COURSE OUTLINE

- Introduction
- Signals and Noise
- Filtering
- Sensors: Temperature Sensors

- Metallic RTDs: principle and fabrication
- RTD Electrical Signal
- Circuits for measurements
- Thermistors

Metal RTD principle

Principle:

- **Resistance R_S** of metal conductors **increases monotonically with temperature T**
- Calibration of resistance versus temperature $R_S(T)$ is accurate and stable
- By measuring resistance variation ΔR_S we get the temperature variation ΔT

Linear behavior of R_S(T) is a good approximation on wide T range for various metals

$$R_S = R_0(1 + \alpha\Delta T)$$

T_0 = reference temperature; $R_0 = R_S(T_0)$;

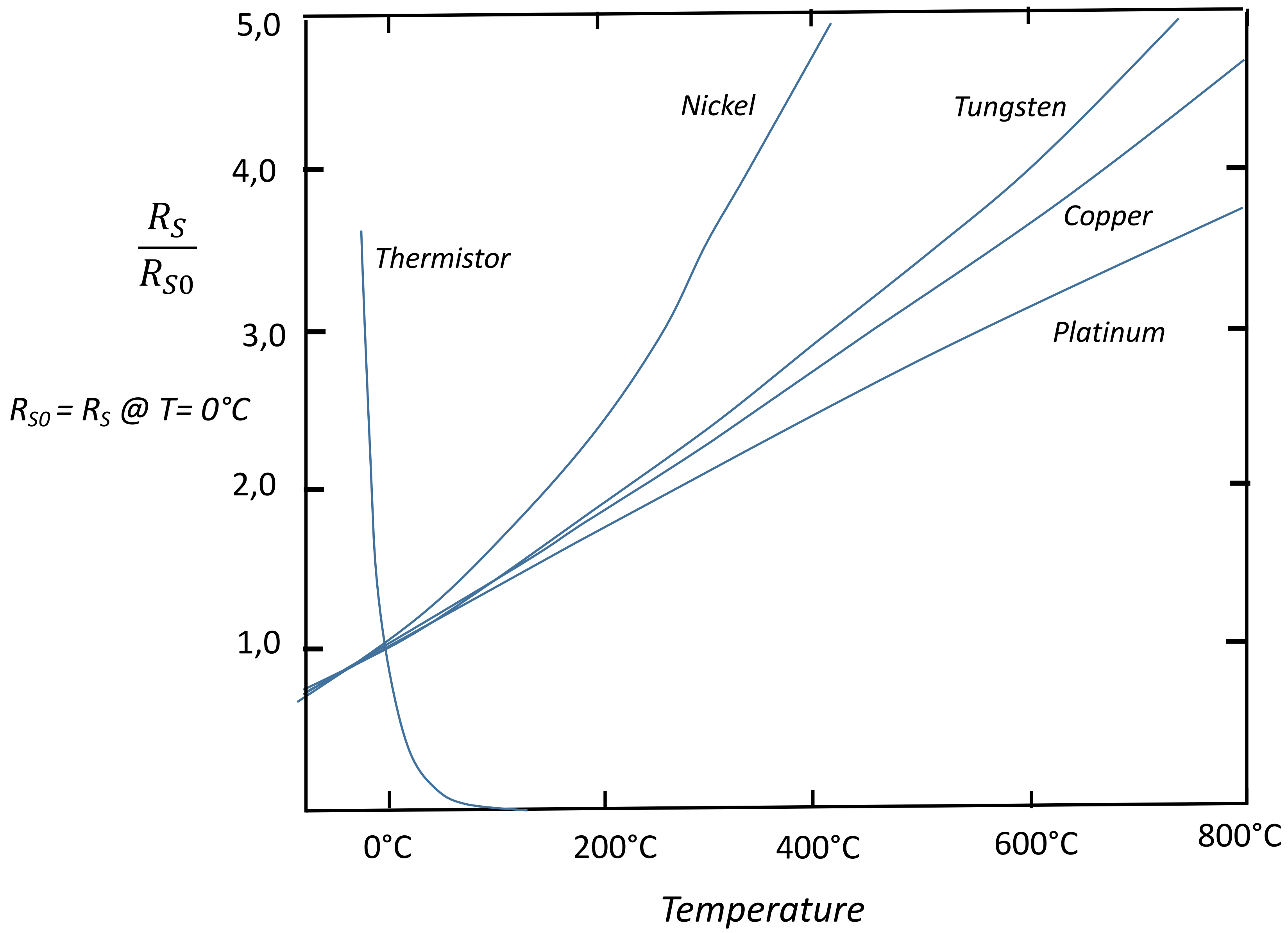
$$\Delta R_S = \alpha\Delta T R_0$$

$\Delta T = T - T_0$; $\Delta R_S = R_S - R_0$

α is called **temperature coefficient of resistance**.
α is around $\approx 4 \cdot 10^{-3}$ for metals currently employed in RTDs

Metal	α
Platinum Pt	$3{,}9 \cdot 10^{-3}$
Copper Cu	$4{,}3 \cdot 10^{-3}$
Tungsten W	$4{,}6 \cdot 10^{-3}$
Nickel Ni	$6{,}8 \cdot 10^{-3}$

Metal RTD principle



Metal RTD technology

Platinum has useful qualities:

- **Chemically inert and resistant to contamination**, hence stable properties
- R_S(T) **linear with very good approximation** from -200°C to about 500°C and with small deviation from linearity up to 800°C
- **small quantity of Pt necessary** in a RTD, cost is not high

Pt is the material of choice in many cases and is used in official metrology to define the International Practical Temperature Scale (from 13,81 K to 903,89 K).

Because of requirements for correct operation, the **RTD fabrication technology is not so simple** :

- The package must be compact and ensure good **thermal contact** of the resistor to the object measured and good **electrical isolation** from it
- **Small size is required with R_0 > some 10 Ω , typically R_0 =100 Ω**, in order to have to measure not very small ΔR_S. Thin wire wrapped in spiral on a support is used
- The mechanical structure must **avoid strain** of the metal wire due to thermal expansion or contraction: the **piezoresistive effect** would cause unwanted resistance variations and consequent errors in ΔT

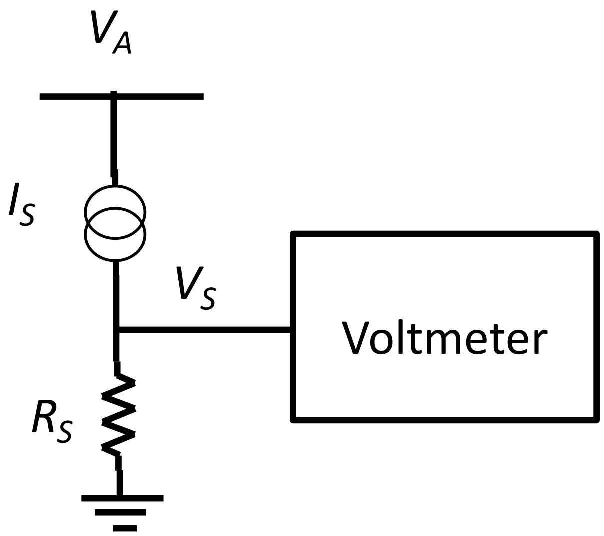
Generation of RTD Electrical Signal

- RTD do not generate an electrical signal, a **power supply is necessary** to get current and voltage in the RTD
- Joule **self-heating** makes the RTD temperature T_S higher than the temperature T_a of the object measured; the difference $\Delta T_S = T_S - T_a$ increases with power dissipation P_S and sensor-to-object thermal resistance R_{th}.
- The maximum tolerable ΔT_S in a given RTD configuration sets a limit P_{Smax} to the power dissipated in the RTD, hence to the **maximum voltage V_S** on the RTD

$$P_S = \frac{V_S^2}{R_S} \qquad P_S \leq P_{S,\max} \qquad \boxed{V_S \leq \sqrt{R_S \cdot P_S}}$$

- The allowed voltage V_S on the RTD is fairly small: e.g. with $R_S \approx 100\ \Omega$ and limit $P_{Smax} = 100\mu W$, the voltage is limited to $V_S < 100 mV$.
- The **voltage variations** to be measured for small variations of temperature are a small fraction of V_S , i.e. they are **definitely small**.

RTD Operation at Constant Current



$$\Delta R_S = f(\Delta T) \approx \alpha R_0 \cdot \Delta T$$

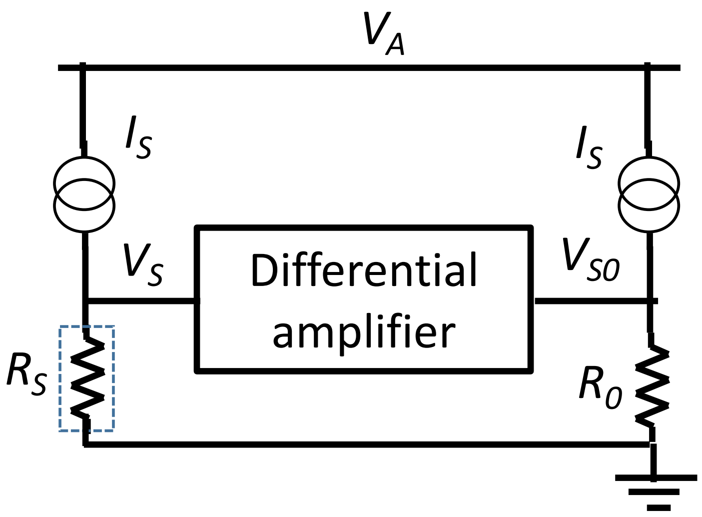
$$V_{S0} = I_S R_0$$

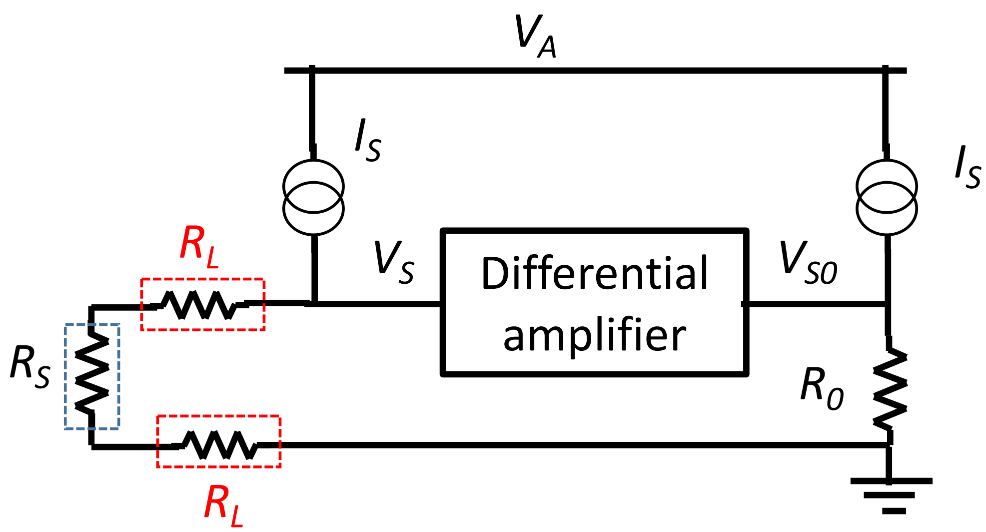
$$\Delta V_S = V_S - V_{S0} = I_S \cdot \Delta R_S = \\ = V_{S0}\frac{\Delta R_S}{R_0} \approx V_{S0}\alpha\Delta T$$

In modern electronics **a simple approach is possible** and practical thanks to the routine availability of current generators :

- R_S is biased with a **constant current** generator I_S
- Voltage V_S on R_S is measured
- At any T, ***V_S* is exactly proportional to *R_S*** : the difference ΔV_S from measured V_S to reference voltage V_{S0} gives an accurate measure of ΔR_S

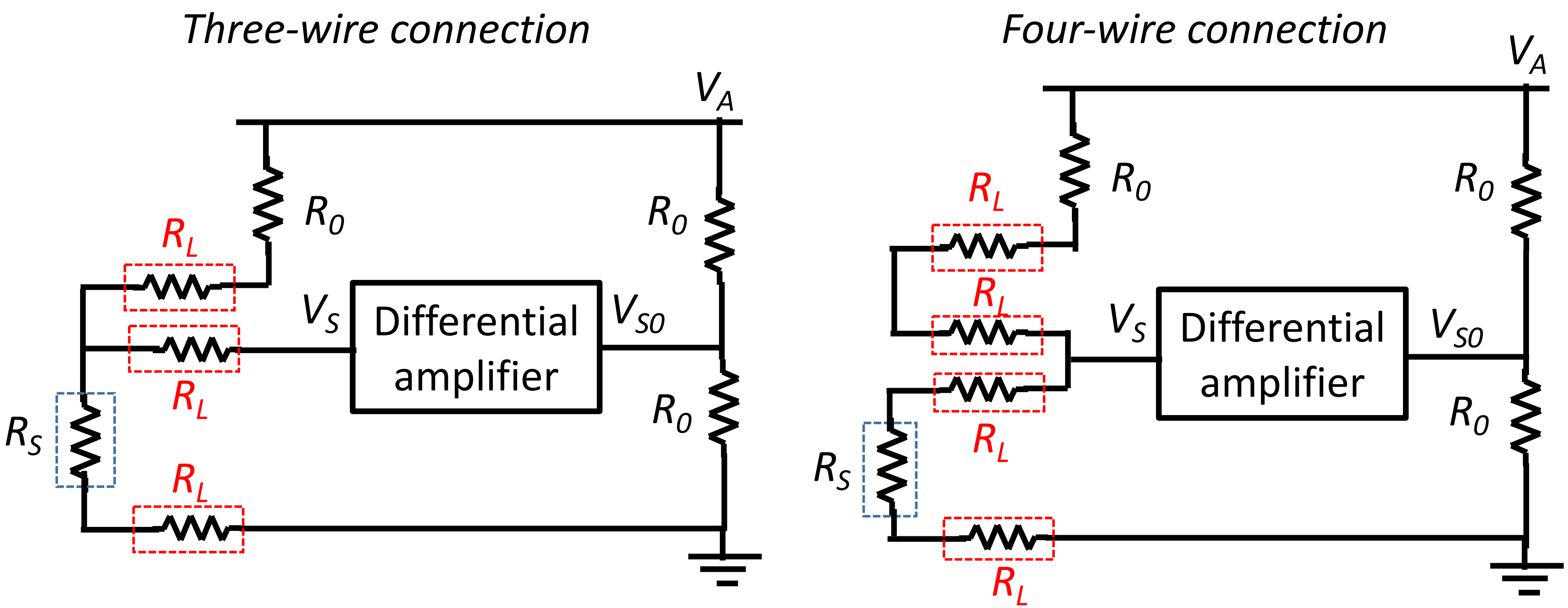
Differential Signal at Constant Current





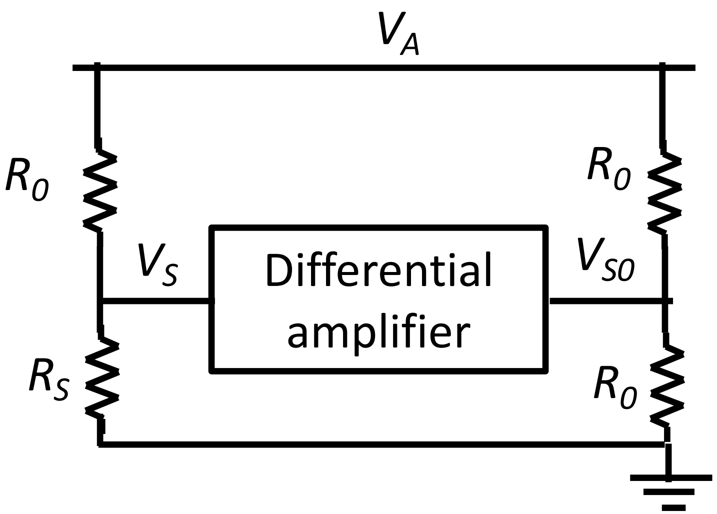
- **Since ΔV_S is much smaller than V_S**, it is advisable to include in the circuit a reference V_{S0} and take **directly differential measurements of ΔV_S**, instead of measuring V_S and then subtracting V_{S0}
- However, in various cases the RTD is placed on a measured object not near to the circuit, the **long connecting wires** have resistance R_L not negligible with respect to R_S and their **effect is significant** and must be taken into account
- In the simplest configuration, called **«Two-wire-connection»,** the two wire resistances are in series with R_S and their voltage drop $2I_S R_L$ is added to V_S, thus causing a significant error in the measured ΔV_S

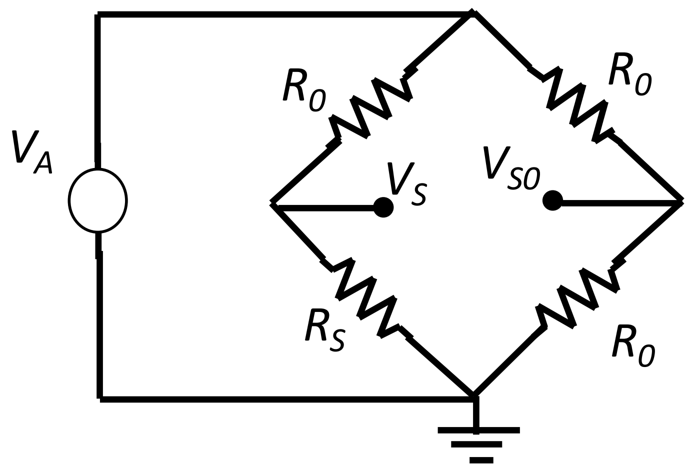
Remote RTD Operation



- «**Three-wire-connection**» adds one R_L to the RTD and one to the balancing resistance R_0 . The R_L of the connection to the differential amplifier is not compensated, but its effect is negligible because the current in it is negligible
- «**Four-wire-connection**» achieves complete simmetry between RTD arm and balancing arm, with complete cancellation of the errors due to wire resistances

RTD Operation in Wheatstone Bridge





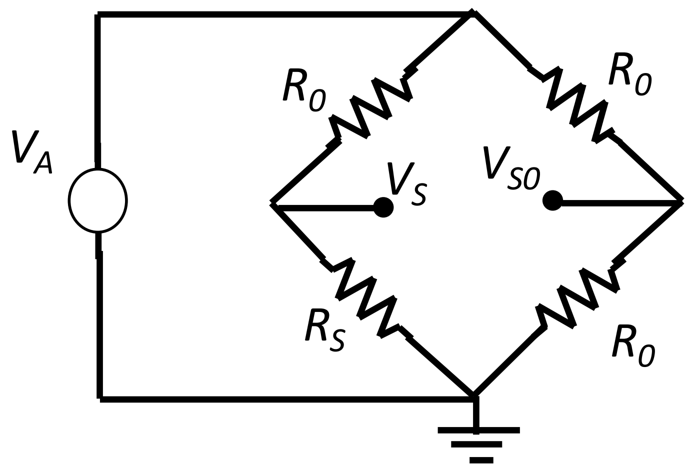
- An alternative configuration, devised when current generators were not available, requires only resistors and due to its simplicity is still widely exploited
- A **voltage divider** is implemented by the ***R_S* of the RTD** in series with a **reference resistor *R_0*** and the variations of the divider output voltage corresponding to the variations of R_S are measured
- This is the principle of the **Wheatstone bridge**, invented in 1833 by Samuel Hunter Christie and popularized by Charles Wheatstone and usually drawn as sketched above at right

RTD Linear Operation in Wheatstone Bridge

$$R_S = R_0 + \Delta R_S$$

$$V_{S0} = V_A \frac{R_0}{R_0 + R_0} = \frac{V_A}{2}$$

$$V_S = V_A \frac{R_S}{R_0 + R_S}$$



For **small resistance variation** ***ΔR_S*** *$< 0,05\ R_0$* the voltage variation ΔV_S is **approximately linear** with ΔR_S and can be computed by first-order development

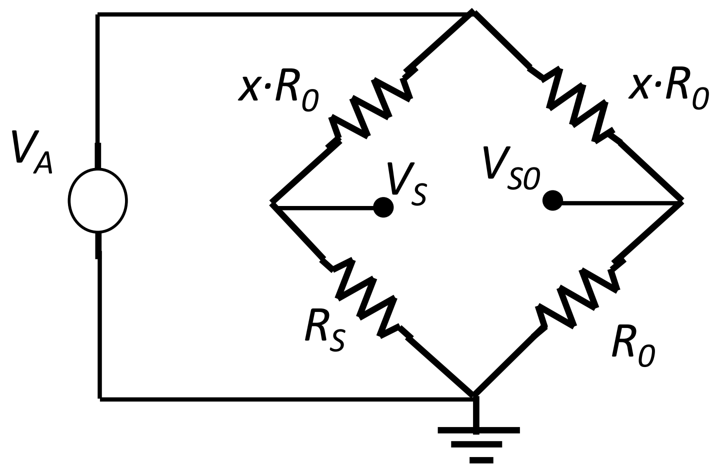
$$\Delta V_S = \Delta R_S \left(\frac{dV_S}{dR_S}\right)_{R_S = R_0} = \frac{V_A}{4}\frac{\Delta R_S}{R_0} = \frac{V_A}{4}\alpha\Delta T$$

RTD Linear Operation in Wheatstone Bridge

$$R_S = R_0 + \Delta R_S$$

$$V_{S0} = V_A \frac{R_0}{R_0 + xR_0} = \frac{V_A}{1+x}$$

$$V_S = V_A \frac{R_S}{xR_0 + R_S}$$

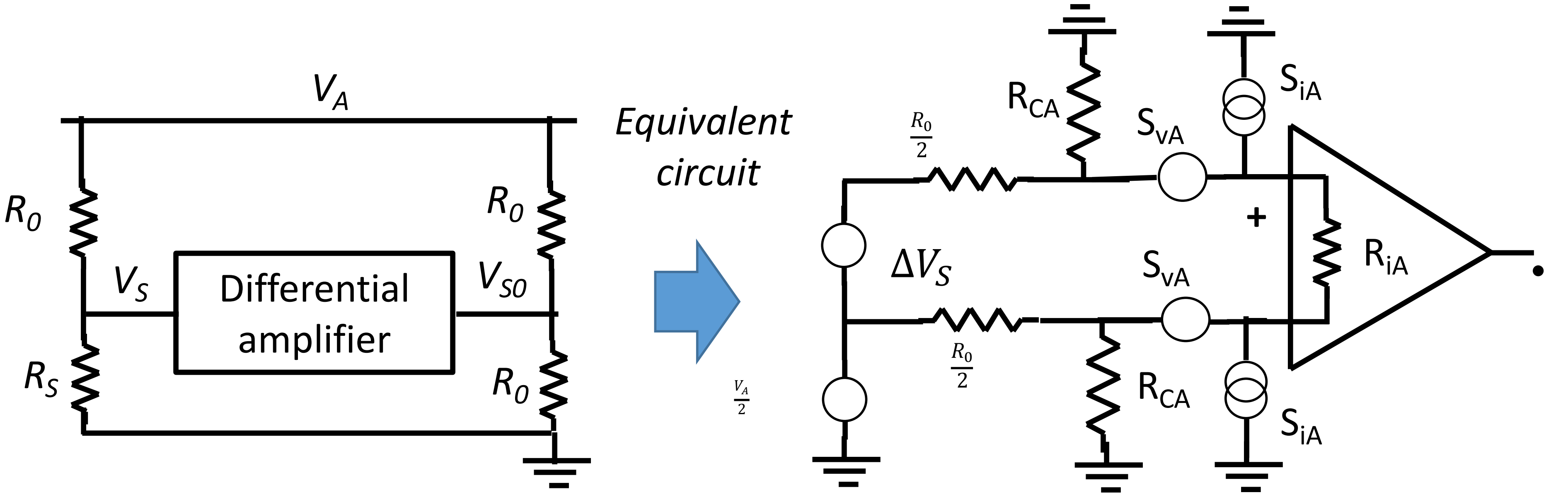


The Wheatstone bridge can be employed with **any ratio x** of the voltage divider, i.e. R_S can be in series with a resistor x·R_0 with any value of the factor x. However, it is intuitive and readily verified that **with x=1 the highest output ΔV$_S$** is obtained

$$\Delta V_S = \left(\frac{dV_S}{dR_S}\right)_{R_S=R_0} \Rightarrow \Delta R_S = V_A \frac{x}{(1+x)^2} \frac{\Delta R_S}{R_0}$$

$$\max\left[\frac{x}{(1+x)^2}\right] = \frac{1}{4} \quad for \quad x = 1$$

About RTD Preamplifiers



Since the **source resistance is low**, typically R_0=100 Ω:

- for the input differential resistance $\mathbf{R_{iA}}$ and the input-to-ground resistance $\mathbf{R_{CA}}$ **moderately high** values are sufficient
- the contribution of the input current noise generators is reduced, the input **voltage noise generators are dominant**

Since the differential signal ΔV_S is accompanied by a **high common mode signal $V_A/2$** :

- adequate **CMRR** is required **at the frequency of the supply V_A** , which can be selected at several kHz for reducing the 1/f noise contribution

Thermistors

- **Commonly used temperature transducers called Thermistors** are made of semiconductor ceramic materials, oxides of Cr, Mn, Fe, Co, Ni
- The dependence of thermistor resistance R on temperature is strikingly different from RTDs (see the plot in slide 29): strongly **nonlinear, decreases with increasing temperature** and the R values are **much larger** (some 100 kΩ at room temperature) and have much **greater relative variation**
- The resistance-temperature relationship can be described by the equation

$$R = \exp\left(\frac{B}{T}\right)$$

- where **T is the absolute temperature** in Kelvin degrees, B is constant. B is called characteristic temperature of the termistor and usually ranges from 2000 K to 4000 K.
- Making reference to the resistance value R_0 at a known reference temperature T_0 we get

$$R = R_0 \exp\left[B\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$

Thermistors

- Thermistors can be made **much smaller** than RTDs.
- The smaller mass enables them to respond **more quickly** to temperature variations
- The **smaller size**, however, makes **less efficient the dispersion of the self-heating** power, which must be limited to low level
- The basic advantage of thermistors with respect to RTDs is **higher sensitivity**, i.e. larger relative variation $\Delta R/R$ for a given ΔT, which eases measurements of very small ΔT
- The main disadvantages are **lower accuracy and lower reproducibility** and strongly nonlinear characteristics, which limit the application of thermistors in automatic control systems