Hewlett-Packard Classroom Series

Practical Temperature Measurements

Agenda

- **Background, history**
- Mechanical sensors
- Electrical sensors
  - Optical
    Pyrometer
  - RTD
  - Thermistor, IC
  - Thermocouple
- Summary & Examples

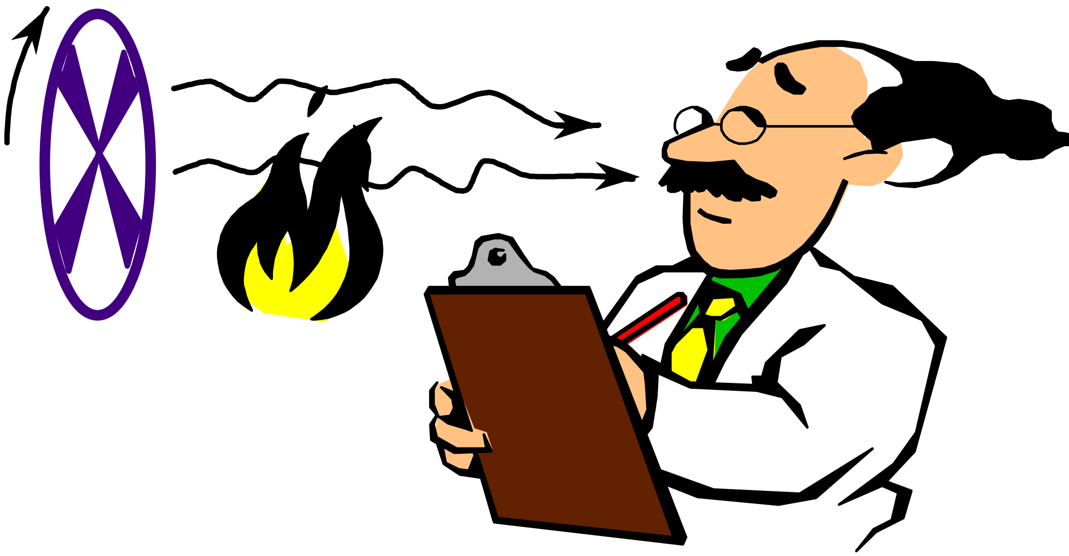
What is Temperature?

- A scalar quantity that determines the direction of heat flow between two bodies
- A statistical measurement
- A difficult measurement
- A mostly empirical measurement

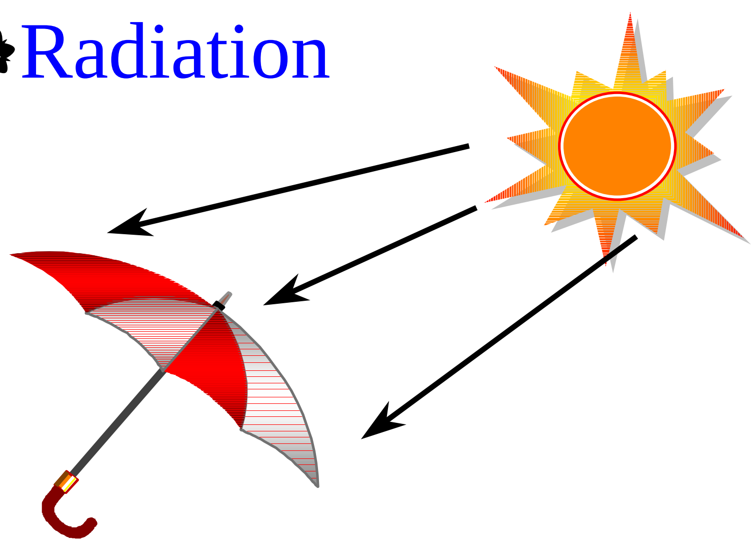
How is heat transferred?

- Conduction
  - Metal coffee cup

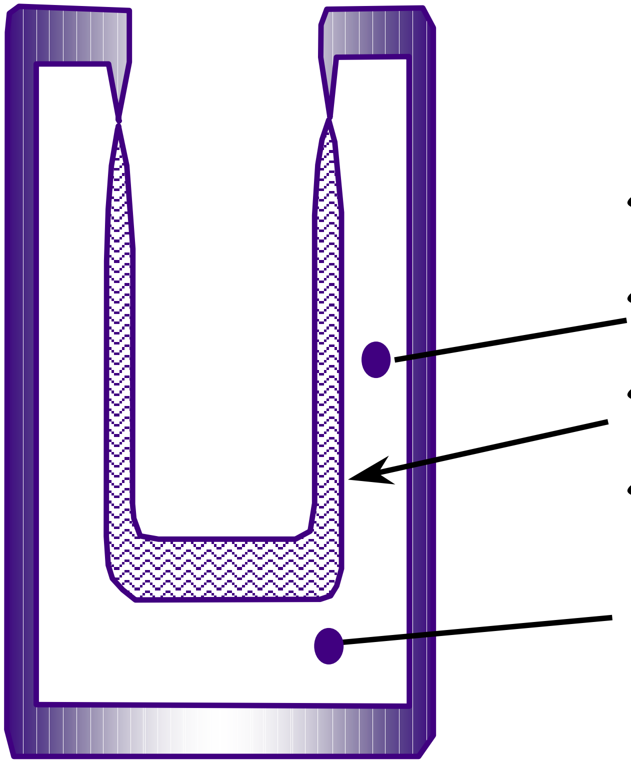
- Convection



- Radiation

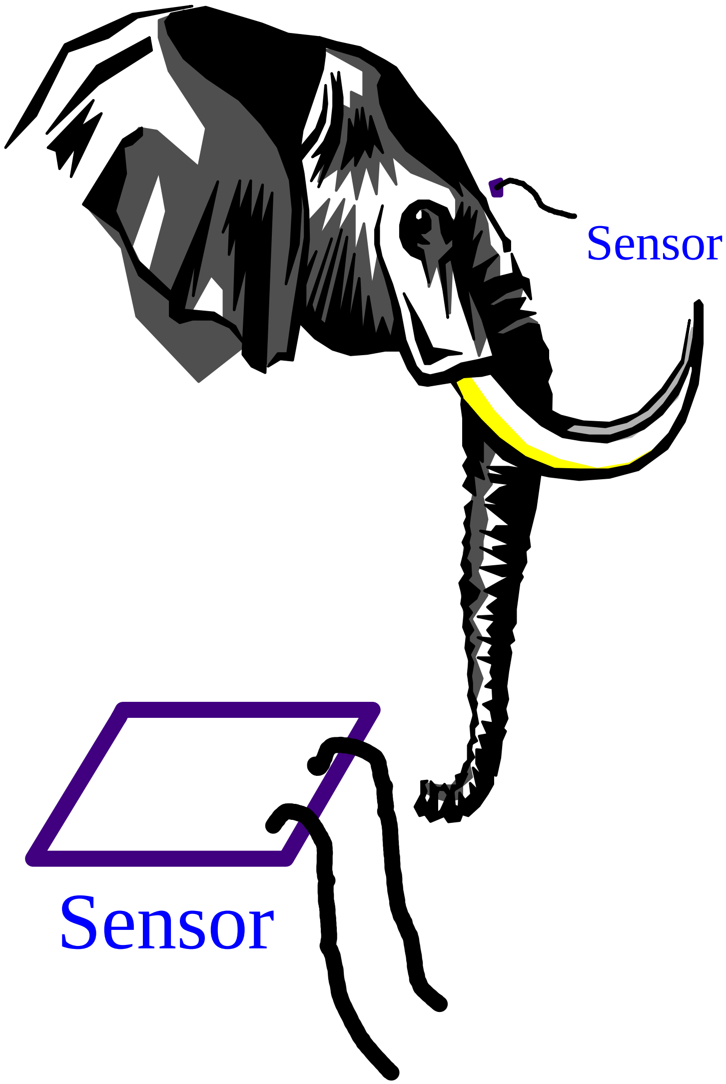


The Dewar



- Glass is a poor conductor
- Gap reduces conduction
- Metallization reflects radiation
- Vacuum reduces convection

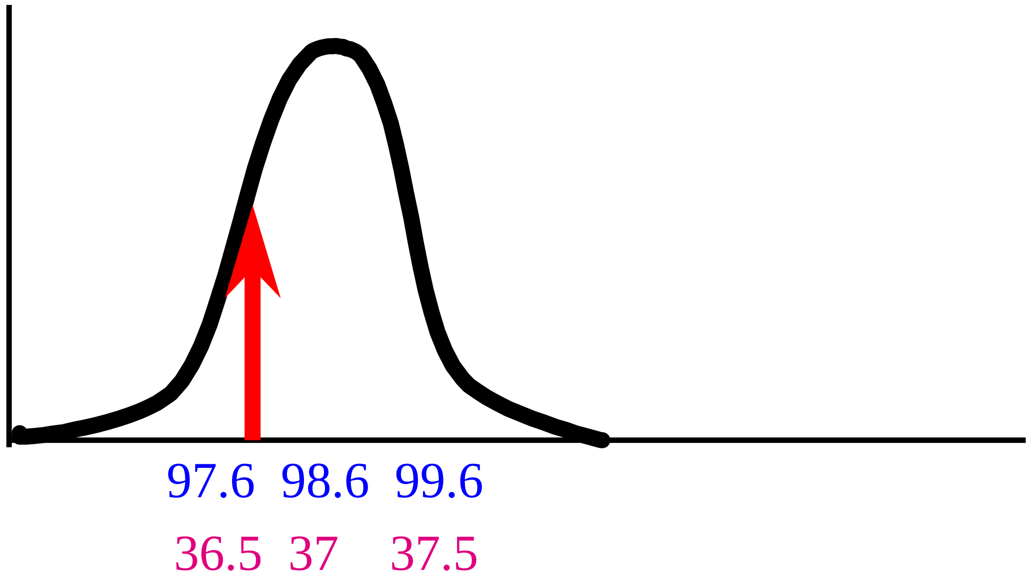
Thermal Mass

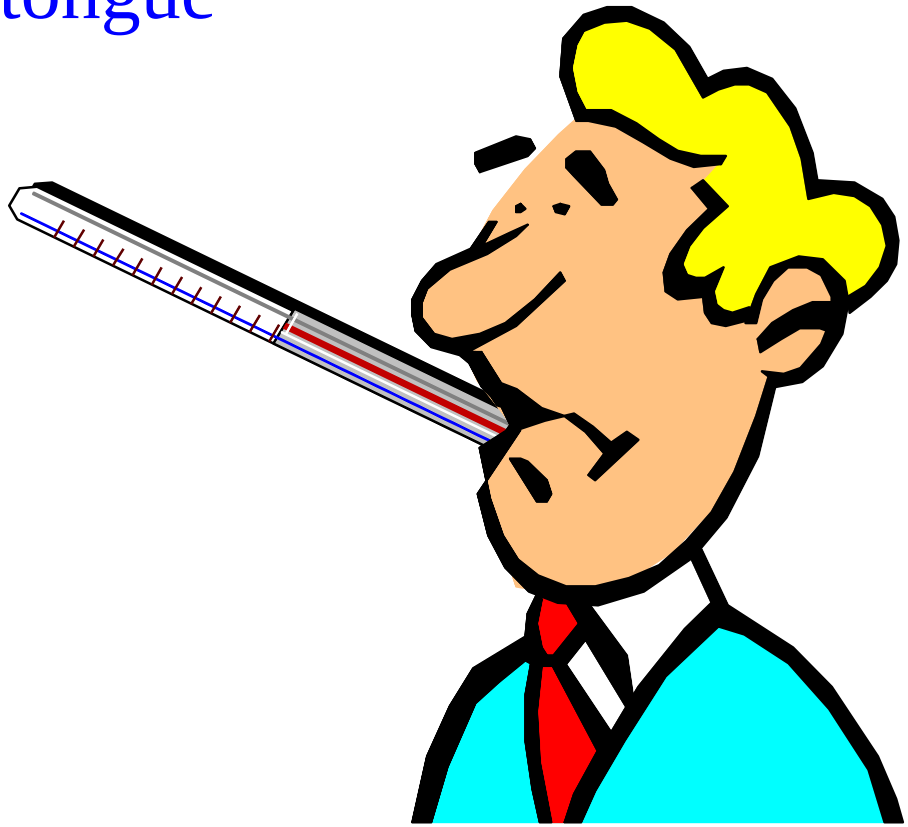


- Don't let the measuring device change the temperature of what you're measuring.
- Response time =
  - f{Thermal mass}
  - f{Measuring device}

Temperature errors

- What is YOUR normal temperature?
- Thermometer accuracy, resolution
- Contact time
- Thermal mass of thermometer, tongue
- Human error in reading

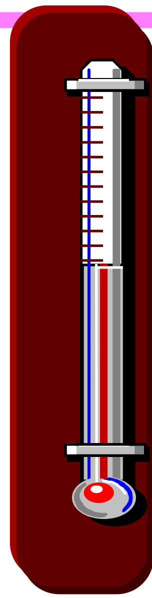




History of temperature sensors

- 1600 ad
- 1700 ad

- Galileo: First temp. sensor
  - pressure-sensitive
  - not repeatable



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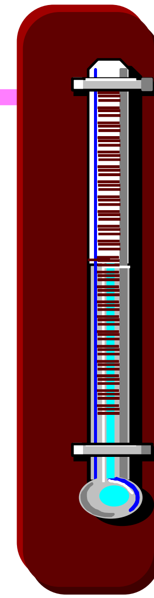
- Early thermometers
  - Not repeatable
  - No good way to calibrate



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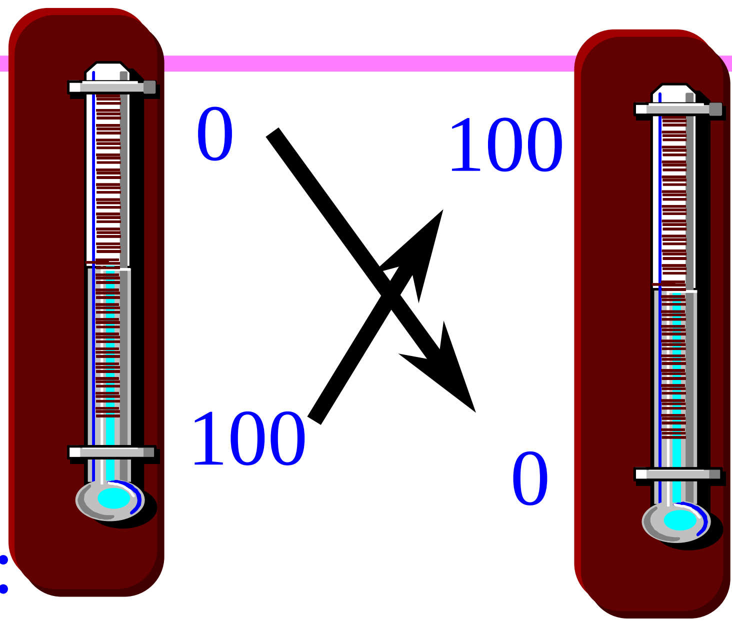
- Fahrenheit
  - Instrument Maker
  - 12*8=96 points
  - Hg: Repeatable
  - One standard scale

The 1700's: Standardization

- 1700 ad
- 1800 ad



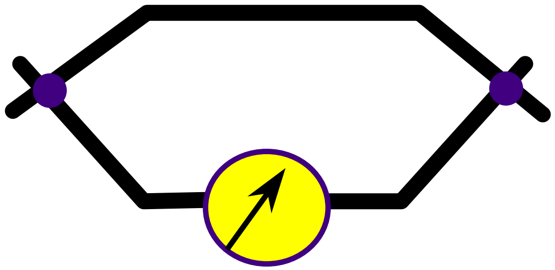
- Thomson effect
  - Absolute zero

- Celsius:
- Common, repeatable calibration reference points

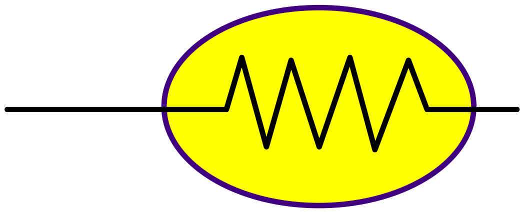
- "Centigrade" scale

1821: It was a very good year

- 1800 ad
- 1900 ad



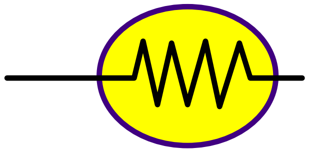
- The Seebeck effect



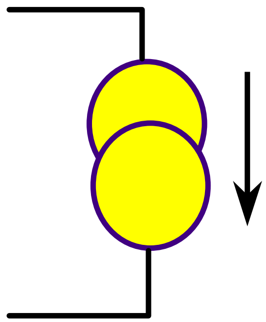
- Davy: The RTD
- Pt 100 Ω @ O deg.C

The 1900's: Electronic sensors

- 1900 ad
- 2000 ad



- Thermistor



- 1 uA/K
- IC sensor
- IPTS 1968
- IPTS 1990
- "Degree Kelvin">> "kelvins"
- "Centigrade">> " Celsius"

Temperature scales

	Absolute zero	Freezing point H_2O	Boiling point H O $_2$
Celsius	-273.15	0	100
Kelvin	0	273.15	373.15
Fahrenheit	-459.67	32	212
Rankine	0	427.67	671.67

- "Standard" is "better":
  - Reliable reference points
  - Easy to understand

IPTS '90: More calibration points

- 273.16: TP H2O
- 234.3156: TP Hg

Large gap

- 83.8058: TP Ar
- 54.3584: TP O2
- 24.5561: TP Ne
- 20.3: BP H2
- 17 Liq/vapor H2
- 13.81 TP H2
- 3 to 5: Vapor He

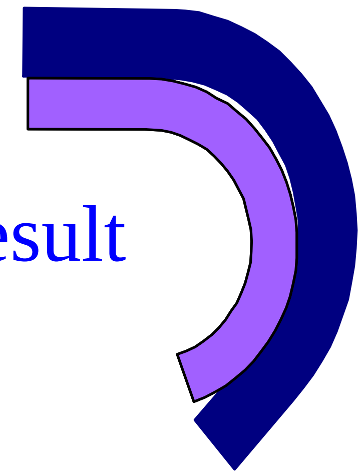
- 1357.77: FP Cu
- 1337.33: FP Au
- 1234.93: FP Ag
- 933.473: FP Al
- 692.677: FP Zn
- 505.078: FP Sn
- 429.7485: FP In
- 302.9146: MP Ga

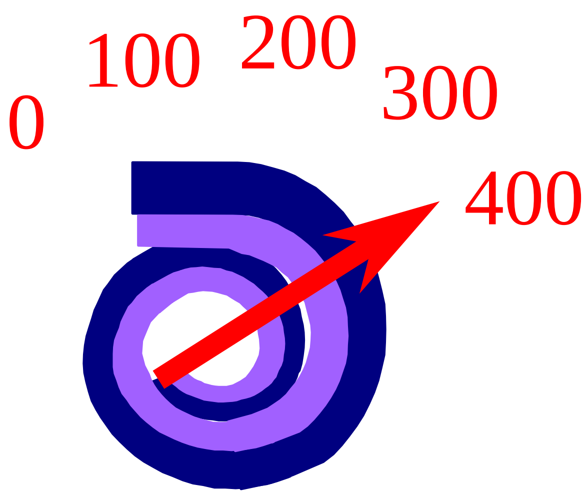
Agenda

- Background, history
- **Mechanical sensors**
- Electrical sensors
    - Optical
      Pyrometer
    - RTD
    - Thermistor, IC
    - Thermocouple
- Summary & Examples

Bimetal thermometer

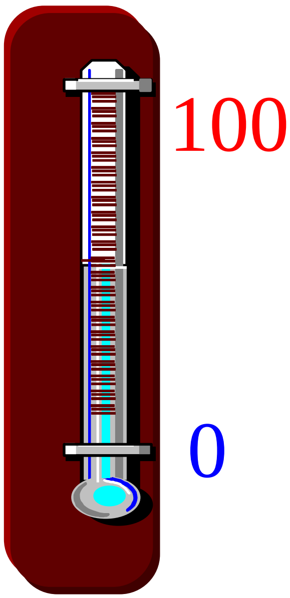
- Two dissimilar metals, tightly bonded
- Forces due to thermal expansion
- Result

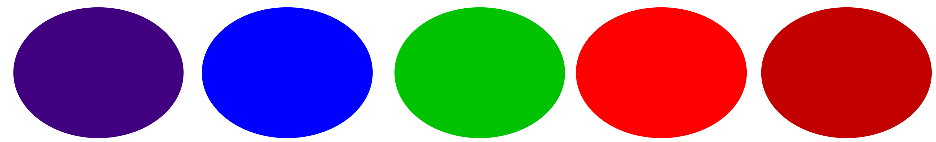




- Bimetallic thermometer
  - Poor accuracy
  - Hysteresis
- Thermal expansion causes big problems in other designs:
  - IC bonds
  - Mechanical interference

Liquid thermometer; Paints





- Thermally-sensitive paints
  - Irreversible change
  - Low resolution
  - Useful in hard-to-measure areas

- Liquid-filled thermometer
  - Accurate over a small range
  - Accuracy & resolution= f(length)
  - Range limited by liquid
  - Fragile
  - Large thermal mass
  - Slow

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- **Electrical sensors**
  - **Optical Pyrometer**
  - RTD
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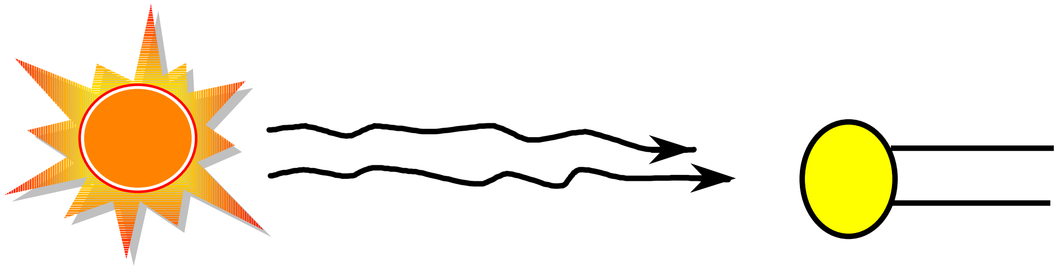
Optical Pyrometer



- Infrared Radiation-sensitive
- Photodiode or photoresistor
- Accuracy= f{emissivity}
- Useful @ very high temperatures
- Non-contacting
- Very expensive
- Not very accurate

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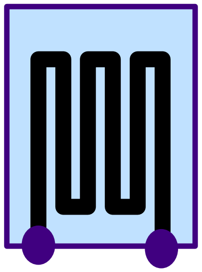
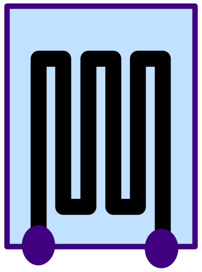
Resistance Temperature Detector



- Most accurate & stable
- Good to 800 degrees Celsius
- Resistance= f{Absolute T}
- Self-heating a problem
- Low resistance
- Nonlinear

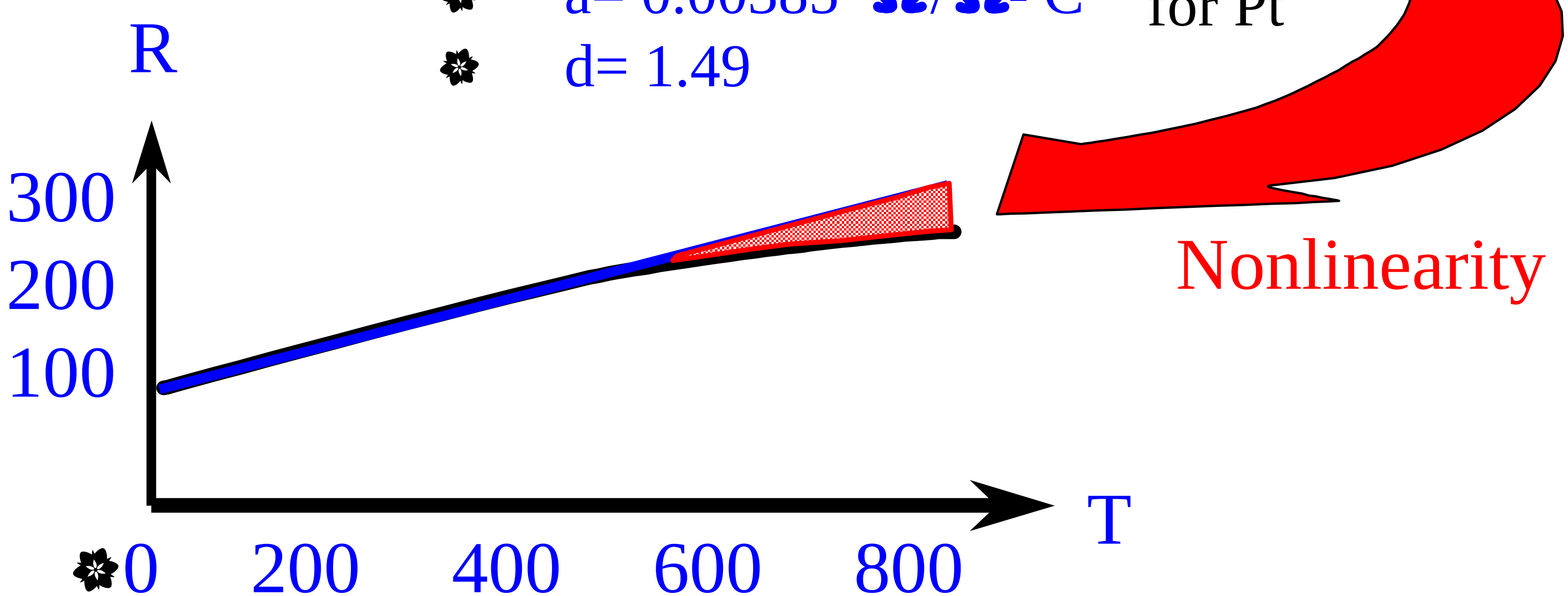
RTD Equation



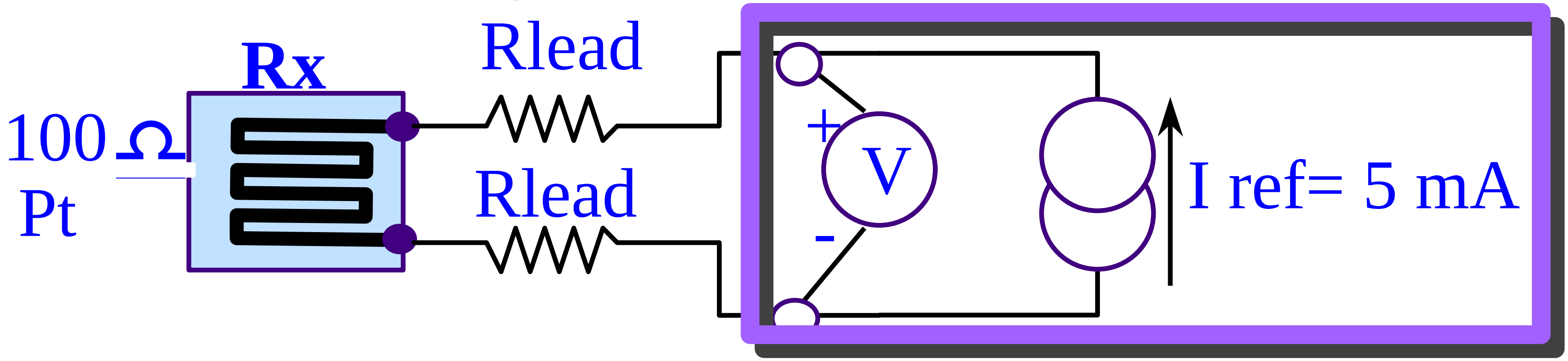
- R= 100 Ohms @ O° C
- Callendar-Van Deusen Equation:

For T>OC: $R=Ro(1+aT) - Ro(ad(.01T)(.01T-1))$

- $Ro=100\,\Omega$ @ O° C
- $a= 0.00385\ \Omega/\Omega\text{-}^{\circ}C$ for Pt
- d= 1.49

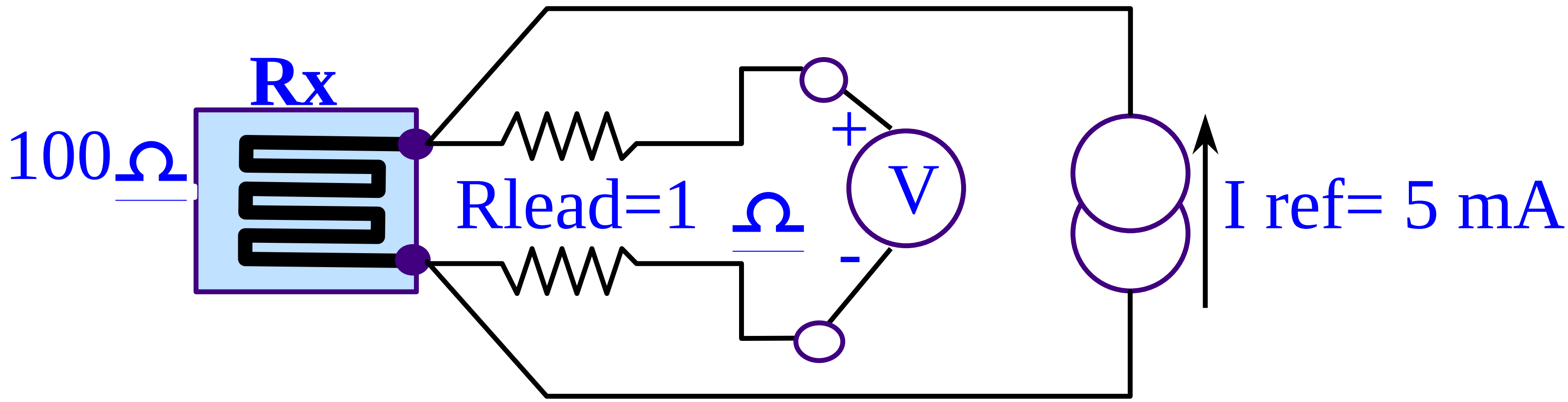


Measuring an RTD: 2-wire method



- R= Iref*(Rx + 2* Rlead)
  - Error= 2 Ω/.385= more than 5 degrees C for 1 ohm Rlead!
- Self-heating:
  - For 0.5 V signal, I= 5mA;   P=.5*.005=2.5 mwatts
  - @ 1 mW/deg C,   Error = 2.5 deg C!
- Moral: Minimize Iref; Use 4-wire method
  - If you must use 2-wire, NULL out the lead resistance

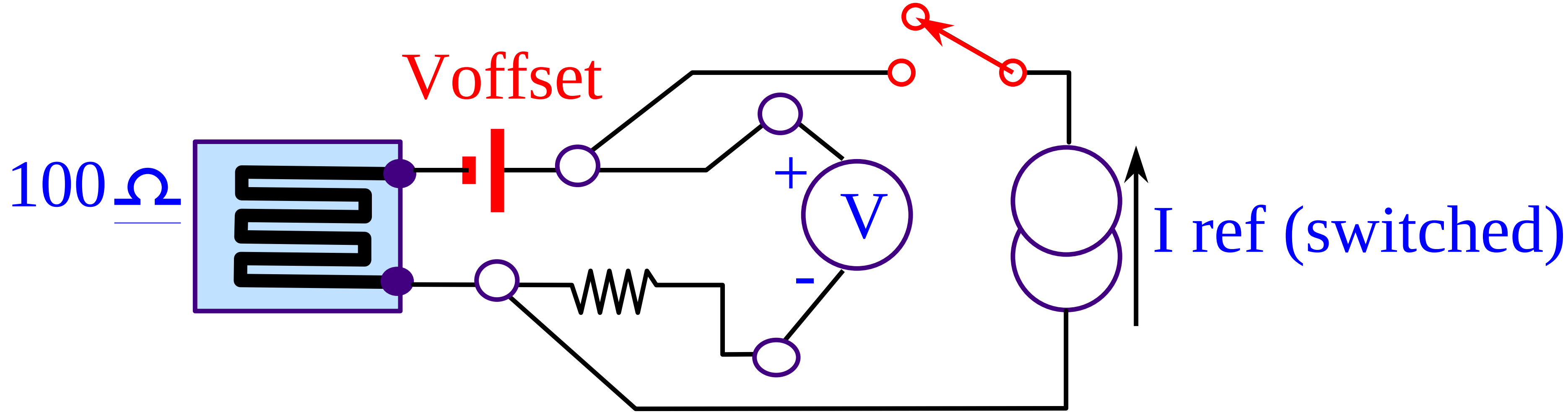
The 4-Wire technique



- R= Iref * Rx
  - Error not a function of R in source or sense leads
  - No error due to *changes* in lead R

  - Twice as much wire
  - Twice as many scanner channels
  - Usually slower than 2-wire

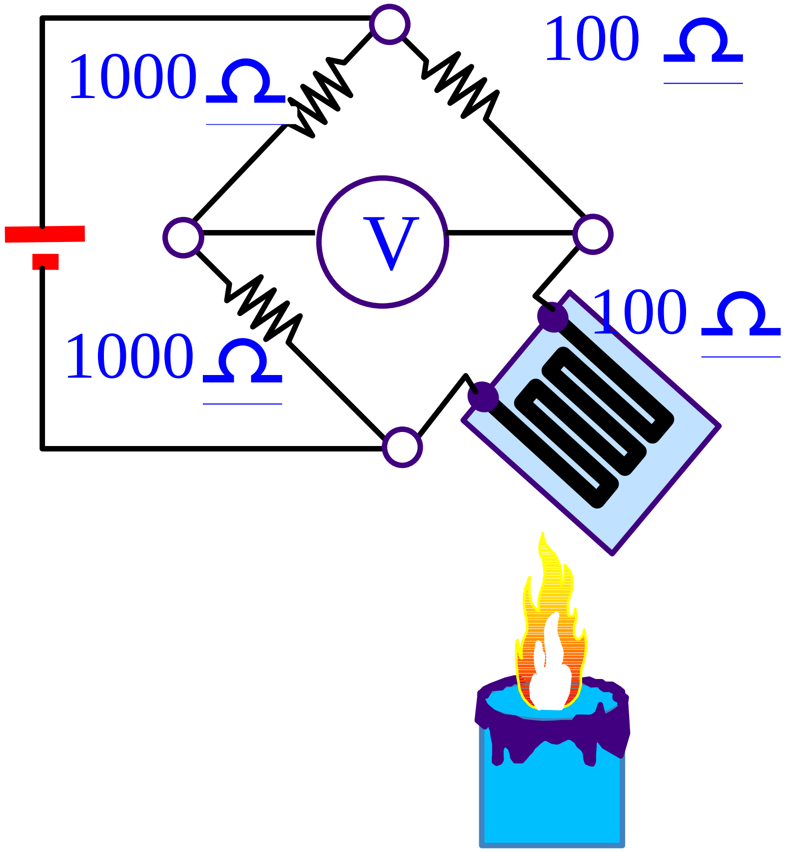
Offset compensation



- Eliminates thermal voltages
  - Measure V without I applied
  - Measure V *With* I applied

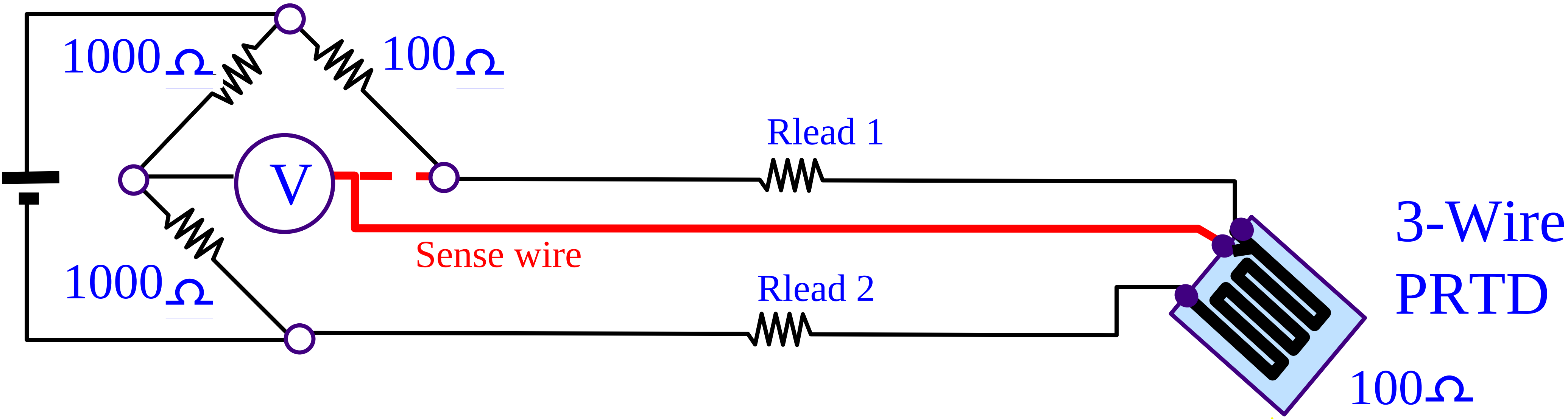
$$R = \frac{\Delta V}{\Delta I}$$

Bridge method



- High resolution (DMM stays on most sensitive range)
- Nonlinear output
- Bridge resistors too close to heat source

3-Wire bridge



- Keeps bridge away from heat source
- Break DMM lead (dashed line); connect to RTD through 3rd "sense" wire
- If Rlead 1= Rlead 2, sense wire makes error small
- Series resistance of sense wire causes no error

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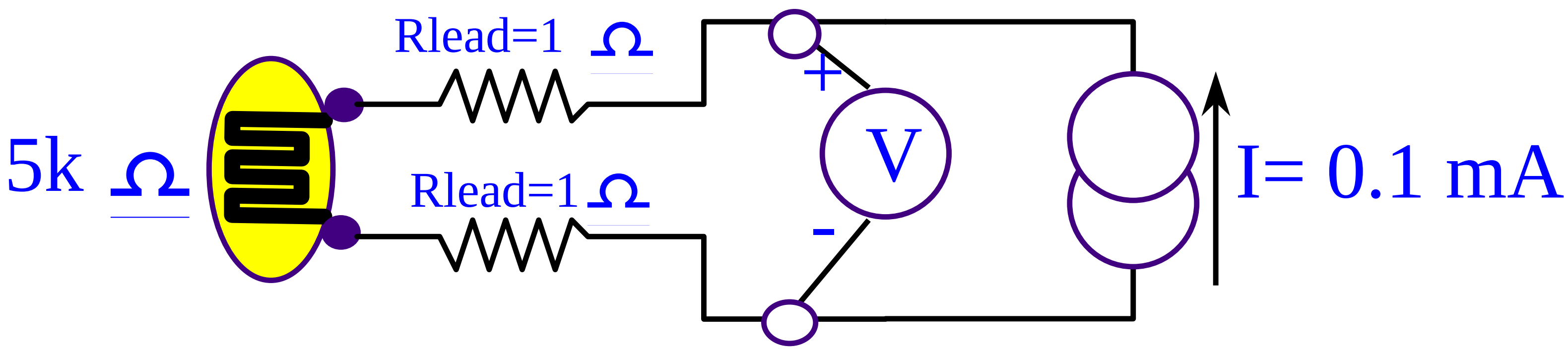
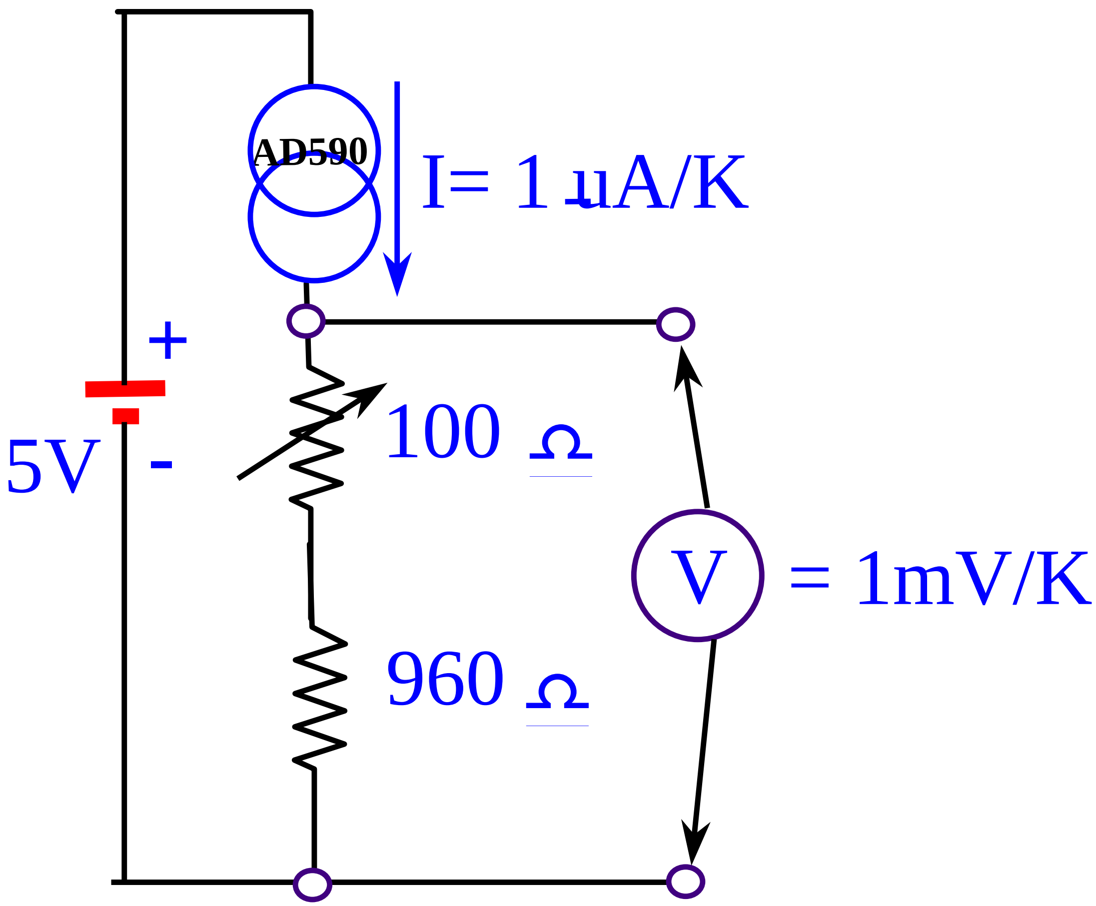
Electrical sensors: Thermistor



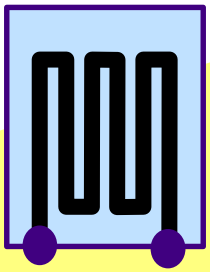
- Hi-Z; Sensitive: 5 kΩ @ 25C; ΔR = 4%/deg C
- Limited range
- 2-Wire method: R= I * (Rthmr + 2*Rlead)
  - Lead R Error= 2Ω/400= 0.005 degrees C
- Low thermal mass: High self-heating
- Very nonlinear

I.C. Sensor



- High output
- Very linear
- Accurate @ room ambient
- Limited range
- Cheap

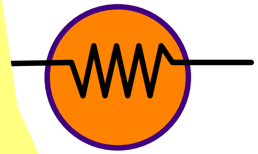
Summary: Absolute T devices



RTD

- Most accurate
- Most stable
- Fairly linear

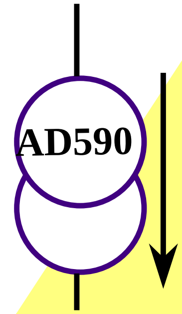
- Expensive
- Slow
- Needs I source
- Self-heating
- 4-wire meas.



Thermistor

- High output
- Fast
- 2-wire meas.

- Very nonlinear
- Limited range
- Needs I source
- Self-heating
- Fragile



I.C.

- High output
- Most linear
- Inexpensive

- Limited variety
- Limited range
- Needs V source
- Self-heating

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    - Optical Pyrometer
    - RTD
    - Thermistor, IC
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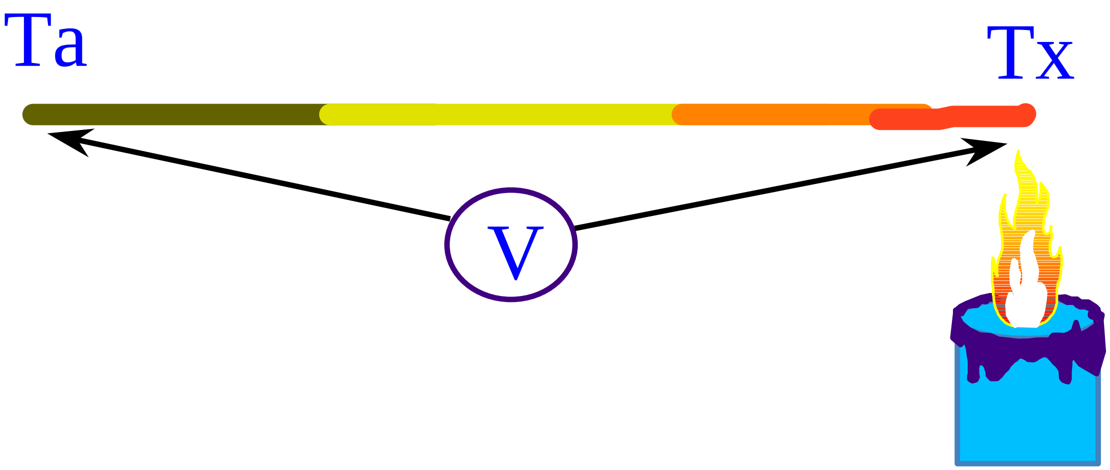
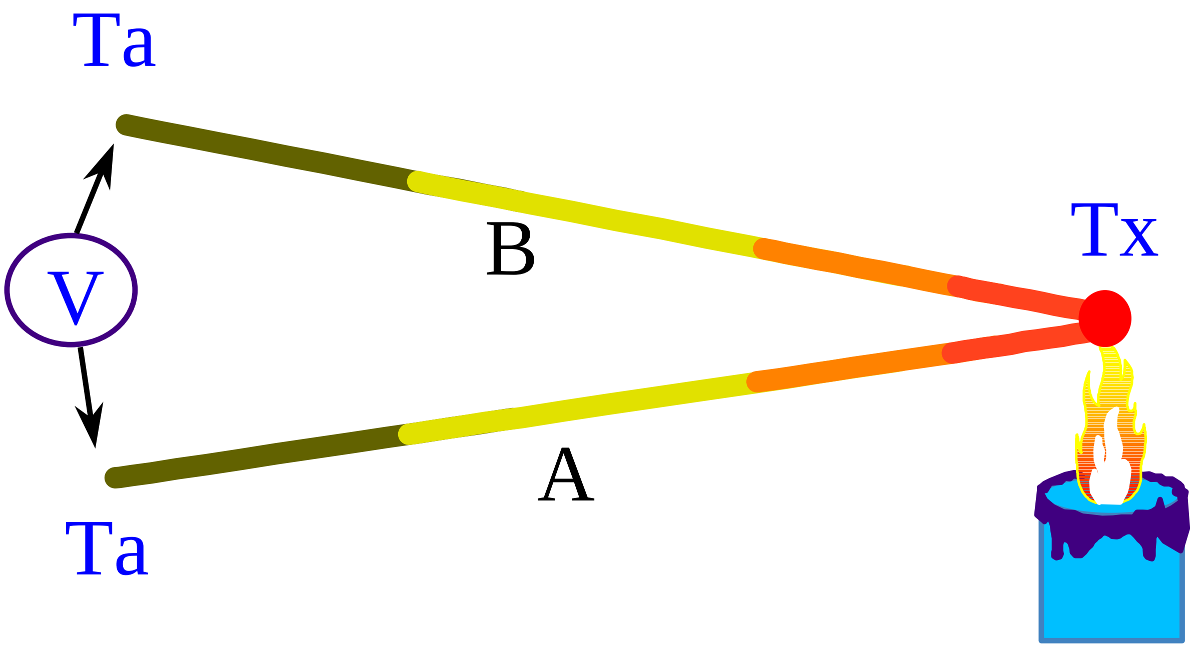
Thermocouples
The Gradient Theory



$$V = \int_{Ta}^{Tx} e(T)\, dT$$

- The WIRE is the sensor, not the junction
- The Seebeck coefficient (e) is a function of temperature

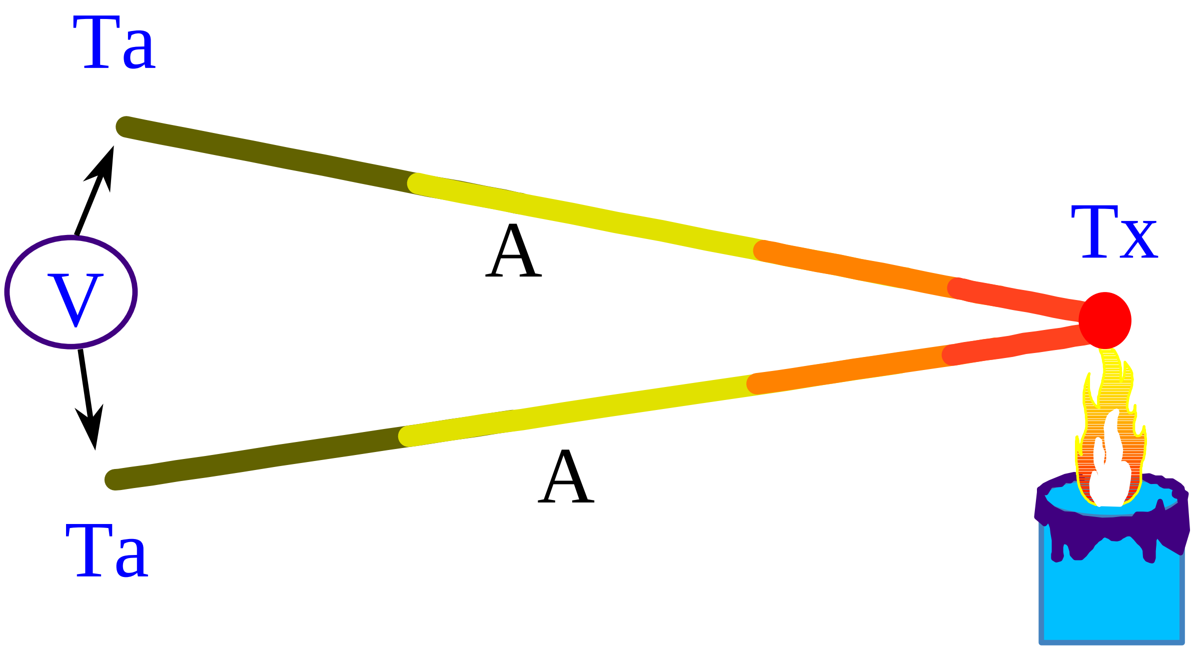
Making a thermocouple



$$V = \int_{Ta}^{Tx} e_A \, dT + \int_{Tx}^{Ta} e_B \, dT$$

- Two wires make a thermocouple
- Voltage output is nonzero if metals are not the same

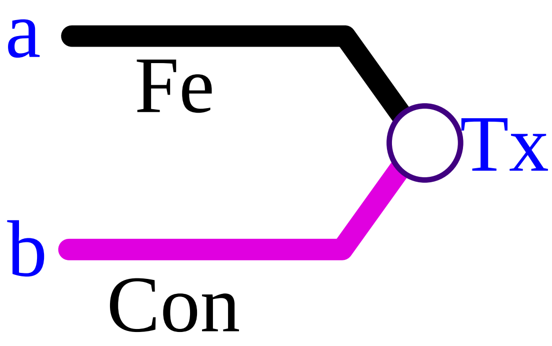
Gradient theory also says...



$$V = \int_{Ta}^{Tx} e_A \, dT + \int_{Tx}^{Ta} e_A \, dT = 0$$

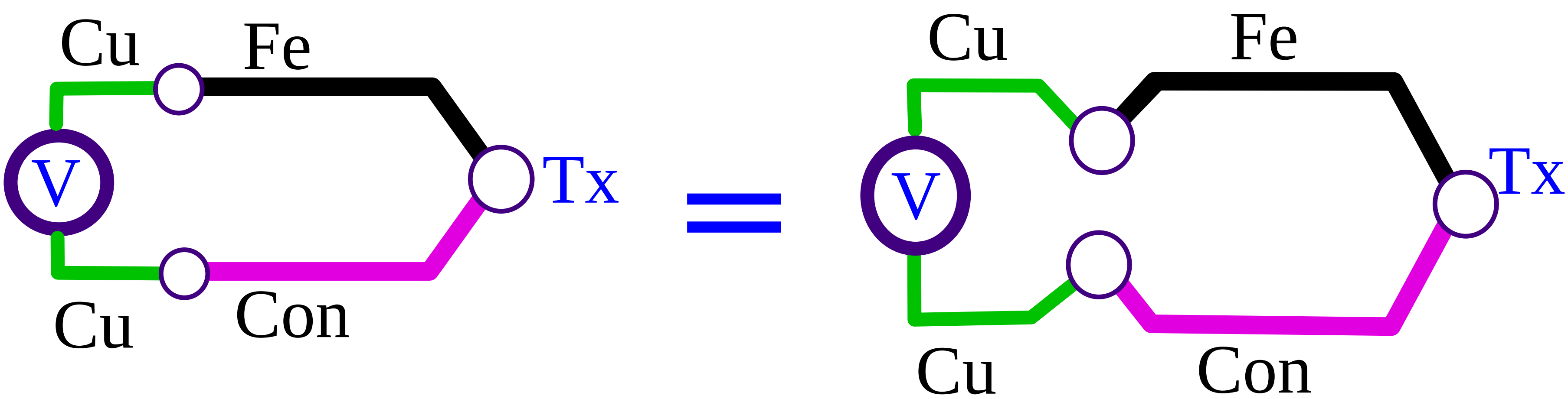
- If wires are the same type, or if there is one wire, and both ends are at the same temperature, output= Zero.

Now try to measure it:



- Theoretically,
  Vab= f{Tx-Tab}

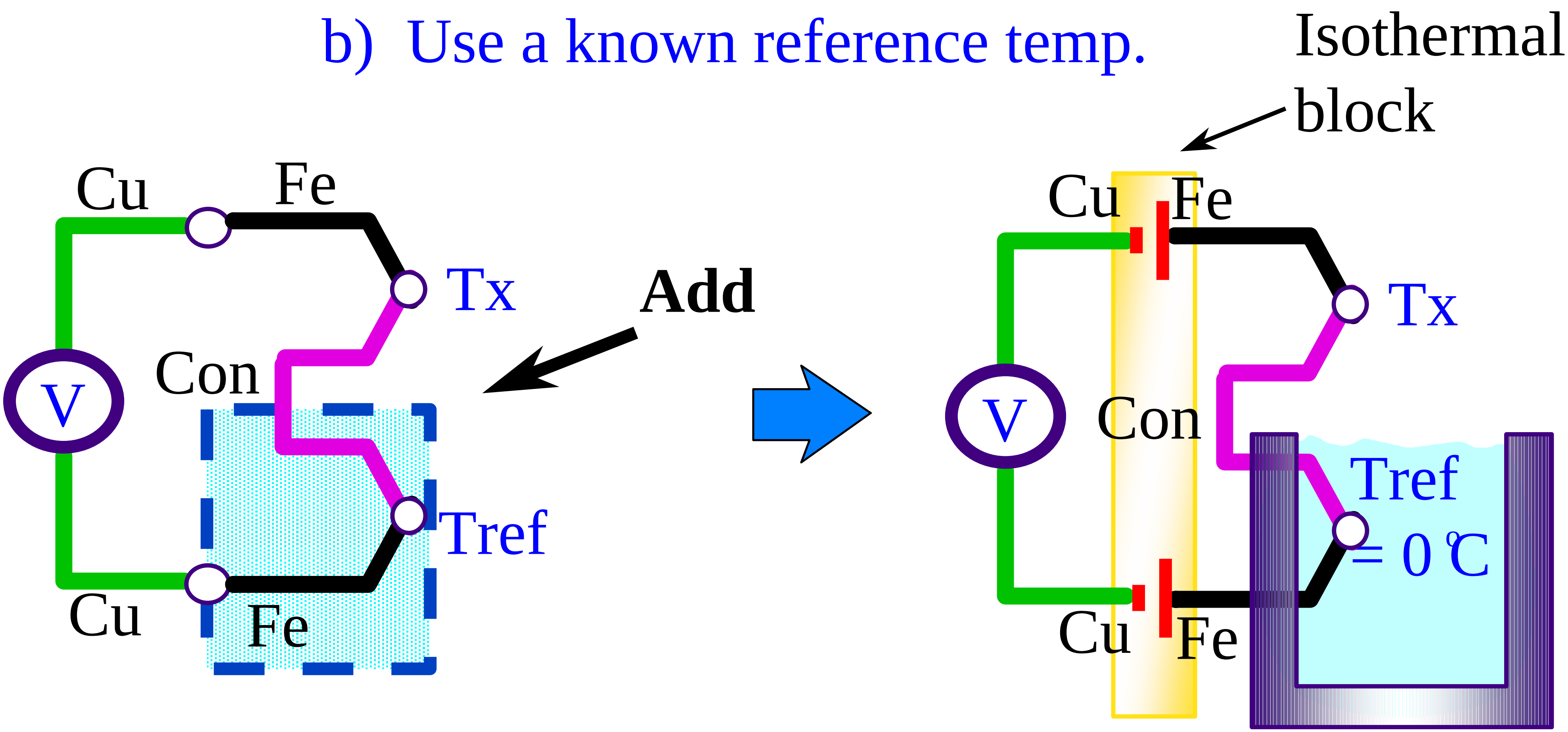
- But, try to measure it with a DMM:



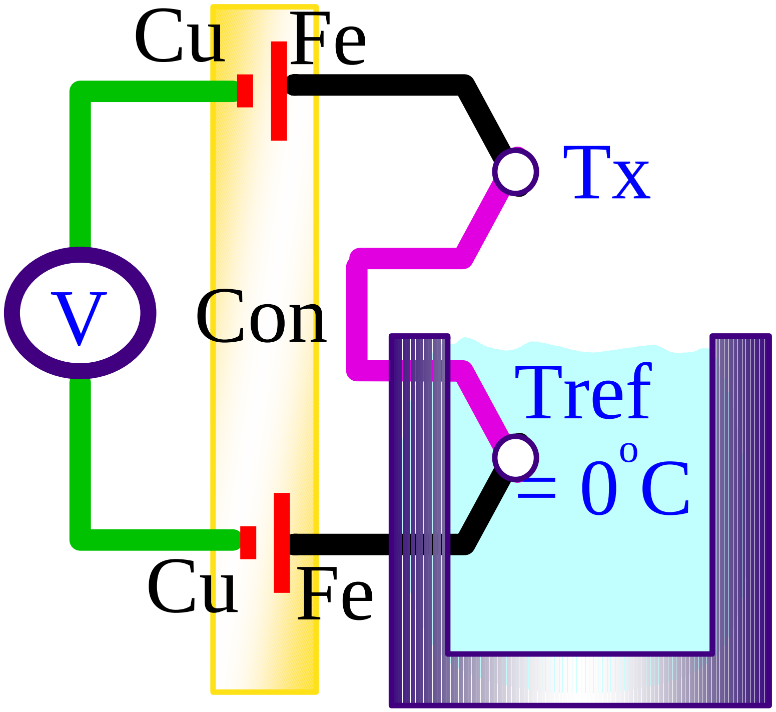
- Result: 3 unequal junctions, all at unknown temperatures

Solution: Reference Thermocouple

- Problems: a) 3 different thermocouples,
  b) 3 unknown temperatures
- Solutions: a) Add an opposing thermocouple
  b) Use a known reference temp.



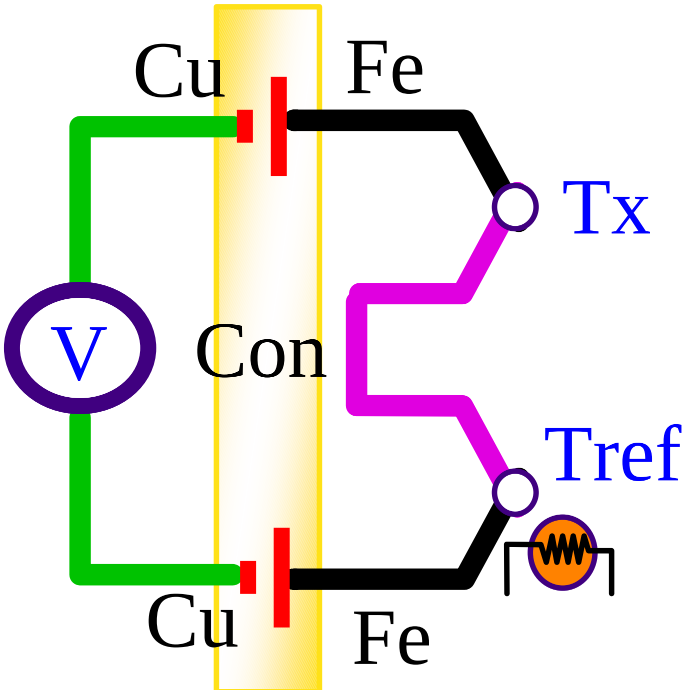
The Classical Method



- If both Cu junctions are at same T, the two "batteries" cancel
- Tref is an ice bath (sometimes an electronic ice bath)
- All T/C tables are referenced to an ice bath
- V= f{Tx-Tref}

- Question: How can we eliminate the ice bath?

Eliminating the ice bath

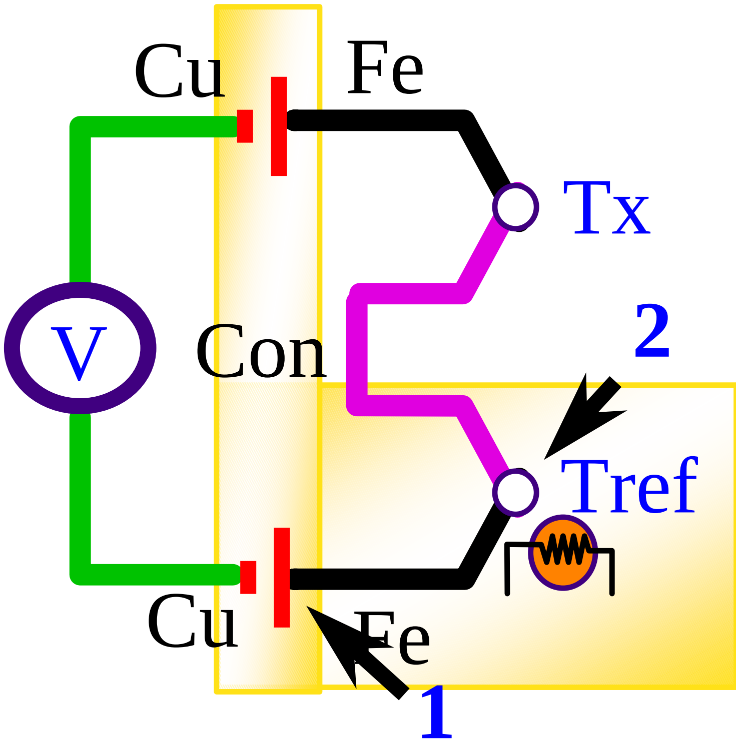


- Don't force Tref to icepoint, just measure it
- Compensate for Tref mathematically:

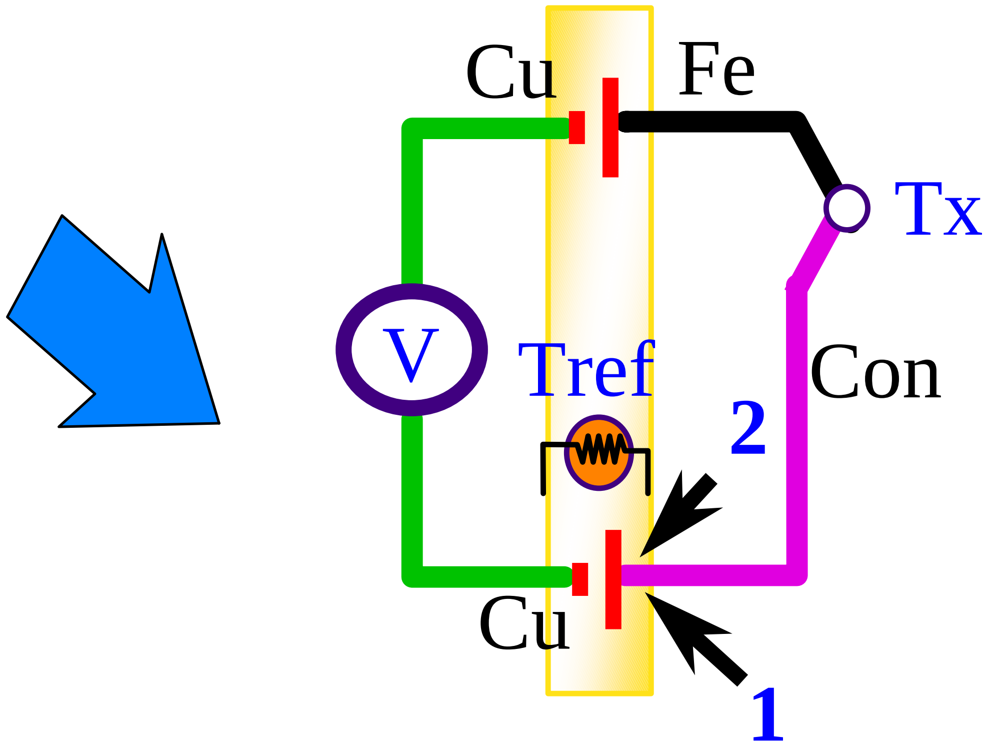
$$V = f\{\, Tx\big|_{Tice} - Tref\big|_{Tice} \,\}$$

- If we know $Tref\big|_{Tice}$, we can compute Tx.

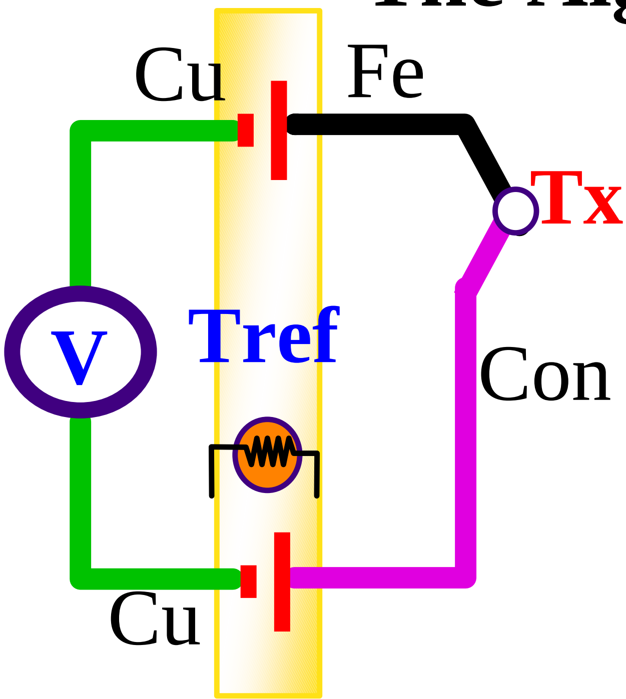
Eliminating the second T/C



- Extend the isothermal block
- If isothermal, V1-V2=0

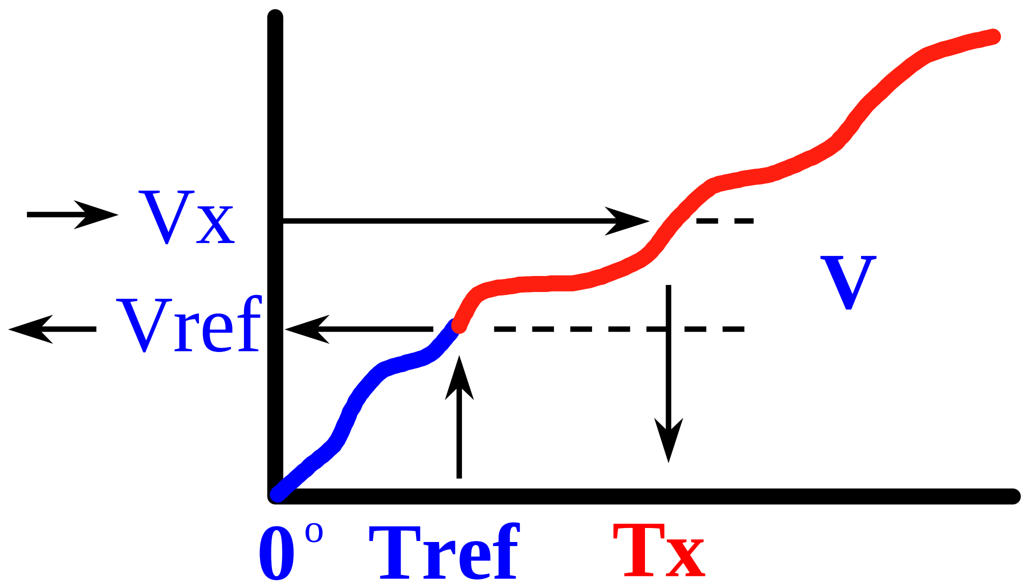


The Algorithm for one T/C

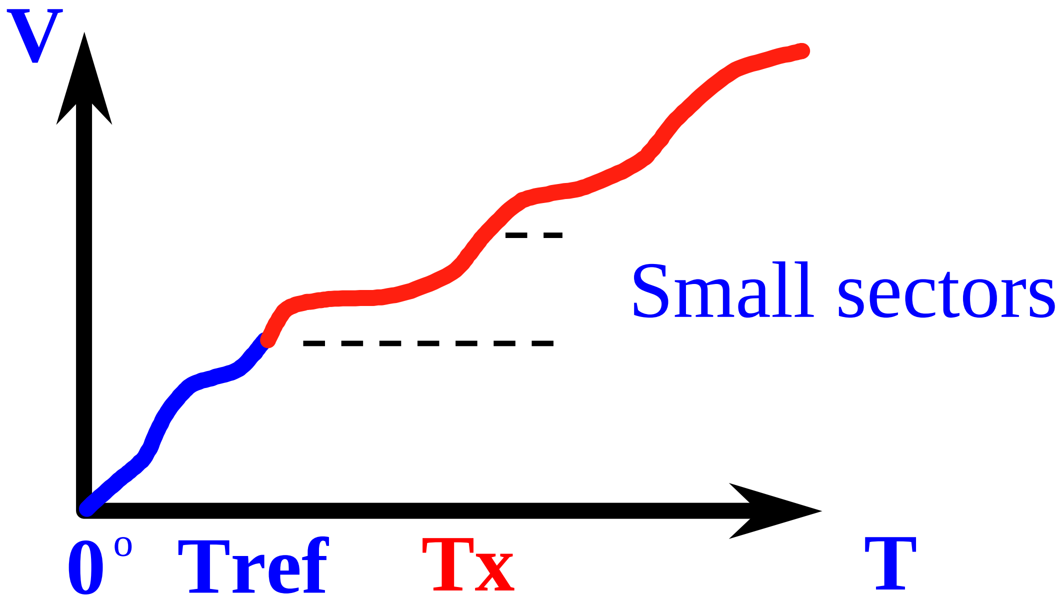


- Measure Tref: RTD, IC or thermistor
- Tref ==> Vref @ O° C for Type J(Fe-C)
- Know V, Know Vref: Compute Vx
- Solve for **Tx** using Vx

Compute
Vx=V+Vref

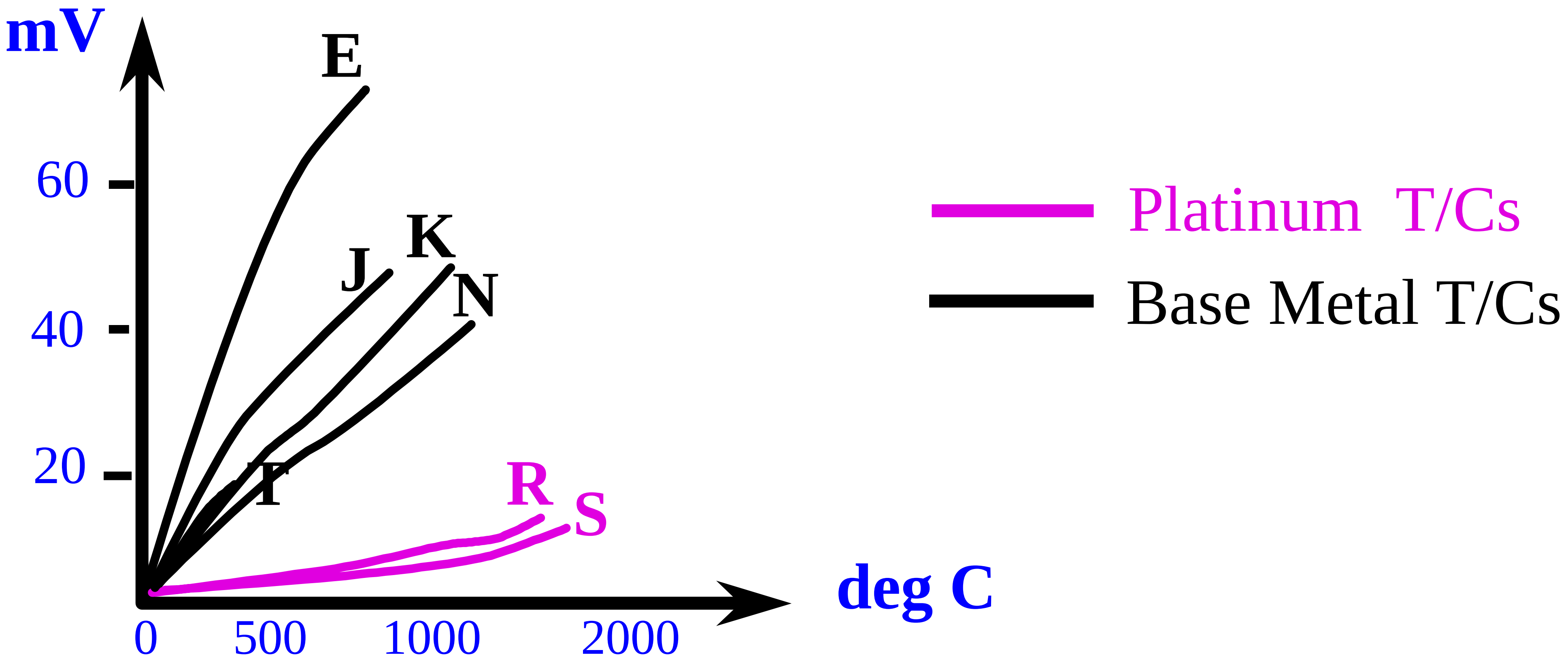


Linearization



- Polynomial: $T = a_0 + a_1 V + a_2 V^2 + a_3 V^3 + \ldots\ a_9 V^9$
- Nested (faster): $T = a_0 + V(a_1 + V(a_2 + V(a_3 + \ldots\ldots)))))))))$
- Small sectors (faster): $T = T_0 + bV + cV^2$
- Lookup table: Fastest, most memory

Common Thermocouples



- All have Seebeck coefficients in MICROvolts/deg.C

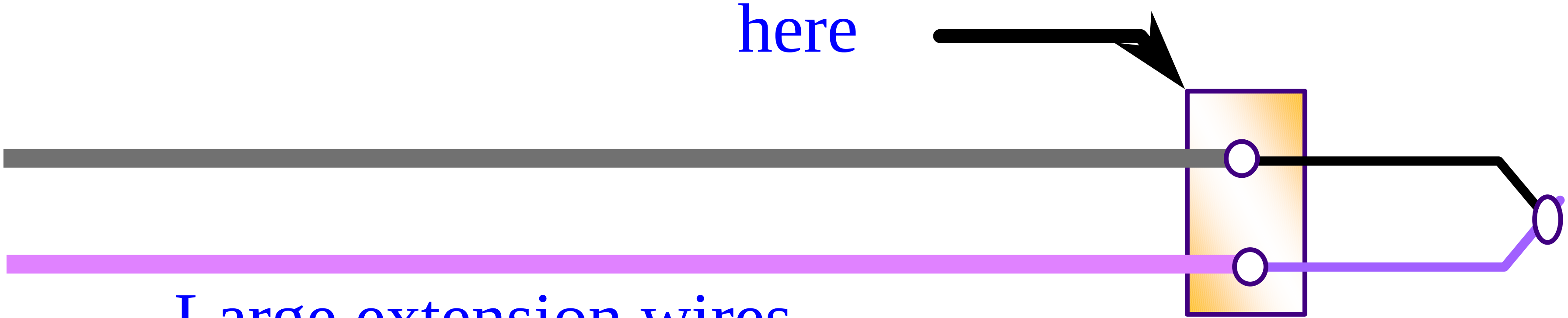
Common Thermocouples

Type	Metals	Seebeck Coeff: µV/C
J	Fe-Con	50
K	Ni-Cr	40
T	Cu-Con	38
S	Pt/Rh-Pt	10
E	Ni/Cr-Con	59
N	Ni/Cr/Si-Ni/Si	39

- Microvolt output is a tough measurement
- Type "N" is fairly new.. more rugged and higher temp. than type K, but still cheap

Extension Wires

- Possible problem here

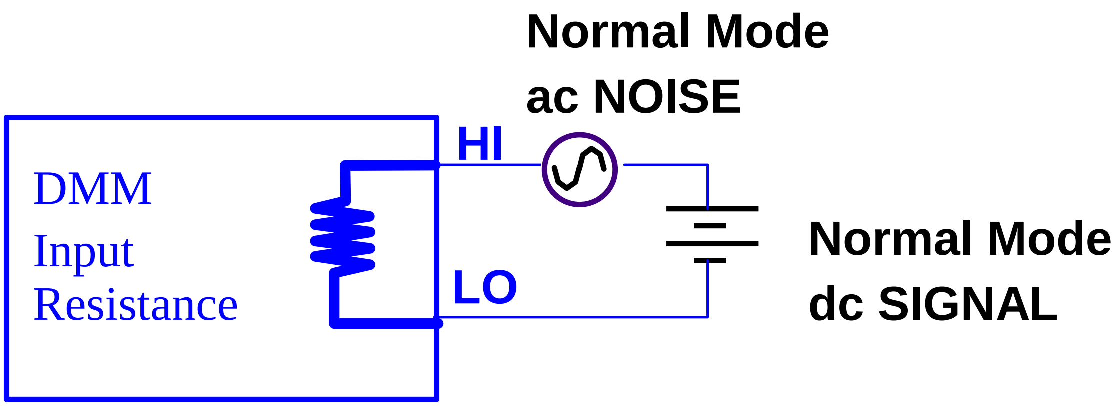


Large extension wires

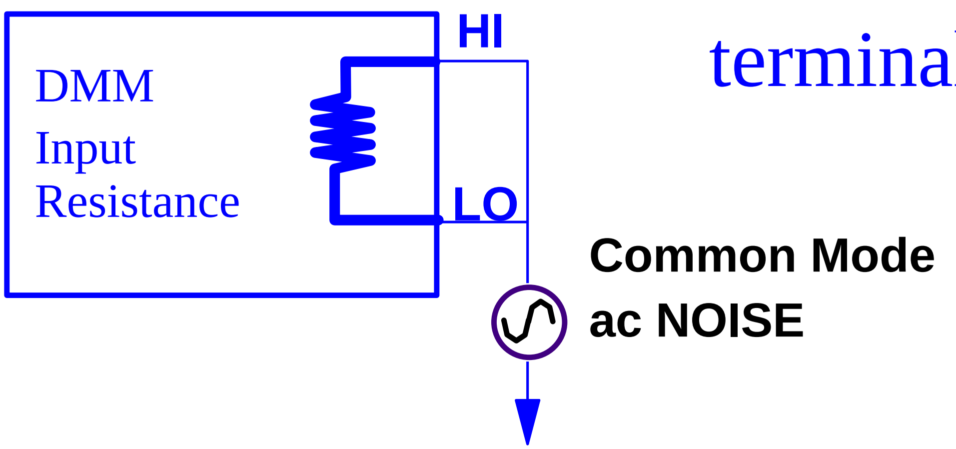
Small diameter measurement wires

- Extension wires are cheaper, more rugged, but not exactly the same characteristic curve as the T/C.
- Keep extension/TC junction near room temperature
- Where is most of the signal generated in this circuit?

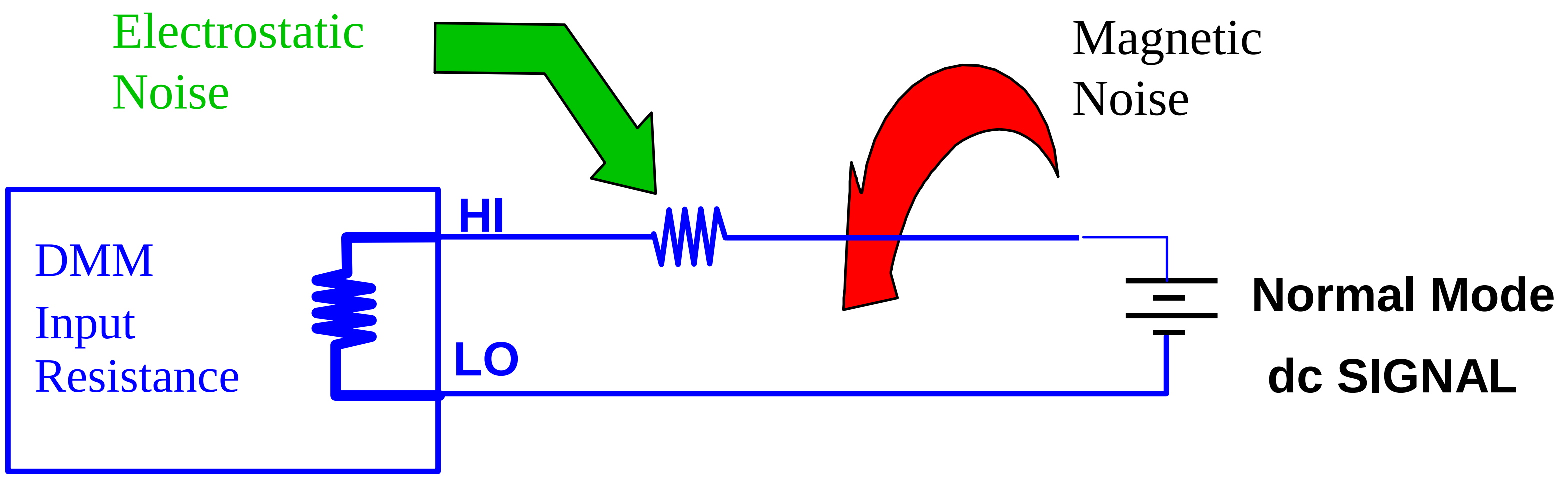
Noise: DMM Glossary



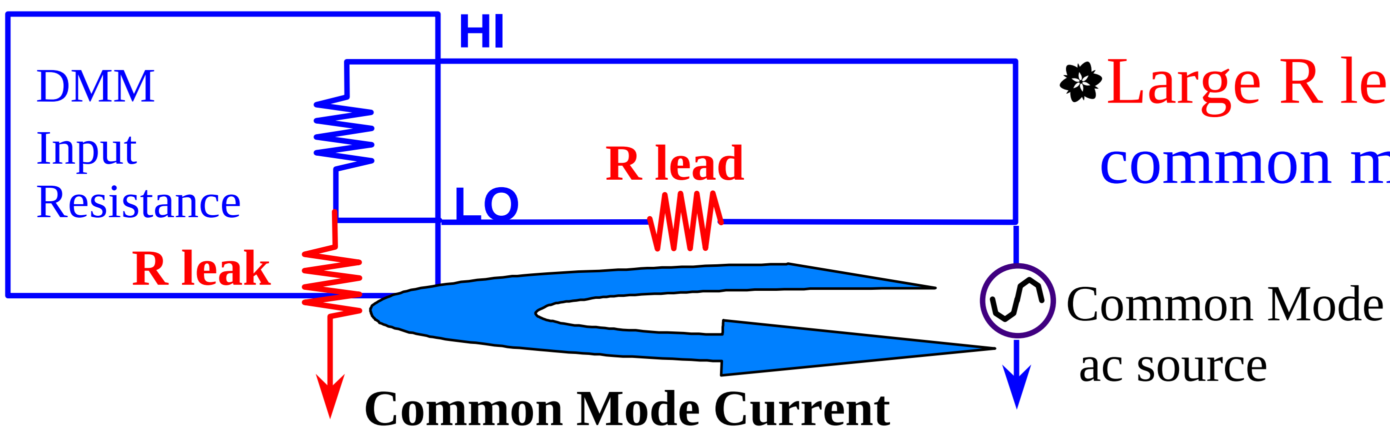
- Normal Mode: In series with input
- Common Mode: Both HI and LO terminals driven equally



Generating noise

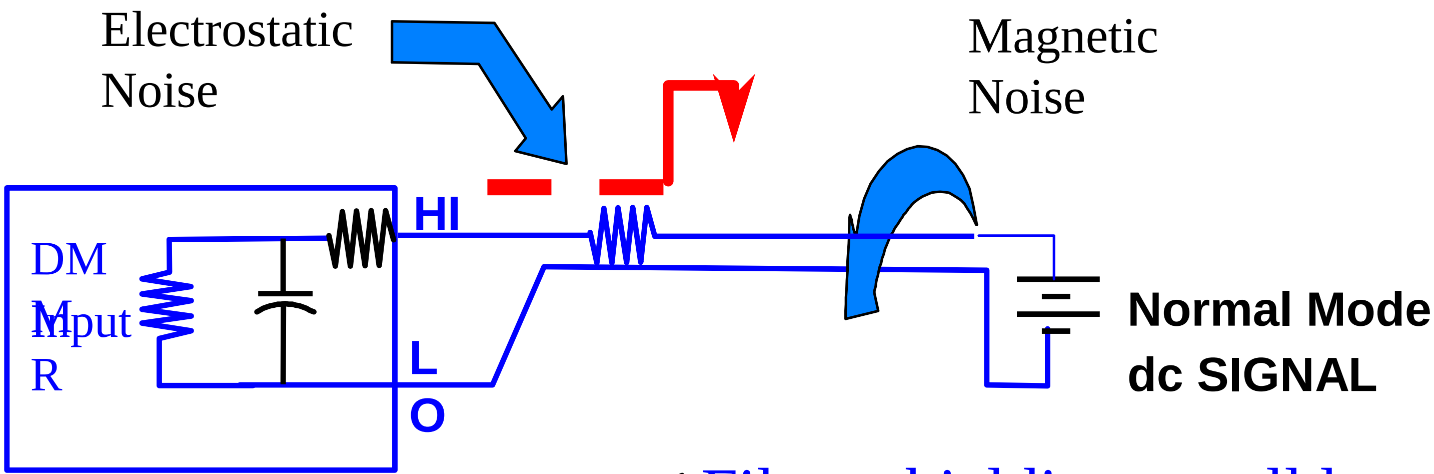


- Large surface area, high Rlead: Max. static coupling
- Large loop area: Max. magnetic coupling

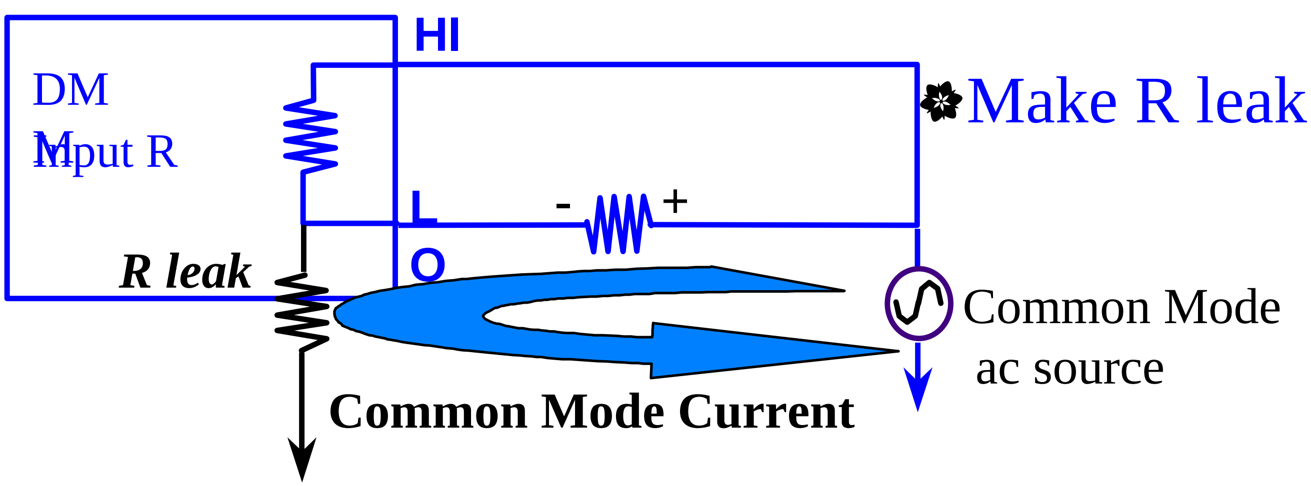


- Large R lead, small R leak: Max. common mode noise

Eliminating noise



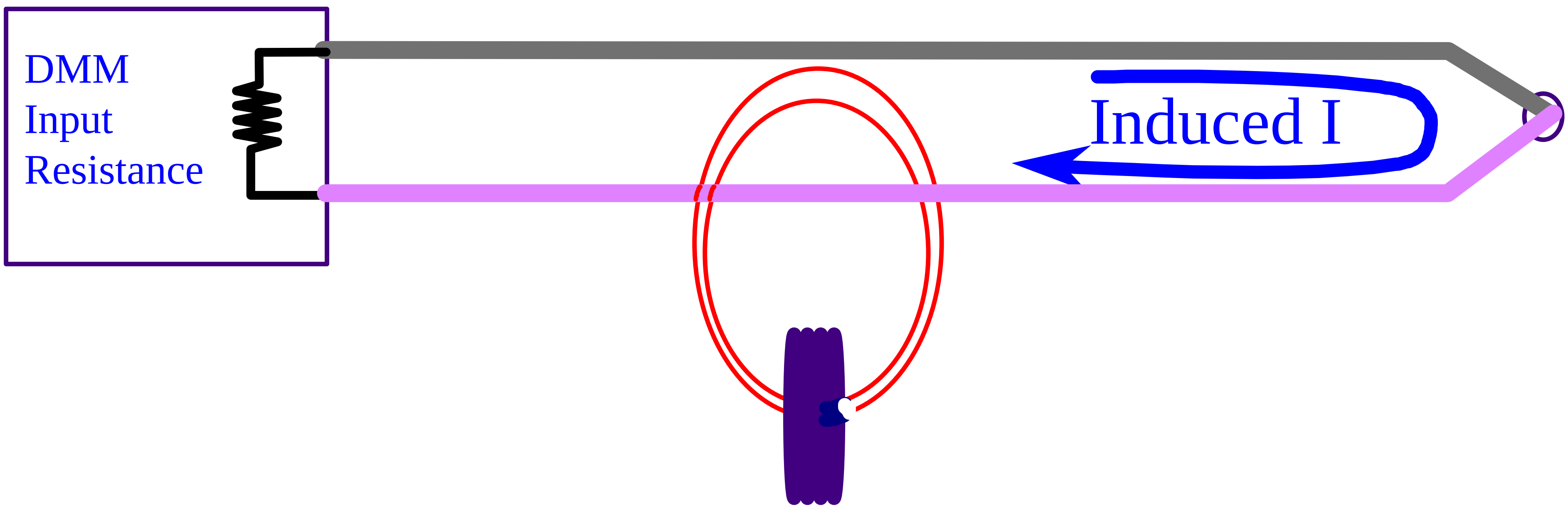
- Filter, shielding, small loop area
  (Caution: filter slows down the measurement)



- Make R leak close to ∞

Magnetic Noise

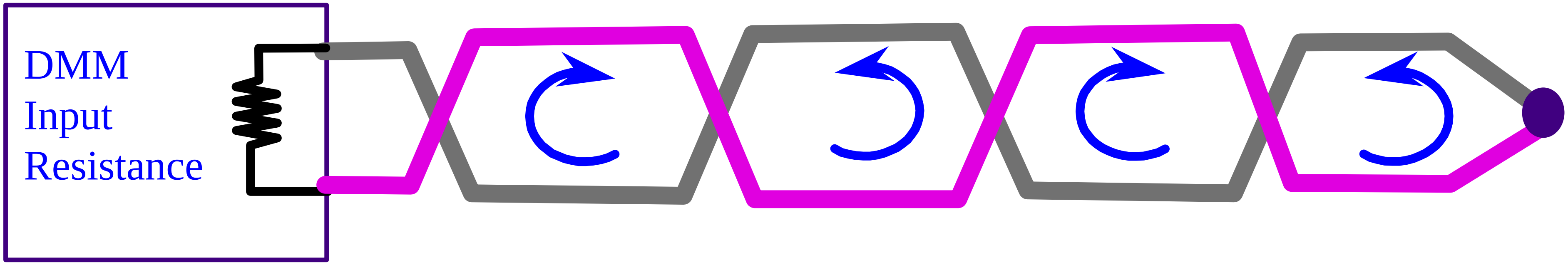
- Magnetic coupling



- Minimize area
- Twist leads
- Move away from strong fields

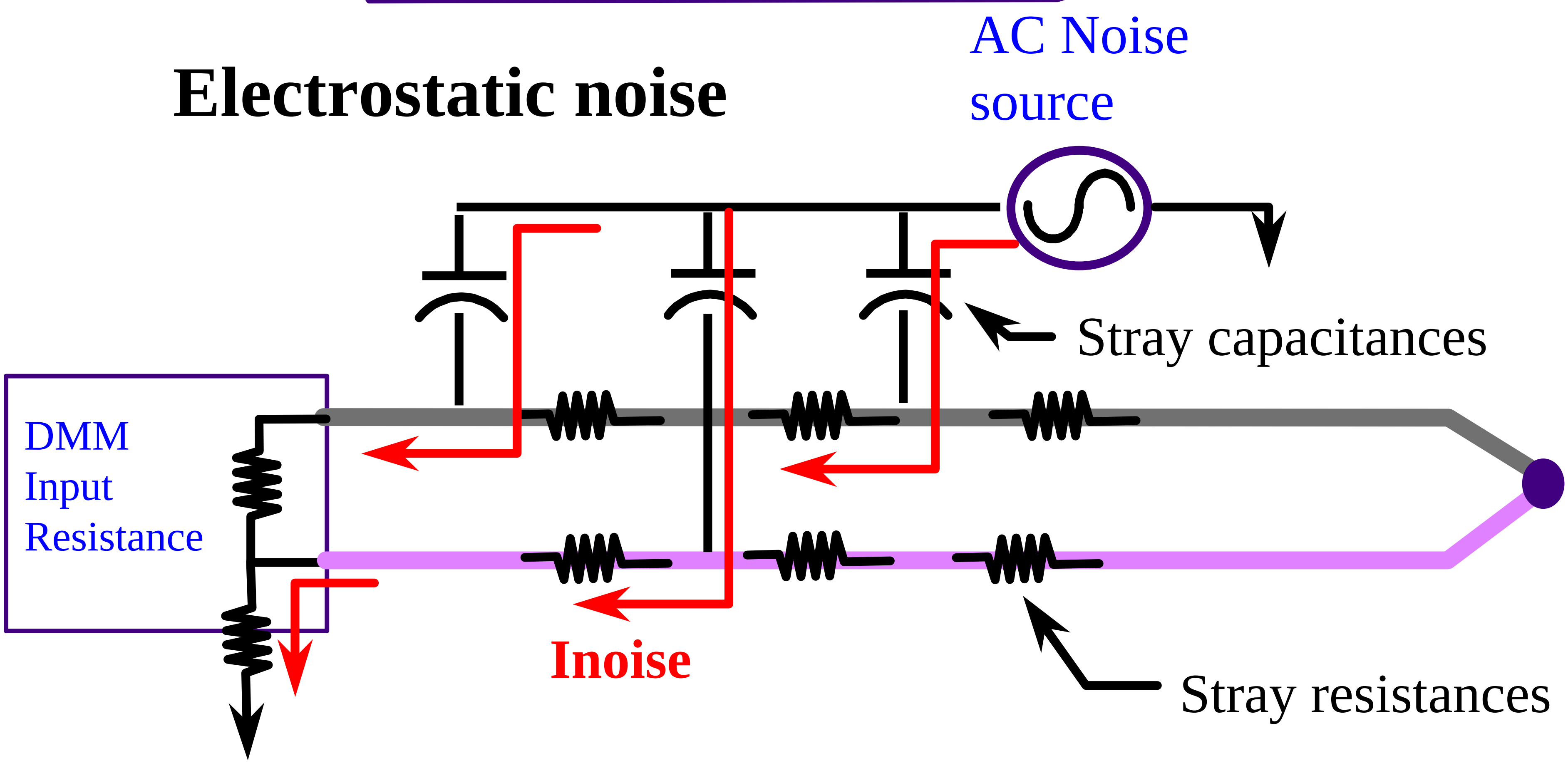
Reducing Magnetic Noise

- Equal and opposite induced currents



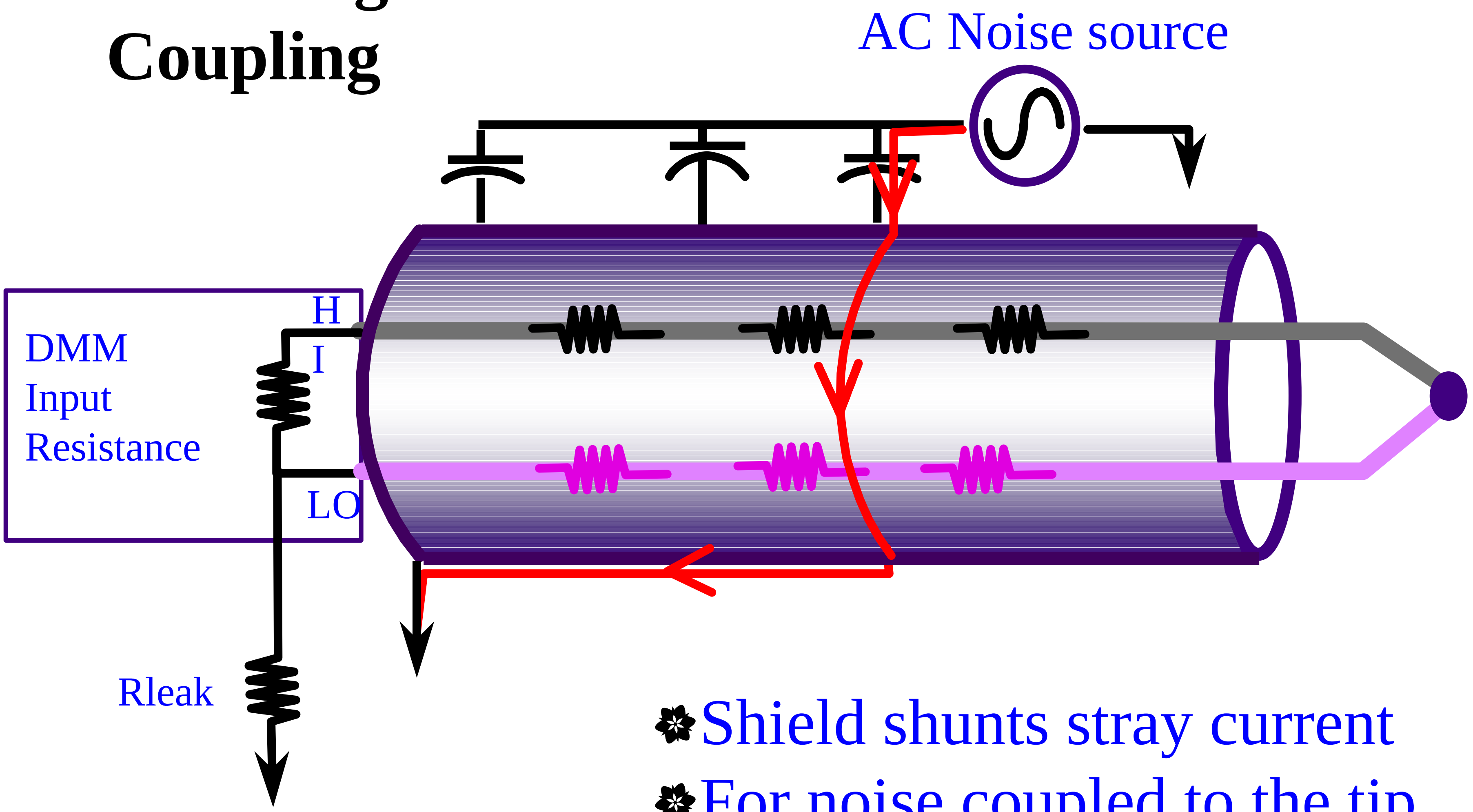
- Even with twisted pair:
  - Minimize area
  - Move away from strong fields

Electrostatic noise



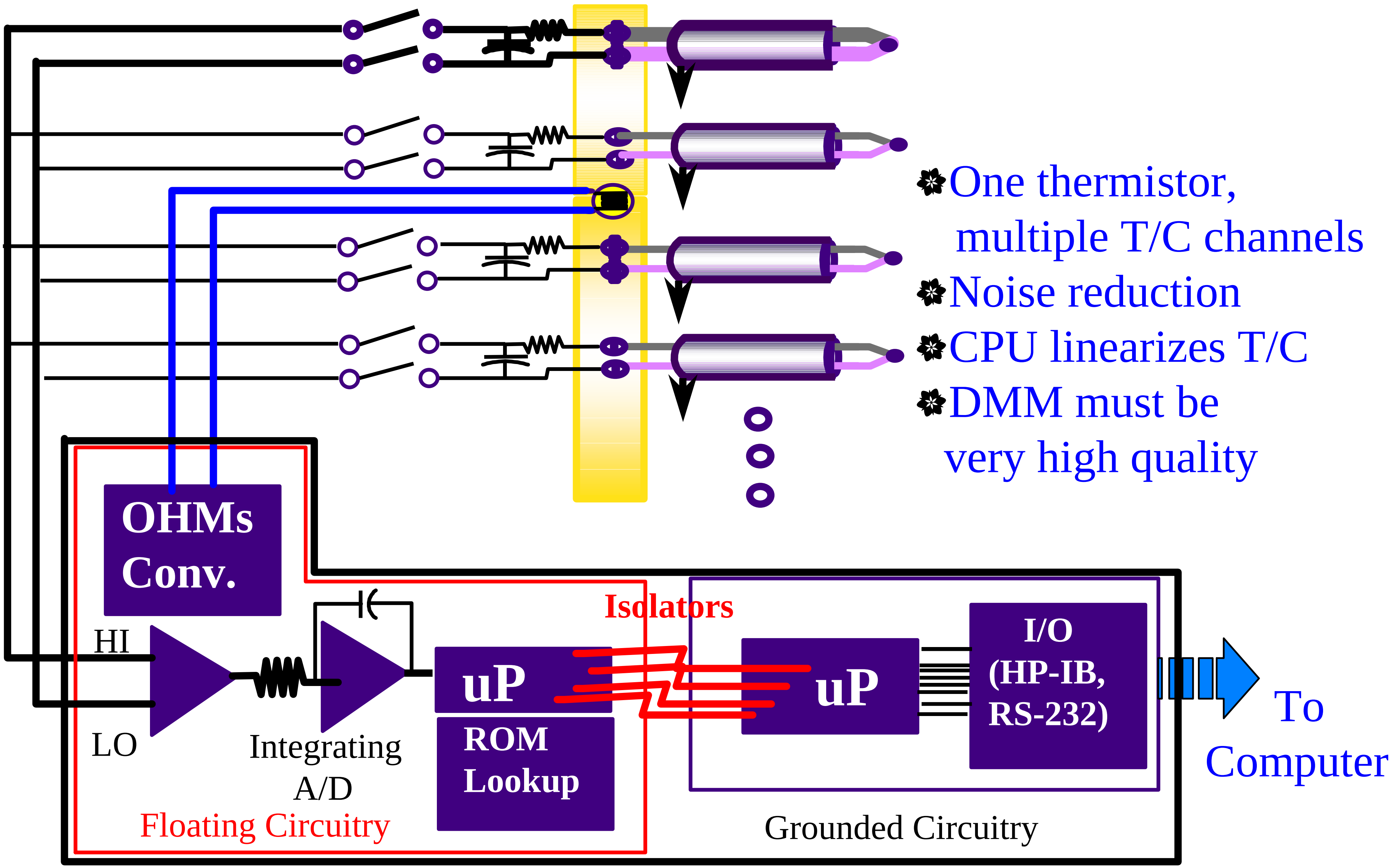
- Stray capacitance causes I noise
- DMM resistance to ground is important

Reducing Electrostatic Coupling



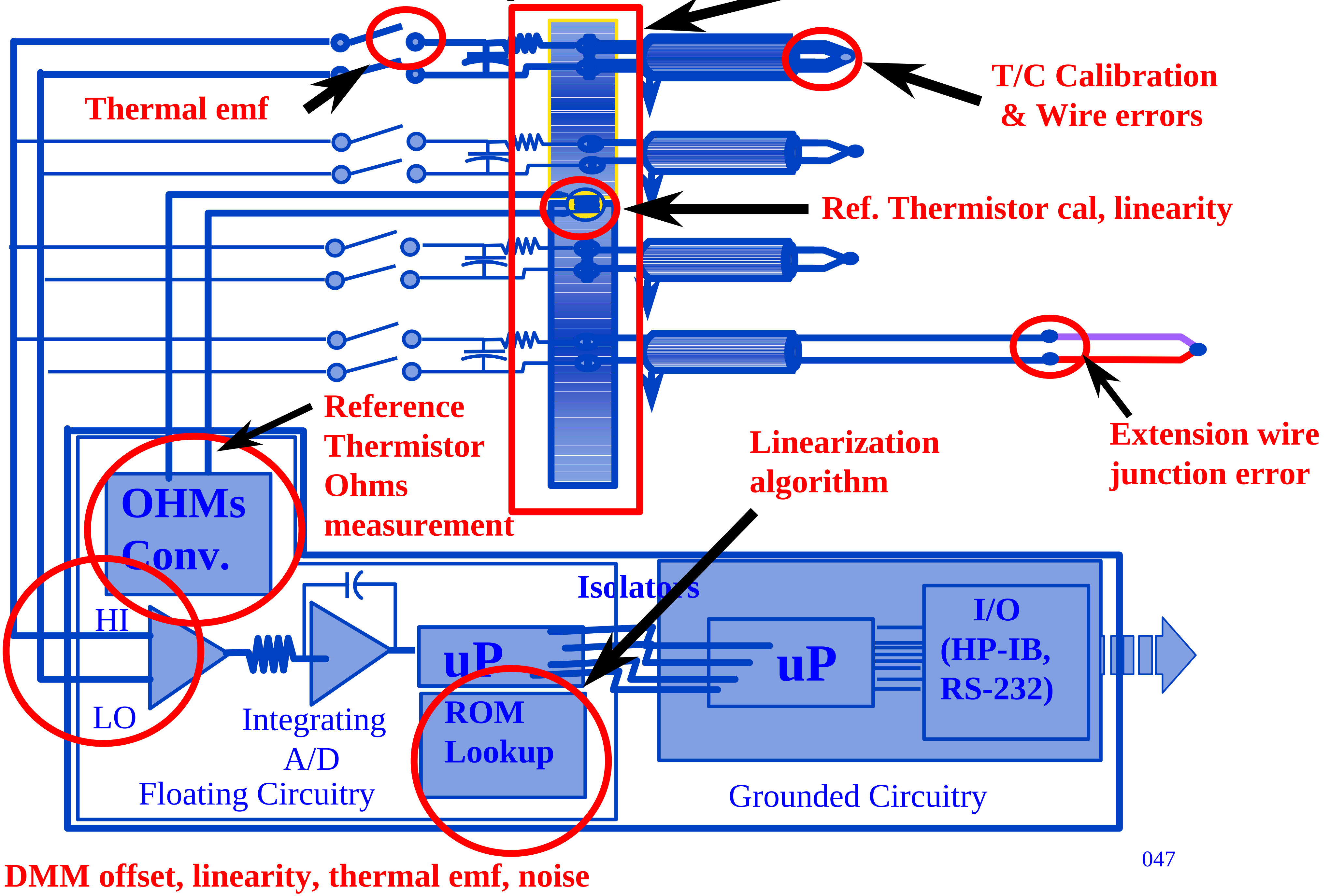
- Shield shunts stray current
- For noise coupled to the tip, Rleak is still important

A scanning system for T/Cs



- One thermistor, multiple T/C channels
- Noise reduction
- CPU linearizes T/C
- DMM must be very high quality

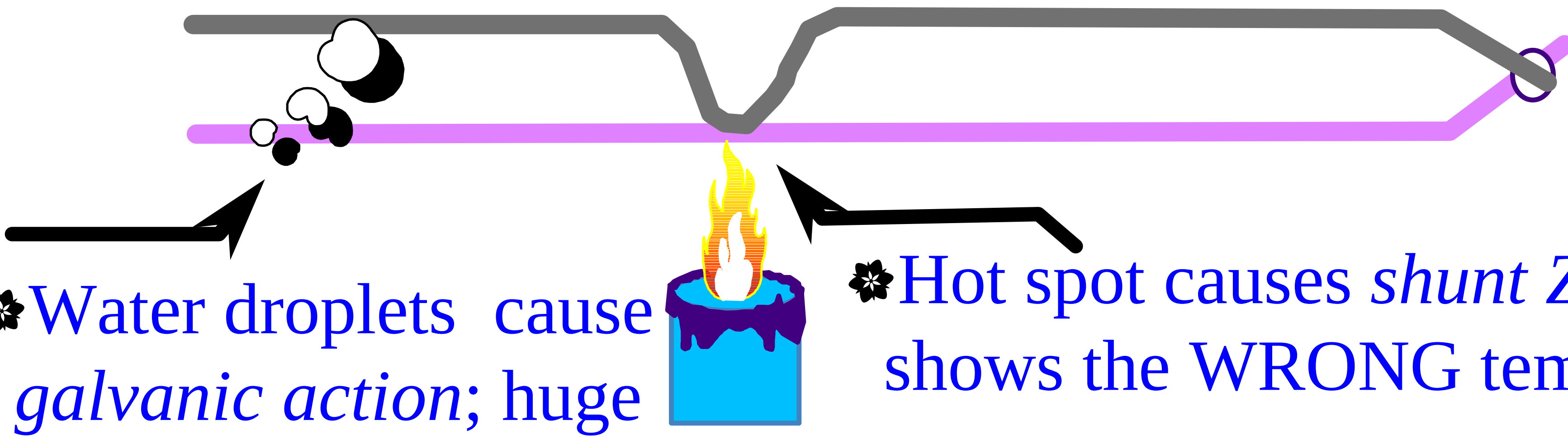
Errors in the system



Physical errors

- Shorts, shunt impedance
- Galvanic action
- Decalibration
- Sensor accuracy
- Thermal contact
- Thermal shunting

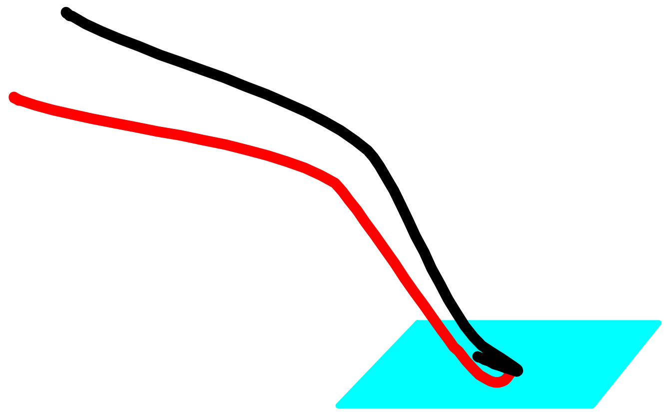
Physical Errors



- Water droplets cause *galvanic action*; huge offsets
- Hot spot causes *shunt Z*, meter shows the WRONG temperature

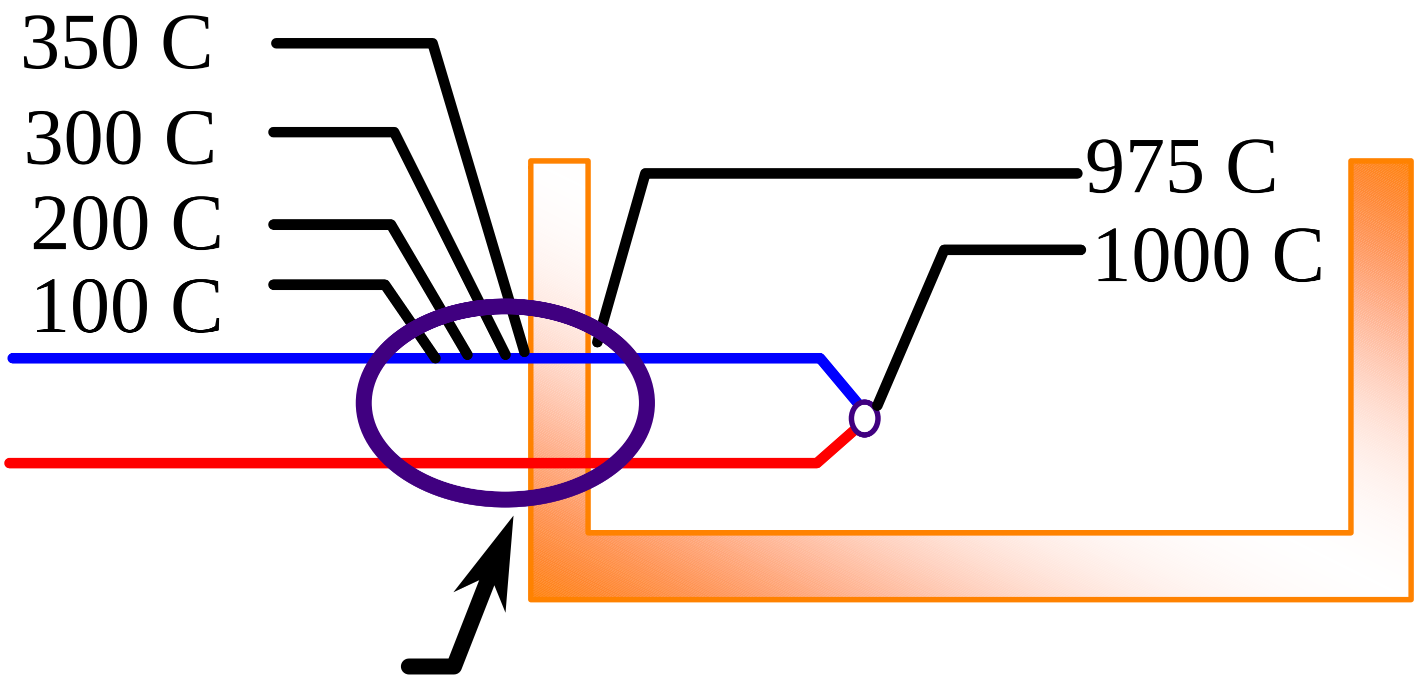
- Exceeding the T/C's range can cause permanent offset
- Real T/C's have absolute accuracy of 1 deg C @ 25C: Calibrate often and take care

Physical error: Thermal contact



- Make sure thermal mass is much smaller than that of object being measured

Physical errors: Decalibration



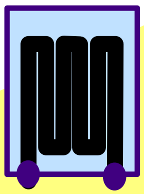
This section produces the ***ENTIRE*** signal

- Don't exceed Tmax of T/C
- Temp. cycling causes work-hardening, decalibration
- Replace the GRADIENT section

Agenda

- Background, history
- Mechanical sensors
- Electrical sensors
  - Optical Pyrometer
  - RTD
  - Thermistor, IC
  - Thermocouple
- **Summary & Examples**

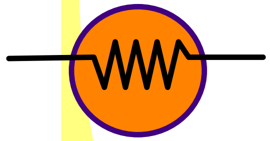
The basic 4 temperature sensors



RTD

- Most accurate
- Most stable
- Fairly linear

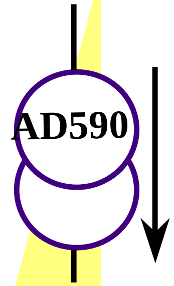
- Expensive
- Slow
- Needs I source
- Self-heating
- 4-wire meas.



Thermistor

- High output
- Fast
- 2-wire meas.

- Very nonlinear
- Limited range
- Needs I source
- Self-heating
- Fragile

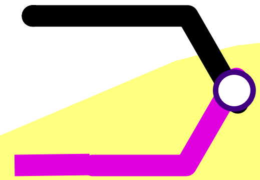


I.C.

- High output
- Most linear
- Cheap

- Limited variety
- Limited range
- Needs V source
- Self-heating

Absolute temperature sensors



Thermocouple

- Wide variety
- Cheap
- Wide T. range
- No self-heating

- Hard to measure
- Relative T. only
- Nonlinear
- Special connectors

Summary

- Innovation by itself is not enough...
  you must develop standards
- Temperature is a very difficult,
  mostly empirical measurement
- Careful attention to detail is required

Examples

Measurement	***Sensor***
Photochemical process control:	RTD (most accurate)
Flower petal:	Thermistor (lowest thermal mass)
Molten glass:	Optical pyrometer (hi temp, no contact)
Induction furnace:	RTD (if <800C); or T/C (Beware magnetic I noise)
100 degree Heat aging oven:	Any of the 4 sensors