

# THERMOMETRY

## above 1 Kelvin

Florence LEVY-BERTRAND  
from the Highly correlated systems team



# THERMOMETRY above 1 K

- Introduction
- Thermometer types
- Measurement techniques
- Regulation and magnetic field issues
- Conclusion

# INTRODUCTION

Determination of a temperature  $\underline{T}$  with :

- Thermometer = device with reproducible  $f(\underline{T})$
- Primary thermometer =  $f(T)$  is predictable
- Secondary thermometer =  
 $f(T)$  needs to be calibrated with primary thermometers

# INTRODUCTION

In practice :

- Primary thermometer are (non exhaustive) :
  - gas, vapor or noise thermometers
  - impractical for daily uses
  - used for metrology purposes
- Secondary thermometer are :
  - of various types : resistance, diode ...
  - to be carefully chosen for a given purpose

# PRIMARY THERMOMETERS

Gas thermometers :  $PV=NRT$

$N$  = known gas quantity

$V$  = known volume

$P$  = measure

⇒ determination of  $T$

(tricky and only ok while some gas is left ... above low  $T$ )

# PRIMARY THERMOMETERS

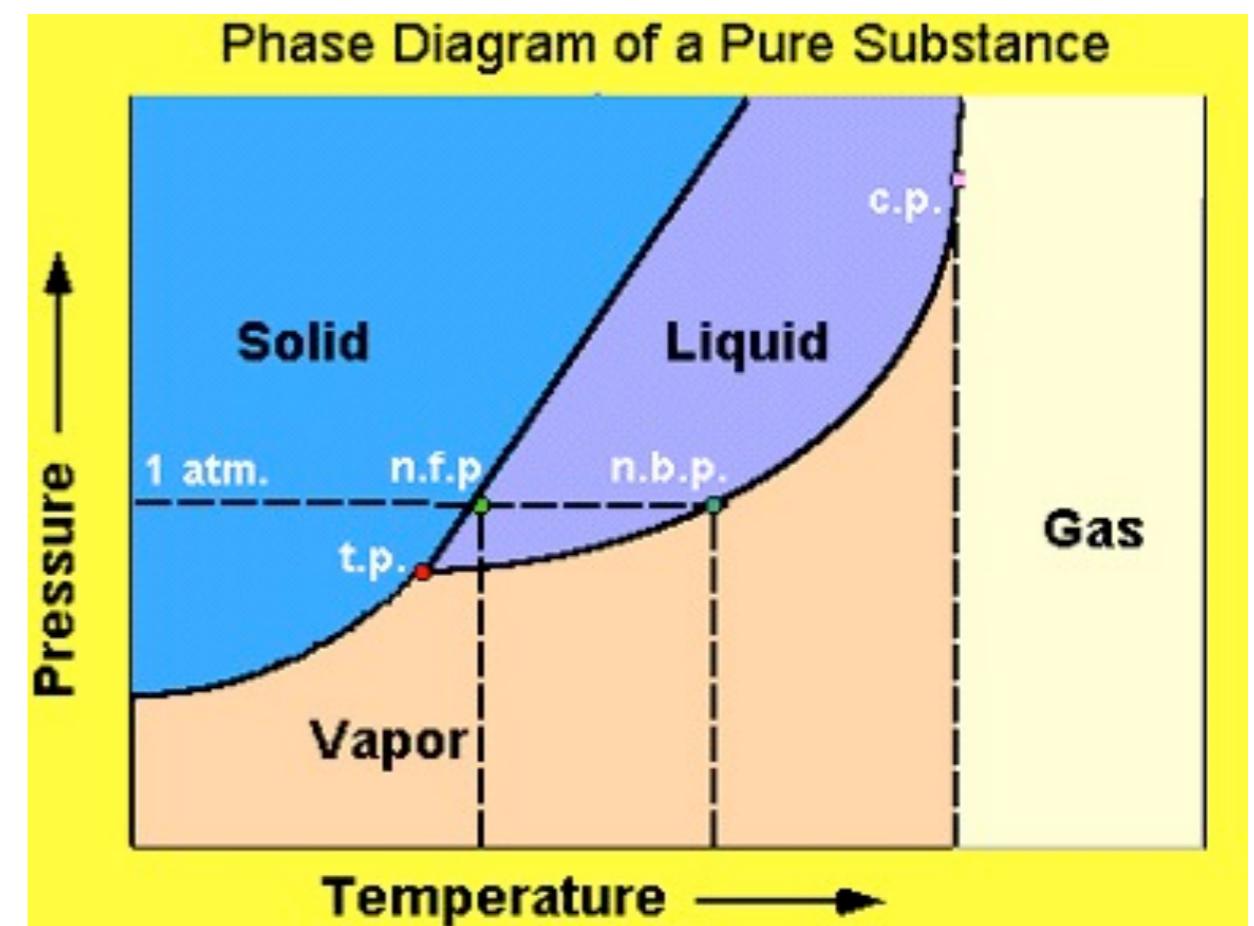
Vapor thermometers : vapor/liquid coexistence

P = measure when the equilibrium is reached

⇒ determination of T

liquid/vapor used :  $^3\text{He}$ ,  $^4\text{He}$ ,  $\text{N}_2$ ,  $\text{O}_2$

magnetic field independent



<http://invsee.asu.edu/srinivas/liquidmod/states.html>

# PRIMARY THERMOMETERS

Magnetic thermometers :  $M = CH/T$

(for paramagnetic substance)

$C$  = Curie constant

$H$  = applied magnetic field

$M$  = measure

⇒ determination of  $T$

# THERMOMETERS TYPES

Secondary thermometers : sensor choice ?



Quality of measurement :  
temperature range, resolution, reproducibility



Experimental constraints :  
size, power dissipation, thermal response time



Environment :  
magnetic field, vibration, ultra high vacuum



Finance and utility :  
cost and interchangeability (standard curve)

## Secondary thermometers from Lakeshore website

	Temperature Range	Standard Curve	Below 1 K	Can be used in radiation	Performance in magnetic field	
1.	Diodes					
	Silicon	1.4 K to 500 K	x		Fair above 60 K	
	GaAlAs	1.4 K to 500 K			Fair	
2.	Positive Temperature Coefficient RTDs	resistance				
	Platinum	14 K to 873 K	x		x	Fair above 30 K
	Rhodium-Iron	0.65 K to 500 K		x	x	Fair above 77 K
3.	Negative Temperature Coefficient RTDs	resistance				
	Cernox™	0.10 K to 325 K		x	x	Excellent above 1 K
	Cernox™ HT	0.10 K to 420 K		x	x	Excellent above 1 K
	Germanium	0.05 K to 100 K		x	x	Not recommended
	Carbon-Glass	1.4 K to 325 K			x	Good
	Ruthenium oxide*	0.01 K to 40 K	x	x	x	Good below 1 K
4.	Other					
	Thermocouples	1.2 K to 1543 K	x			Fair
5.	Capacitance	1.4 K to 290 K				Excellent

# DIODE

Principe : semiconductor, voltage is measured across a p-n junction.

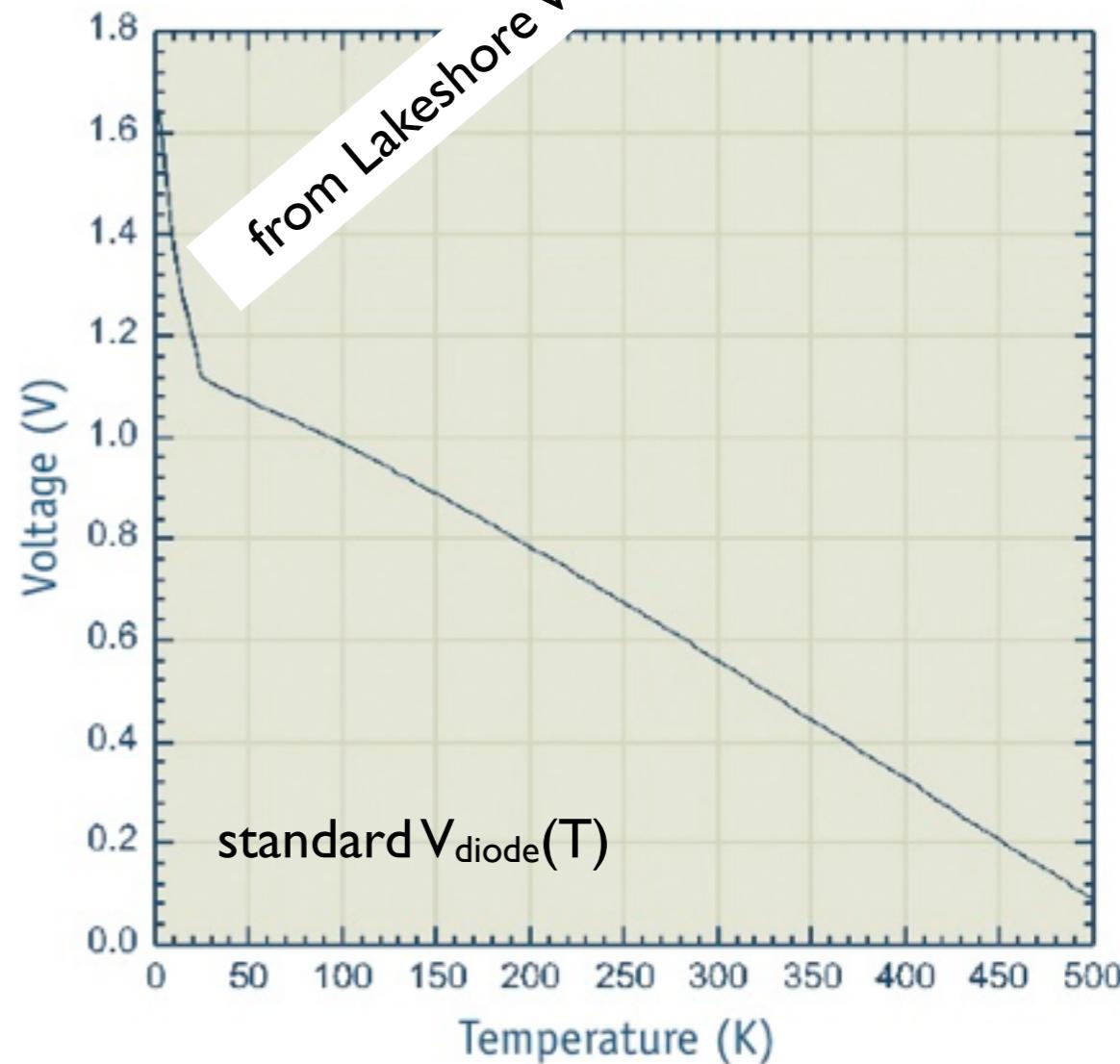
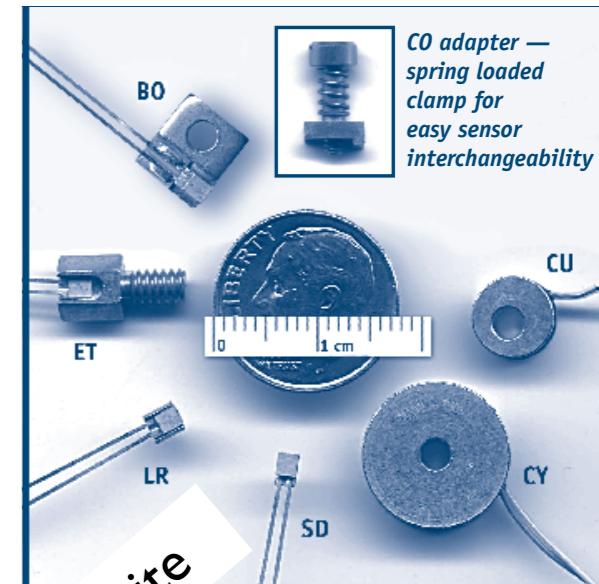
Most common type : SILICON

Temperature range : 1.4 K - 500 K

Interchangeability : yes  
standard calibration within  $\pm 0.3$  K

Cost : from 180\$ (robust)

Magnetic Field :  
sensitive, orientation issue ( $H//I$  is better)



# RESISTANCE : positive T coefficient

Principle :  
metallic,  $R(T)$  decreases with  $T$ .

Example : PLATINUM

Temperature range : 14 K - 800 K

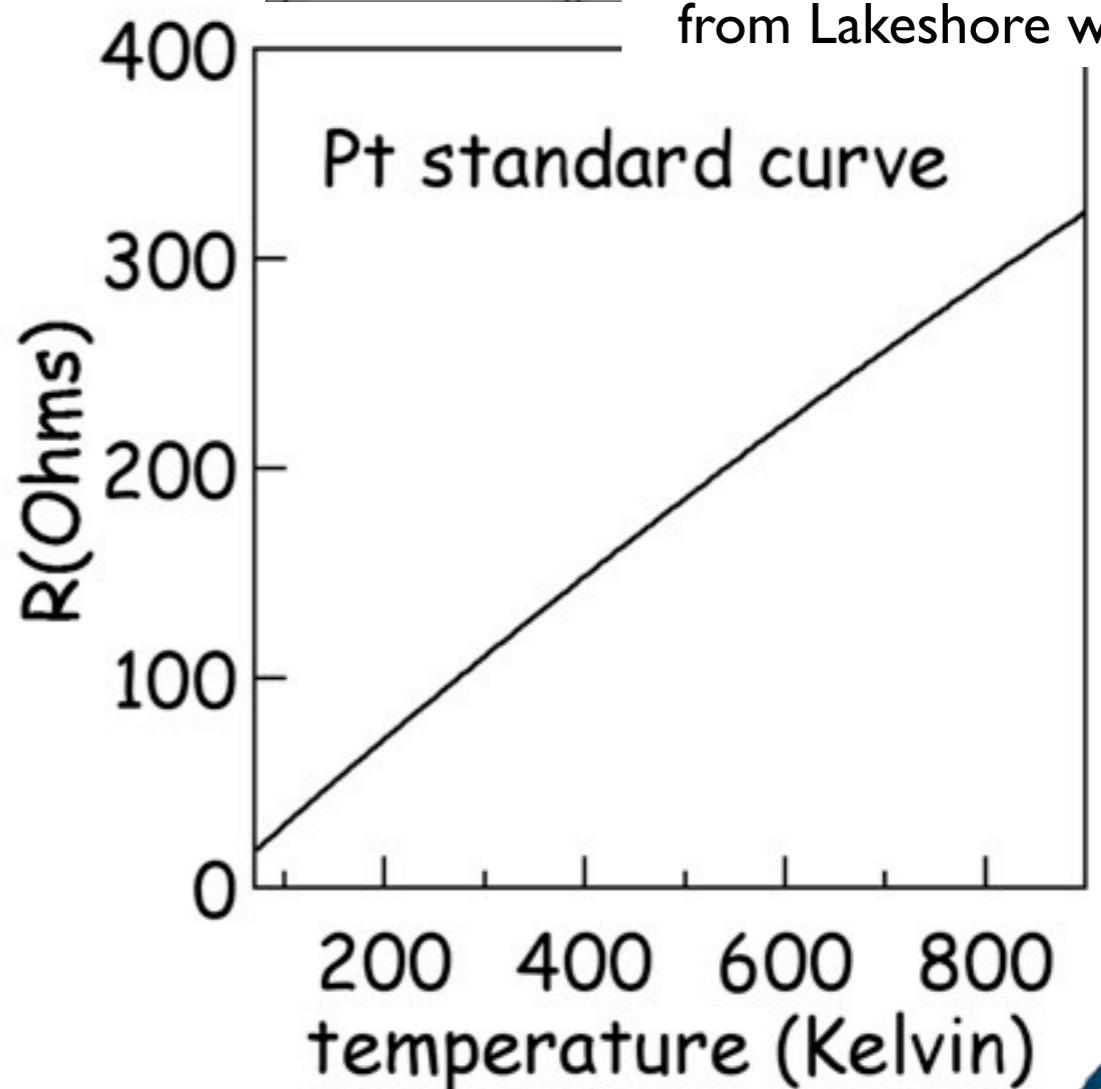
Interchangeability : down to 70 K  
standard calibration within  $\pm 0.3$  K  
METROLOGY application

Cost : from 82\$ (fragile)

Magnetic Field :  
sensitive



from Lakeshore website



# RESISTANCE : positive T coefficient

Principle :  
metallic :  $R(T)$  decreases with  $T$ .

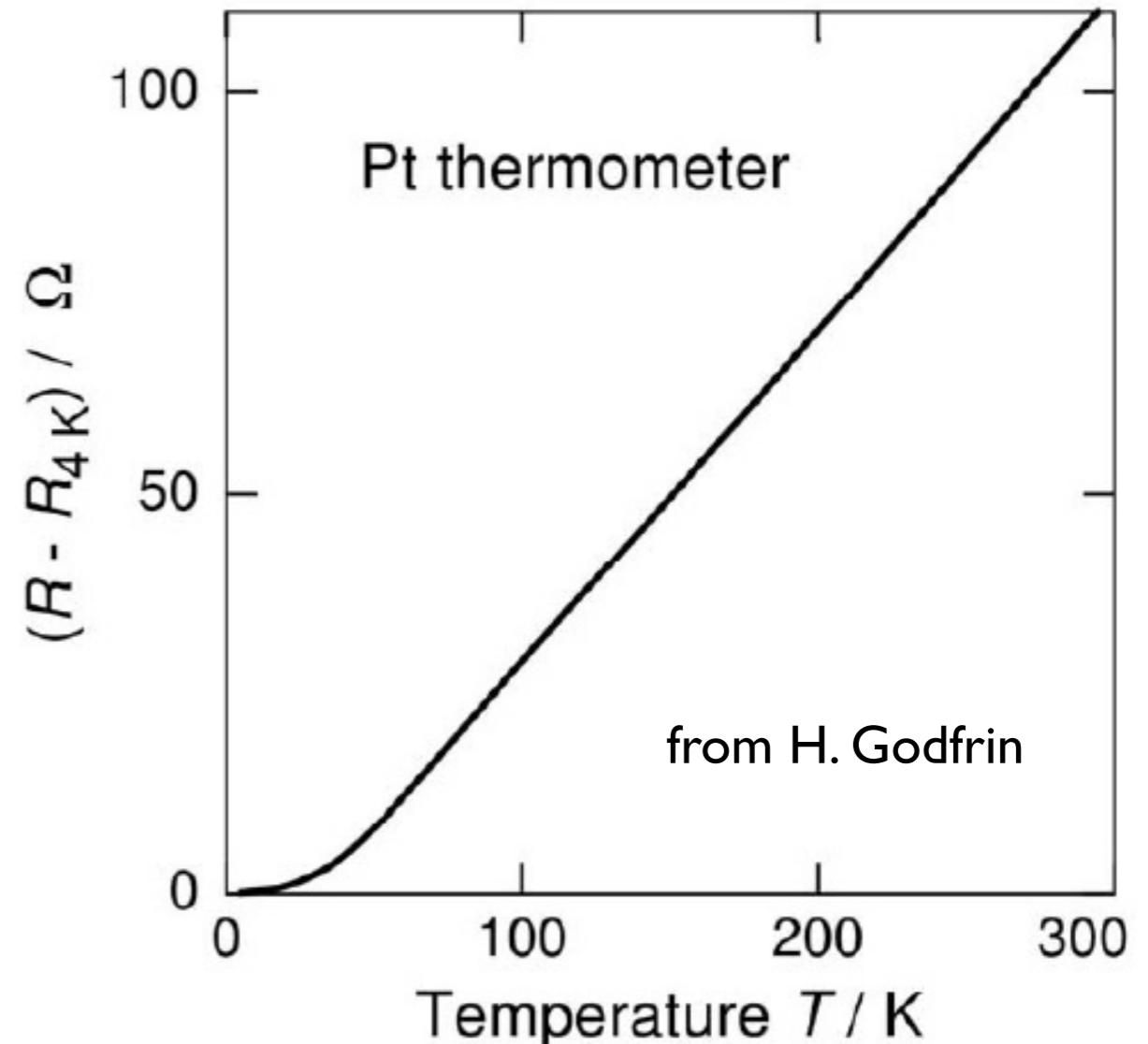
Example : PLATINUM

Temperature range : 14 K - 800 K

Interchangeability : down to 70 K  
standard calibration within  $\pm 0.3$  K  
METROLOGY application

Cost : from 82\$ (fragile)

Magnetic Field :  
sensitive



from H. Godfrin

$$\begin{aligned}A &= 3.9083 \times 10^{-3} \text{ }^{\circ}\text{C}^{-1} \\B &= -5.775 \times 10^{-7} \text{ }^{\circ}\text{C}^{-2} \\C &= -4.183 \times 10^{-12} \text{ }^{\circ}\text{C}^{-4}\end{aligned}$$

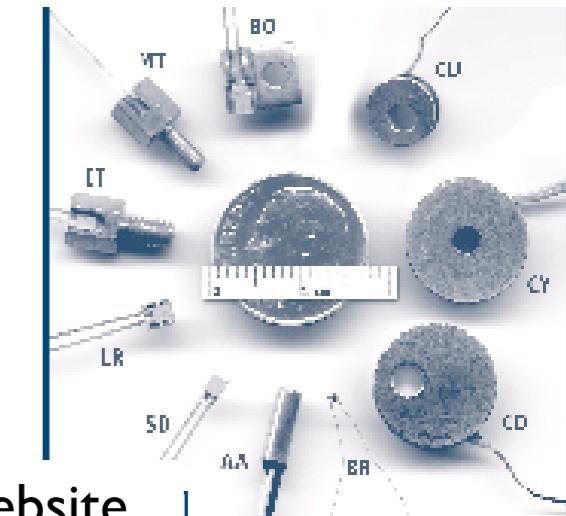
$$R_T = R_0 [1 + AT + BT^2 + CT^3(T - 100)] \quad (-200 \text{ }^{\circ}\text{C} < T < 0 \text{ }^{\circ}\text{C}),$$

$$R_T = R_0 [1 + AT + BT^2] \quad (0 \text{ }^{\circ}\text{C} \leq T < 850 \text{ }^{\circ}\text{C})$$

# RESISTANCE : negative T coefficient

Principle :  
semiconductors,  $R(T) \uparrow$  as  $T \downarrow$ .

Type : CERNOX (replacement of Carbon-glass)



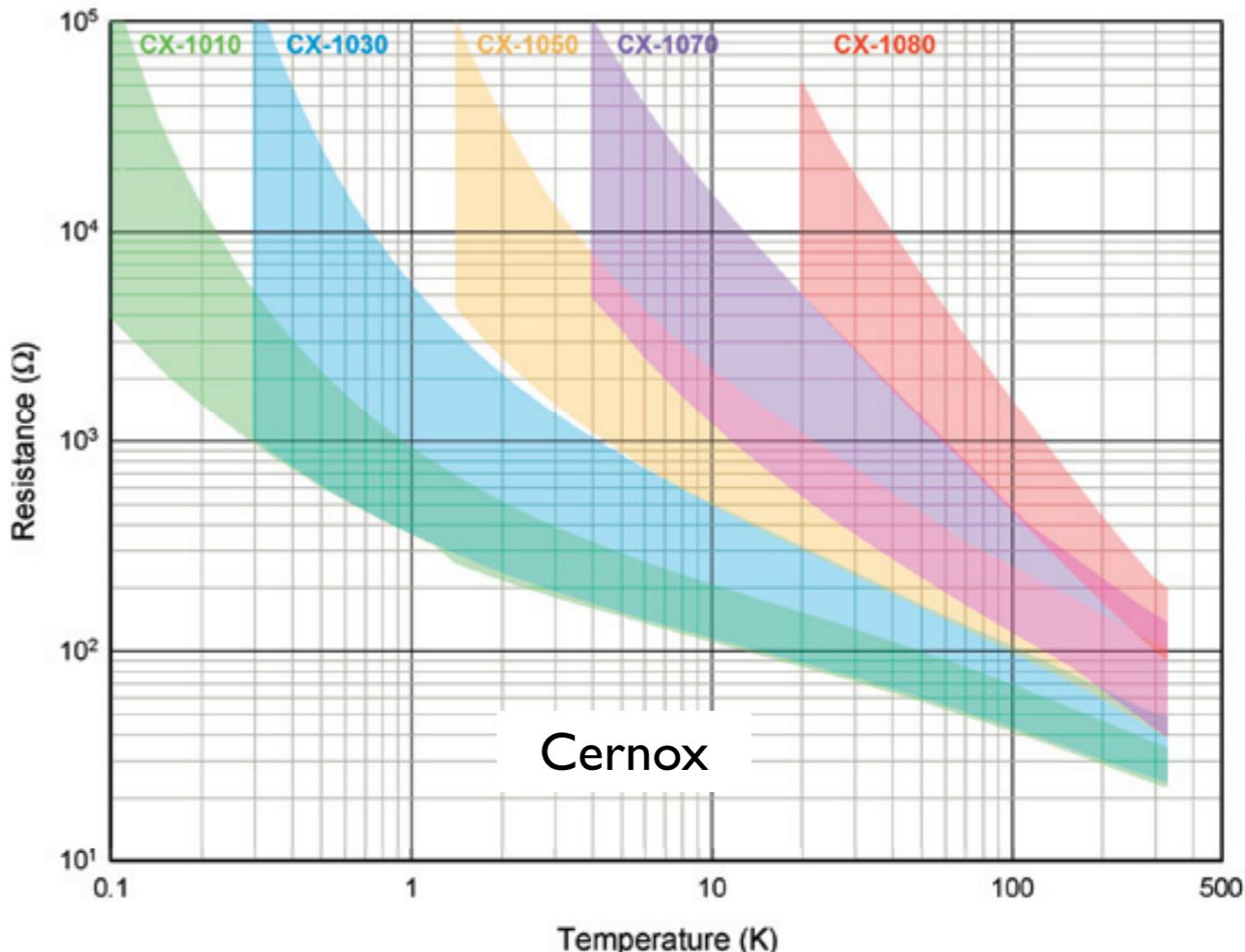
from Lakeshore website

Temperature range :  
0.1 K - 420 K owing doping level

Interchangeability : NO

Cost : from 100\$ (quite robust)

Magnetic Field :  
 $|\Delta T| < 0.4$  K for  $T > 4$ K and  $H < 8$ T  
→ useful under field



# RESISTANCE : negative T coefficient

Principle :  
semiconductors,  $R(T) \uparrow$  as  $T \downarrow$ .

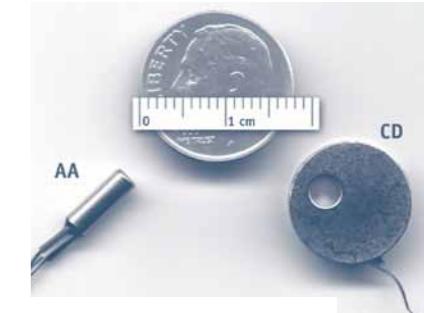
Type : Carbon-glass

Temperature range : 1.4 K - 100 K

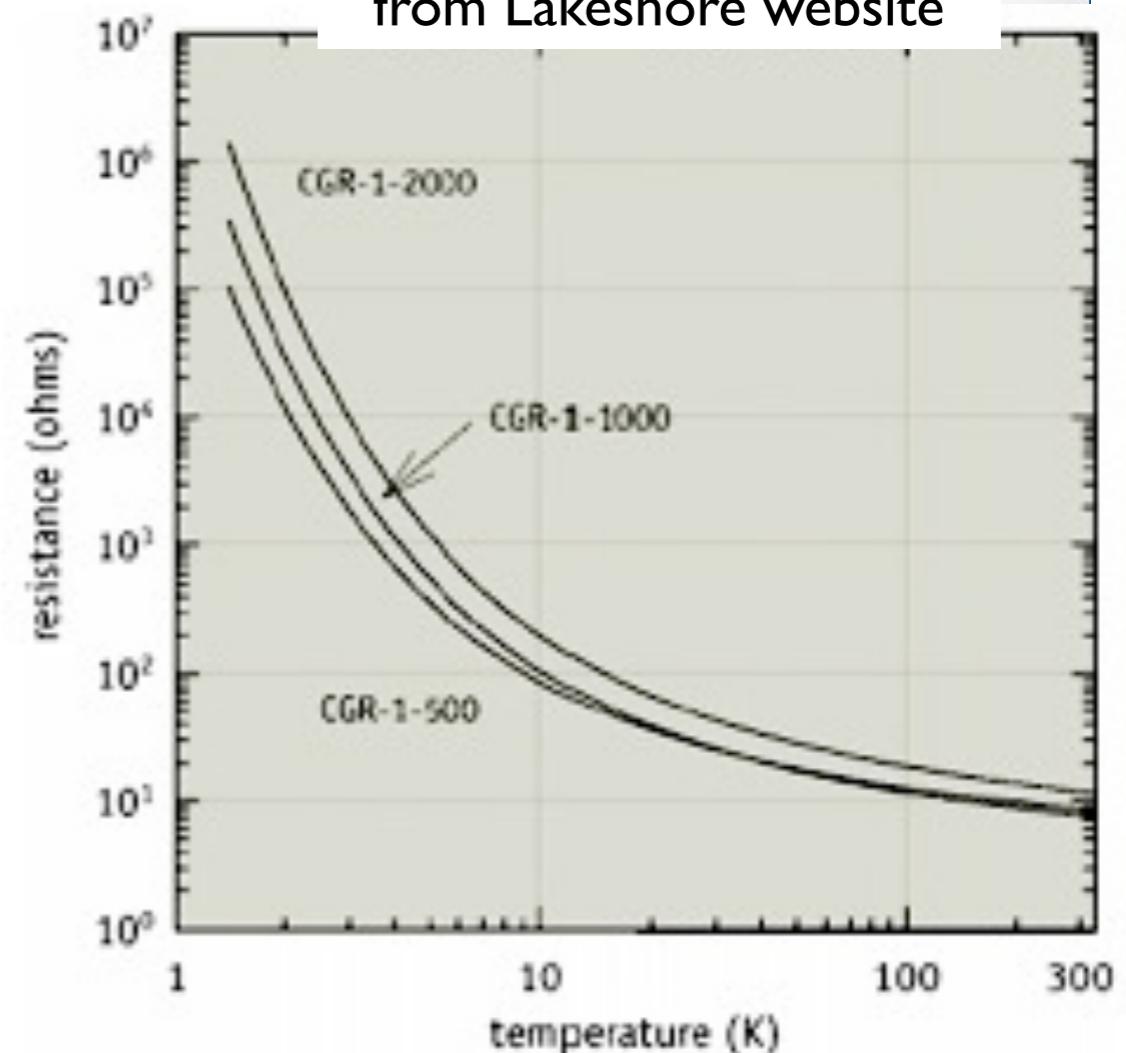
Interchangeability : no

Cost : from 276\$

Magnetic Field : ok up to 20 T (<4%)  
magnetoresistance less than Cernox



from Lakeshore website



# RESISTANCE : negative T coefficient

Principe :  
semiconductors,  $R(T) \uparrow$  as  $T \downarrow$ .

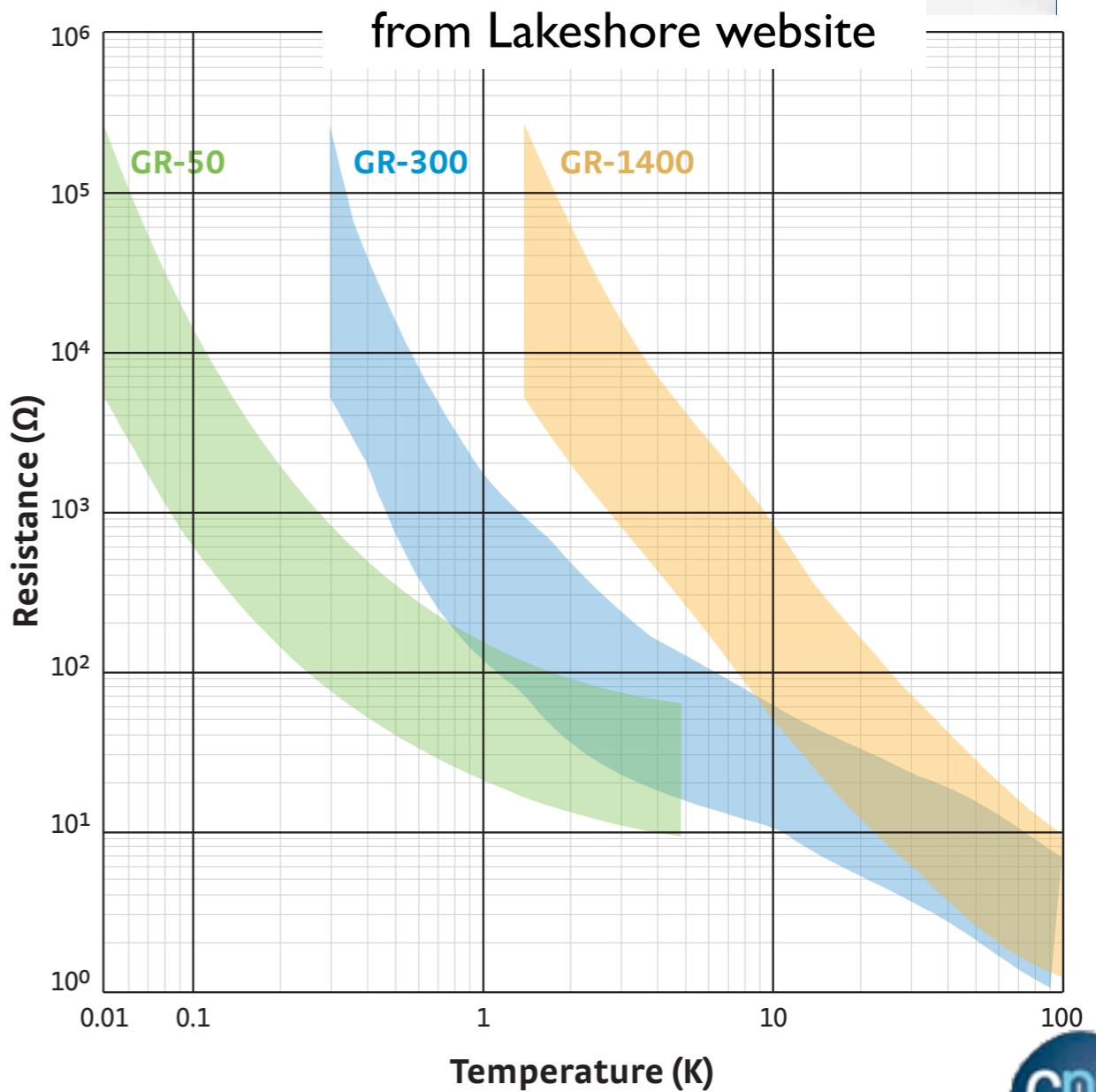
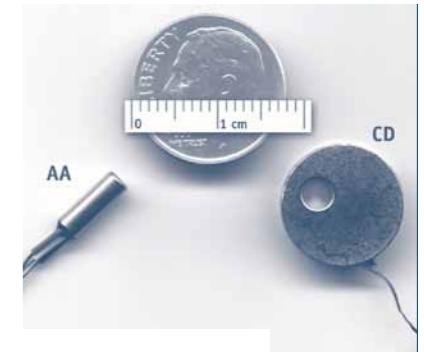
Type : Germanium (Ge)

Temperature range : **0.05 K - 100 K**  
very accurate and sensitive.

Interchangeability : no

Cost : from 286\$ (fragile)

Magnetic Field : sensitive



# RESISTANCE : negative T coefficient

Principle :  
semiconductors,  $R(T) \uparrow$  as  $T \downarrow$ .

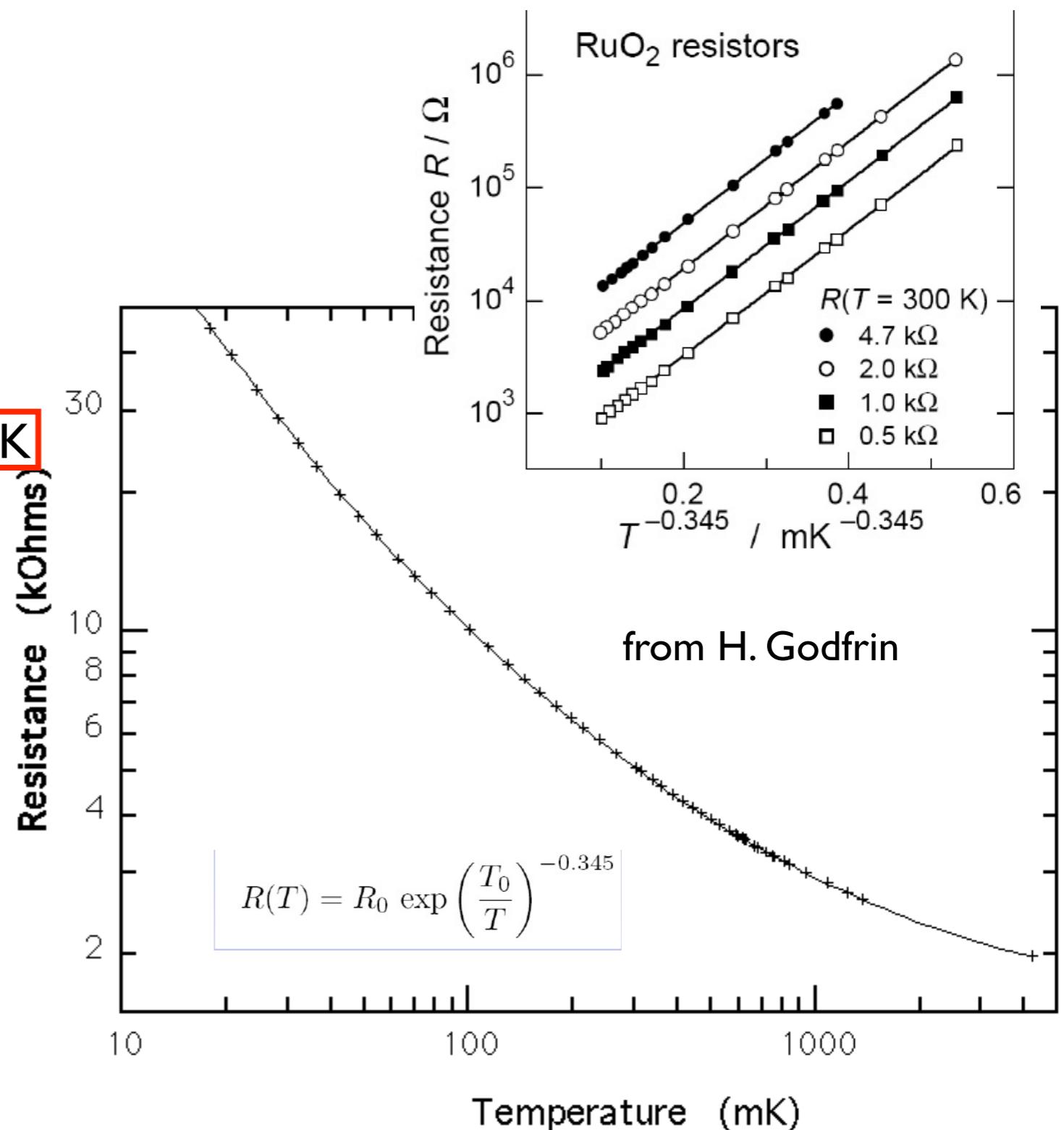
Type : Ruthenium Oxide ( $\text{RuO}_2$ )

Temperature range : 0.01 K - 40 K

Interchangeability :  
yes but error up to 5K

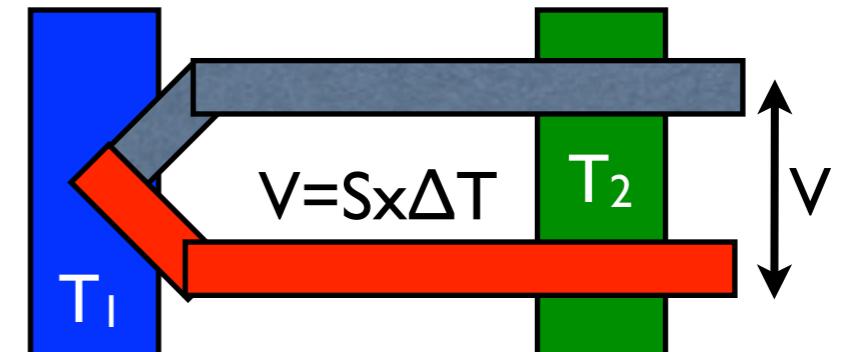
Cost : from 99\$

Magnetic Field :  
useful below 1K but sensitive



# THERMOCOUPLE

Principle : Seebeck effect,  $V=Sx\Delta T$   
junction of positive and negative thermoelements



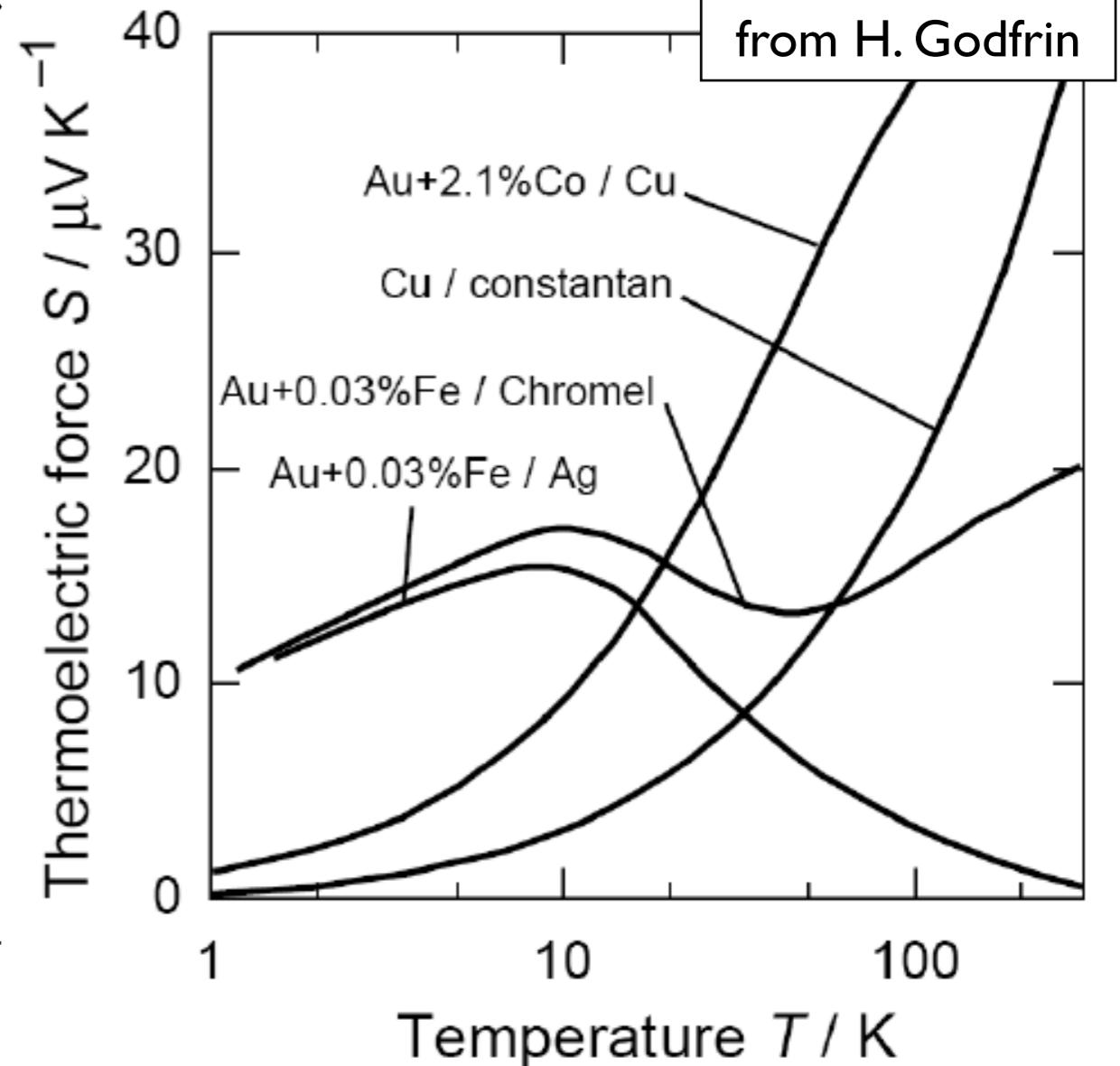
Example type : «Chromel-Gold/Iron 0.07%»  
negative thermoelt = Au + 0.07% Fe  
positive thermoelt = Ni-Cr alloy

Temperature range : 1.2 K - 1500 K

Interchangeability : yes

Cost : from 50\$,  
small, robust, easy to measure

Magnetic Field : sensitive see lakeshore data



# CAPACITANCE



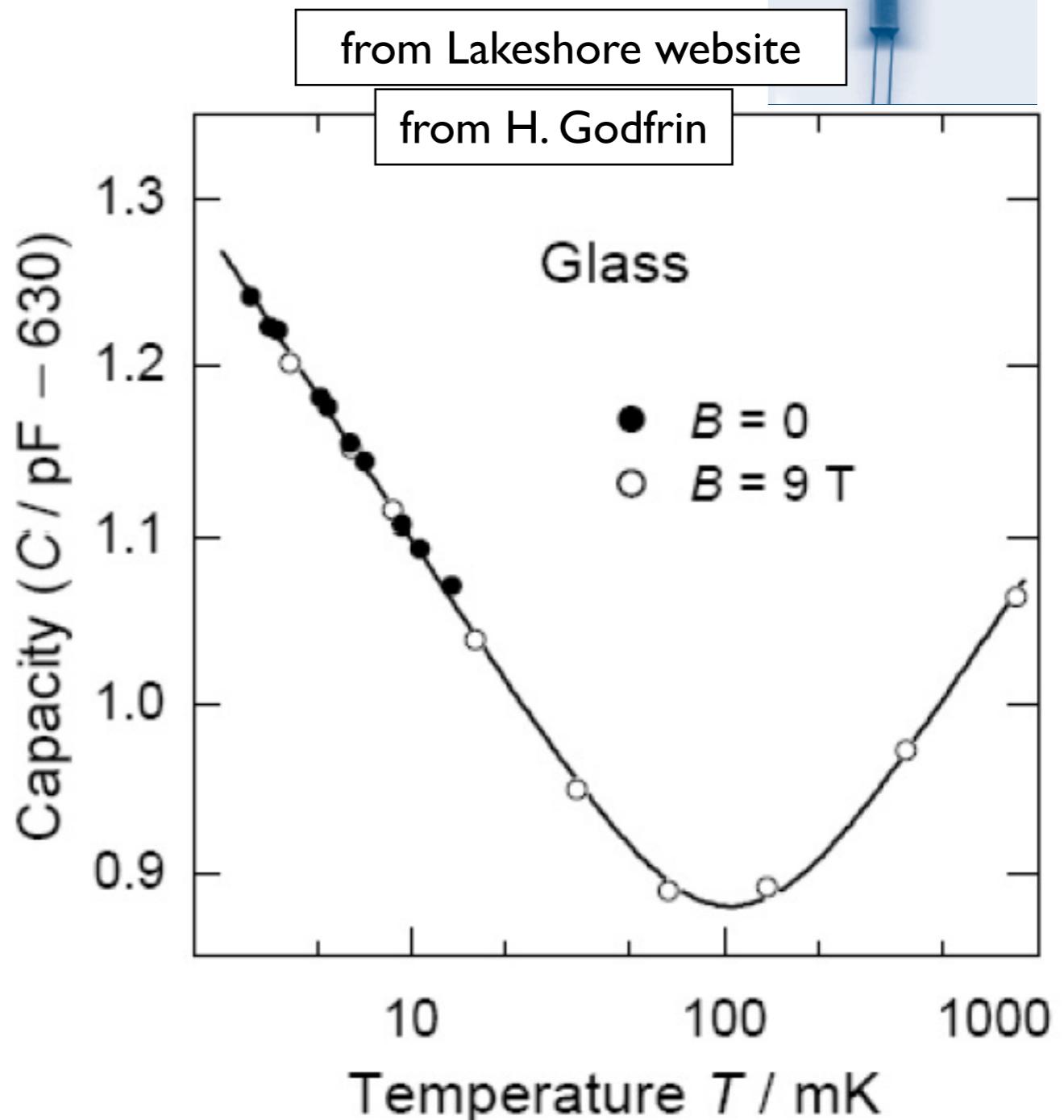
Principle :  $C(T)$ ,  
NO variation with field  $B$ ,  
!!! variation with thermal cycling.

Purpose :  
precise regulation under field  $B$   
in complement to a thermometer

Temperature range : 1.4 K - 290 K

Interchangeability : no

Cost : from 440\$

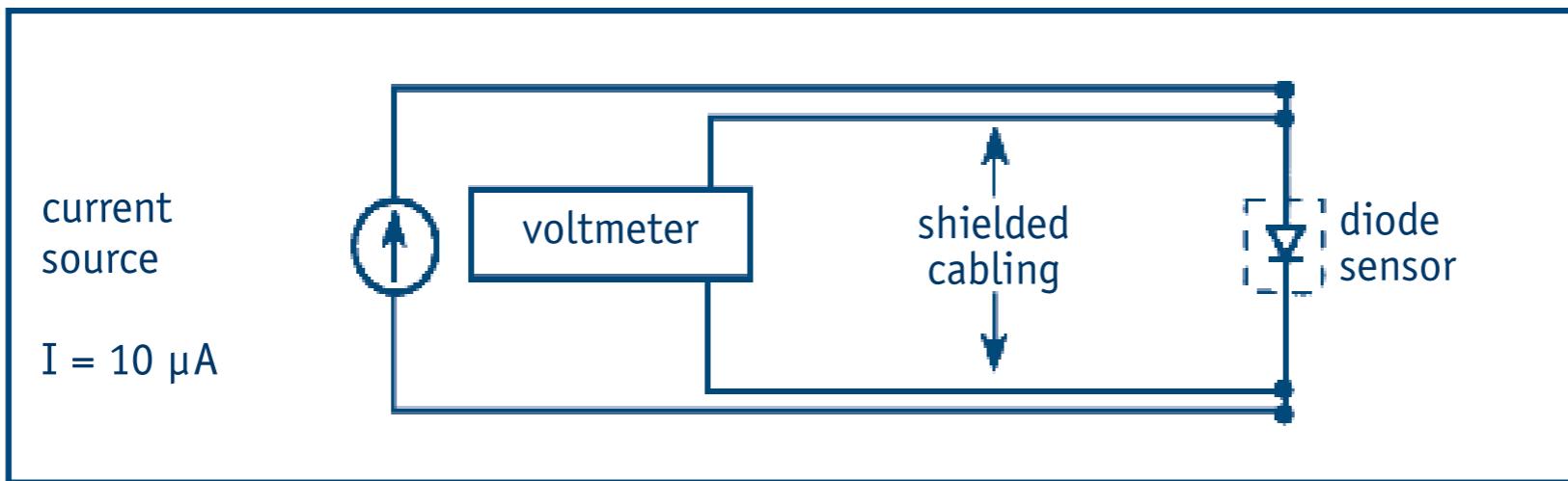


# MEASUREMENT TECHNICS

- diode set-up
- resistance set-up
- general requirements (including wiring precautions)
- general Wheatstone bridge technique

# DIODE SET- UP

from Lakeshore website



**Figure 2 – Typical diode sensor instrumentation schematic**

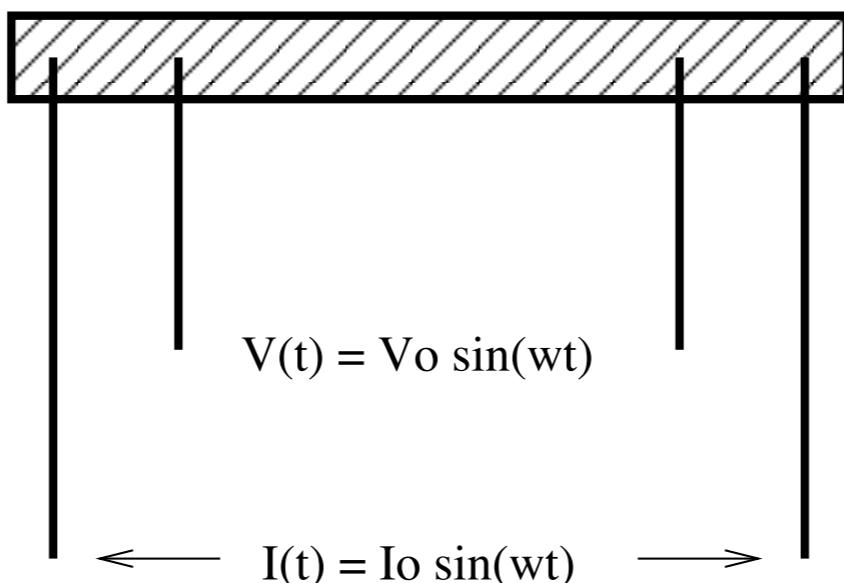
$$I = 10\mu\text{A} \rightarrow V(300 \text{ K}) = 0.5 \text{ V} \text{ and } V(77 \text{ K}) = 1 \text{ V}$$

!Wiring!: noise currents produce shift in measurement  
Solution :AC-filters

# RESISTANCE SET- UP

## 4 LEADS TECHNIQUE (with a lock-in)

Input :AC current  $I \rightarrow$  Output :AC voltage  $V$



Determination of  $R$  by  $V=RI$   
TO GET RID OF THE RESISTANCE OF THE WIRES

When  $R$  decreases linearly with  $T$  : single current excitation  $\sim 1\text{mA}$  (ex : Pt)

When  $R$  strongly  $\uparrow$  as  $T \downarrow$  : current must be varied from  $\sim 0.01\mu\text{A}$  to  $\sim 1\text{mA}$  (ex: cernox)

# MEASUREMENT TECHNICS

## General requirements :

- **measurement set-up impedance** :  $Z_{\text{set-up}} \gg Z_{\text{thermometer}}$

- **grounding** : ONE reference for all instruments and cryostat

→ to avoid current flows and thus voltage offsets

- **reduce AC signal interference** : problem : wires = antennas

i/ **continuous conductive shielding** connect to the ground from the cryostat to the instruments

ii/ **twisted and short wires pairs** (= bad antenna)

iii/ if needed additional AC-filters

# MEASUREMENT TECHNICS

## General requirements :

- wiring thermalization to avoid heat load into the thermometer
- thermal contact of the thermometer : screw, clamp, GE varnish ...
- thermometer self-heating ? (test/adapt the current value)
- configuration between thermometer and sample : good thermal contact ?
- time constant of the sensor (sensor construction + thermal contact and distance from the heater ...)

# MEASUREMENT TECHNICS

## The Wheatstone bridge :

to measure small changes of resistance (capacitance or inductance)

R

three known resistances,  $R_3$  **can be adjusted**

$R_x$

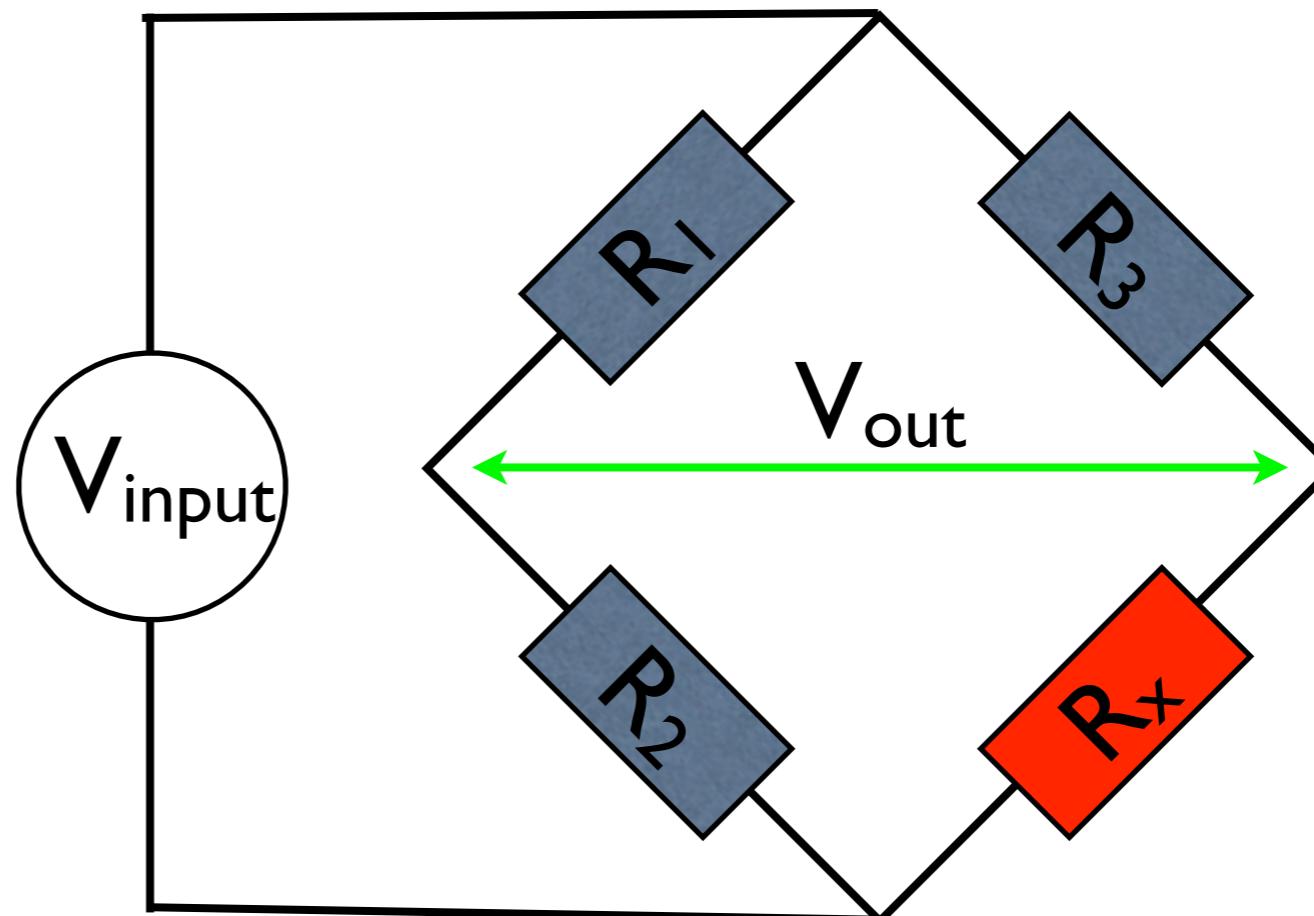
sensor resistance : to be determined

**Bridge balance**

**when  $V_{out} = 0$**

**then**

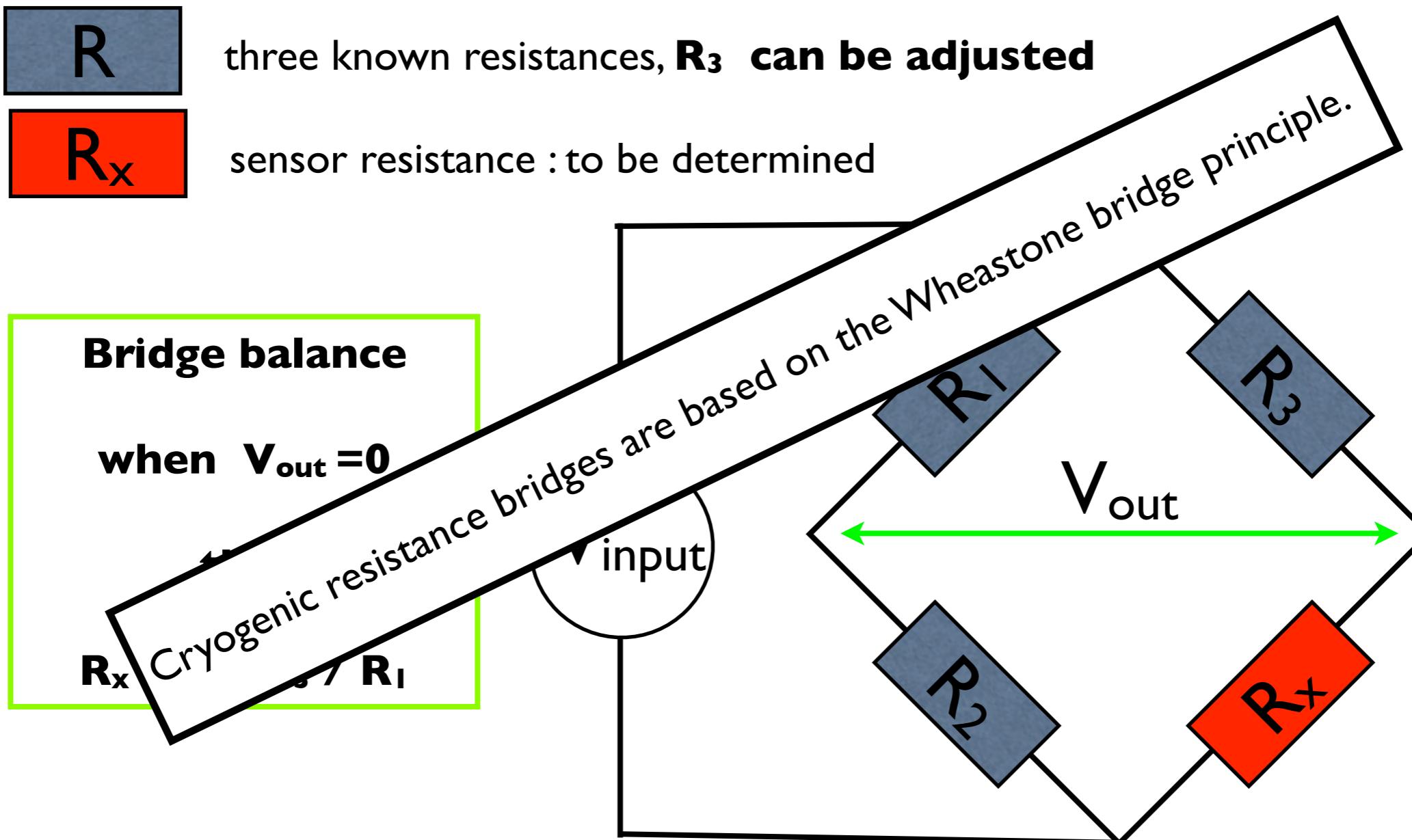
$$R_x = R_2 \cdot R_3 / R_1$$



# MEASUREMENT TECHNICS

## The Wheatstone bridge :

to measure small changes of resistance (capacitance or inductance)



# REGULATION ISSUE

How to adjust the heat Q to regulate a temperature ?

PID technique : commonly used

P = proportional,  $Q = P \cdot (T_{set} - T_{meas})$

I = integral,  $Q = I \cdot \sum (T_{set} - T_{meas})$

D = derivative,  $Q = D \cdot d(T_{set} - T_{meas})/dt$

P ~ on/off regulation

I ~ smooth the P regulation (if I is not too high, otherwise T wobbles)

D ~ fasten the regulation IF the measurement is not too noisy

# REGULATION ISSUE

How to REALLY regulate a temperature under a magnetic field ?

## **Regulation on a capacitance**

(or on an insensitive sensor but very few other type are available)

1°/  $H = 0 \text{ T}$  : regulation on a sensor  $R$

-> determination of the capacitance value at  $T : C$

2°/  $H$ -sweep : regulation to maintain  $C$  constant (bridge technique)

# THERMOMETRY above 1 K

Needs : range ? precision ? regulation stability ? cost ?

thermometer type  
measurement settings  
calibration checks ?  
regulation settings

