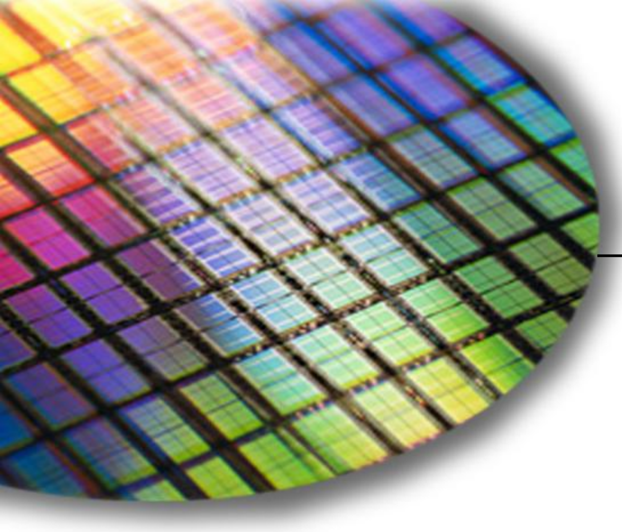


The World Leader in High-Performance Signal Processing Solutions

Understanding and Applying Digital Potentiometers

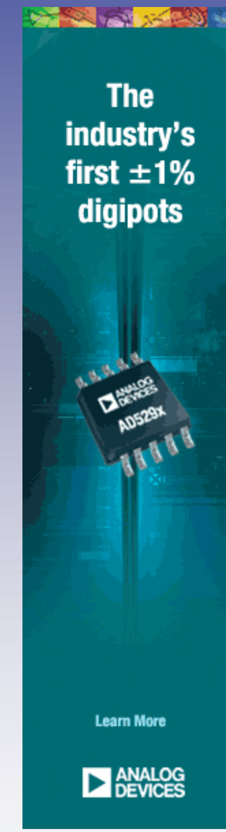
Chris Hyde   Dave Lunsetter

ANALOG DEVICES Digi-Key CORPORATION

ANALOG DEVICES

Agenda

- Pots vs DigiPots vs DACs
- Considerations for Successful Designs
- Applications
- Summary and Support



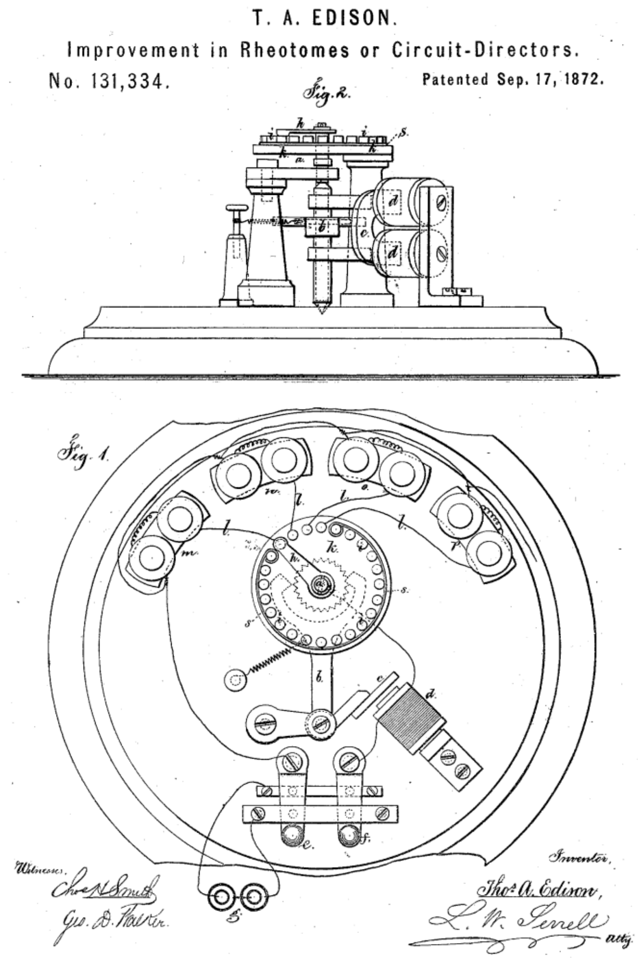
Common Potentiometer Uses & Considerations

- Adjustment
  - Trimming
  - Set points
  - Level Adjustment
  - gains
- Measurement
  - Position Sensor

- Voltage
- Current
- Power
- Resistance
- Resistor Tolerance
- Temperature Coefficient
- Resolution
- Linearity
- Taper
- Use issues
- Reliability
- Size, cost

Potentiometers – Useful tools for >100 years

- Invented by Thomas Edison
- Evolved from circuit switch
- Materials and Size has improved
- Basically the same >100 years later



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Mechanical vs Digital Potentiometers

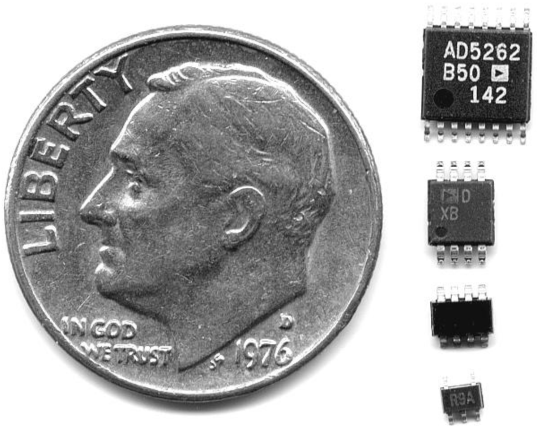
Mechanical Pots

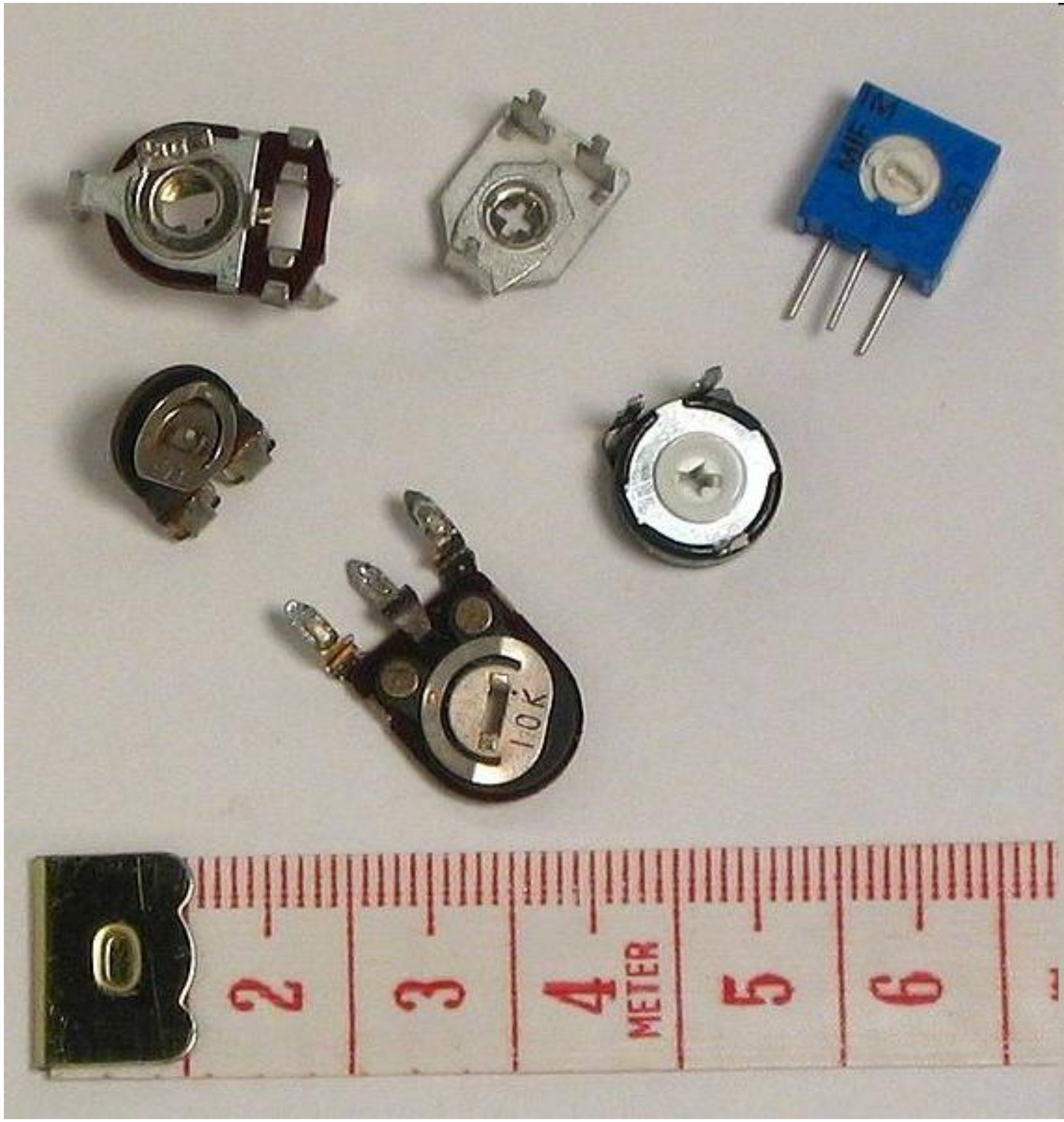
- Wide range of Voltage & Currents
- Mechanical Wiper Interface and movement
  - Contact Resistance
  - Linkage (Vibration, Shock, Wear)
- Materials tradeoffs
  - Carbon – Noisy, Reliability
  - CerMet – Cost, Power
  - Wire – Accuracy, Range

Digital Pots

- Programmable
- Reliability
  - No mechanical wear/Change
- Poly or Thin-Film Resistors
  - Precision, TempCo, Noise
- Controlled structure
- Small Size
- Voltage between Supply Rails (to +/- 15V or 0 to 30V)
- Low (~3mA) current levels

Compact Digital POTs

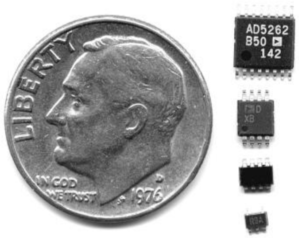


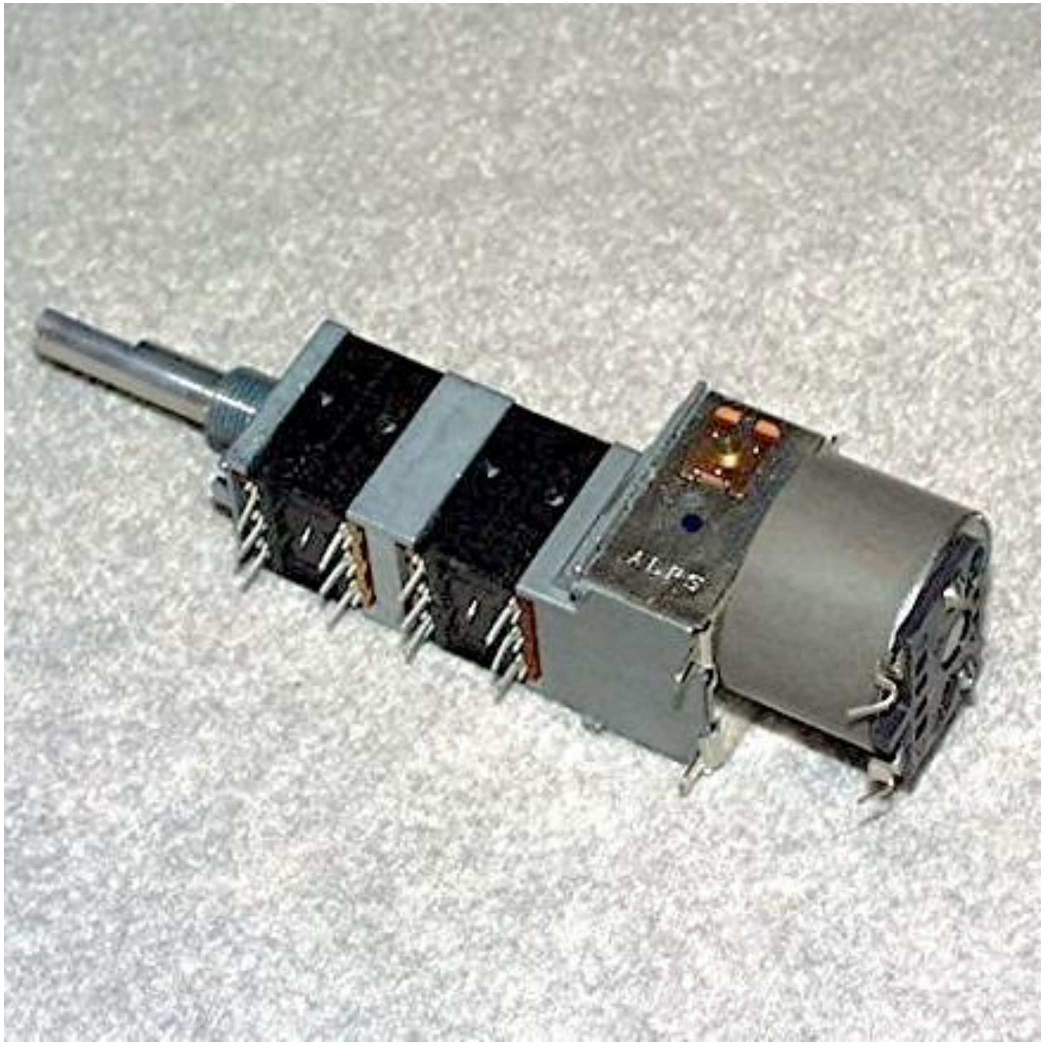


- **PACKAGES**
  - **TSSOP-16 Lead 5 x 6.4 mm**
  - **uSOIC-8 Lead 3 x 4.9 mm**
  - **SOT-8 Lead 2.9 x 3 mm**
  - **SC70-6 Lead 2 x 2.1 mm**

Pot Photo Source: Wikipedia

The Real Difference is BIG !



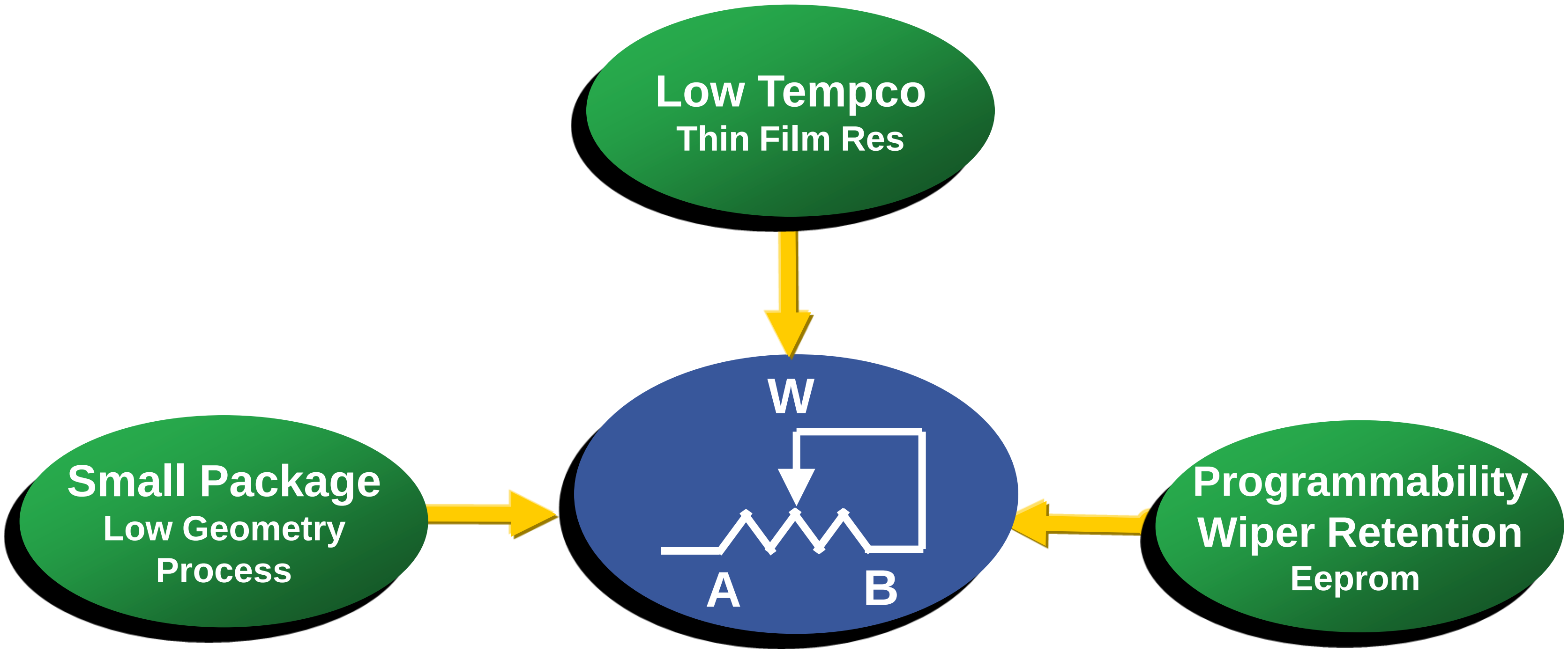


- To get the same Programmability as a Digital Pot, The tradeoff is BIG
  - In both Size and Cost !

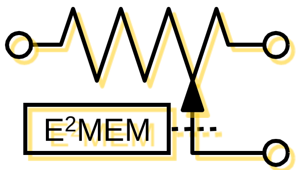
IC Digital Potentiometers Also Known As

- Digital Pot
- DigiPot
- RDAC
- E^2POT
- DCP
- Programmable Resistor
- Variable Resistor (VR)

Key DigiPot Requirements

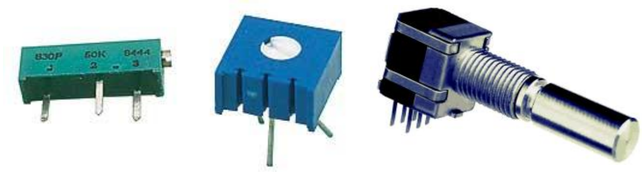


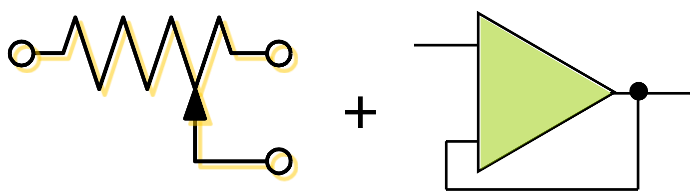
DAC & DigiPOTs – What's the difference?



- Memory Options
- Volatile, Non Volatile
- One time programmable
- Voltage or Rheostat
- Control Features

Replace





Alternative

Low Resolution DAC

- Can generate larger voltages as V-Divider

- Output voltage determined by output range of DAC

DAC

- Higher Accuracy
- Integrated
- V or I Out

Building Blocks

Ideal for level setting and control

Current output DAC Sets Gains

VERIFIED CIRCUIT

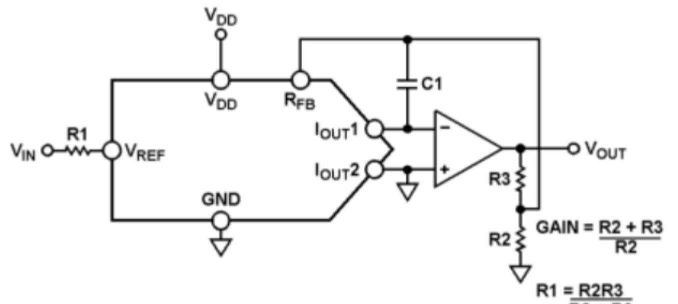
This an Analog Devices **Verified Circuit** which has been designed and proven to work by ADI applications engineers. To learn more and/or browse our Verified Circuit library, please visit Verified Circuits Home. Have feedback or questions on this circuit? Please contact us.

Verified Circuit: Programmable Gain Element using the AD5426/32/43 DAC

Printer Friendly Version (PDF)

Circuit Function and Benefits

The circuit described in this document provides a programmable gain function using a multiplying DAC and an operational amplifier. The maximum gain value and the temperature coefficient are set by the external resistors and the resolution of the gain is set by the DAC.



NOTES
1. ADDITIONAL PINS OMITTED FOR CLARITY.
2. C1 PHASE COMPENSATION (1pF TO 2pF) MAY BE REQUIRED IF A1 IS A HIGH SPEED AMPLIFIER.

Figure 1: Increasing Gain of a Current-Out DAC

Products Used in This Circuit

AD5426 : High Bandwidth CMOS 8-Bit Serial Interface Multiplying D/A Converter
Data Sheet Rev A, 05/2005

AD5432 : High Bandwidth CMOS 10-Bit Serial Interface Multiplying D/A Converter
Data Sheet Rev A, 05/2005

AD5443 : High Bandwidth CMOS 12-Bit Serial Interface Multiplying D/A Converter
Data Sheet Rev A, 05/2005

AD8065 : High Performance, 145 MHz *FastFET*™ Op Amp
Data Sheet Rev G, 01/2006

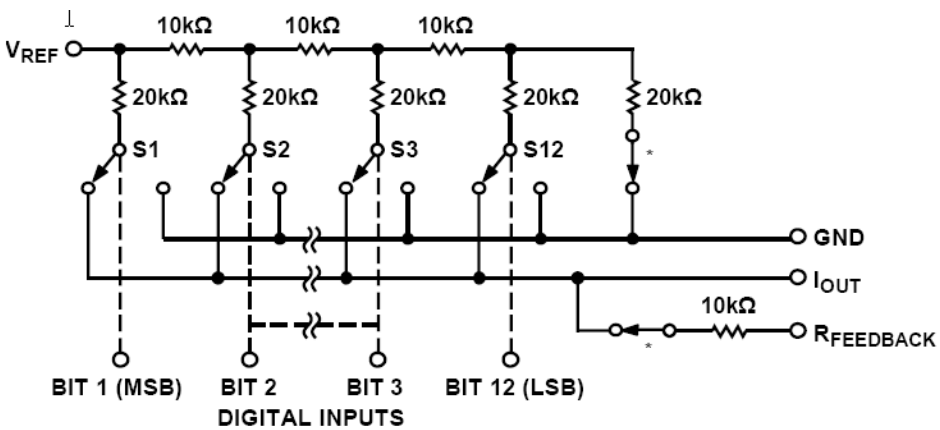
Product samples can be requested from the respective product pages.

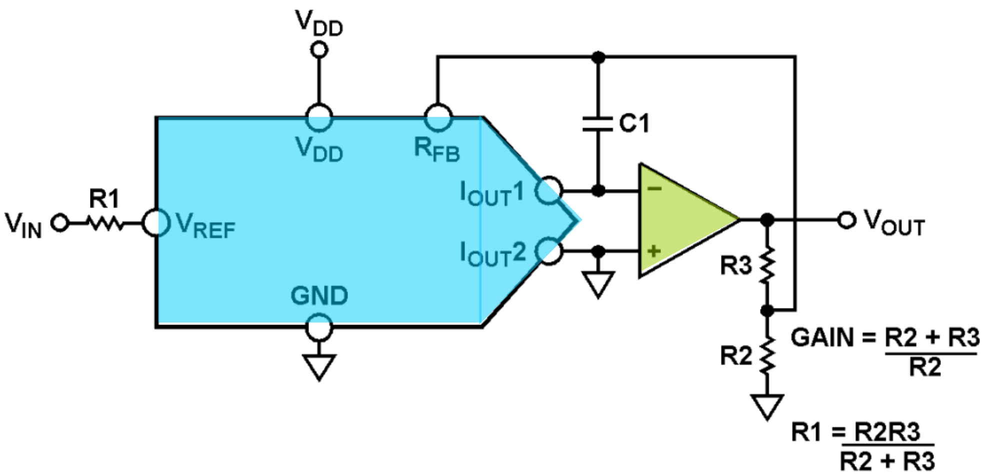
Evaluation & Design Tools

Evaluation Boards

- EVAL-AD5426EB

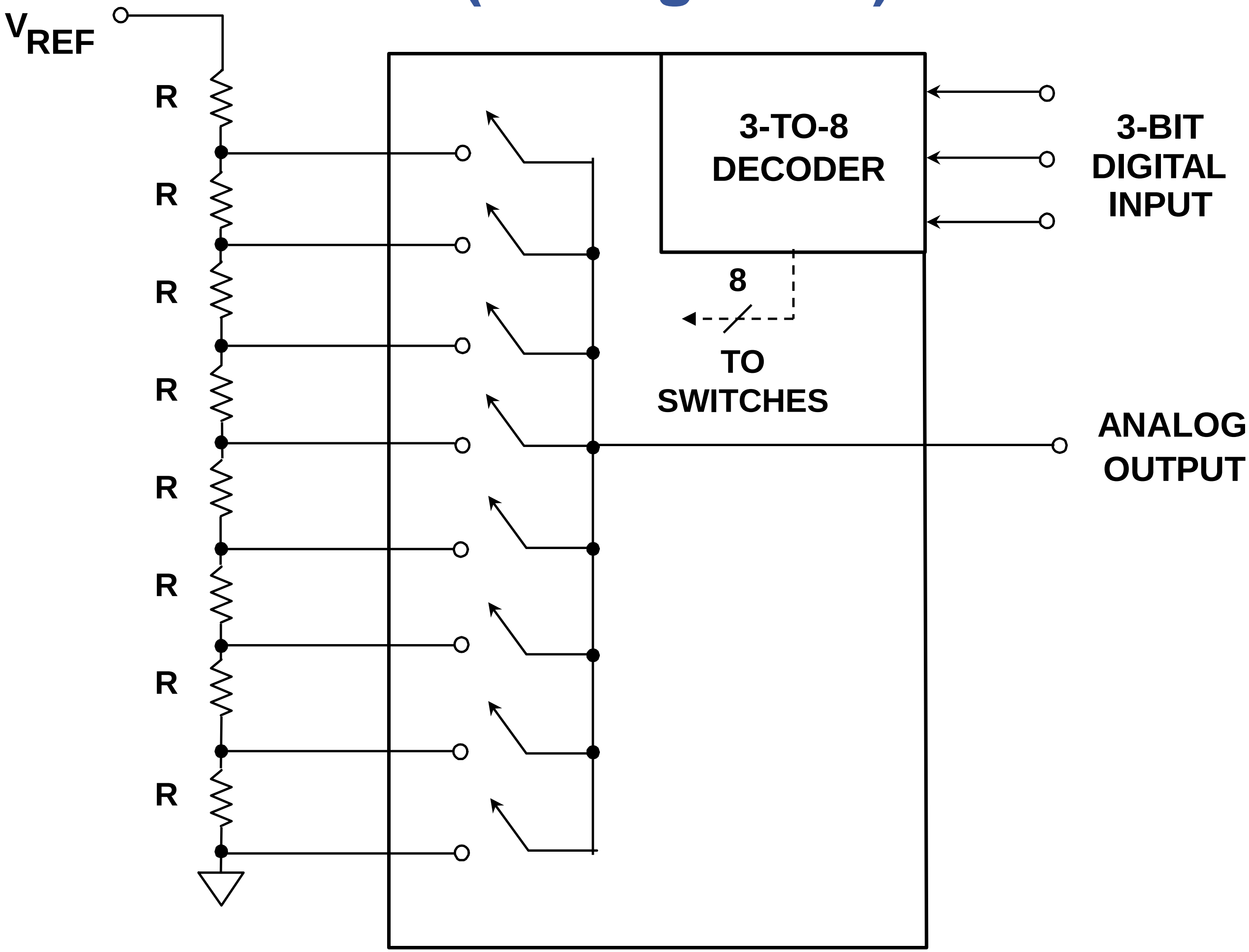
Current Out DAC as Pot



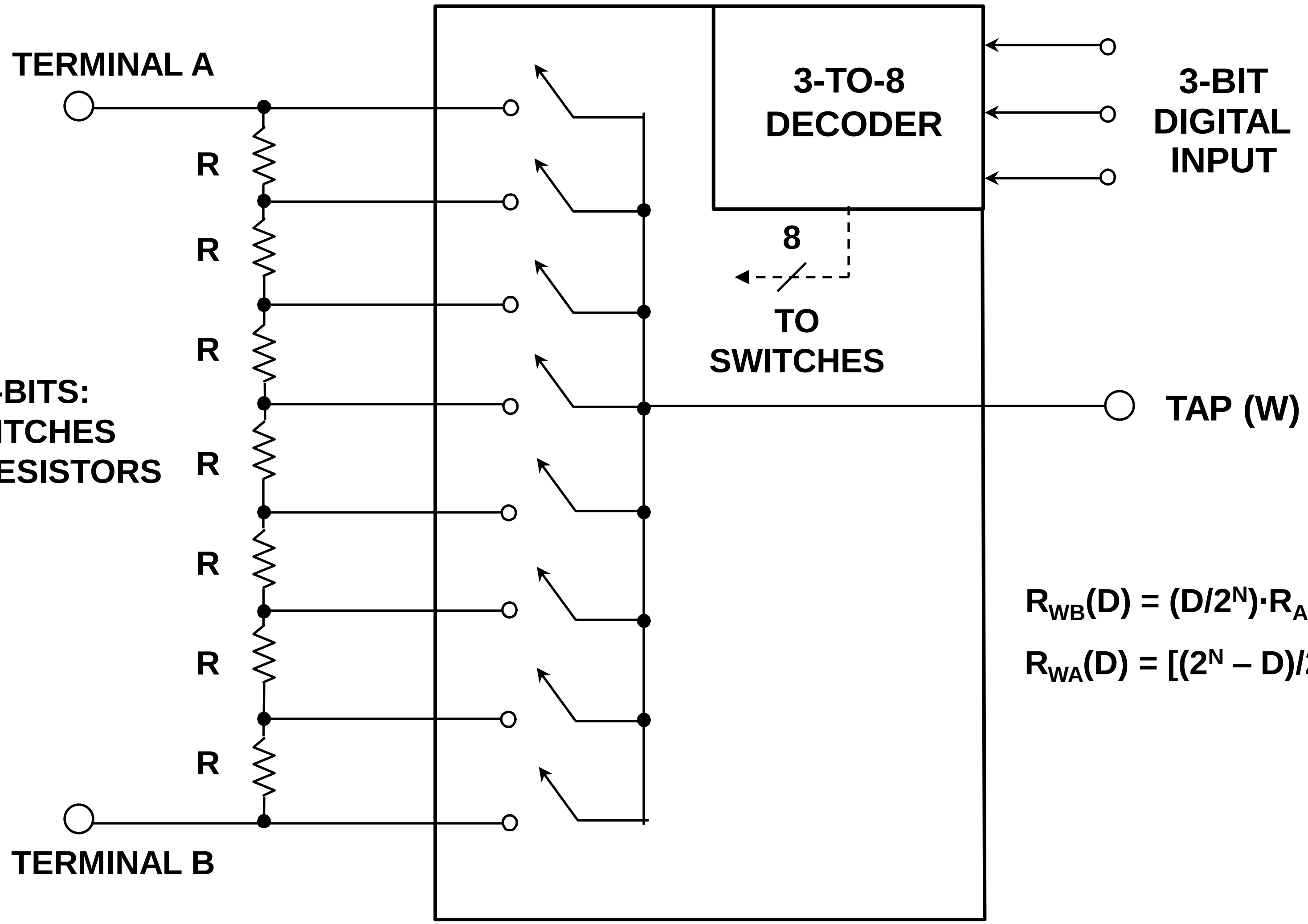


- Wide range possible (N bit DAC)
- VOUT = -Gain × VIN × (D/2^-N)
- Needs Virtual Ground (Op Amp) to maintain linearity

Simplest Voltage Output Thermometer DAC: The Kelvin Divider ("String DAC")



A Slight Modification to a String DAC Yields a "Digital Potentiometer"

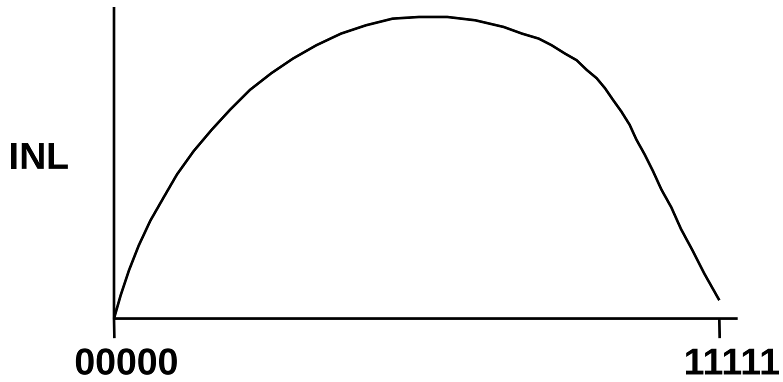


FOR N-BITS:
2N SWITCHES
AND RESISTORS

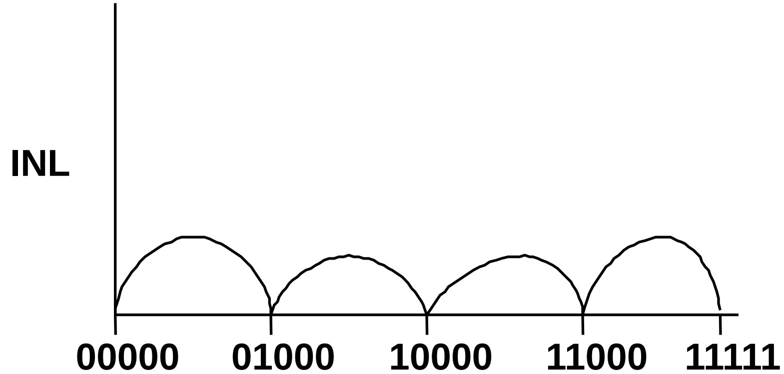
$R_{WB}(D) = (D/2^N) \cdot R_{AB} + R_W$

$R_{WA}(D) = [(2^N - D)/2^N] \cdot R_{AB} + R_W$

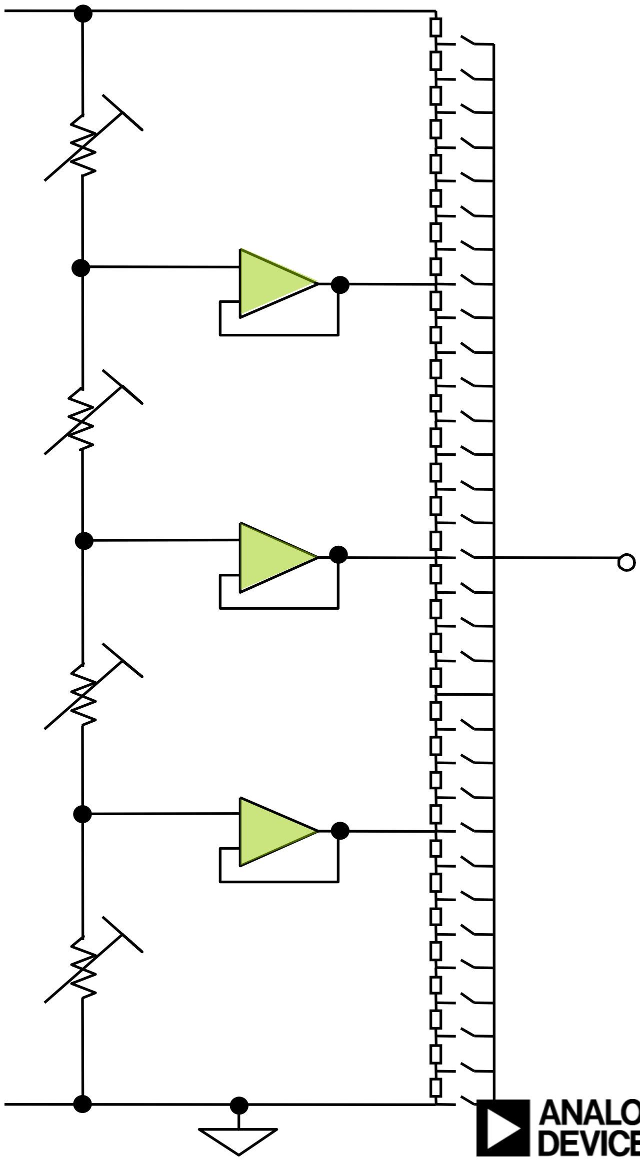
Trimming the INL of a String DAC (If Required)



MAIN DAC - No trim components present



MAIN DAC - Trimmed



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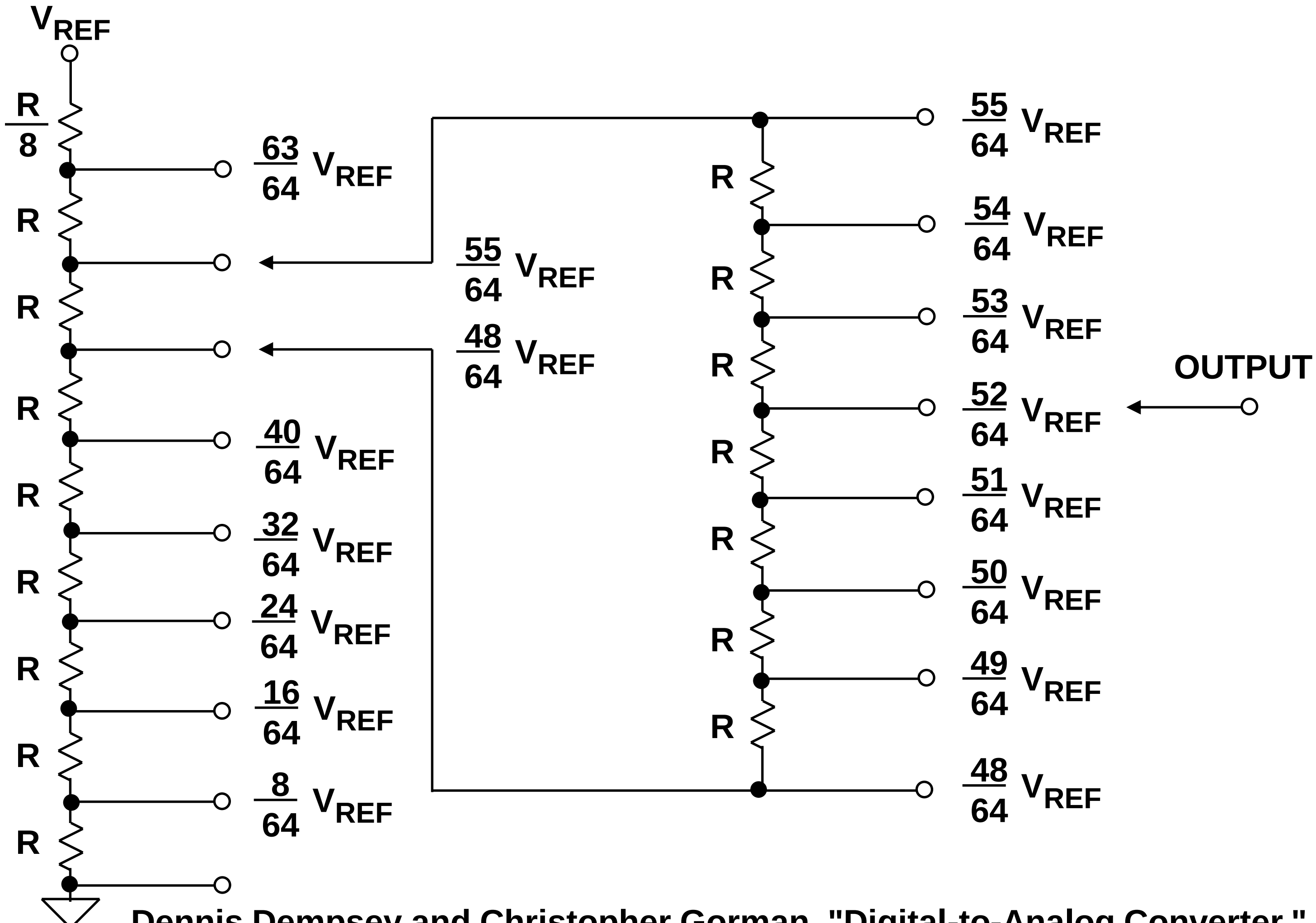
Segmented Unbuffered String DACs Use Patented Architecture

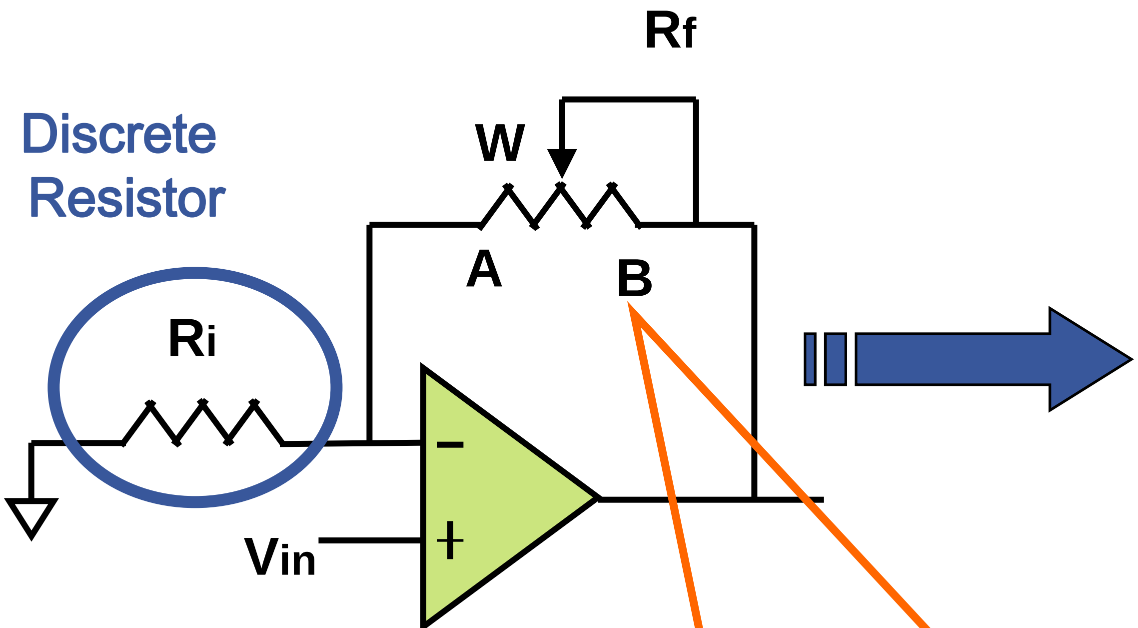


Dennis Dempsey and Christopher Gorman, "Digital-to-Analog Converter," U.S. Patent 5,969,657, filed July 27, 1997, issued October 19, 1999.

DigiPot Characteristics

- Resolution (wiper steps):
  - 32 (5-Bits) to 1024 (10-Bits)
- Nominal End-to-End Resistance:
  - 1kΩ to 1MΩ
- End to end Resistance Tolerance
  - ±20% typical, Though ±30% are out there
- End-to-End Resistance Temperature Coefficient:
  - 35ppm/°C (Thin Film Resistor String), 500ppm/°C (Polysilicon Resistor String)
- Number of Channels:
  - 1, 2, 3, 4, 6
- Interface Data Control:
  - SPI, I2C, Up/Down Counter Input
  - Increment/Decrement Input
- Terminal Voltage Range:
  - +15V, ±15V, +30V, +3V, ±3V, +5V, ±5V
- Memory Options:
  - Volatile (No Memory)
  - Nonvolatile E2MEM
  - One-Time Programmable (OTP) - One Fuse Array
  - Two-Time Programmable - Two Fuse Arrays

Variable Gain Control



Great use for DigiPot
Good in this position for V and I limitations

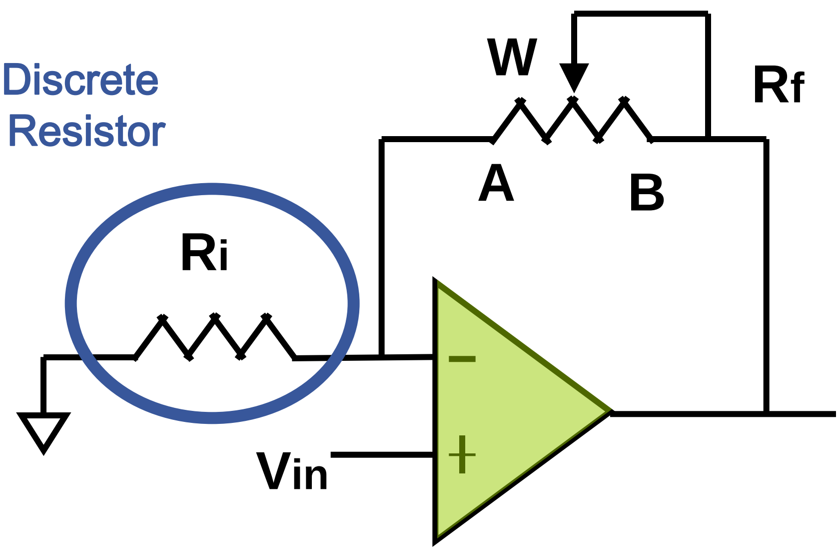
LCD Contrast/Brightness

Sensor Calibration

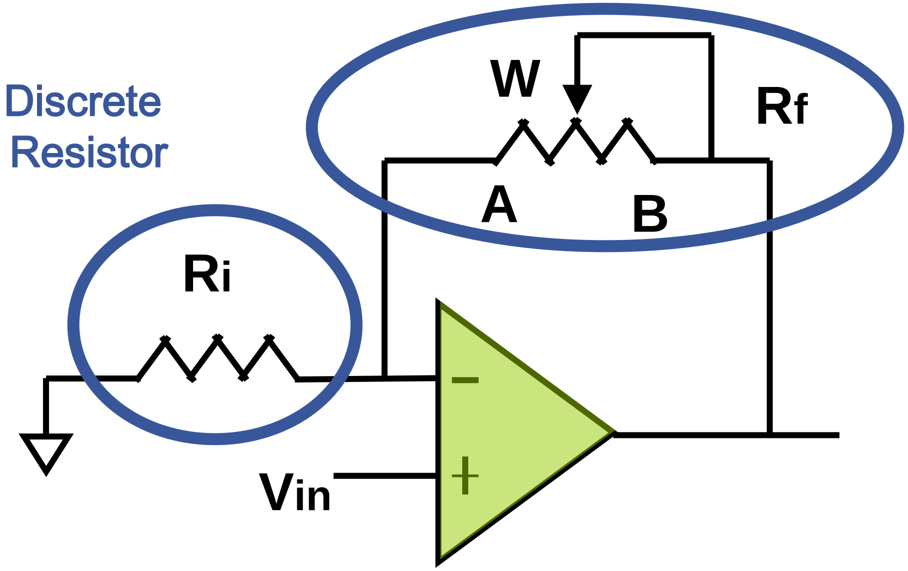
Digital Volume

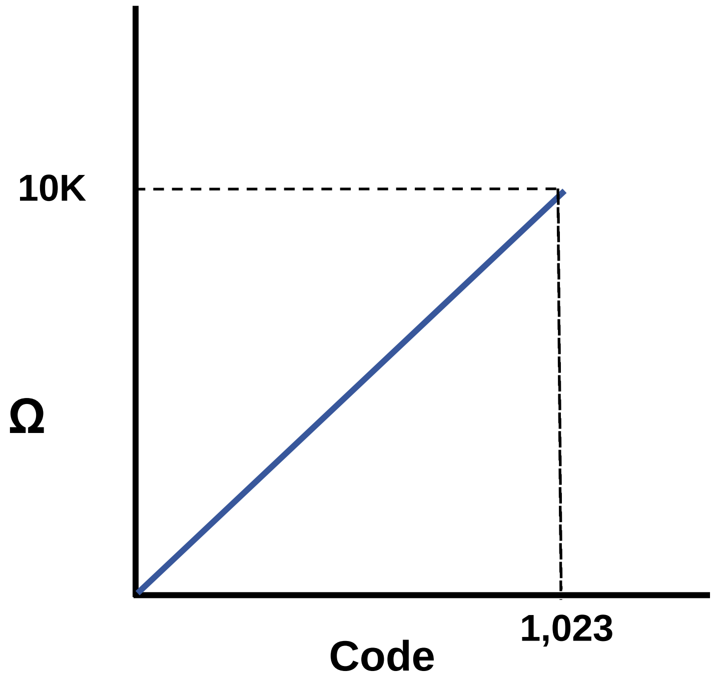
R-Tol Variation Errors – Rheostat Mode

Discrete
Resistor

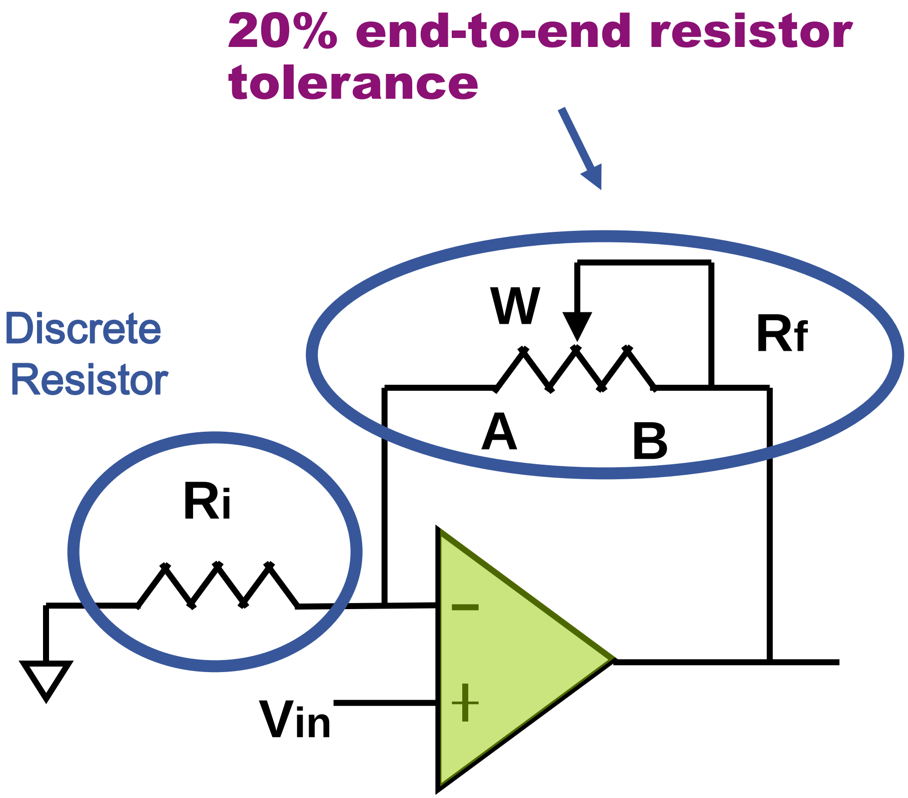


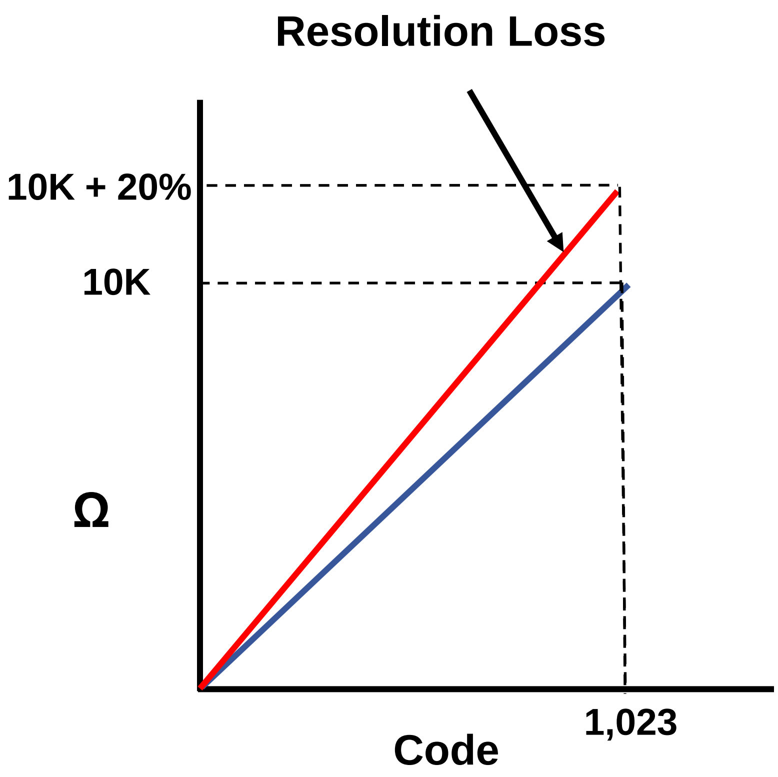
R-Tol Variation Errors – Rheostat Mode



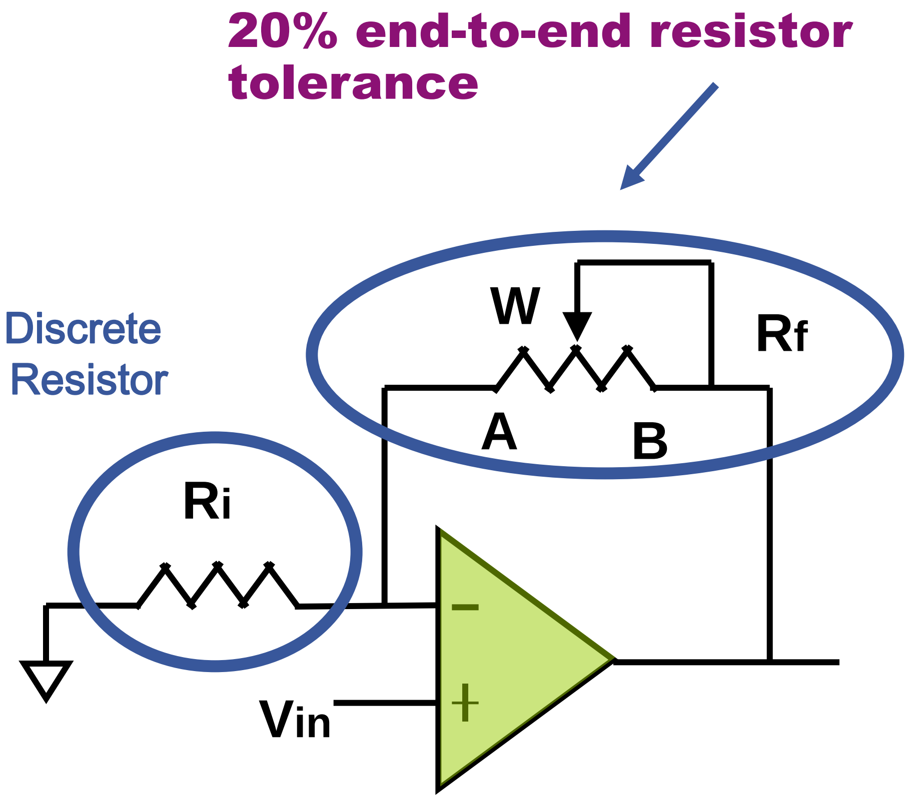


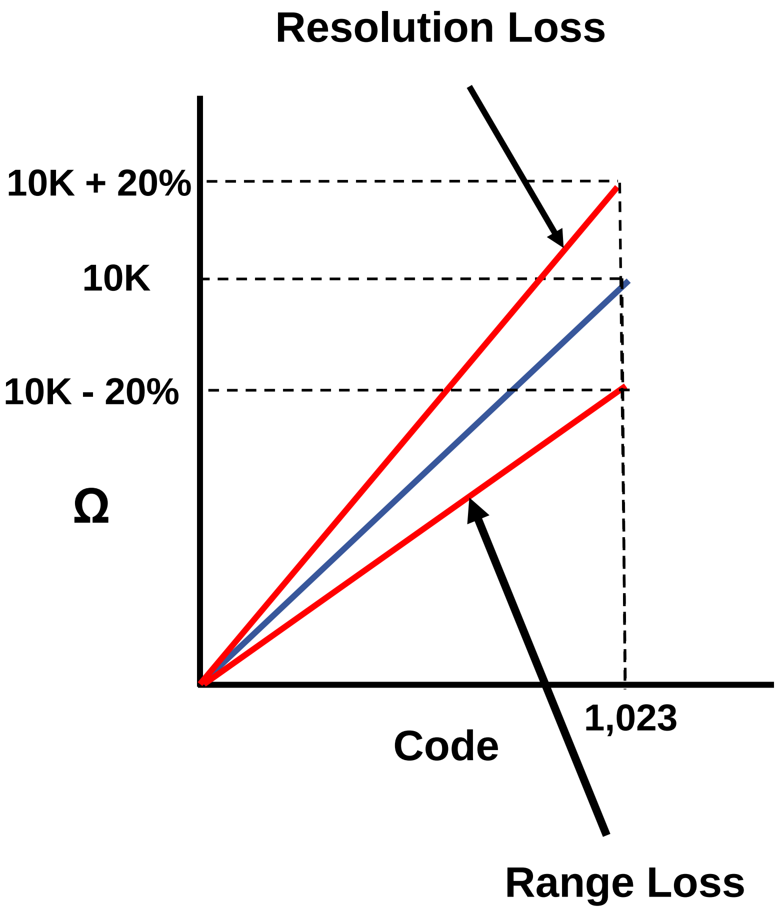
R-Tol Variation Errors – Rheostat Mode





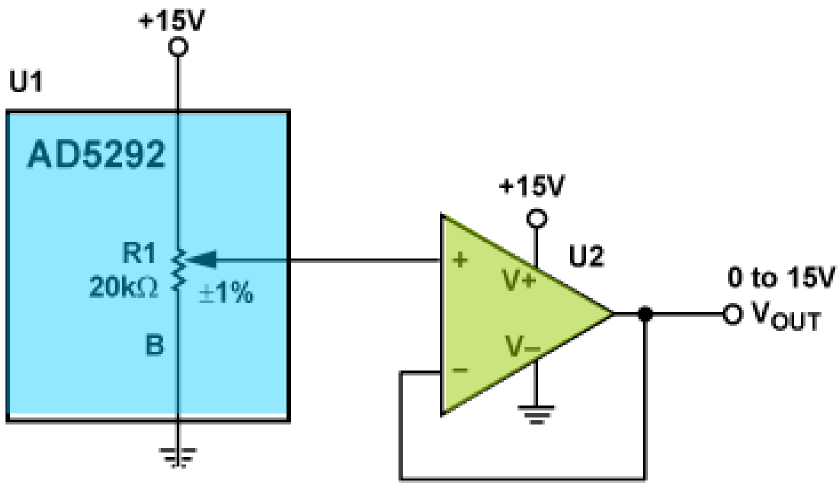
R-Tol Variation Errors – Rheostat Mode



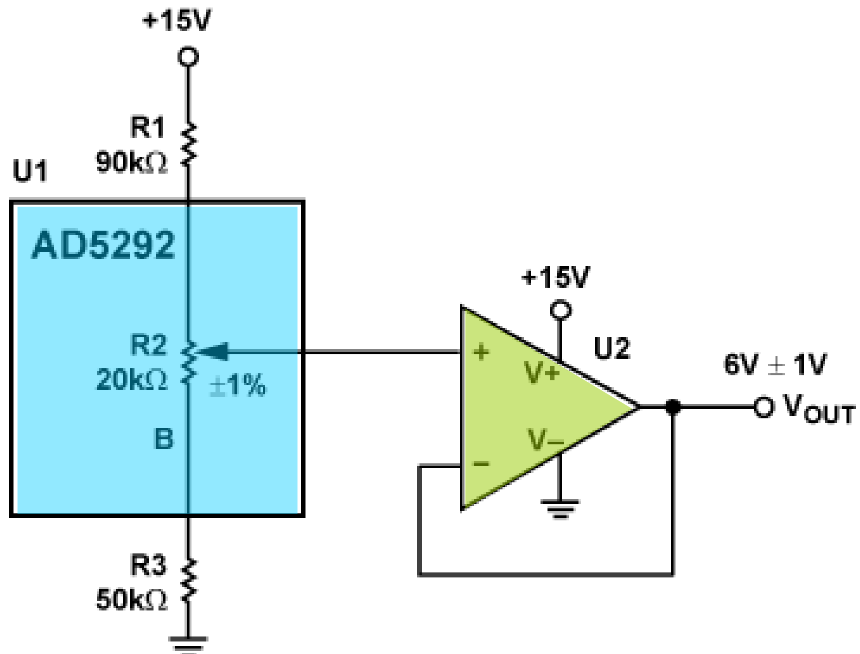


ANALOG DEVICES

R-Tol Variation Errors – DAC Mode



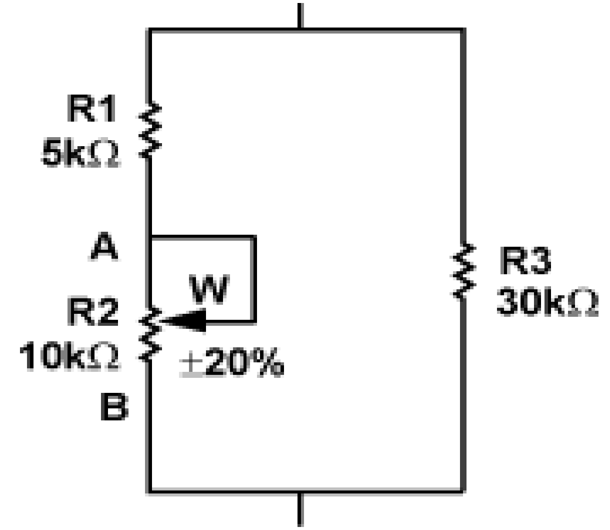
Ratiometric

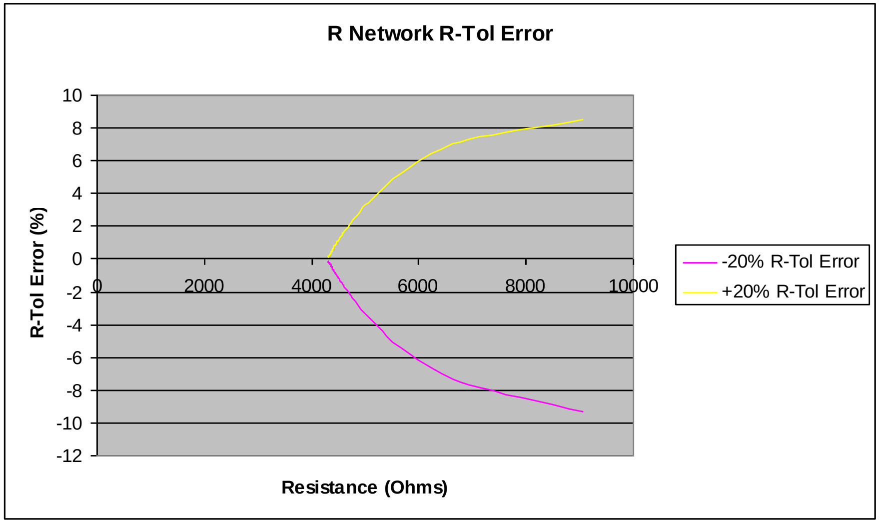


Optimise Range/Resolution

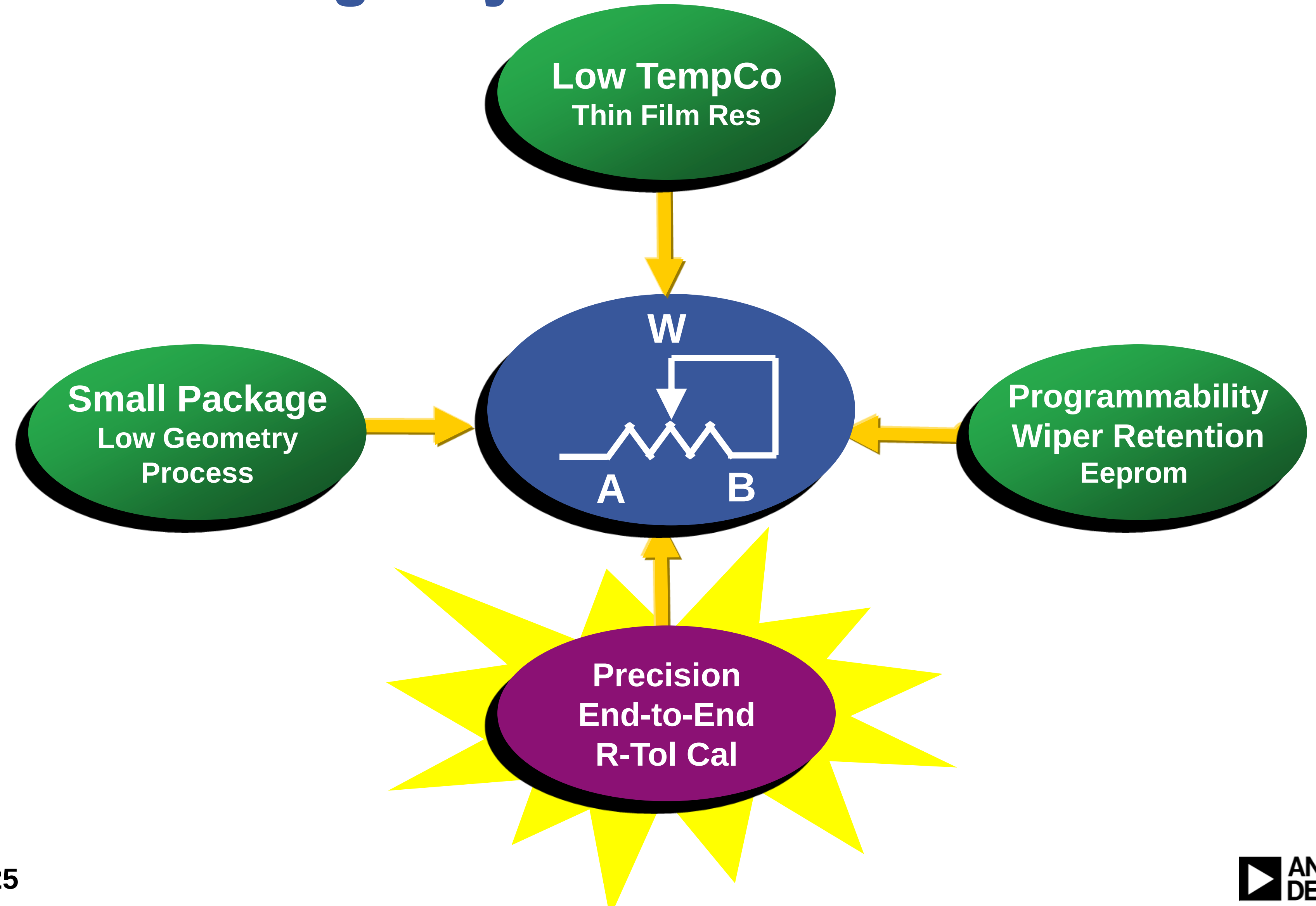
Current R-Tol "Fixes"

- Combine precision discrete resistors in parallel and serial configuration
  - Reduced range
- Manually match discrete resistors
  - Impact manufacturing cost
- R-Tol error stored in Memory in Factory
  - Still lose up to 30% or range or resolution
  - End-to-End resistance is code dependant
  - Linearity error or Tempco error not included
  - Average error stored…difficult to estimate max error
- Use a dual channel RDAC
  - Channel matching within die ~1%

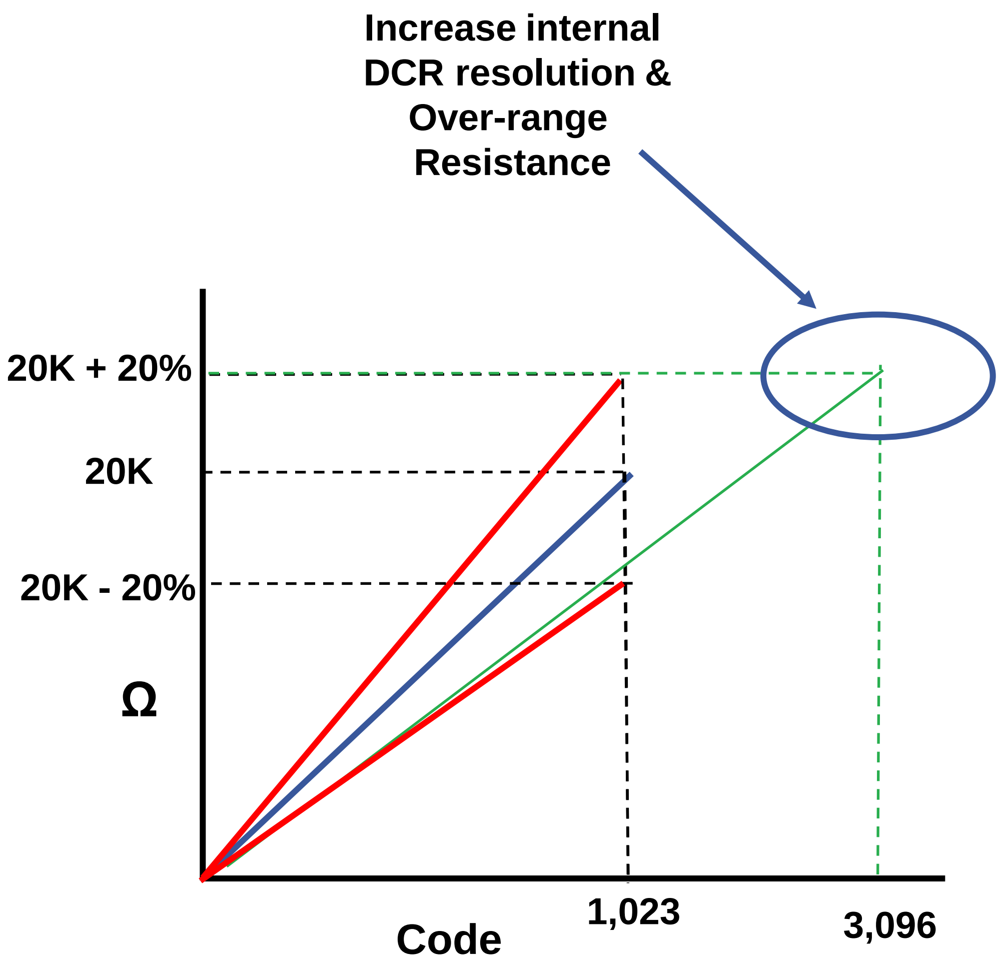


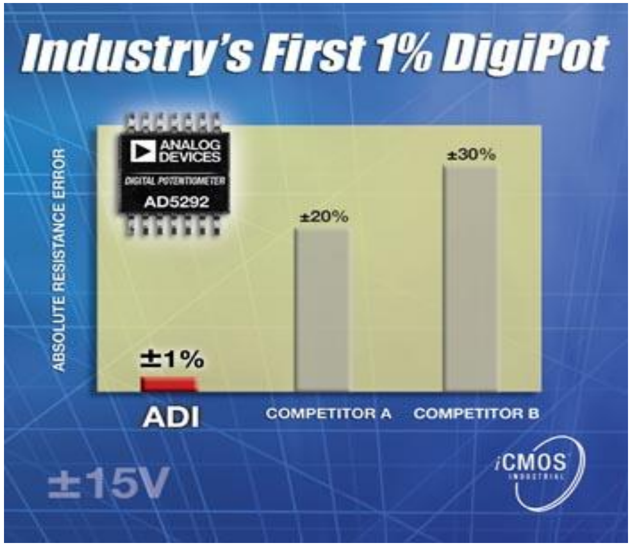


ADI Breaks New Ground – Again !
Precision Digitally Controlled Potentiometers



DigiPots CAN be High Precision
AD529x – 1% Tolerance





- Offset and Gain factors measured and stored in factory
  - No customer calibration required
  - No loss of range or resolution
  - +/-1% R_{AB} Tolerance guaranteed over temperature

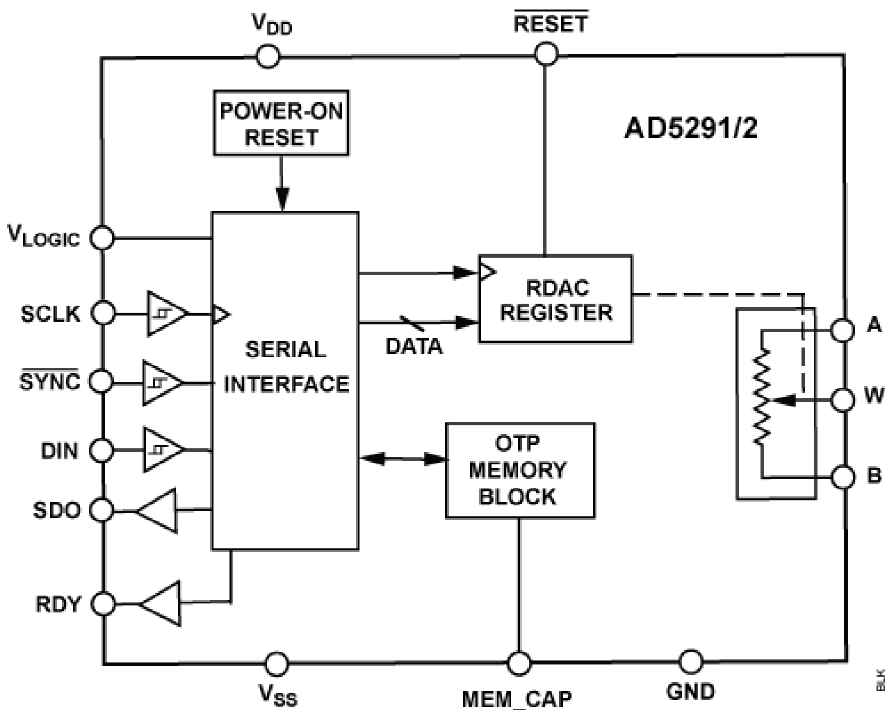
AD5291/2 – 256/1024 Tap, 30V or ±15V 1% R-Tolerance and 20-TP Wiper Memory

KEY FEATURES

- Single-Channel, 256/1024 Tap resolution
- 20 kΩ, 50 kΩ and 100 kΩ Nominal Resistance
- Calibrated 1% Nominal Resistor Tolerance
- +4.5V to +30V Single-Supply Operation
- ±4.5V to ±15V Dual-Supply Operation
- 20-TP – 20-Time Programmable Memory

Applications

- Mechanical potentiometer replacement
- Instrumentation: gain, offset adjustment
- Programmable voltage to current conversion
- Programmable filters, delays, time constants
- Programmable power supply
- Sensor calibration



Temp
-40°C to 105°C

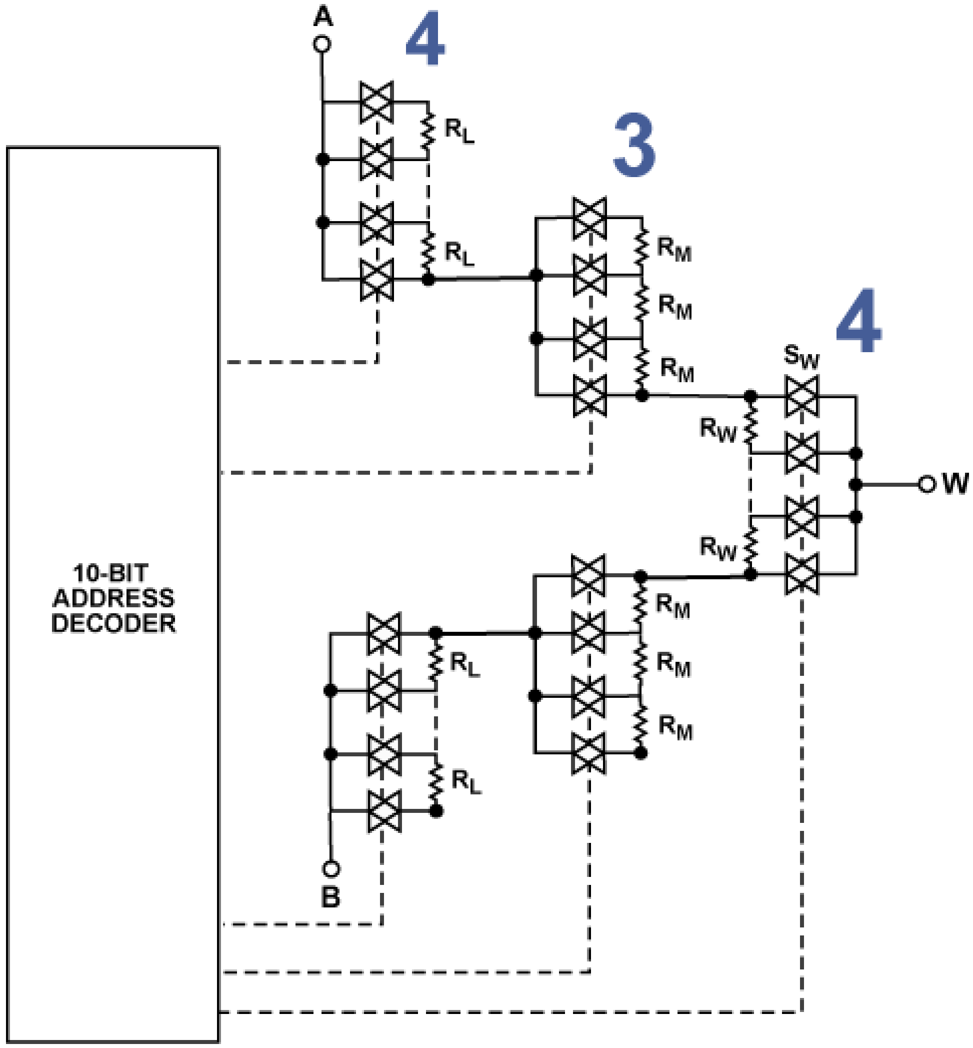
Samples Date
Sampling

Price @ 1K
AD5291: $2.29 AD5292: $2.62

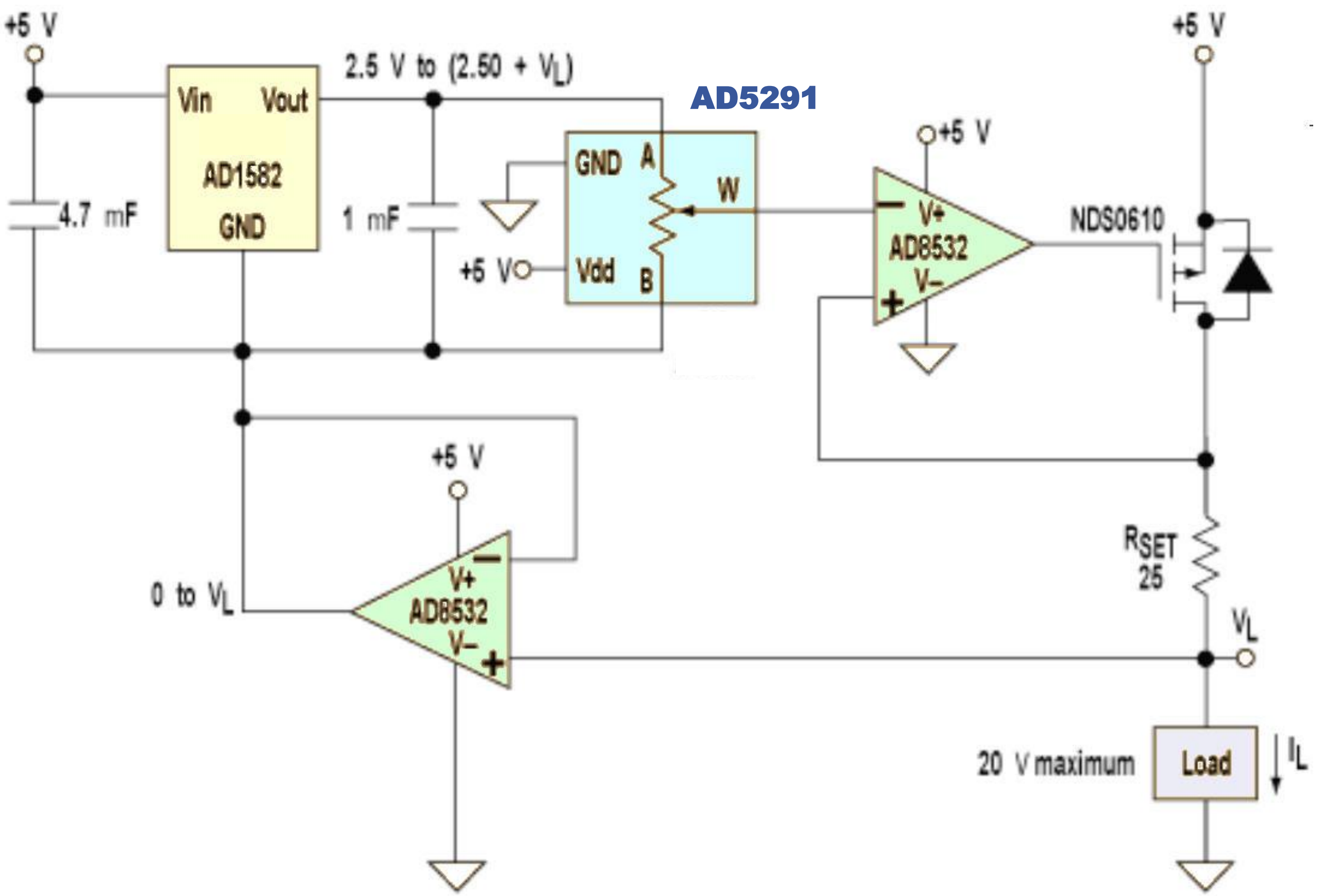
ANALOG DEVICES

RDAC Architecture

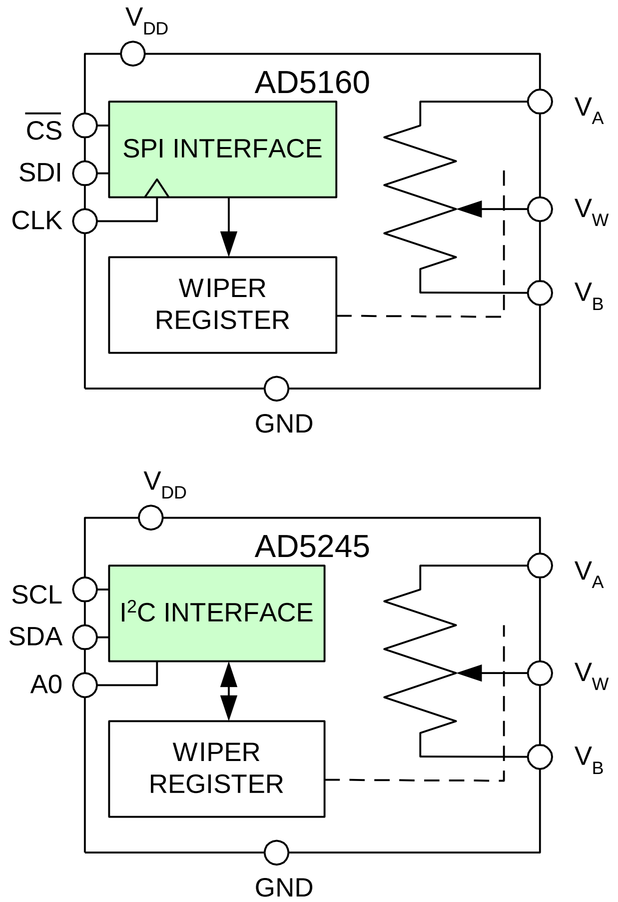
- 11-bit resolution internally
- Triple-String architecture made up of:
  - 4-Bit MSB String
  - 3-Bit MID String
  - 4-Bit LSB String
- Thin Film can vary by ±10% so RDAC is oversized
- Offset + Gain coefficients measured in Factory Test and stored in on chip memory
- R_{AW} = (2047 – 2*code – offset +1) * gain



Precision Programmable 100 mA Current Source



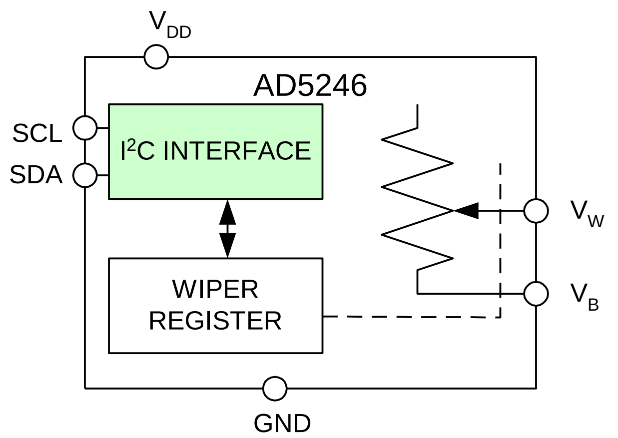
AD5160 & AD5245 Compact Digital POTs – SOT-8 (2.9 x 3mm)



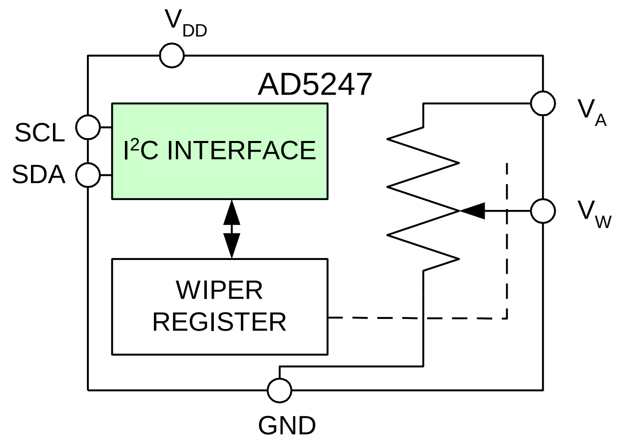
- **FEATURES**
  - **SPI (AD5160) Or I^2C (AD5245) Interface**
  - **256 Position Resolution**
  - **5k, 10k, 50k, 100k Ohms End-to-End Resistance**
  - **Low Tempco 35ppm/ºC**
  - **SOT-8 (2.9 x 3mm)**
  - **Power ON Reset to Midscale**
  - **Low Cost**

Ultra Compact Digital Potentiometers

AD5246 2-Terminal Rheostat

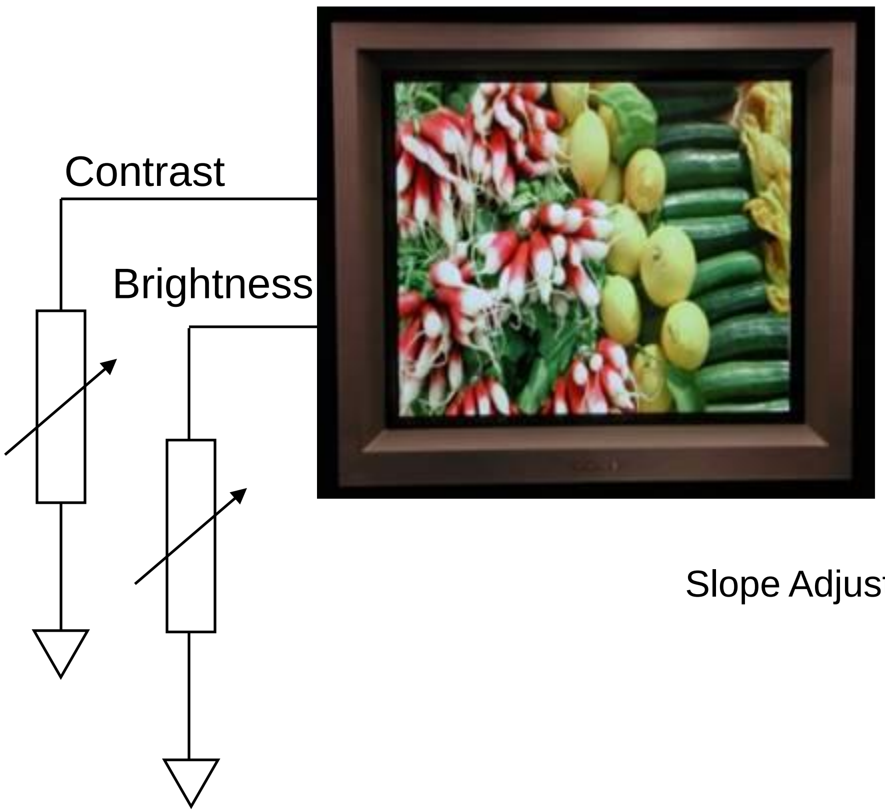


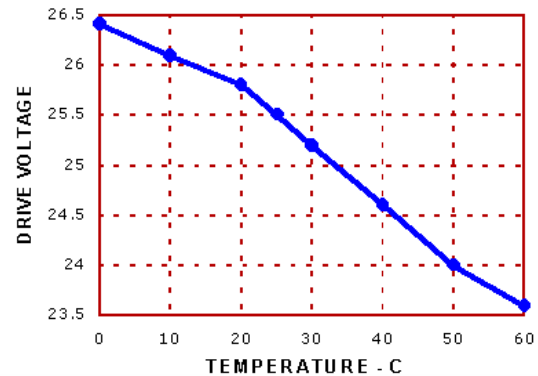
AD5247 3-Terminal Potentiometer Divider

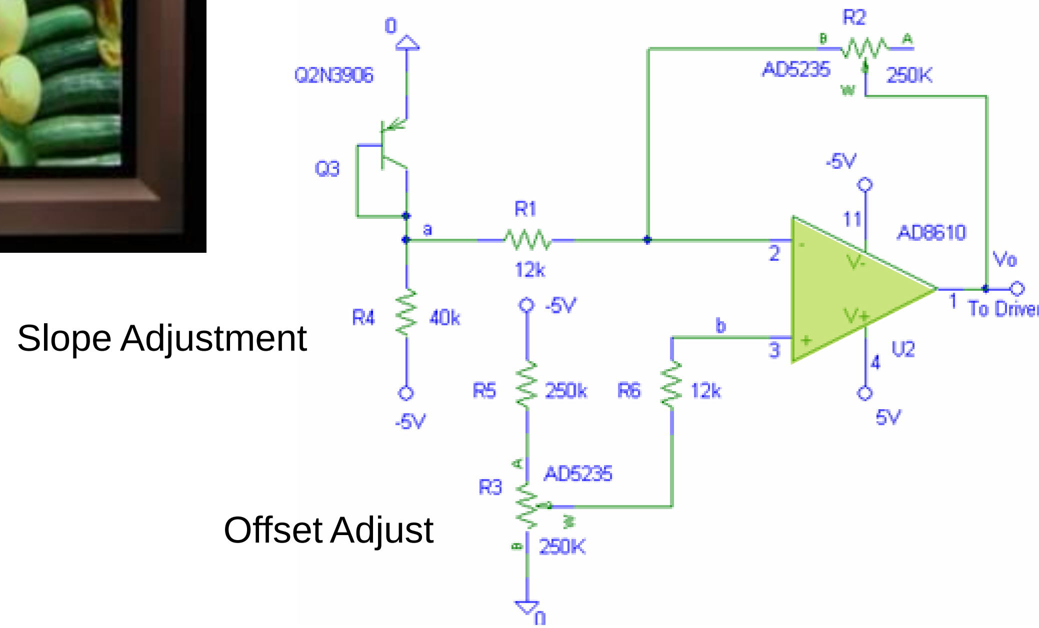


- **FEATURES**
  - **SC70-6: 2 mm x 2.1 mm**
  - **128 Positions**
  - **5k, 10k, 50k, 100k Ohms End-to-End Resistance**
  - **Low Tempco 35 ppm/ºC**
  - **I²C interface**
    - **Wiper Position Read Back**
  - **Power ON Reset to Midscale**
  - **Low Cost**

LCD Display Bias Adjustment for Brightness & Contrast

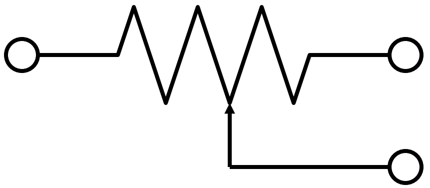


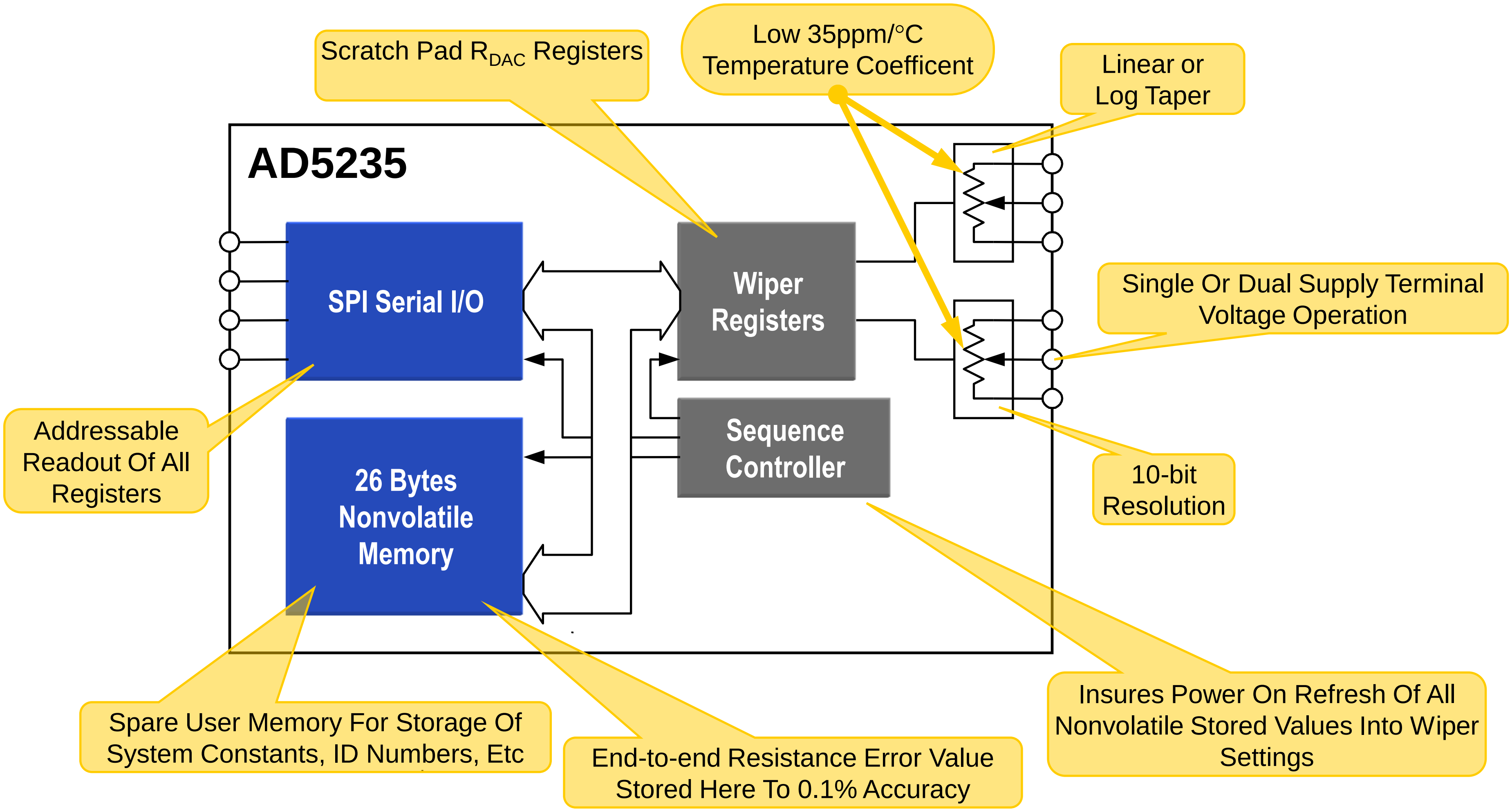




Contrast Compensation

AD5235 – NV Dual 10-Bit with 35ppm/°C Tempco





Using Digital Potentiometers for Audio Applications

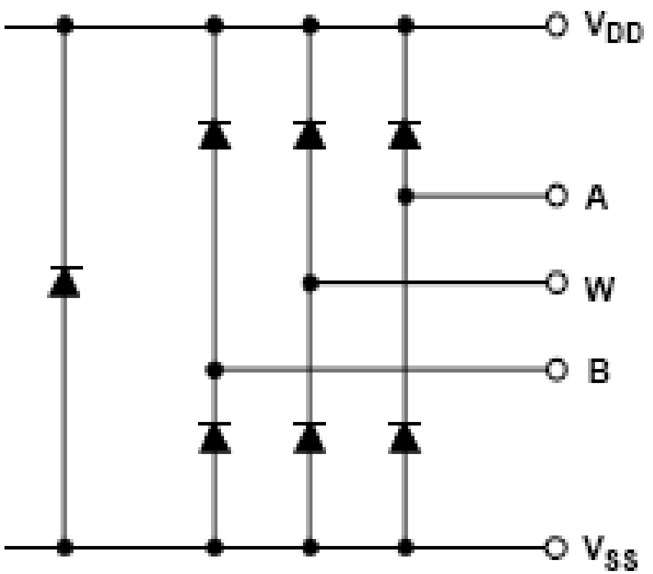
- Digital potentiometers (pots) have largely replaced mechanical pots for volume control in modern electronics
- Their benefits Include:
  - Higher Reliability
  - Digital Control
  - Potentially Better Resolution
  - Potentially Better Channel to Channel Matching
  - Better Stability

Using Digital Potentiometers for Audio Applications

- However, there are several things one must consider when designing an audio control circuit with a digital pot that may not be immediately obvious
- These include:
  - Audio signal voltage range
  - Power-up sequence
  - Potentiometer tolerance issues
  - Position of wiper at power-up
  - Zipper noise
  - Audio adjustment step uniformity

Audio Signal Voltage Range Should Not Exceed V_{DD} or Drop Below V_{SS}

- All ADI pots are designed with internal ESD protection diodes, as shown in this diagram of the internal structure of one of their devices
- This design allows for some protection for transient voltages above V_{DD} and below V_{SS}, but one should not allow voltages to exceed V_{DD} or drop below V_{SS} under normal circumstances



ANALOG DEVICES

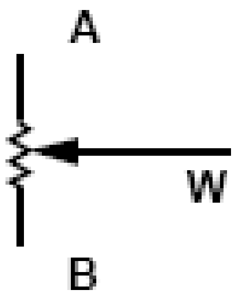
Power-up Sequence for Digital Pots

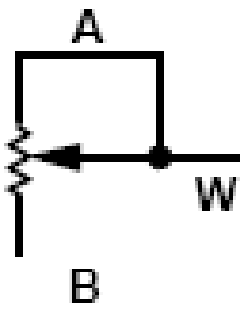
- Because of the ESD protection diodes, as seen on the previous slide, one must be careful not to apply a voltage to terminals A, W, or B prior to powering the device
- Otherwise, the diodes are forward biased such that V_{DD} and V_{SS} may be powered unintentionally and could adversely affect the system
- To prevent possible damage to the device or other parts on the board, one should power the board with the following sequence:
  - 1st) Ground, V_{DD}, and V_{SS}
  - 2nd) Digital inputs
  - 3rd) Terminals A, B, and W

ANALOG DEVICES

Resistor Divider vs. Rheostat Configuration in Audio Applications

- The potentiometer can be connected either as a resistor divider (upper diagram) or as a rheostat (lower diagram)
- Generally, one should not configure it in rheostat mode because the resistance will typically drift with a change in temperature
- Also, the tolerance of most digital pots varies by as much as +/-20%, so it can be difficult to get matching resistance in stereo applications
- By configuring the potentiometer as a resistor divider, one can overcome this problem because the output voltage is only dependent on the relative position of the wiper (ratio-metric output) and not on the precise value of the resistance of the pot





Start-up Position of Wiper

- Unlike a mechanical pot, a digital pot may not return to the same position it was in before power-down when power is re-applied
  - Some do have non-volatile memory (EEPROM) which will automatically restore the last setting stored into the EEPROM at power-up
  - Many are designed to return to mid-scale at power-up
  - However, some have a completely random power-up state
- One must decide how to ensure that the audio comes on in a predictable way at power-up

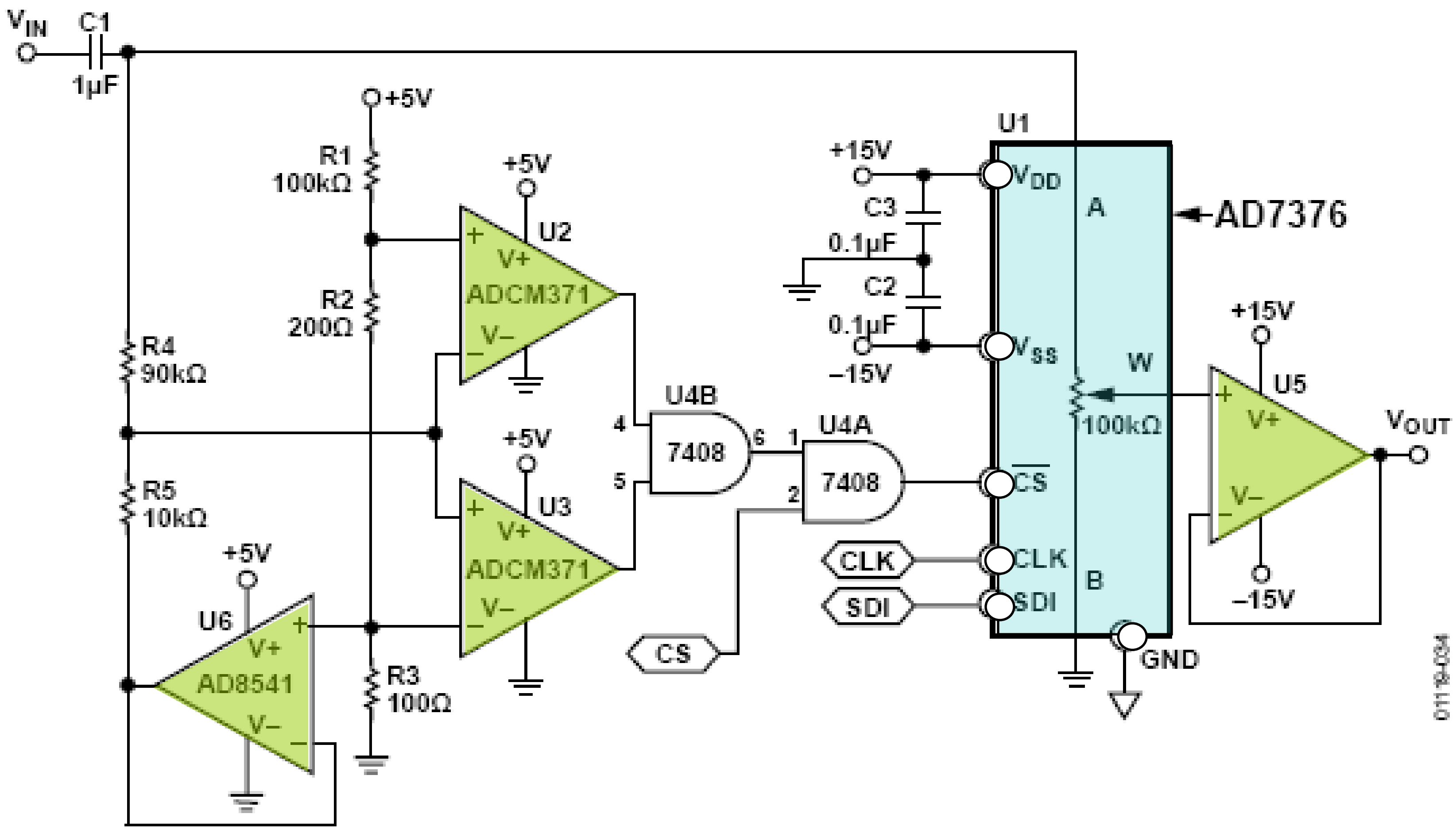
Start-up Position of Wiper

- The most obvious choice is to chose a part with EEPROM, such as the AD5232. This is often the best choice, but other methods can also solve the problem.
- Some parts, such as the AD7376, are capable of receiving and loading wiper position data via SPI while in a low-power sleep mode. Thus, the wiper position can be sent by the processor to the device before the audio signal is passed to the output.
- Another alternative is to keep the digital pot powered continuously, even while the rest of the circuit is turned off. This can be practical, even for battery powered products, because many of ADI's digital pots draw less than 3uA of current.

Solving "Zipper" Noise

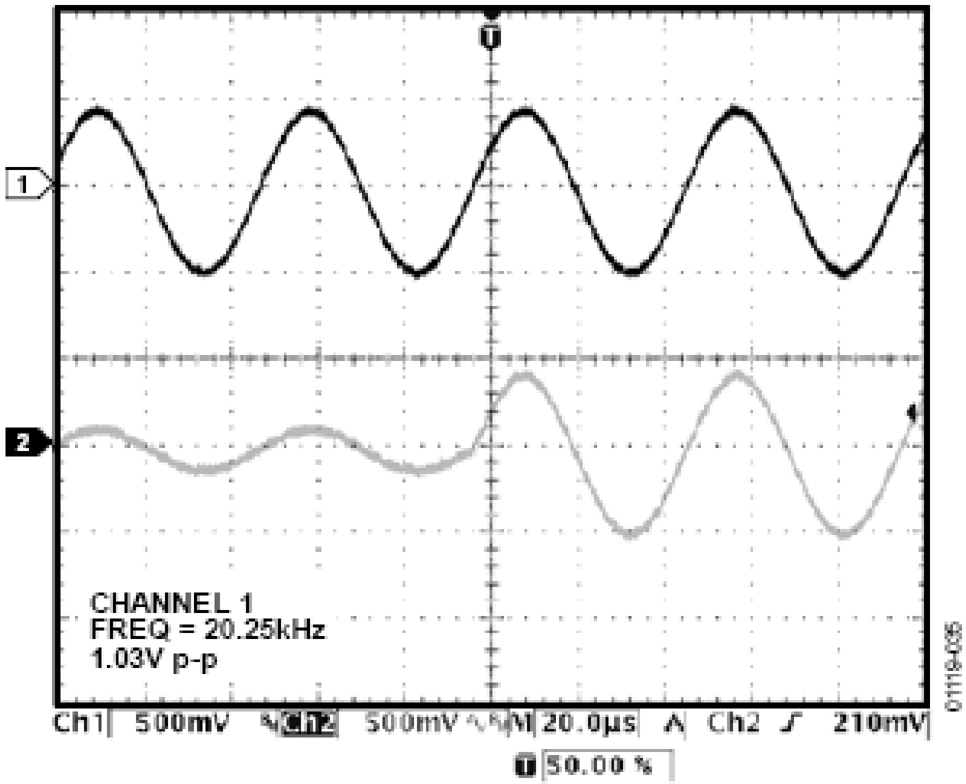
- Another issue unique to digital pots is "zipper" noise
- Zipper noise results from abrupt changes in continuity of the signal while the wiper position is changing in a digital pot
- ADI has come up with a circuit that minimizes zipper noise by only allowing wiper position updates when the audio signal crosses the zero axis
- This method allows the audio sine wave to remain relatively smooth rather than have a discontinuity in voltage when the wiper position changes
- The following two slides show a schematic of the zero-crossing detector circuit and the resultant waveforms of the input and output signals

Zero-Cross Detection Circuit to Reduce "Zipper" Noise



Oscilloscope View of Input and Output Waveforms Showing Volume Level Change Utilizing the Zero-Cross Detect Circuit

Note the smooth transition of gain with no glitch



NOTES
1. THE LOWER TRACE SHOWS THAT THE VOLUME LEVEL CHANGES FROM QUARTER SCALE TO FULL SCALE, WITH THE CHANGE OCCURRING NEAR THE ZERO-CROSSING WINDOW.

Attaining Audio Adjustment Step Uniformity

- The human ear recognizes changes in volume on a logarithmic decibel (dB) scale rather than a linear scale. Therefore, most mechanical audio pots have a logarithmic taper, which allows the user to get a fairly uniform change in volume throughout the adjustment range.
- Most digital pots are linear, which means that if configured as a simple voltage divider, setting the wiper to mid-range only attenuates the signal by about 6dB (20 x log(0.5) = -6dB).
- One can compensate for this either by selecting a pot with more taps or by adding additional circuitry that produces a more "logarithmic type" output with a linear change in the digital pot.

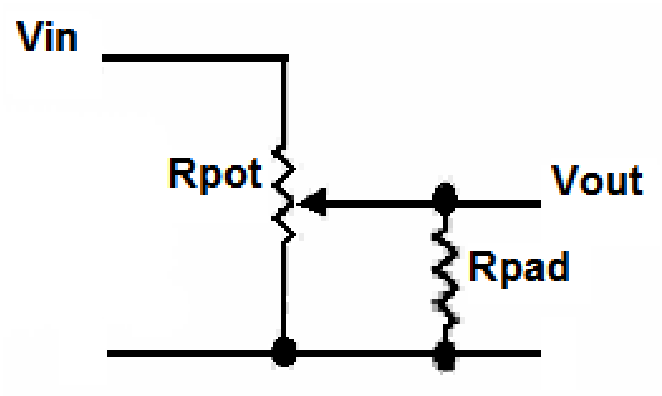
Attaining Audio Adjustment Step Uniformity

- Simpler approach - Select digital pot with more taps
  - Controller only uses a subset of total taps to create a pseudo log taper with software look-up table
  - Number of taps required for sufficient resolution is very dependent on the application

- Drawback
  - Usually, digital pots with more taps are more expensive
  - One only uses a fraction of the available taps, therefore not utilizing its full potential

Attaining Audio Adjustment Step Uniformity

- The alternative to selecting a part with more taps is to add circuitry to emulate a logarithmic output
- Many circuits have been designed to accomplish this, but they all present trade-offs between effectiveness, complexity, and cost
- One of the simplest and most common approaches is to place a “pad” resistor in parallel with the wiper terminal and the lower terminal of the pot, as shown below



$$\frac{Vout}{Vin} = \frac{R2 \parallel Rpad}{R1 + R2 \parallel Rpad}$$

Logarithmic Taper Circuit

- Good results can be obtained using an Rpad value of about 10% of the digital pot's full-scale value, but the best value could be anywhere from 5% to 25%, depending on the particular application
- The advantages of this circuit include:
  - It's simplicity
  - Small additional space
  - Relatively effective
- The circuit has two primary disadvantages:
  - The impedance, as seen by the audio source, varies with wiper position, so one must drive it with a low impedance source
  - It may be more difficult to match stereo channels than without the pad resistor because the output now depends on the actual value of the pot, and not just its wiper position

General Recommendations for Using Digital Pots for Audio

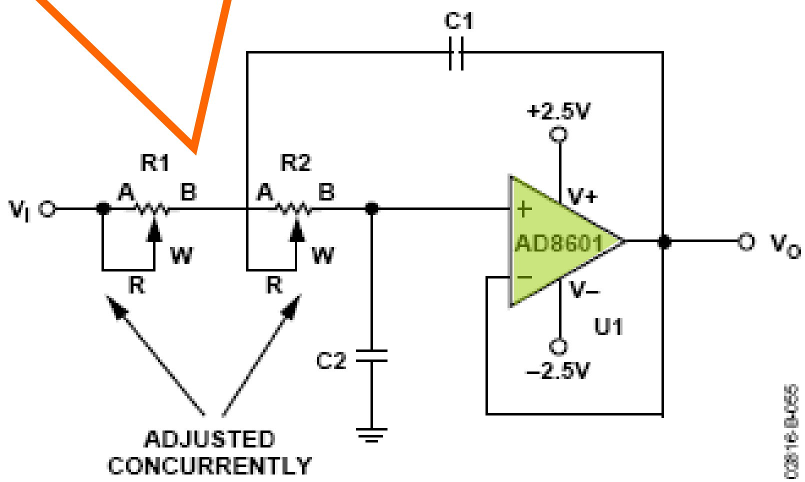
- Determine the number of “usable” taps required to get the resolution you need. Generally, a quality audio system would have at least 64 taps
- Use good layout techniques
  - Short traces
  - Good ground planes (isolate digital from analog domains as much as possible)
  - Use the better quality 0.1uF X7R type ceramic capacitors on all V_{DD} and V_{SS} pins rather than the lower grade Y5V capacitors
- Consider implementing a zipper noise reduction circuit similar to the one shown in this presentation

General Recommendations for Using Digital Pots for Audio

- Minimize the effects of loose tolerance and temperature drift by using the pots in voltage divider mode rather than rheostat mode
- Consider using dual channel devices because these parts have superior matching characteristics (better than 0.1% typically)
- For the highest quality audio pots, check the Total Harmonic Distortion (THD) specs. All of them are pretty good, but some can be as low as 0.003%

Programmable Low Pass Filter

The AD5235 digiPOT used for a 2nd order Sallen-Key low pass Anti-Alias filter.



$$\frac{V_O}{V_i} = \frac{\omega_f^{\,2}}{S^2 + \frac{\omega_f}{Q} S + \omega_f^{\,2}}$$

$$\omega_O = \sqrt{\frac{1}{R1\,R2\,C1\,C2}}$$

$$Q = \frac{1}{R1\,C1} + \frac{1}{R2\,C2}$$

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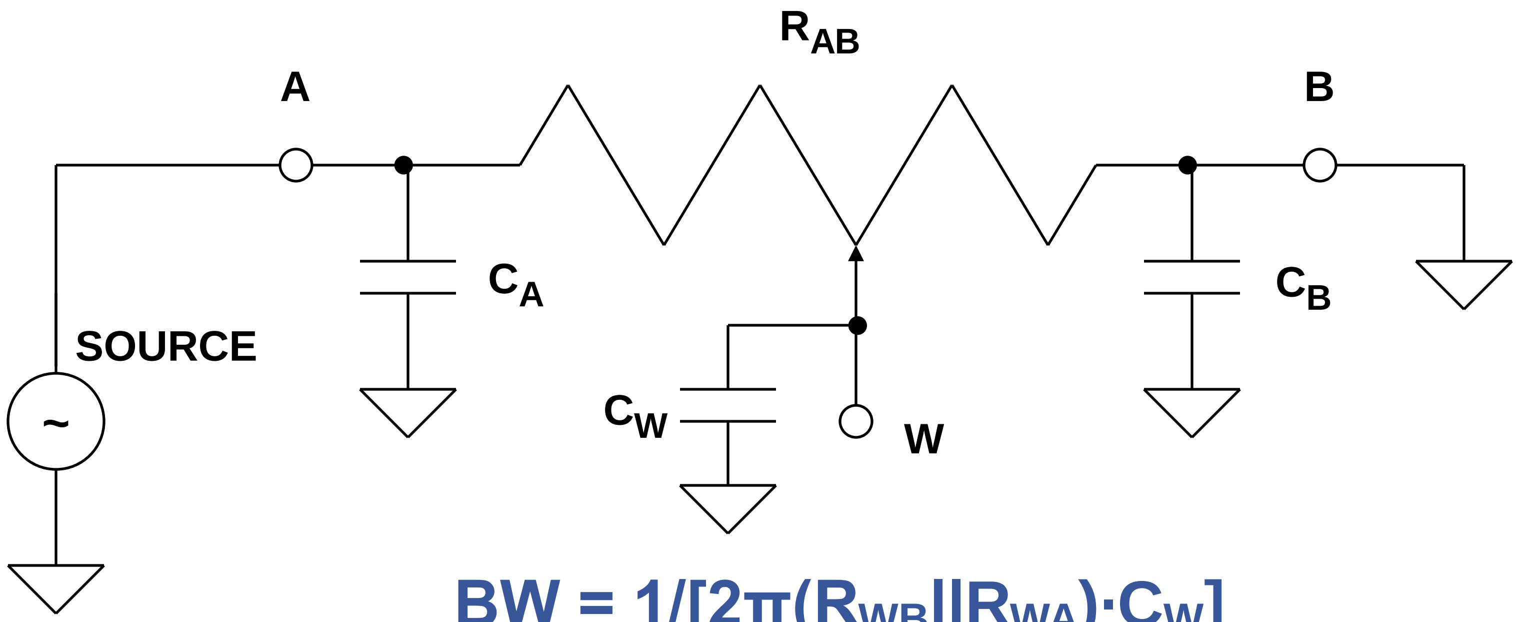
AC Considerations of Digital Pots Bandwidth Model



$$BW = 1/[2\pi(R_{WB}||R_{WA})\cdot C_W]$$

FOR AD5245:

$C_{A,B}$ = 90pF
C_W = 95pF

R_{AB}	BW
5kΩ	1.0MHz
10kΩ	500kHz
50kΩ	100kHz
100kΩ	50kHz

BW MEASURED FROM A TO W WITH B GROUNDED, MIDSCALE CODE, DRIVEN FROM A LOW IMPEDANCE SOURCE

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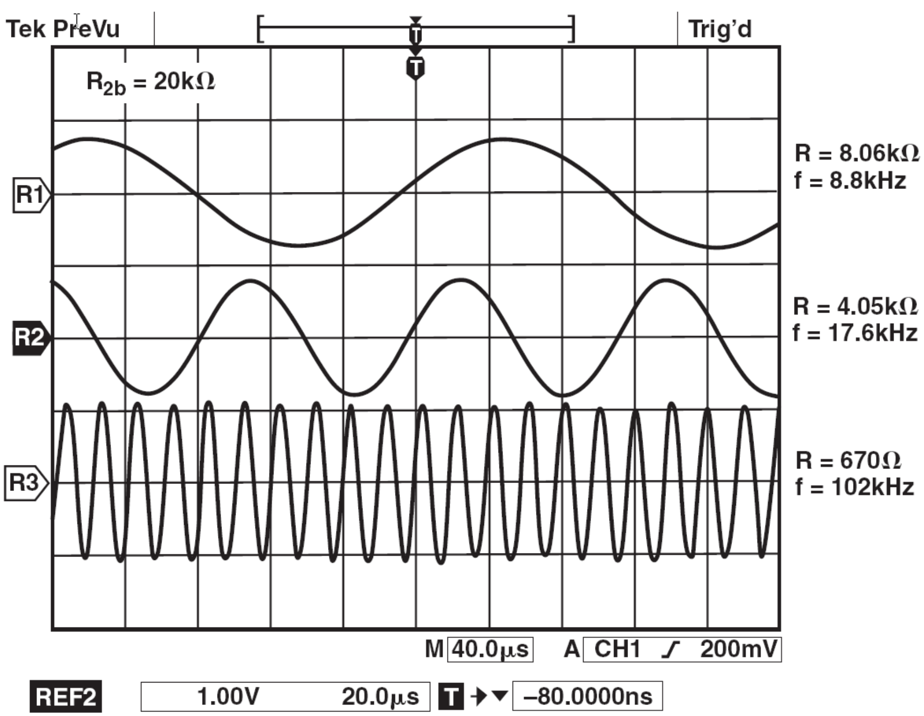
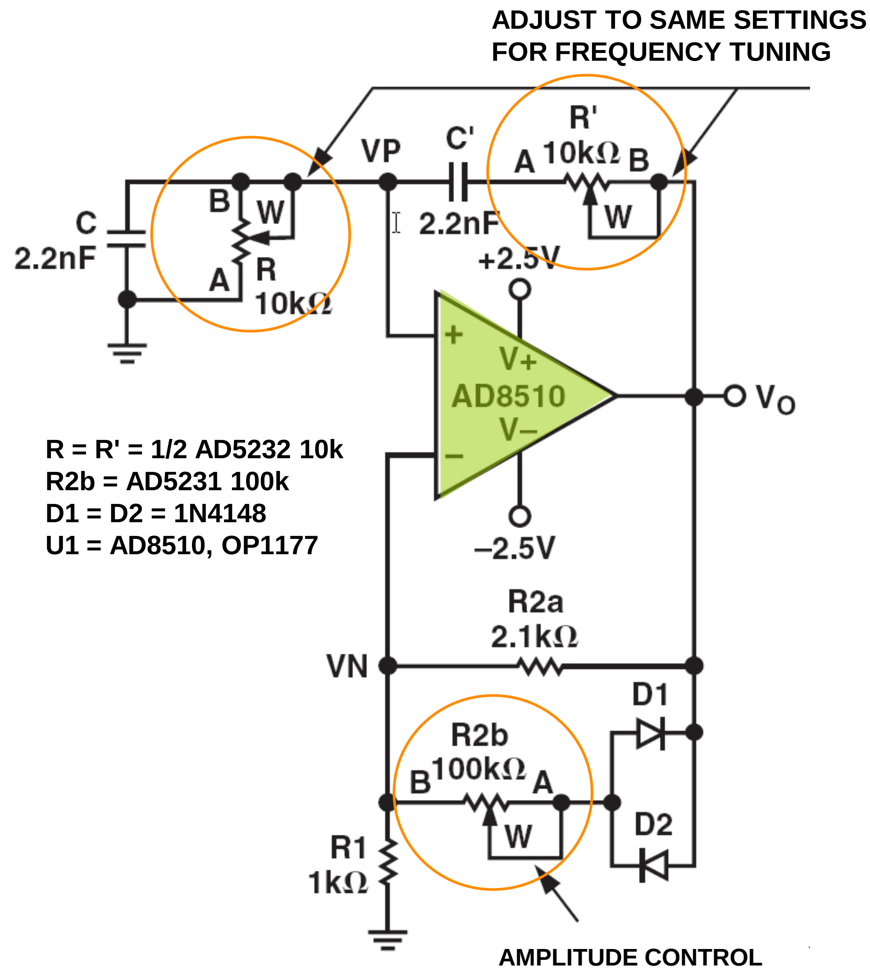
Programmable Wien-Bridge Oscillator with Amplitude Stabilization

- F from 10kHz to 200 kHz





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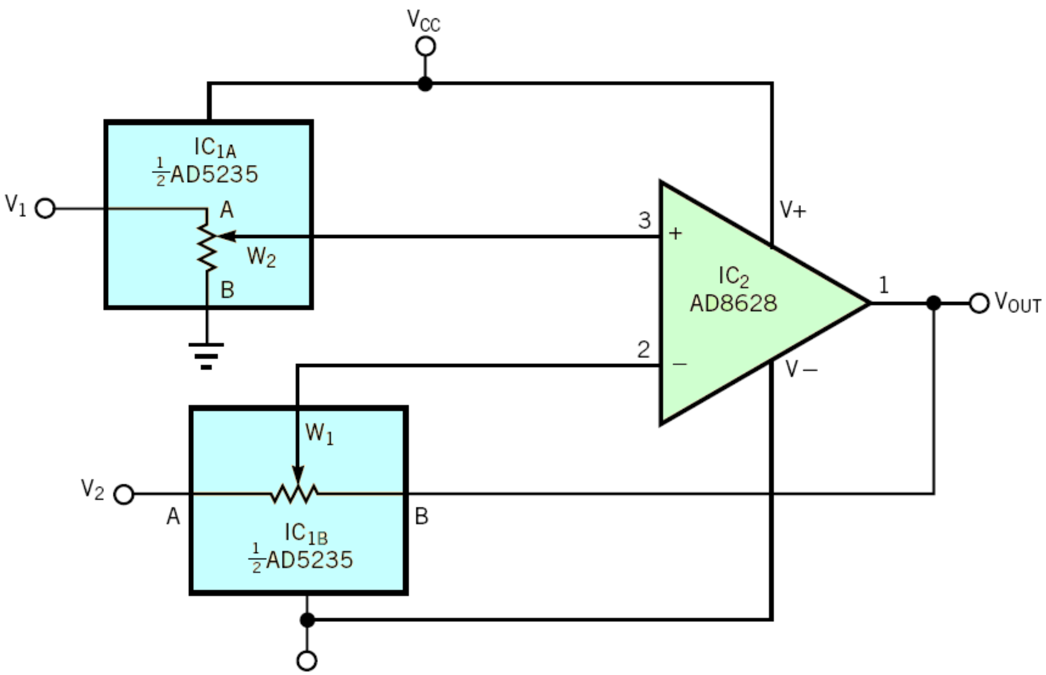
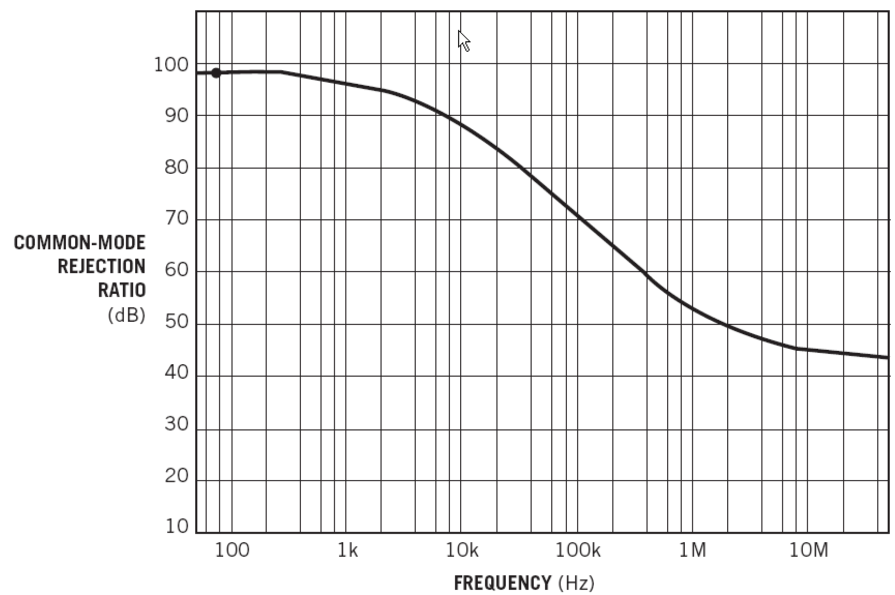
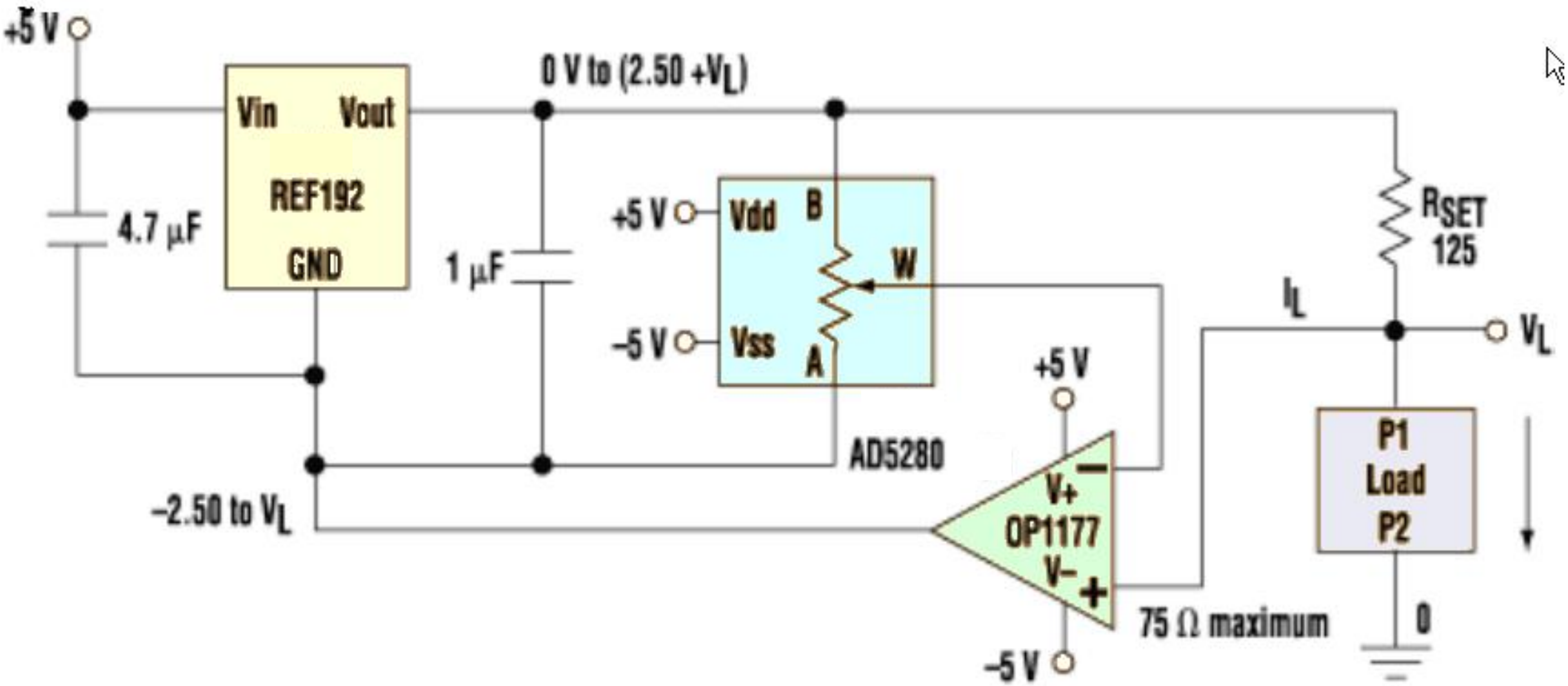
Programmable Differential Amp



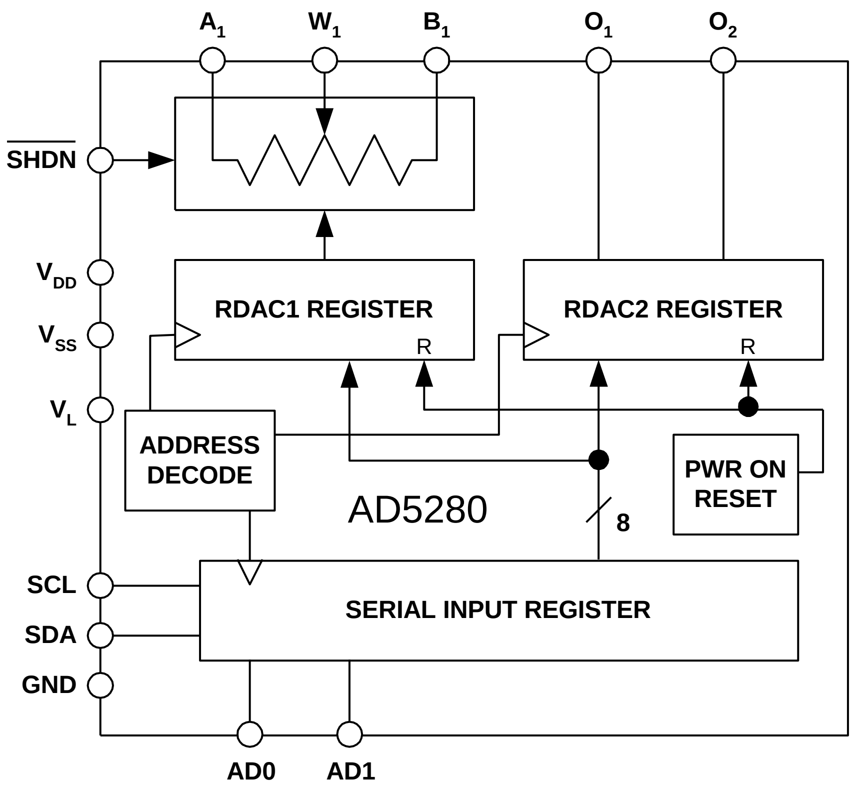
- Op amp used to save costs
- Use a chopper for Low drift
- Dual Digipot allows tighter matching of resistors



Programmable 4-20 mA Current Source



AD5280/AD5282: +15V Operation Single/Dual, 8-Bit, Low TC, I²C Compatible Digital Potentiometer



AD5280 contains 1 POT/Package
AD5282 contains 2 POTs/Package

- **20 kΩ, 50 kΩ and 200 kΩ End-to-End Terminal Resistances, <50ppm/°C**
- **+15 V Single-Supply or ±5 V Dual Supply Operation**
- **2-Wire I²C Compatible Serial Data Input & Output**
- **Wiper Shutdown (SHDN) allows for low power sleep state**
- **Power ON reset places wiper in center position at Power ON**

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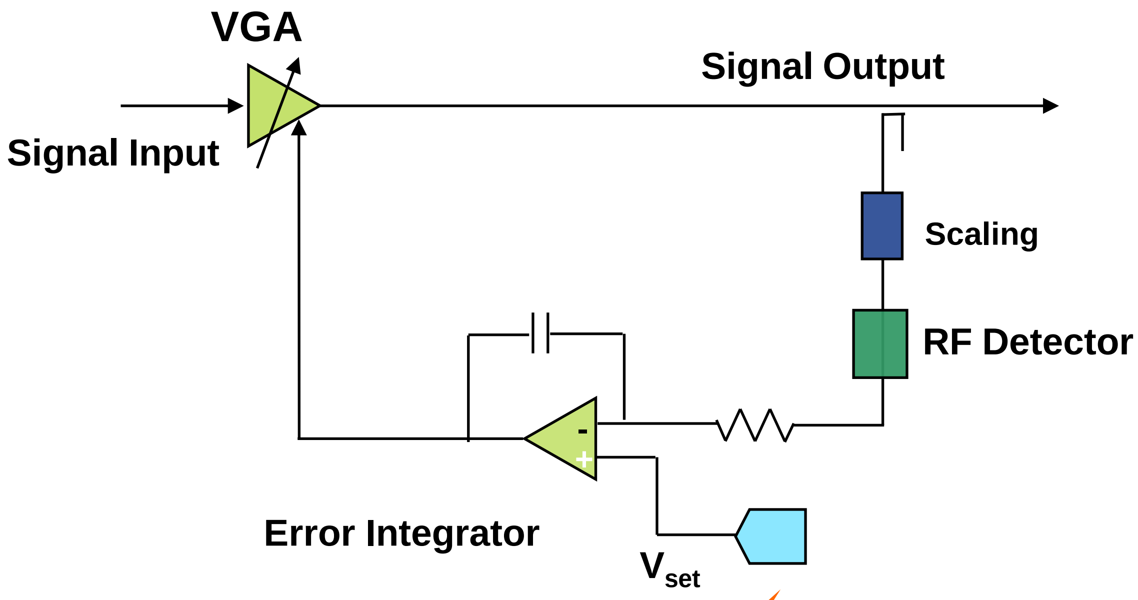
Digitally Controlled Potentiometers Additional Important Considerations

- Voltage Restrictions
  - Must be between the rails
- Current Restrictions
  - Resistor setting dependant ie @1K=5.5mA @10k= 0.55mA
- Power Supply Sequencing
  - VDD then VSS & Digital signals then VA/VB/VW
- Power On settings
  - See Datasheet
- Memory Issues
  - EEPROM Retention varies Most >= 100,000 cycles
- Resistance
- Interface
  - Readback, Diasy Chain, Up/Dw, Inc/Dec

Control Chain: Voltage Level Setting

Example: Base-station Gain / PA Control



A DigiPOT or nanoDAC or set control voltages to control the VGA.

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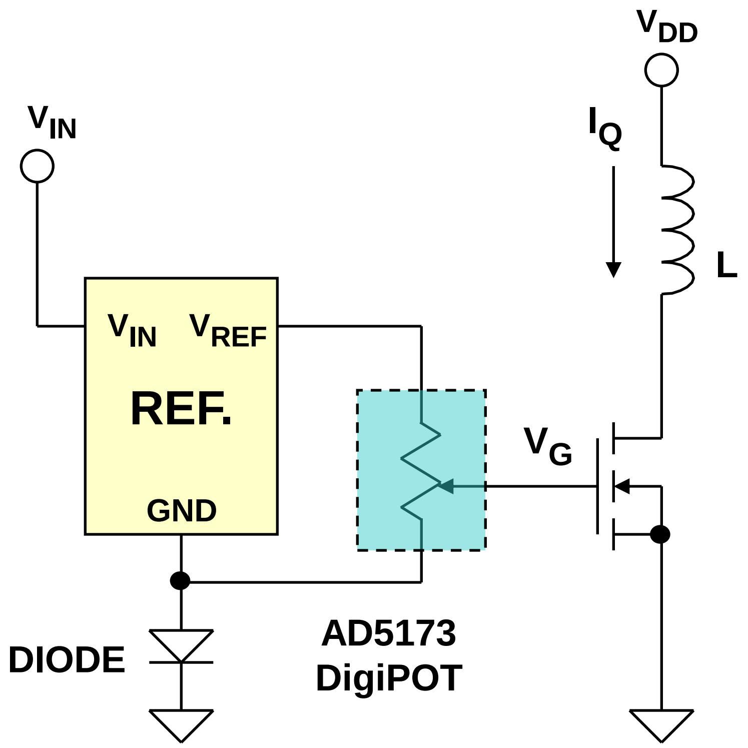
Control Chain: Voltage Level Setting

Example: Base-station Gain / PA Control



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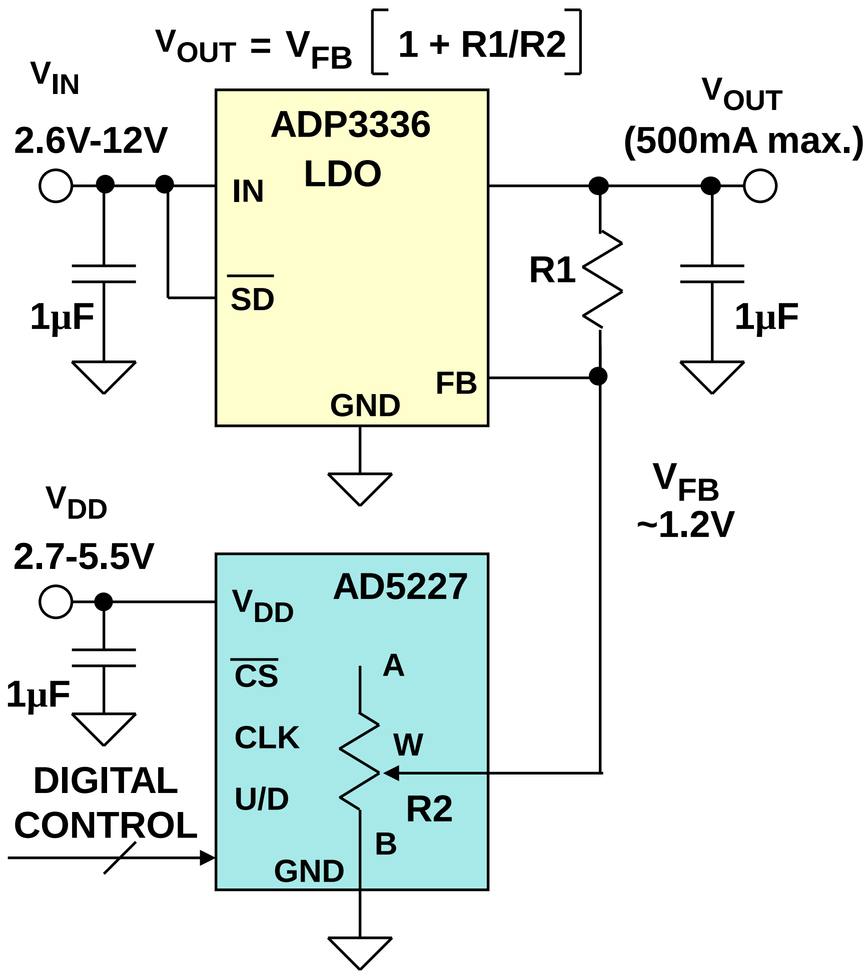
Programmable Power Supply



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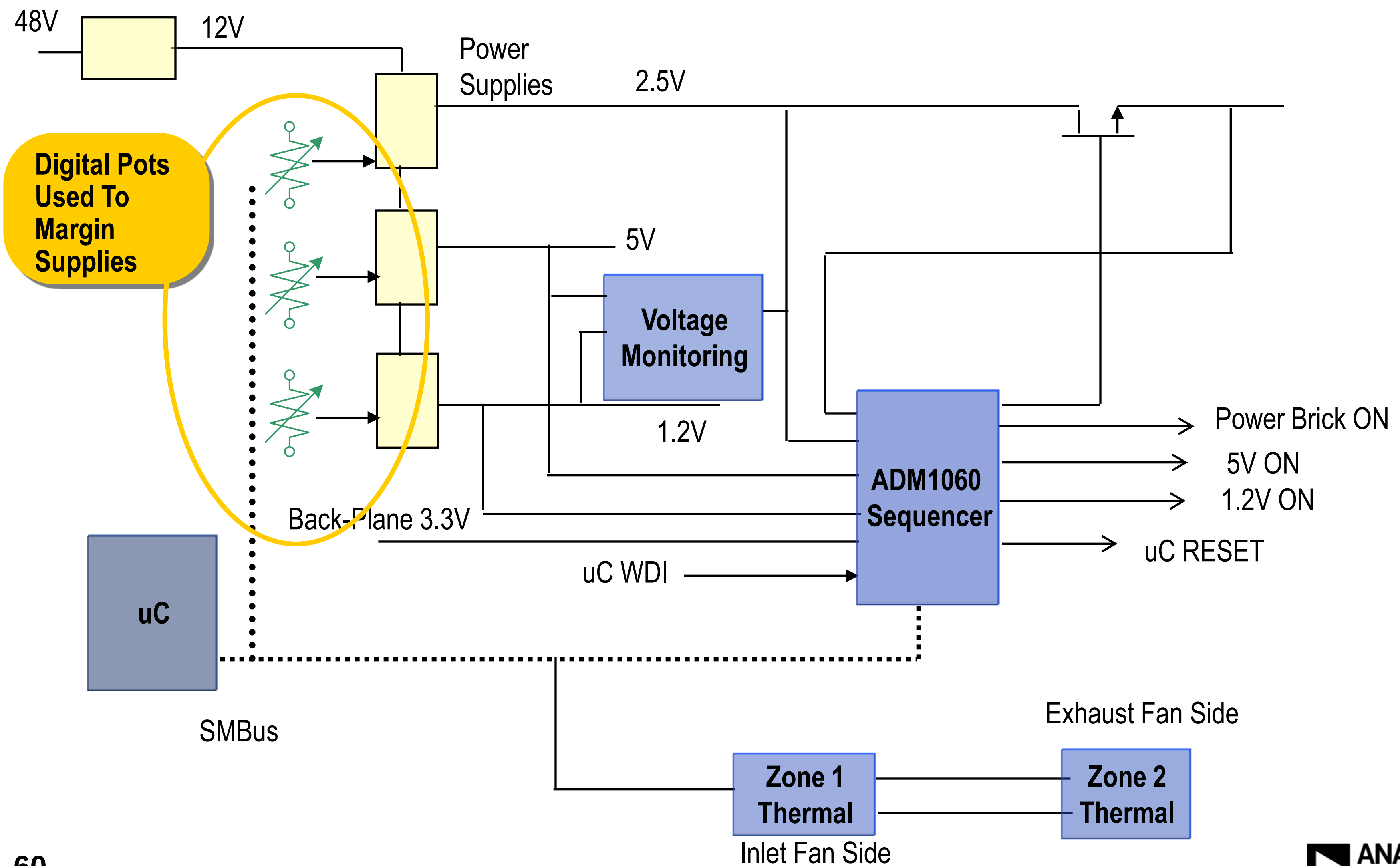
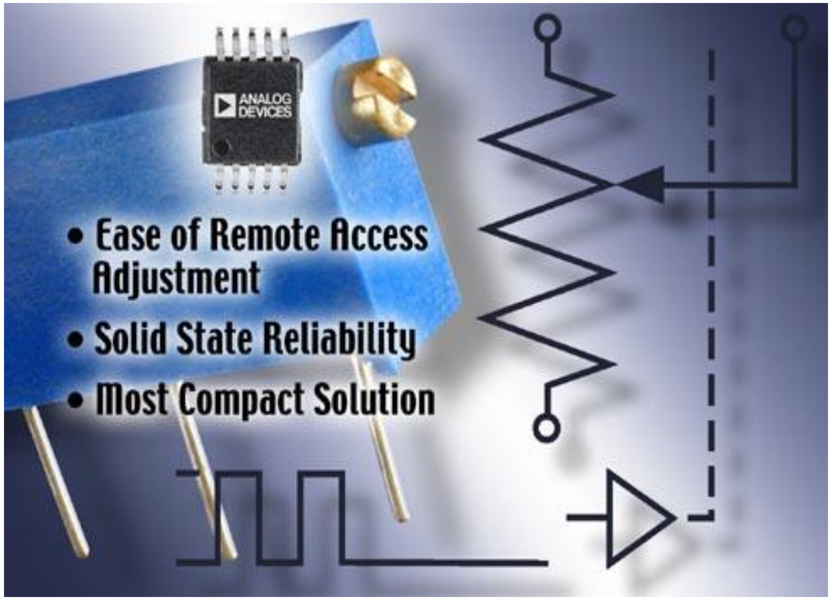
System Level Requirement
Voltage Margining



DigiPots vs. Mechanical Pots

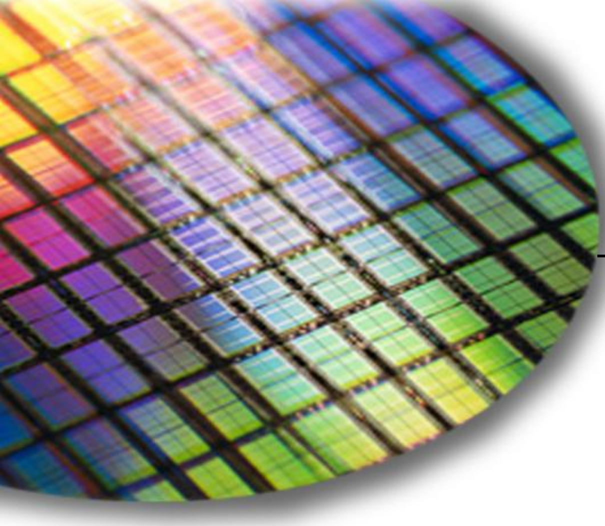
- Digital Potentiometers offer many advantages for replacement of Mechanical Potentiometers in new designs ...
  - No mechanical wear-out
  - No screwdriver access holes required
  - No vibration sensitivities, improved stability of wiper setting versus time
  - Potential for corrosion significantly reduced in humid environments
  - Faster adjustment time
  - IC packaging is more compact than trimmer packages

  - Disadvantages
    - Lower voltage & Current ratings



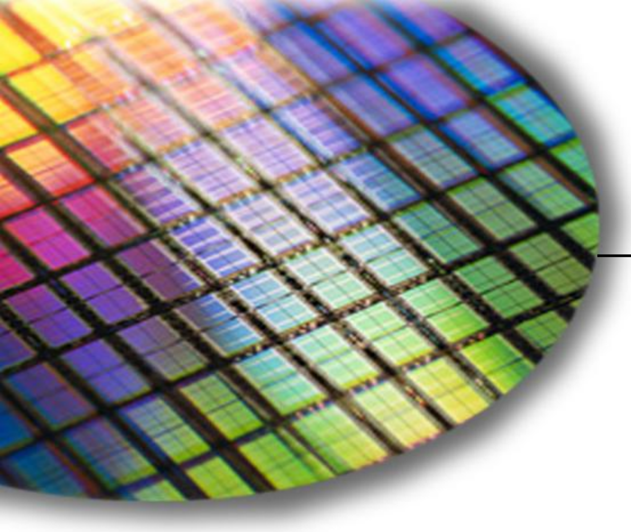
Where to Start?

- How many Taps?
  i.e. the "step size" (aka resolution)
- How many channels ?
- What resistor value ?
- Volatile (no memory) or Non Volatile (memory)?



ADI's
Digitally Controlled Resistors

- Highest Precision > to 1%
- Best TempCo
- Smallest Package/Taps
- Wide Selection
  - Voltage – to +- 15V or 0-30V
  - R's - 1k to 1M
  - Memory – NV, OTP, Volitile
  - Control – SPI,I2C, U/D, Inc/Dec
- Value/Cost



Thanks!

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