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

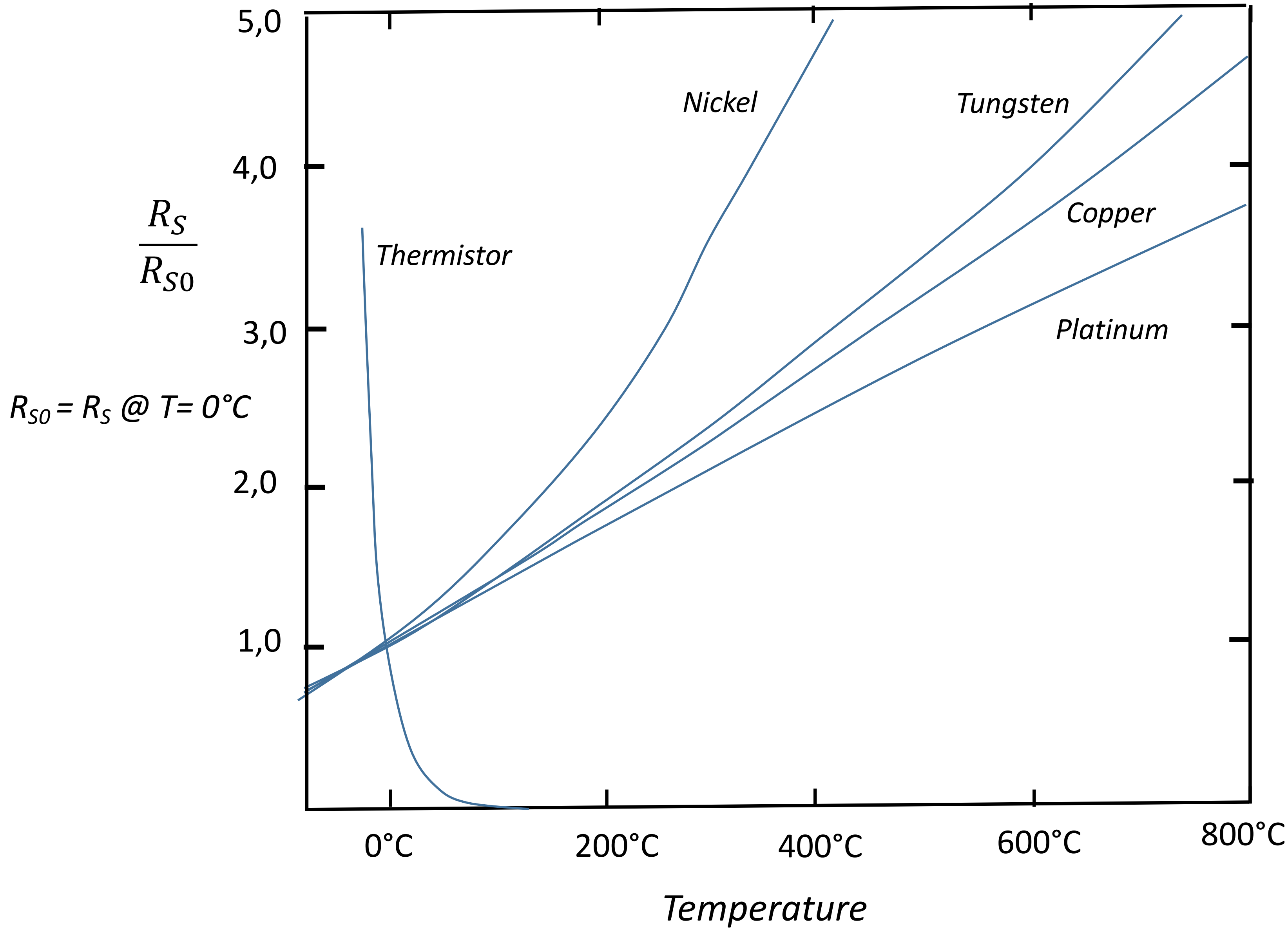
$R_S = R_0(1 + \alpha\Delta T)$ T_0 = reference temperature; $R_0 = R_S(T_0)$;

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

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

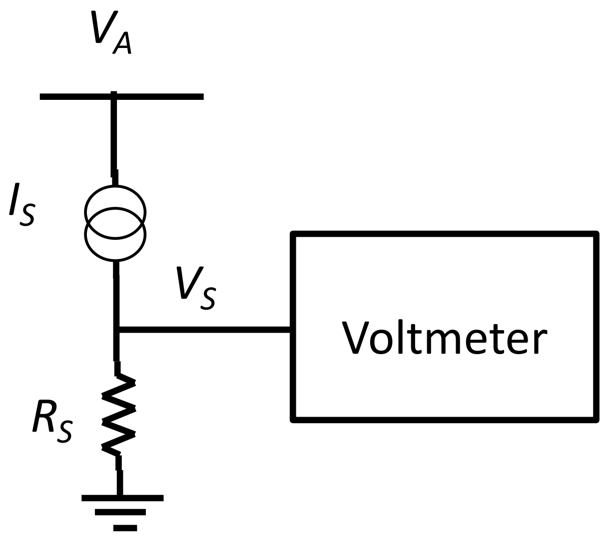
Generation of RTD Electrical Signal

- 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 $V_S < 100mV$.
- 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



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

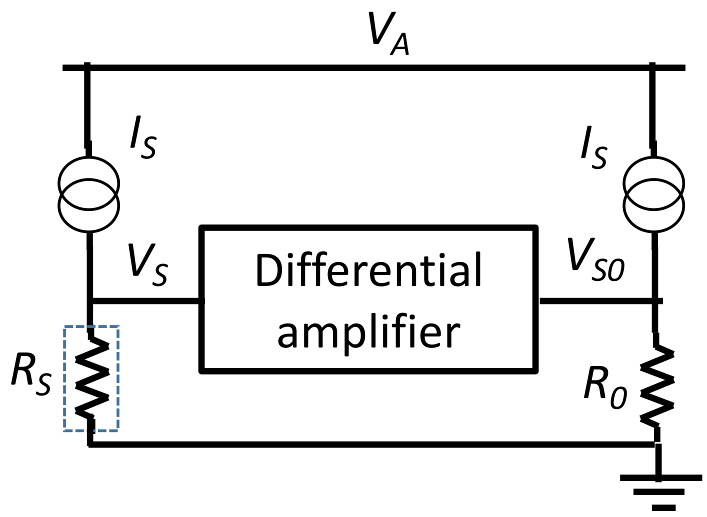
$$V_{S0} = I_S R_0$$

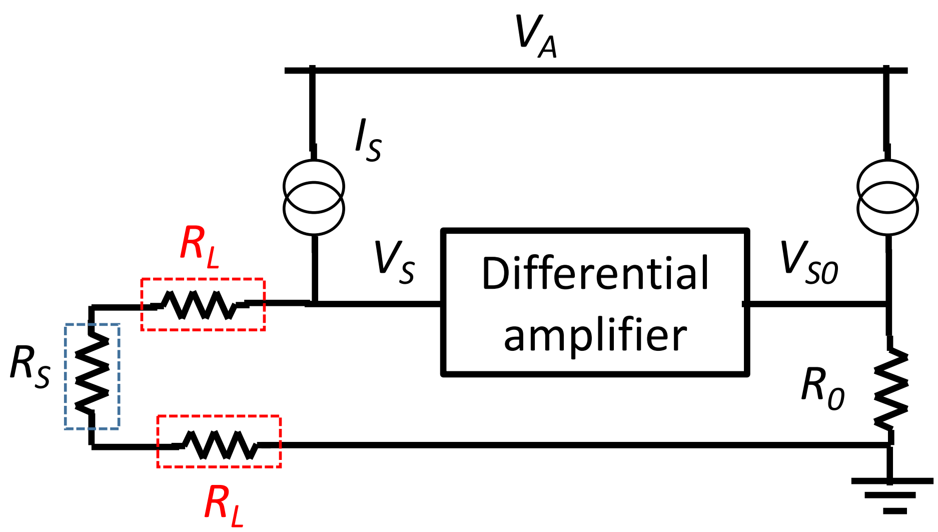
$$\Delta V_S = V_S - V_{S0} = I_S \cdot \Delta R_S = \\ = V_{S0} \frac{\Delta R_S}{R_0} \approx V_{S0} \alpha \Delta T$$

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
- ΔR_S is an accurately known function of $\Delta T = T - T_0$, in many cases approximately linear

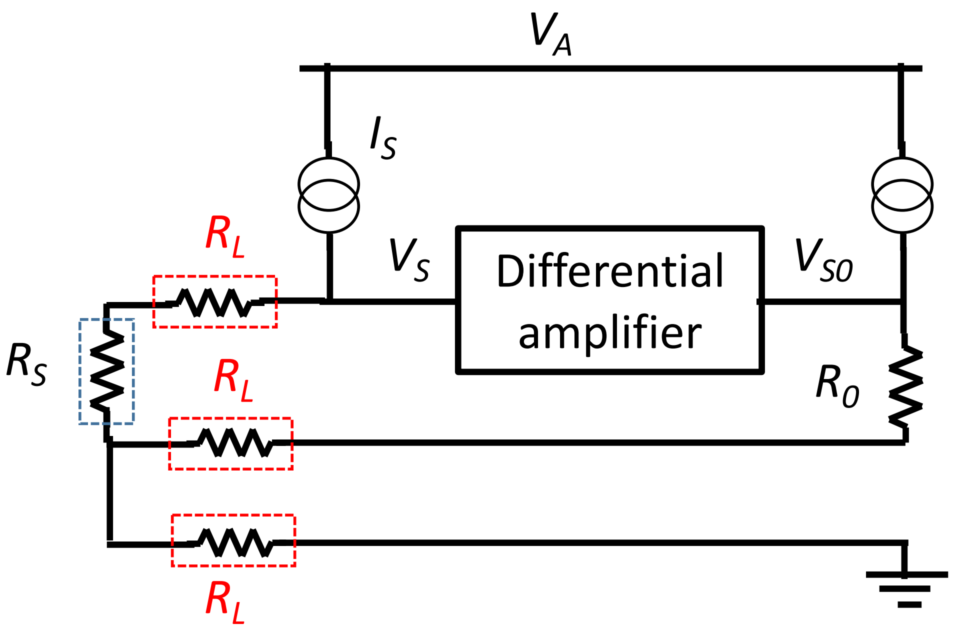
Differential Signal at Constant Current





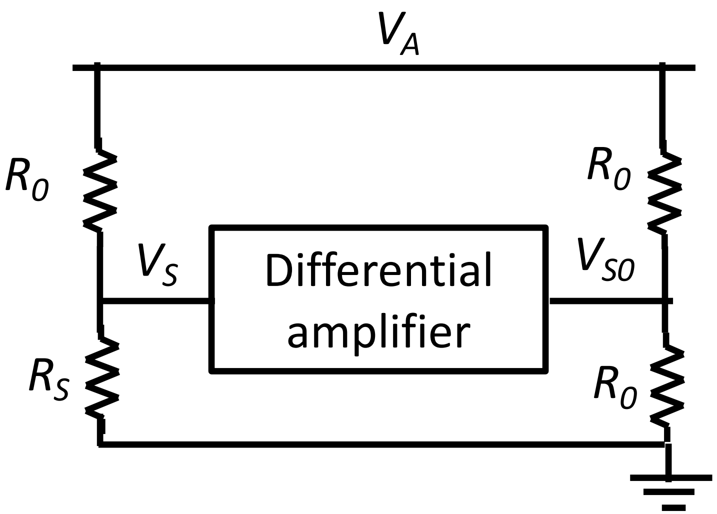
- Since ΔV_S is much smaller than V_S , it is advisable to include in the circuit a reference V_{S0} and take **directly differential measurements of ΔV_S ,** instead of measuring V_S and then subtracting V_{S0}
- However, in various cases the RTD is placed on a measured object not near to the circuit, 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

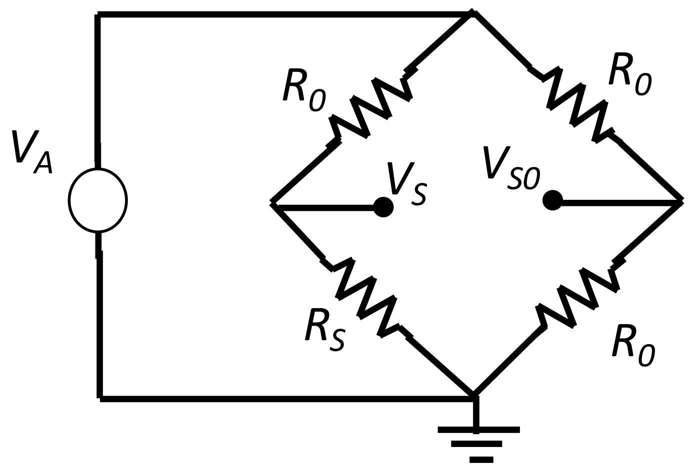
Remote RTD Operation



- Errors in ΔV_S due to wire resistances R_L are avoided by a **«Three-wire-connection».** Both the reference arm and the RTD arm include in series a wire resistance R_L ; the third wire resistance R_L is inserted in the common return to the circuit ground

RTD Operation in Wheatstone Bridge





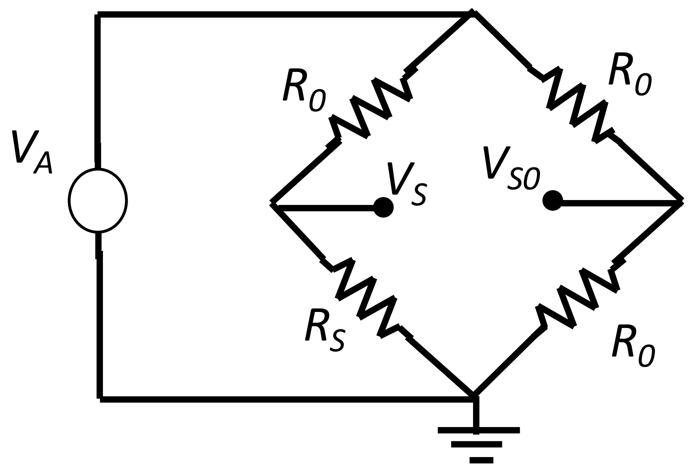
- An alternative configuration, devised when current generators were not available, requires only resistors and due to its simplicity is still widely exploited
- A **voltage divider** is implemented by the $\boldsymbol{R_S}$ **of the RTD** in series with a **reference resistor** $\boldsymbol{R_0}$ and 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** $\Delta R_S < 0{,}05\ R_0$ the voltage variation ΔV_S is **approximately linear** with ΔR_S and can be computed by first-order development

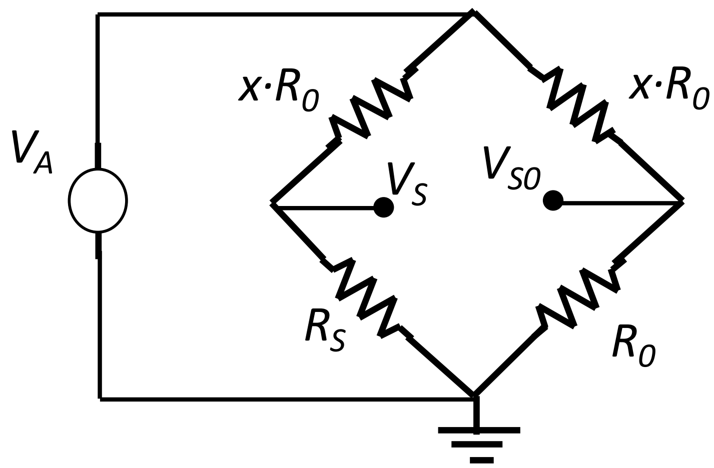
$$\Delta V_S = \Delta R_S \left(\frac{dV_S}{dR_S}\right)_{R_S = R_0} = \frac{V_A}{4}\frac{\Delta R_S}{R_0} = \frac{V_A}{4}\alpha \Delta T$$

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

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

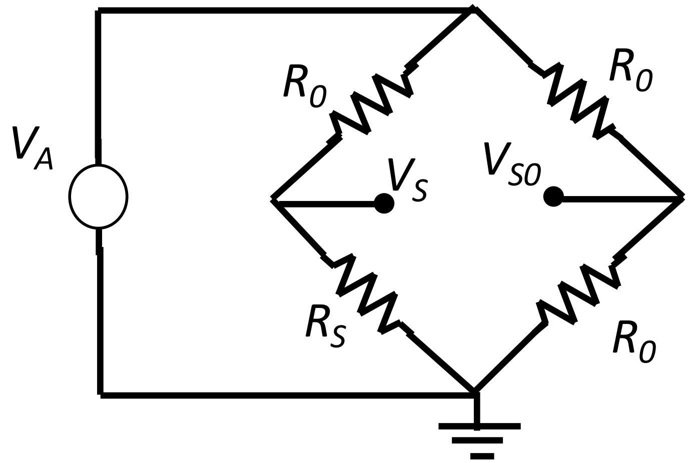
$$\max\left[\frac{x}{(1+x)^2}\right] = \frac{1}{4} \quad for \quad x = 1$$

RTD Nonlinear Operation in Wheatstone Bridge

$$R_S = R_0 + \Delta R_S$$

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

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

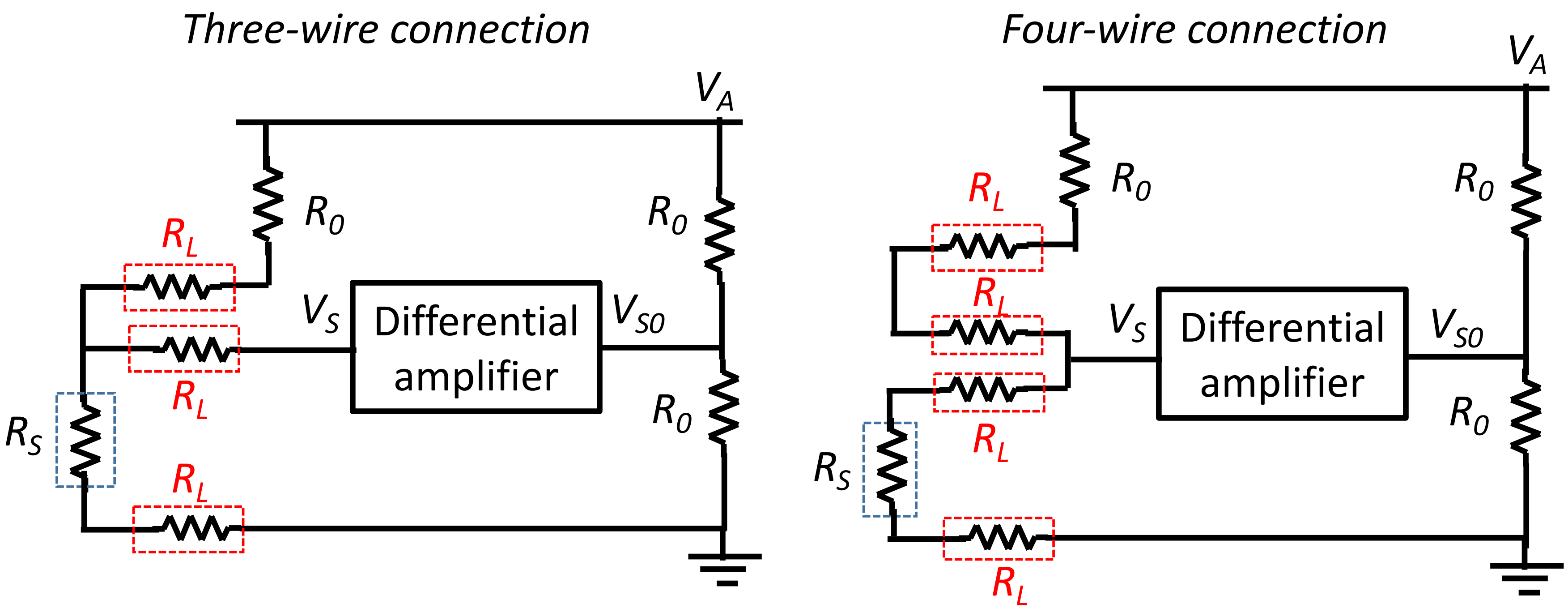


The cheap availability of integrated electronics for digital data processing and storage makes practical to extend the application of the Wheatstone bridge also to cases with **greater variations ΔR_S**, that have a **non-linear but known dependance** of ΔV_S on ΔR_S

$$\Delta V_S = V_S - V_{S0} = V_A \frac{R_0 + \Delta R_S}{2R_0 + \Delta R_S} - \frac{V_A}{2}$$

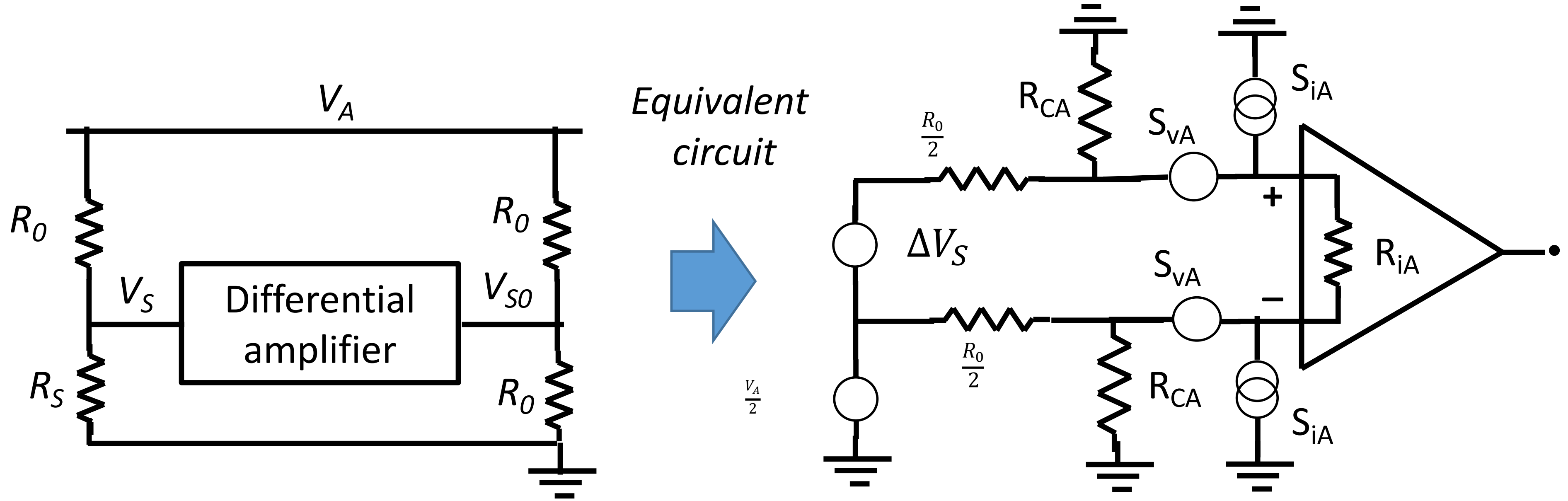
$$= \frac{V_A}{2} \cdot \frac{\frac{\Delta R_S}{2R_0}}{1 + \frac{\Delta R_S}{2R_0}}$$

Remote RTD Operation



- «**Two-wire connection**» causes error also in this case by adding $2R_L$ to R_S
- «**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 (and also cancellation of other minor thermoelectric effects caused by electrical current flowing in conductors with a temperature gradient)

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