,

$$\boxed{\theta_{JA} = \theta_{JC} + \theta_{CH} + \theta_{HA}}$$

T_A (°C) = Temperature of Ambient Air
T_J (°C) = Temperature of Semiconductor Junction
PD (Watts) = Power Dissapated in Semiconductor
θ_{JC} (°C/Watt) = Thermal Resistance (Junction to Case)
θ_{CH} (°C/Watt) = Thermal Resistance (Case to Heat Sink)
θ_{HA} (°C/Watt) = Thermal Resistance (Heat Sink to Air)
θ_{JA} (°C/Watt) = Thermal Resistance (Junction to Air)

The design of a heat sink is based on some empirical measurements made by the heat sink manufacturer, and some empirical measurements made within the enclosure of the final system. The actual mathematics is straightforward. it looks like a simple circuit. Take temperature to be the equivalent of voltage, thermal resistance is now just a simple resistor and the power is considered the same as current. Now this looks like a linear circuit, and in fact the resistances add linearly.



The Equivalent Circuit

Units	High Power Application		Low Power Application	
Watts	100W	10W	10W	1W
°C	145	37*	158*	39
°C /Watt	0.8	0.8	0.8	0.8
°C	65	29	150	38
°C /Watt	0.1	0.1	0.5	0.5
°C	55	28	145	37
°C/Watt	0.3	0.3	12	12
°C	25	25	25	25

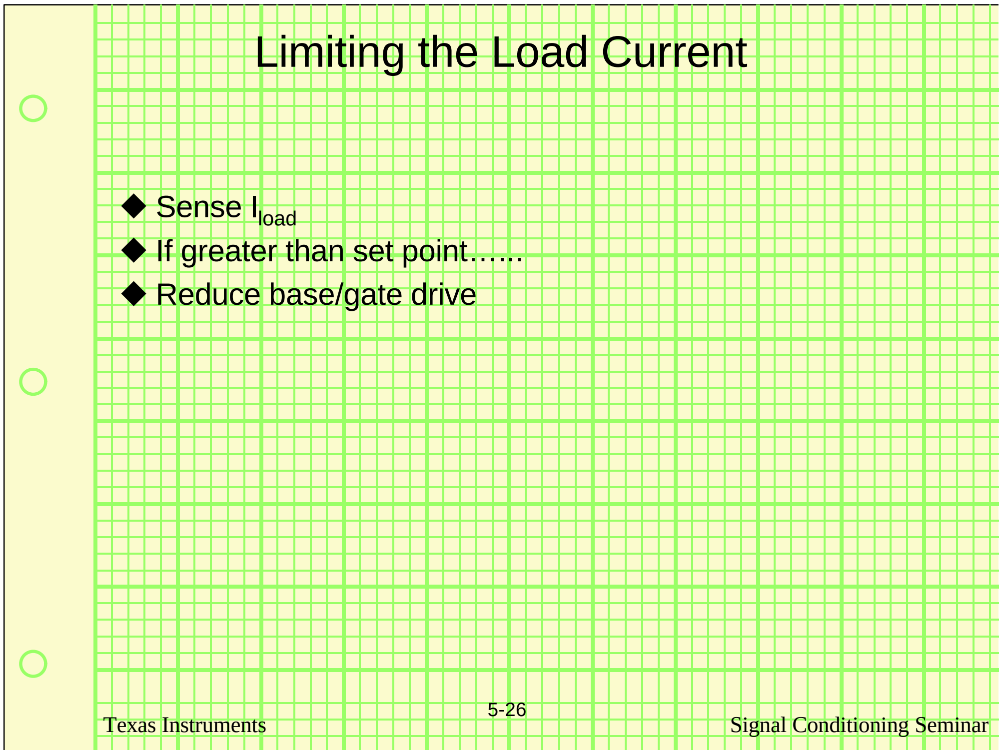
* Note the difference in junction temperature that thermal resistance can make even when operating at the same power level.

This chart compares the performance of two different heat sinks, each at two different power levels. To analyze the equivalent circuit start at ground or at the ambient temperature. Multiply the power by the heat sink thermal resistance, add that to the ambient temperature to find the temperature at the interface between the heat sink and the case.

Now, the power has to pass through the mounting resistance and that resistance is either 0.1 or 0.5°C/W.

With the 10W dissipation can either result in 37°C junction temperature or 158°C junction temperature. This really points out the advantage of getting a highly-efficient heat sink to get the heat out of the device and into the air.

It can be noted that certain things like putting a fan on the heat sink will significantly increase its effectiveness; just open your PC and look at the cooler on the Pentium chip.

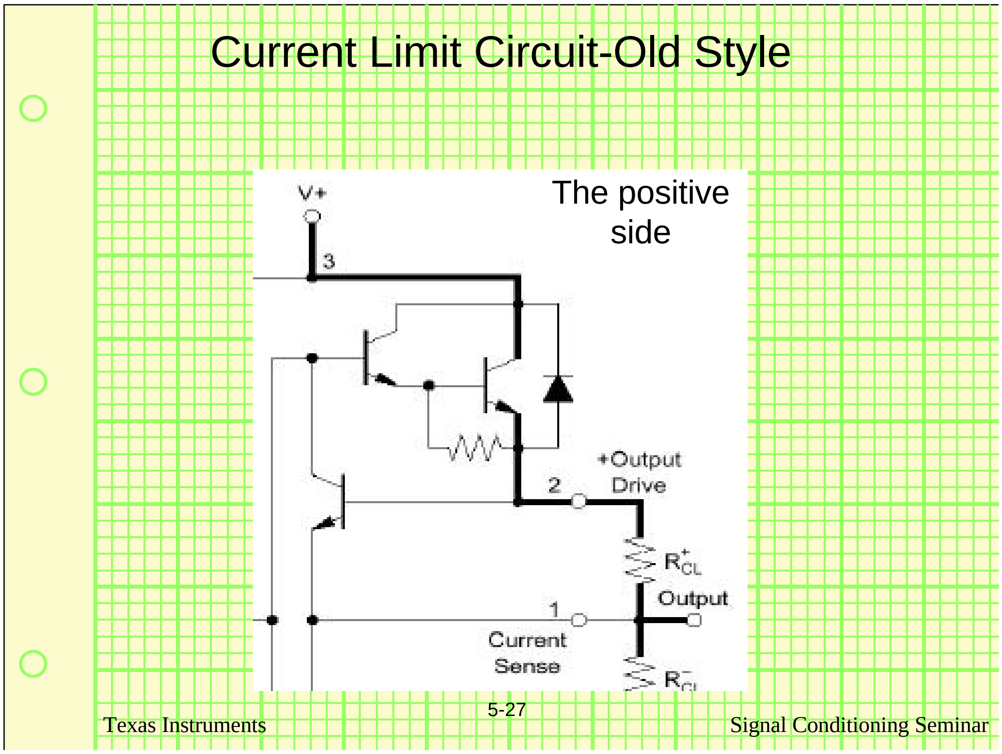


Limiting the Load Current

- ◆ Sense I_{load}
- ◆ If greater than set point……
- ◆ Reduce base/gate drive

Texas Instruments 5-26 Signal Conditioning Seminar

Limiting load current, really simple: sense the current in the load. If it's greater than a set point, reduce the base or gate drive to the output devices.



Current Limit Circuit-Old Style

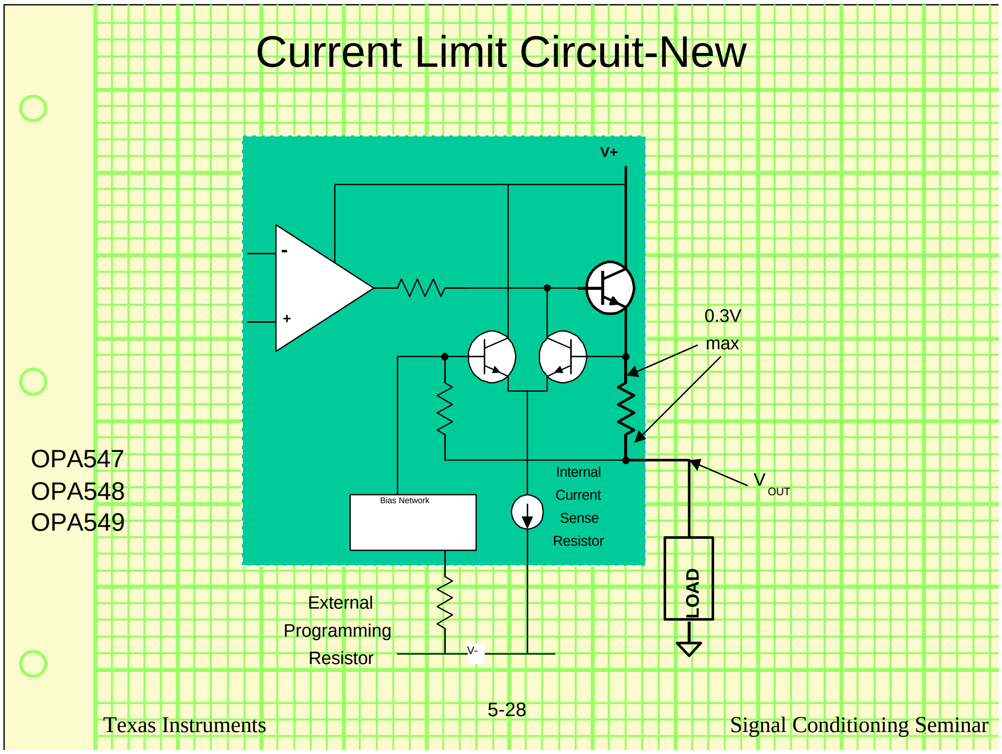
The positive side

Texas Instruments 5-27 Signal Conditioning Seminar

This is the classical current limit circuit. The power flows from the positive supply down through the output device through the current limit set resistor, which is outside of the package, to the load. As the current through the load and through the current limit resistor increases the voltage from Pin 2 to Pin 1 increases. When the voltage reaches 0.7V, nominally the V_{BE} drop of the transistor, it turns on the transistor. And it starts robbing base drive from the output devices. This forms a simple linear control loop.

There are short comings in this circuit. The V_{BE} of the limiting transistor is not a very closely-controlled parameter. From one device to the next within a product a 10- or 20-percent variation could be expected. Another issue is that the V_{BE} drop of a transistor is temperature-dependent. It has a temperature coefficient of -2.2 mV/°C. As the part gets warmer, the current limit is reduced. At least it's going in the right direction.

It should be noted that the current limit resistors are large; they have to carry the full load current load. To change current limit set point requires changing resistors, and these are typically on the order of 0.1 to 0.01Ù. Also the resistance of the copper trace on the board may become significant, as well as socket contact resistance.



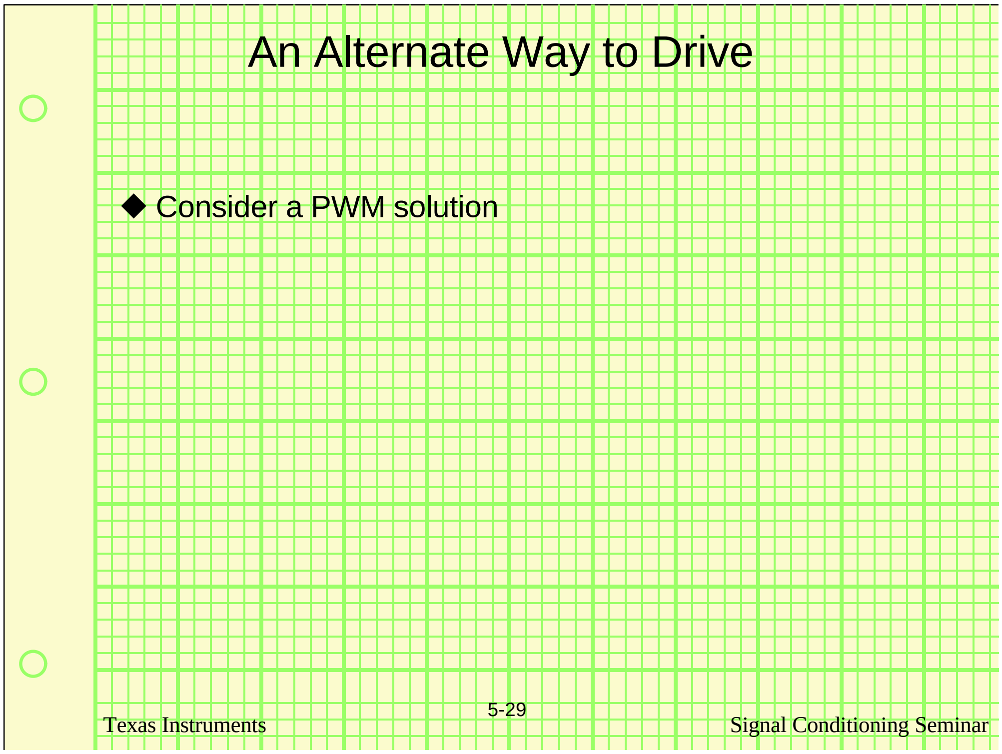
Current Limit Circuit-New

OPA547
OPA548
OPA549

This shows a new current limit circuit available in the OPA547, OPA548, and OPA549. The sense resistor is built inside the package. It is sized to develop about a 0.3V max. That sense voltage is applied to a differential pair. On the other side of the differential pair is applied a bias or set point voltage. When the current through the load becomes high enough, the difference is detected in the differential pair. When it gets high enough, then the differential pair starts robbing the base drive from the output device. This has the advantage that the current limit set point is determined by an external resistor which is simply a signal resistor, it doesn't have to be a big power resistor.

The current limit point can be set by adjusting the voltage on that pin, doesn't have to be a resistor. It can be a voltage from a DAC or a current source.

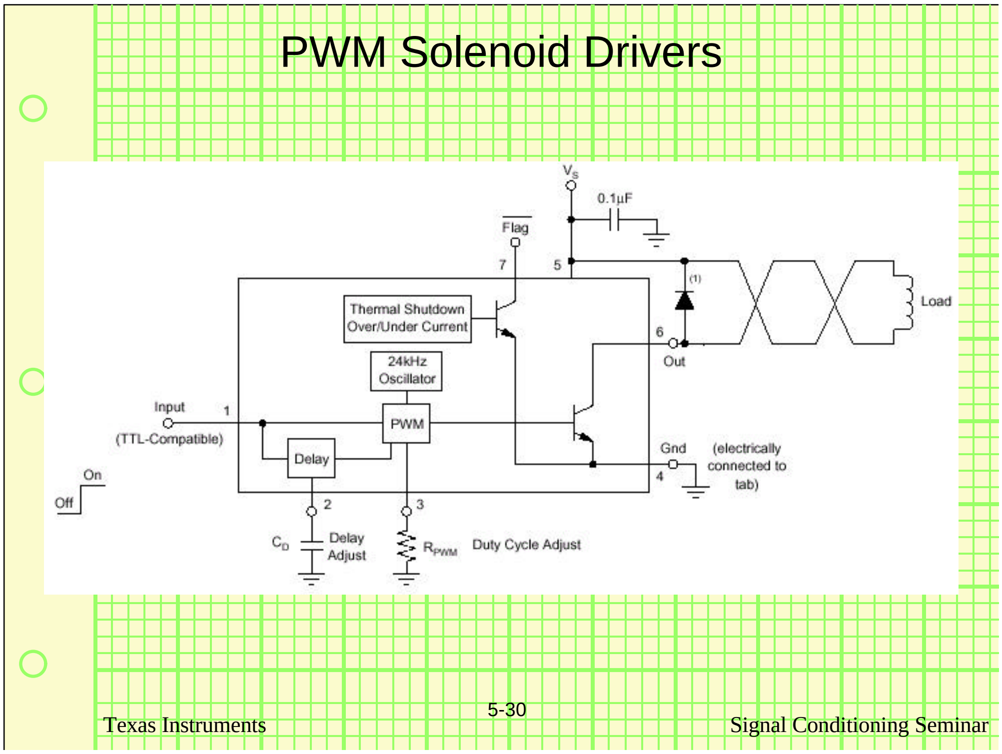
It is now possible to design a digitally-controlled power supply. Given two DACs, one to set the voltage and the other to set the current limit. Total digital control on a power supply. And further, this part runs nicely in current limit so there's no real degradation in performance, and get an accuracy of 10-percent.



An Alternate Way to Drive

- Consider a PWM solution

When looking at alternate ways to drive, consider a PWM solution sometimes.

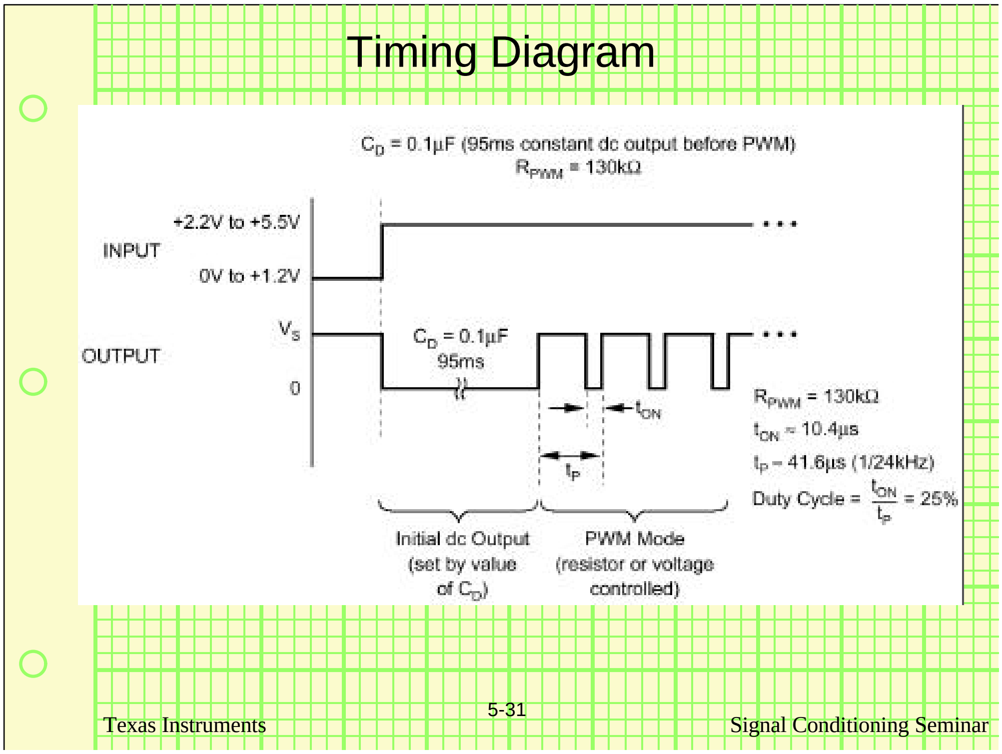


PWM Solenoid Drivers

An ideal solenoid driver applies maximum current to pull the armature in and then drops the current to a lower hold-in value. This gets the best performance from the solenoid while causing the minimum heat in the coil.

The DRV101 shown here allows the user to set the full current time with the selected capacitor and then the duty cycle with the resistor. Turn-on and turn-off are controlled with the signal at pin 1.

The signal at pin 3 needn't be a resistor; it can be a voltage source or a current source. Therefore, it is possible to put this inside a control loop and drive pin 3 with a DAC signal. It is possible to accomplish proportional control over solenoid opening by the pulse-width duty cycle from this driver.



Timing Diagram

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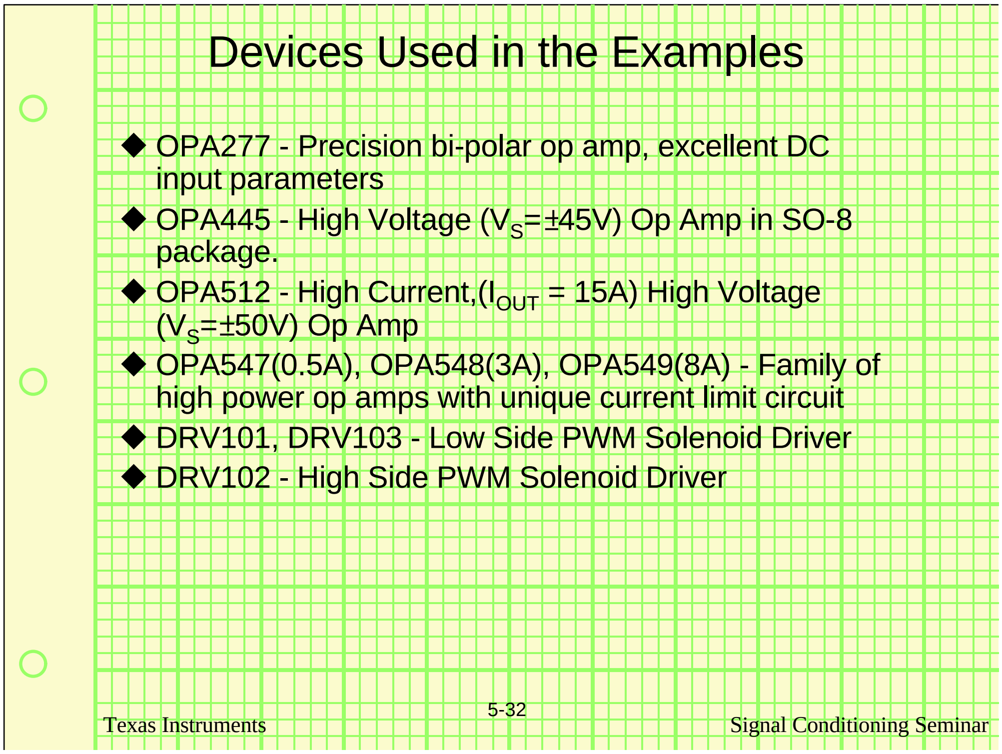
The output waveform of the DRV101. The delay time or time of full on is set by the value of CD. The PWM duty cycle is set by the value of the RDC.

With these devices the power dissipated in the device is minimal. When the device is off the voltage drop across it is full supply but the current through it is zero. When the part is on the current through it is high but the voltage across is is small. In both cases the EI product is near zero and therefore the power lost in the device is very small.



Devices Used in the Examples

- OPA277 - Precision bi-polar op amp, excellent DC input parameters
- OPA445 - High Voltage (V_S=±45V) Op Amp in SO-8 package.
- OPA512 - High Current,(I_{OUT} = 15A) High Voltage (V_S=±50V) Op Amp
- OPA547(0.5A), OPA548(3A), OPA549(8A) - Family of high power op amps with unique current limit circuit
- DRV101, DRV103 - Low Side PWM Solenoid Driver
- DRV102 - High Side PWM Solenoid Driver

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Data sheets are available for these parts on the web at www.ti.com .