Temperature transducers

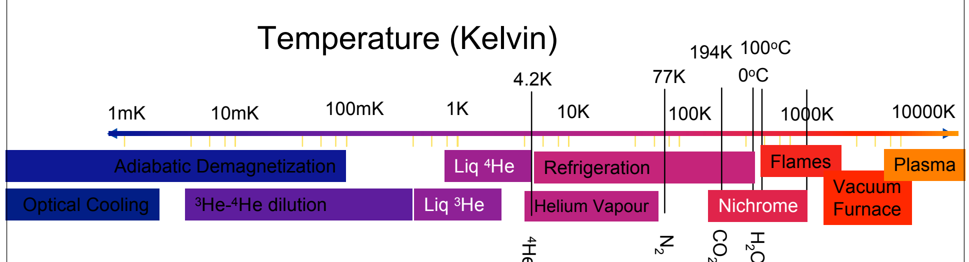
We'll look at some temperature transducers - both as important instruments on their own, but also as examples of transducers in general so we can treat noise, impedance, bandwidth, filtering with a concrete basis.

What is temperature?

•A measure of the thermal energy present in a system. Every degree of freedom (mode of motion or harmonic oscillator) in an object at temperature *T* has $k_B T/2$ of energy. Temperature is a key concept for almost every scientific or engineering process.

Temperature Ranges

Temperatures in the laboratory:

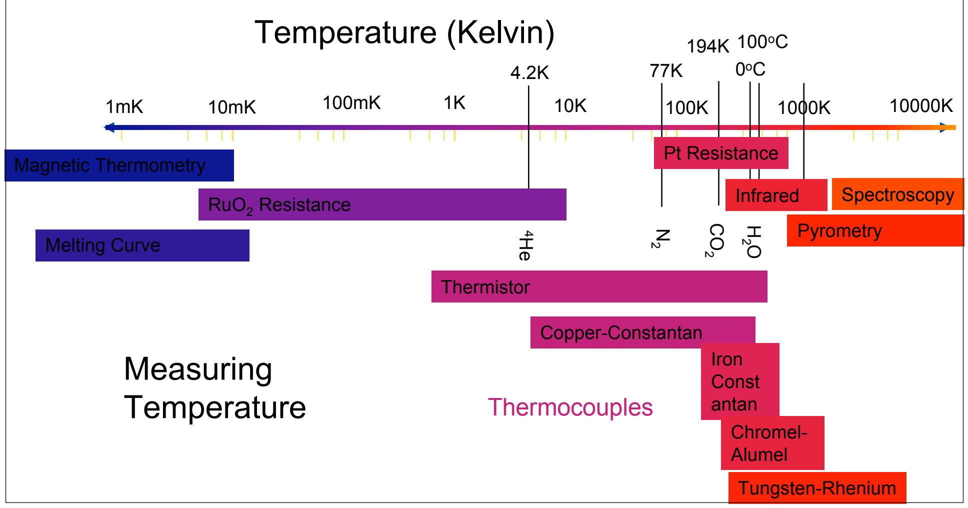


Producing Temperature

Cooling

Heating

Temperature Ranges



Defining Temperature Scales

As with *ANY* measurement, units are critical, and one cannot measure anything without defining the units we use. Calibration is particularly important for temperature, and particularly difficult.

For temperature we use fixed points with a defined temperature and interpolate in between to define the scale. Celcius used ice & boiling water… we now use triple points (and other thermodynamic points) of various substances:

Water: 273.16K

Hydrogen: 13.81K

Oxygen: 54.36K

Tin: 505.12K

Zinc: 692.73K

Gold: 1337.58K

Melting Points

Resistance Thermometry

The electrical resistance through a material is (like most properties of materials) temperature dependent. *WHY?*

Thus, measuring resistance can give a measure of temperature.

This is a secondary thermometer it must be calibrated versus fixed points.

Often called an RTD (resistive temperature device) when metal, or a thermistor when a semiconductor.

Why does resistance vary with temperature?

Answer 1) For a semiconductor, electrons are thermally excited above the bandgap. The lower the temperature, the fewer the electrons, therefore the higher the resistance.

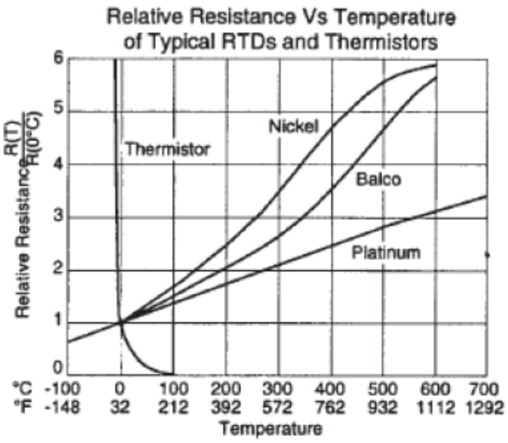
Answer 2) For metals, the dominant loss of energy by conducting electrons is through scattering off *phonons* - the thermal vibration of the atoms. This scattering increases as temperature increases (more vibrations, larger amplitude), therefore resistance increases with temperature.

Resistance Thermometers

$$R = R_0 \left(1 + \alpha(T - T_0) + \beta(T - T_0)^2 + ...\right)$$

Fit to a polynomial form (especially for metal RTDs) using a reference value.

Platinum very linear - used as the most accurate interpolation between fixed points.



Platinum RTDs

Platinum RTD's are a good standard because:

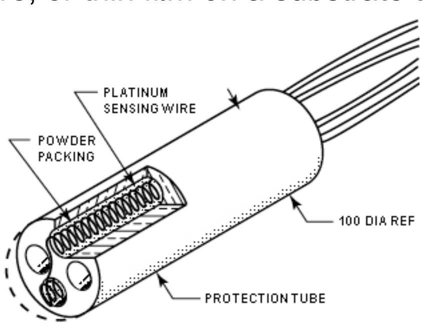
- Highly linear
- Pure material - (reproducible)
- Chemical stability

Typically wire-wound thin Pt wire, or thin film on a substrate to be 100 Ω at 0ºC.

The IEC/DIN standard is pure platinum that is intentionally contaminated with other platinum group metals.

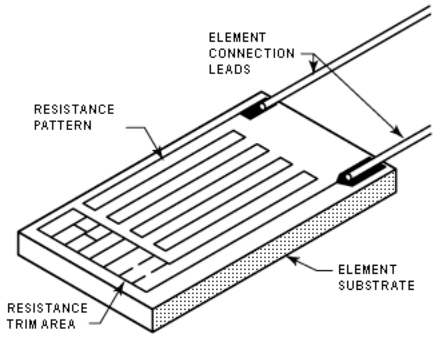
α= 3.908E-3 $(°C)^{-1}$

β= -5.775E-7 $(°C)^{-2}$



~ .385 Ω/ ºC for 0-100 ºC

Platinum RTDs



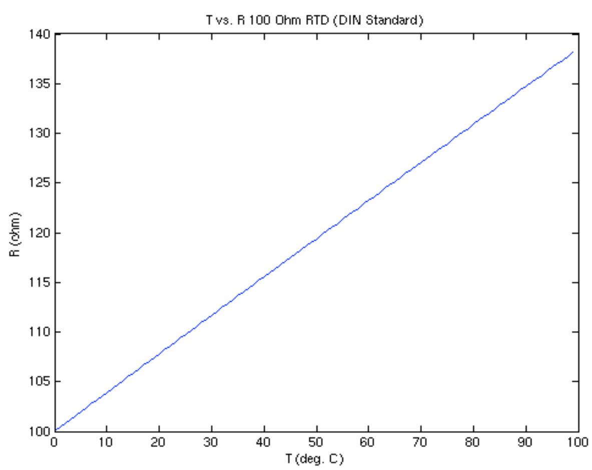
Thin film devices less rugged, but better thermal contact, and resistance can be made much higher (1000Ω devices common).

Platinum RTDs are the only resistance thermometers with international standards. The official method of interpolating between fixed points.

INTERNATIONAL STANDARDS

Standard	Comment	
IEC 751	Defines Class A and B performance for 100Ω 0.00385 alpha Pt RTDs.	
DIN 43760	Matches IEC 751.	
BS-1904	Matches IEC 751.	
JIS C1604	Matches IEC 751. Adds 0.003916 alpha.	
ITS-90	Defines temperature scale and transfer standard.	
Parameter	**IEC 751 Class A**	**IEC 751 Class B**
R_0	100Ω ± 0.06%	100Ω ± 0.12%
Alpha, α	.00385 ± .000063	.00385 ± .000063
Range	−200°C to 650°C	−200°C to 850°C
Res., R_T*	±(.06+.0008|T|−2E-7T²)	±(.12+.0019|T|−6E-7T²)
Temp, T**	±(0.3+0.002|T|)°C	±(0.3+0.005|T|)°C

*Units are Ωs. Values apply to 100Ω Pt RTDs only. Scale by ratio of the R_0s to apply to other ice point resistances.
*Applies to all 0.00385 alpha Pt RTDs independent of ice point, R_0.



- RTDs are very linear devices, but not perfect
- The Callendar-Van Dusen equation approximates the R vs T curve as:

$$R_T = R_0 + R_0\alpha\left[T - \delta\left(\frac{T}{100}-1\right)\left(\frac{T}{100}\right) - \beta\left(\frac{T}{100}-1\right)\left(\frac{T}{100}\right)^3\right]$$

R_T - Resistance of RTD at temperature T

R_0 - Resistance of RTD at 0°C

α - temperature coef. (0.00385 Ω/Ω/°C for Pt)

β - 0 for T > 0, 0.11 for T < 0

δ - ~1.5 (for 0.00385 Pt)

Platinum RTDs

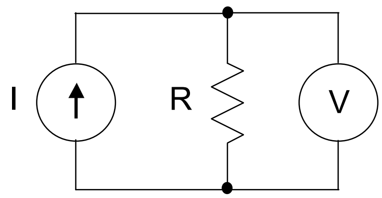
Disadvantages/Concerns:

- Not very small - hence largish heat capacity and moderate response speed.
- Expensive - precision and standardization means careful assembly and post-manufacture trimming
- Durability
- Sensitivity and/or Self-Heating

Measuring Resistance

Ohmmeters source a known current through a resistor and measure the voltage across it:

Why?



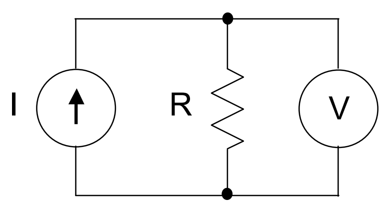
Reduce current!

$$P = I^2 R = (1\text{mA})^2 \times 100\Omega = 100\mu\text{W}$$

Depending on the thermal conductivity of the environment (still air vs. flowing water) this can significantly heat the RTD, yielding a higher temperature than it actually is.

Worst case: ~ 1 ºC per mW of heat

Measuring Resistance-2



With 1 mA sourced, we get

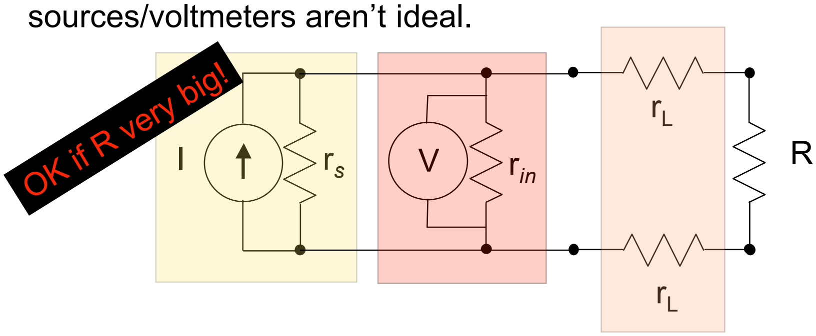
$$V = IR = 1\text{mA} \times 100\Omega = 100\text{mV}$$

But with .385 Ω/ºC, our temperature signal is .385 mV/ ºC

This is not a very sensitive signal for a significant current

Measuring Resistance - 3

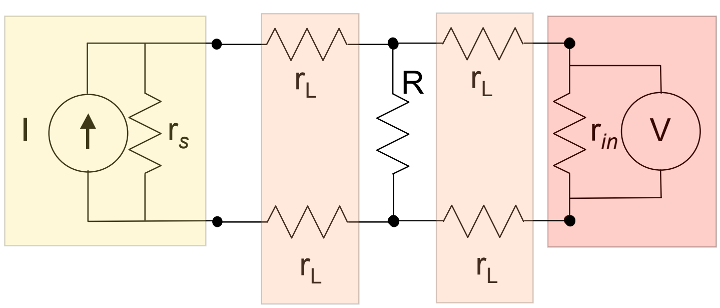
Measuring resistance is actually more complicated than this. All wires have some resistance, and current sources/voltmeters aren't ideal.



Resistance of the leads means that the resistor looks like $R_{eff} = 2r_L + R$

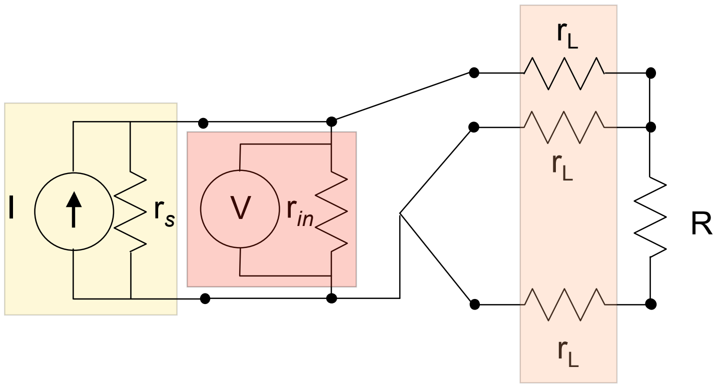
The temperature of these lead wires is ill-defined, and May change differently from the RTD.

4-wire Resistance Measurement



If $r_s >> R$ the current flowing through R is I.
And so the voltage drop across R is IR.
If $r_{in} >> r_L, R$ the current through the voltmeter is small, and the voltmeter will read IR.

3-wire Resistance Measurement



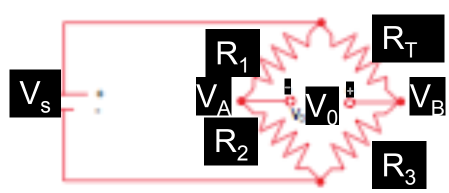
Measure across top two leads, get $2*r_L$

Measure across R, get $2*r_L$+R. Subtract first reading.

Wheatstone Bridge

Using a bridge technique can allow for sensitive null detection

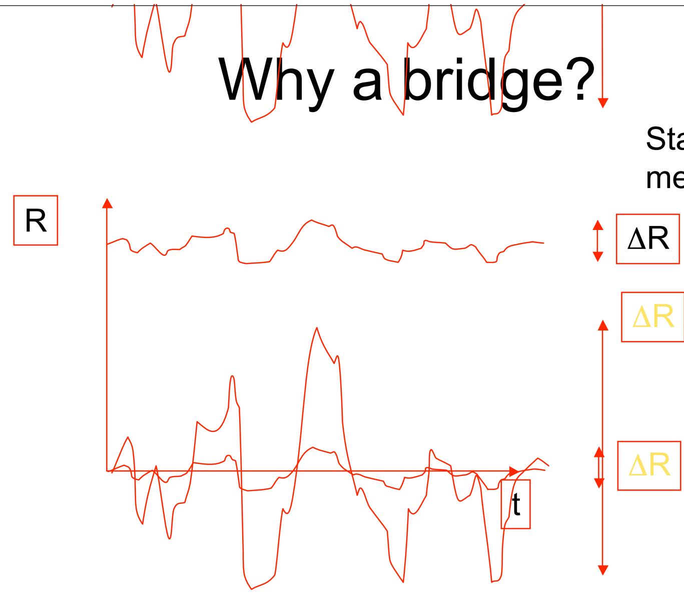
- Using a Wheatstone Bridge configuration removes the signal from the constant R value, and allows for measurement of the change in R sensitively.
- Balance the left-hand bridge ($R_1 = R_2$)
- Try to balance the right-hand bridge ($R_3 = R_T$)
  - Cannot do exactly since R_T is variable
  - Measure the unbalanced signal



$$R_T = R_3\left(\frac{V_S - 2V_0}{V_S + 2V_0}\right)$$

Why a bridge?

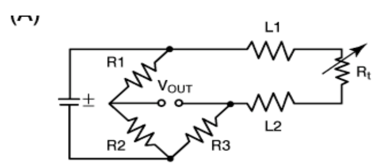
Standard R measurement



Can have more sensitive measurement of the change in R, therefore less current, and less self-heating.

Wheatstone Bridge

- Need to take into account the lead resistances, R_L
  - Assume the leads are of the same material and equal lengths (same R_L) for both
- Unknown lead resistances still lead to an error
  - Same error as if not in bridge network



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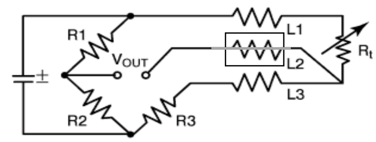
3-Wire Wheatstone Bridge

- A 3-wire RTD reduces the error from the lead-wire resistances by distributing them equally into the bridge network
  - RTD has two red leads (L2, L3), one white lead (L1)
- Error term is small if V_0 is small (e.g., if we choose $R_3 = R_T$)



$$R_T = R_3\left(\frac{V_S - 2V_0}{V_S + 2V_0}\right) - R_L\left(\frac{4V_0}{V_S + 2V_0}\right)$$

Thermistors

- Solid-state semiconductor device
  - Positive temperature coefficient (PTC) devices increases resistance with temperature increase
  - Negative temperature coefficient (NTC) devices decreases resistance with temperature increase
- Relationship between R and T is non-linear, but has a very steep slope
  - Increases the sensitivity of the device
  - Resistance change of 3%/°C
  - Limits range of operation

Thermistors

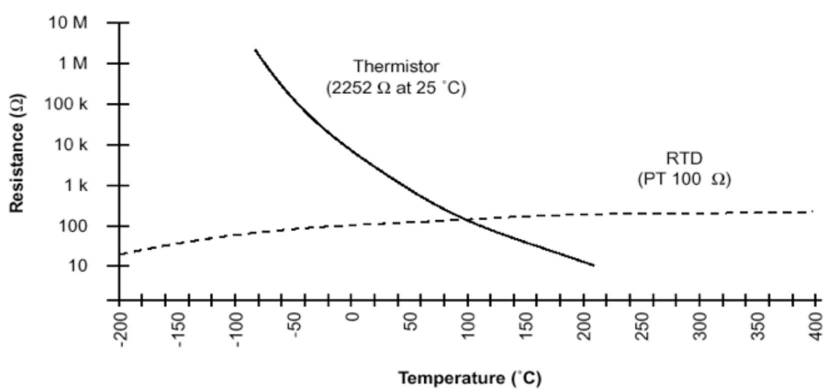
Non-linear resistance vs. temperature means:

- •High sensitivity
- •Reproducibility not as good as Pt RTD
- •Calibration important, and must be done at several points.
- •Resistance can be chosen: Ω to MΩ
- •Temperature range small, but can be chosen in range of interest

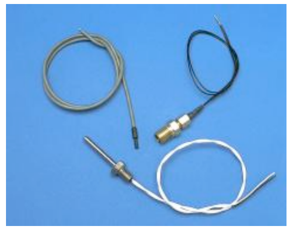
Devices can be tiny - therefore fast response time. Much cheaper than Pt RTDs.

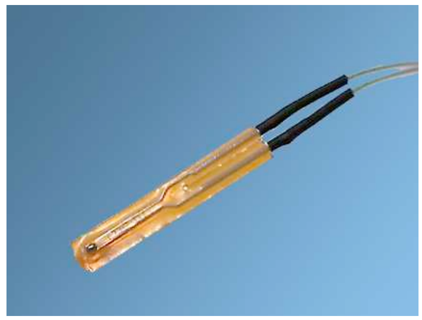
Chemical stability not as good… long term drift due to thermal cycling.

Thermistor vs RTD



Thermistors





Thermistor Functional Form

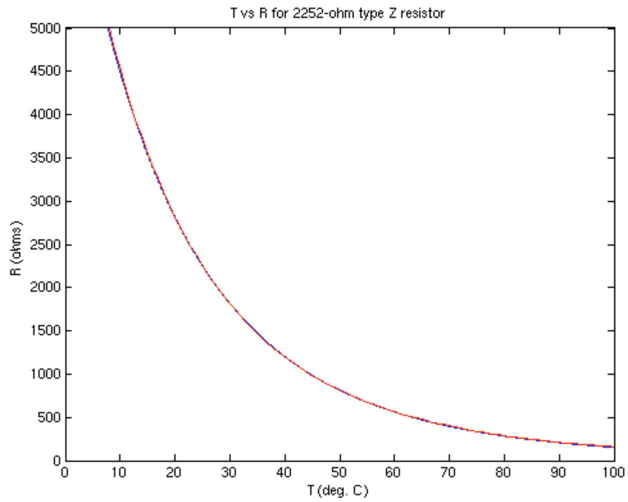
- Relationship between R and T given by the Steinhart-Hart equation

$$\frac{1}{T} = a + b\ln(R_T) + c\ln(R_T)^2 + d\ln(R_T)^3$$

R_T - resistance at temperature T

a, b, c, d - constants given by device manufacturer

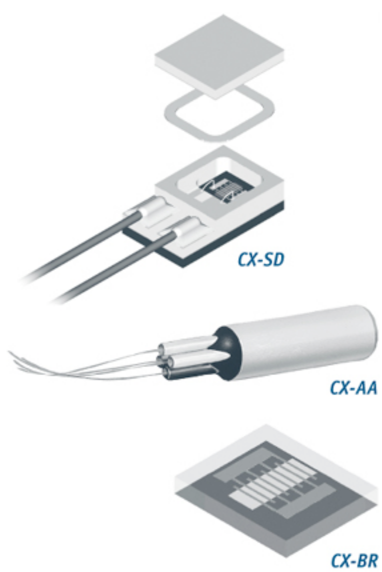
T - temperature in K

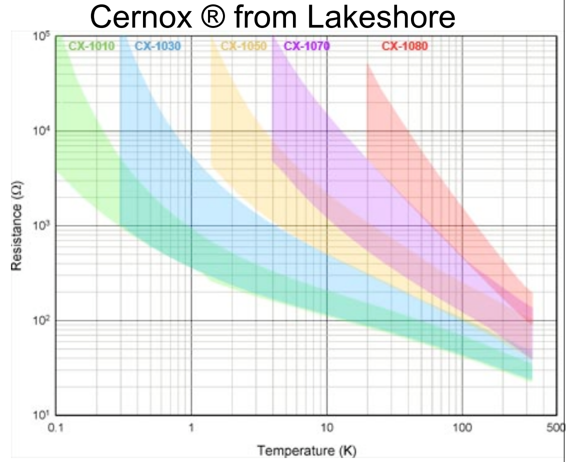


Higher resistance makes lead wire effects negligible. Self-heating problem identical to RTDs - best to still use a bridge.

Cryogenic Sensor

Cernox ® from Lakeshore





Each device must be calibrated for accurate use, but general form is similar, so a 1-pt calibration often used