5 Analog Signal Processing- Data Acquisition

5.1 Analog Measurement Procedures

5.2 Measurement of Resistances

Three- and Four-Wire-Method, Self-Heating
¼-Bridge, ½-Bridge, and Full-Bridge

5.3 Measurement of Capacitances and Inductivities

5.3.1 AC-Current-Bridges

Adjustability

Frequency dependent Adjustability

5.3.2 Measurement with Oszillator

5.3.3 Charge-Transfer Method for Measurement of Capacitances

5.3.4 Power Measurement Method

5.4 Computer-based Data Acquisition

5.1 Analog Measurement Procedures

Why analog measurement procedures?

Most sensors have an analog output signal

Current, voltage, resistance

Low-cost signal processing and realization

No quantization-error and no conversion time

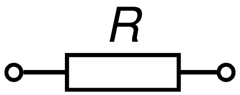
▷ Analog measurement systems can be faster!

5.1 Analog Measurement Procedures

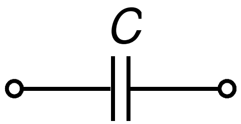
Impedance

$$\underline{Z} = R + jX$$

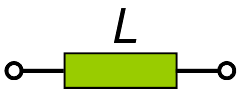
ideal



$$\underline{Z} = R$$

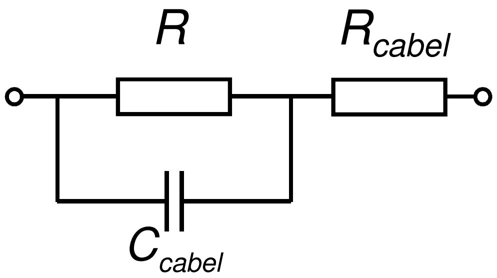


$$\underline{Z}_C = \frac{1}{j\omega C}$$

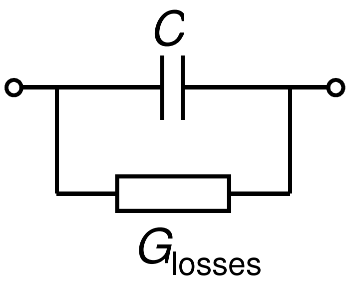


$$\underline{Z}_L = j\omega L$$

real

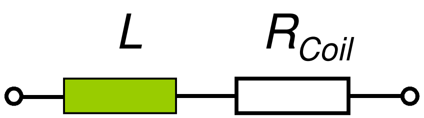


$$\underline{Z} = R_{cabel} + R \,||\, j\omega C_{cabel}$$



$$\underline{Y}_{real} = G_{losses} + jB = G_{losses} + j\omega\, C$$

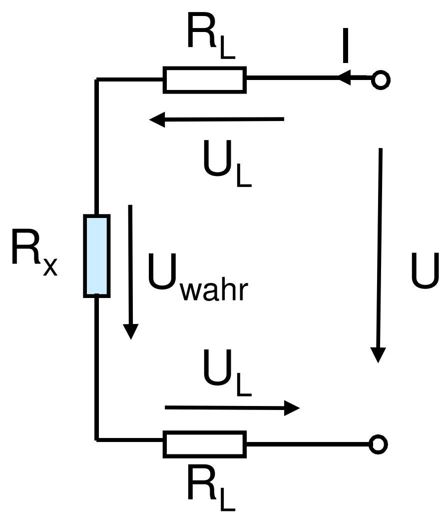
$$\underline{\varepsilon}_r = \varepsilon_r' - j\varepsilon_r'' = \frac{B}{\omega C_0} - j\frac{G}{\omega C_0}$$



$$\underline{Z}_{L,real} = R_{Coil} + j\omega L$$

5.2 Measurement of Resistances
4-Wires-Method

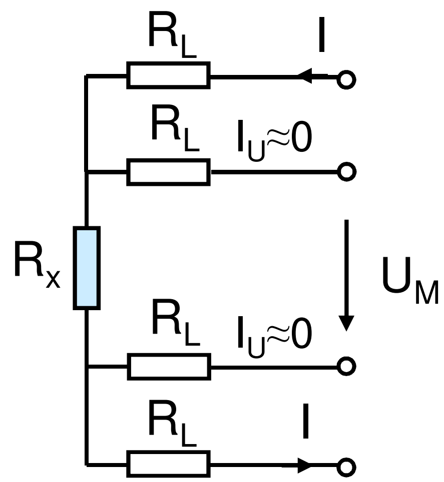
2-Wires-Method



<u>Error by</u>

- Temperature dependence of wires
  ≠Cable length →≠ R_L

4-Wires-Method

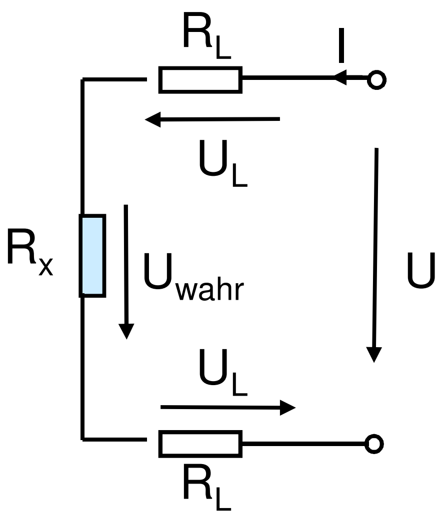


$$R_x = \frac{U_M}{I}$$

Total separation between current- and voltage-wires

5.2 Measurement of Resistances
3-Wires-Method

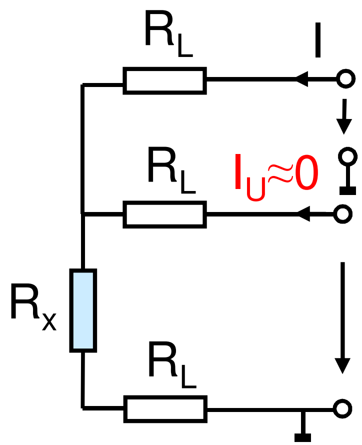
2-Wires-Method



<u>Error by</u>

- Temperature dependence of wires
  ≠Cable length →≠ R_L

3-Wires-Method



$$U_{L3} = (2R_L + R_x)\cdot I$$

$$U_M = (R_x + R_L)\cdot I$$

$$U_{L3} = 2U_M - R_x I$$

$$R_L = \frac{U_M}{I} - R_x$$

$$R_x = \frac{2U_M - U_{L3}}{I}$$

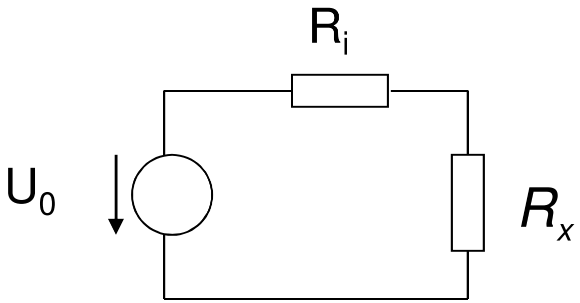
→ Compensation of cable resistance and its temperature dependence

<u>Prerequisit</u>

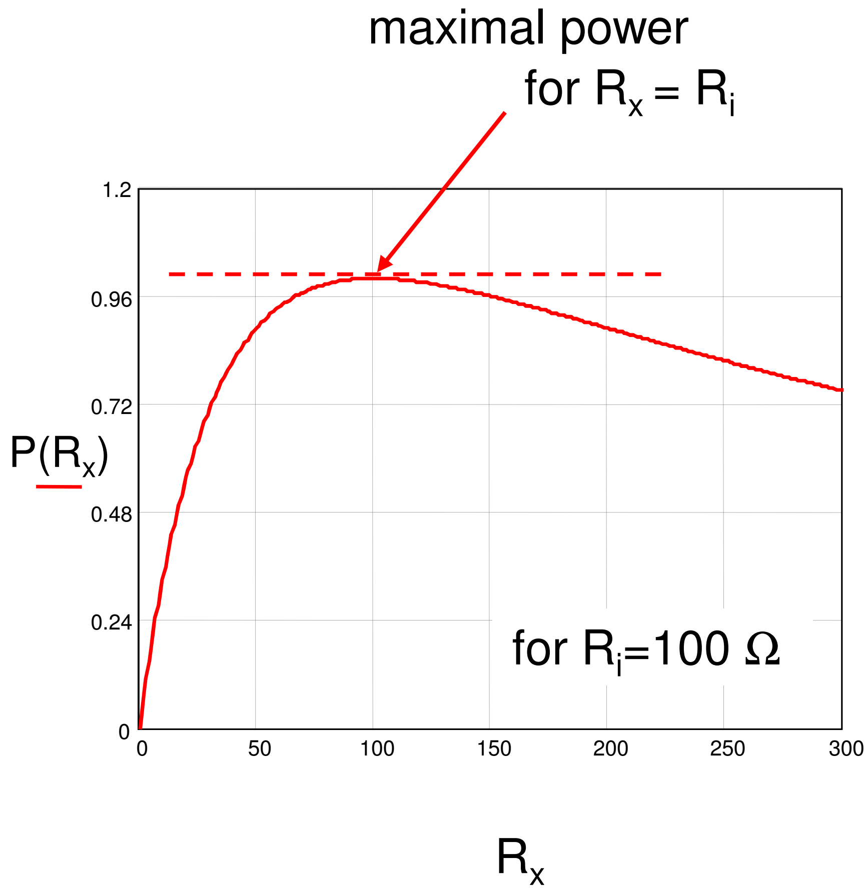
- 3 wires have the identical length and temperature

5.2 Measurement of Resistances

Self-Heating



$$\frac{\partial P}{\partial R_x} = \left(\frac{U_0}{R_i + R_x}\right)^2 \cdot \frac{R_i - R_x}{R_i + R_x}$$



Converted electric power

$$P = I^2 R_x = \left(\frac{U_0}{R_i + R_x}\right)^2 \cdot R_x$$

Self-heating through accumulated heat ΔT_{th}

$$\Delta T_{th} = R_W \cdot P$$

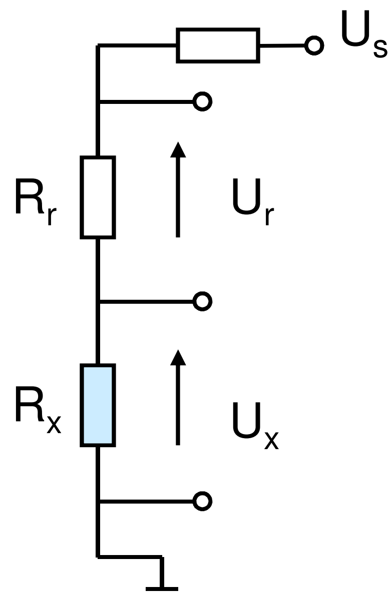
R_w: Heat resistance is dependent on:

- Packaging
- Surrounding media, its temperature and velocity!

5.2 Measurement of Resistances

Comparison with a reference resistance (reference principle)

$$R_x = \frac{U_x}{U_r} R_r$$



R_r and R_x should have the same order of magnitude

→ Resduction of uncertainty through common mode rejection

Typical values $R_r = R_{x,\,max}$

R_r: Reference resistance
R_x: Resistance to be measured

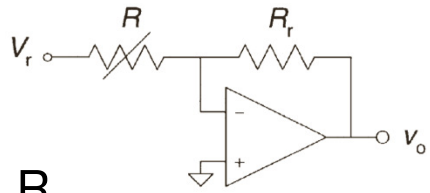
5.2 Measurement of Resistances
Voltage Devider

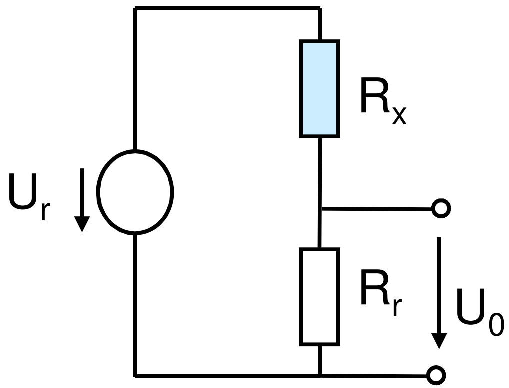
Suitable for high resistance values

$$U_0 = \frac{R_r}{R_r + R_x} \cdot U_r$$

$$R_x = R_r \frac{U_0}{U_r - U_0}$$

Nonlinear, because the current is unknown



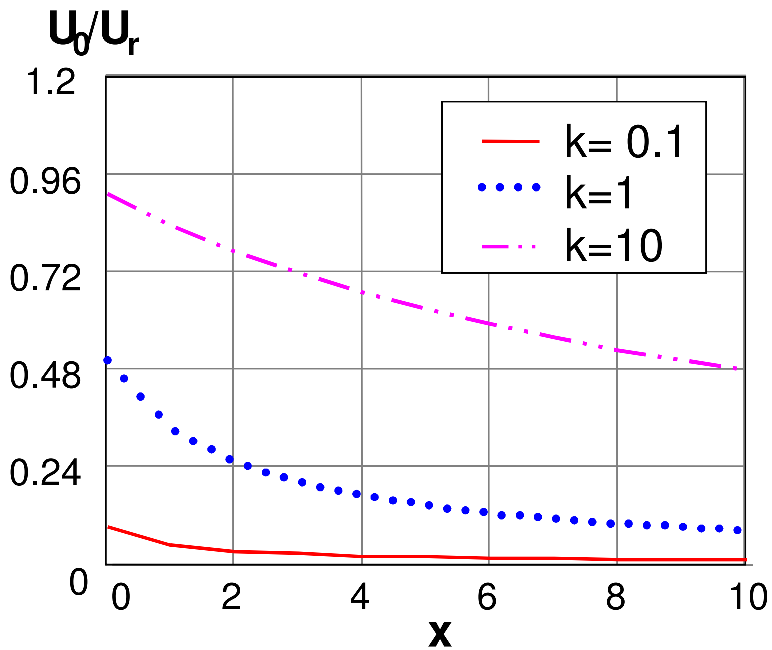


Example:

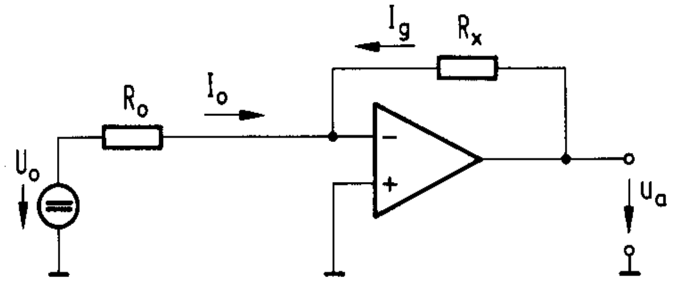
$$R_r = k\ R_0$$

$$R_x = R_0(1 + x)$$

$$\frac{U_0}{U_r} = \frac{k}{k + 1 + x}$$

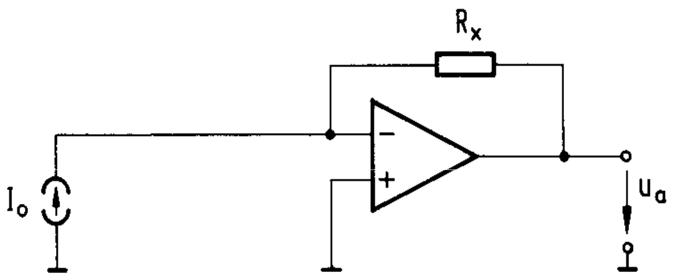


5.2 Measurement of Resistances
Inverting Amplifier



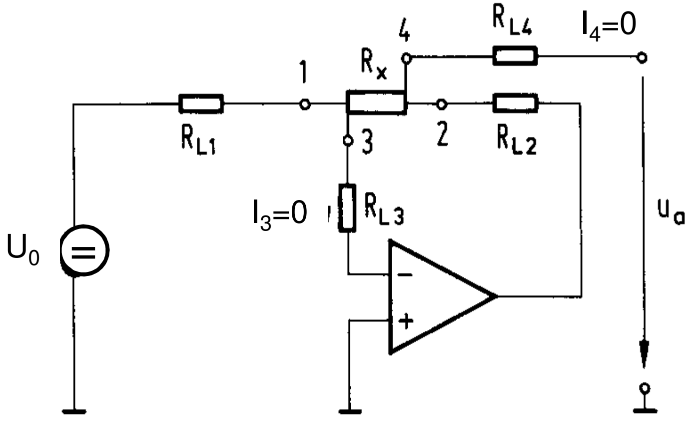
Supply with a constant voltage

$$U_a = -\frac{U_0}{R_0} R_x$$



Supply with a constant current

$$U_a = -I_0 R_x$$



4 –Wires-connection and constant current supply

$$U_a = -I_0 R_x$$

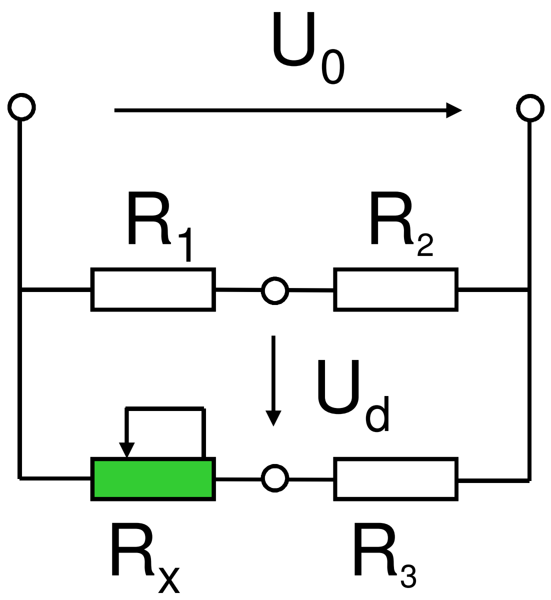
Offset-currents and offset-voltages are problematic if resistances have small changes!

5.2 Measurement of Resistances
Wheatstone-Bridge

$$U_d = U_0 \left(\frac{R_2}{R_1 + R_2} - \frac{R_3}{R_3 + R_x} \right)$$

$$= \frac{R_2 \cdot R_x - R_1 \cdot R_3}{(R_1 + R_2) \cdot (R_3 + R_x)} U_0$$

$$R_1 = R_2 = R_3 = R$$



Bridge Voltage

$$U_d = U_0 \left(\frac{1}{2} - \frac{R}{R + R_x} \right)$$

Dependence on R_x is nonlinear!

Sensitivity

$$E = \frac{\partial U_d}{\partial R_x} = \frac{-R}{(R + R_x)^2} U_0$$

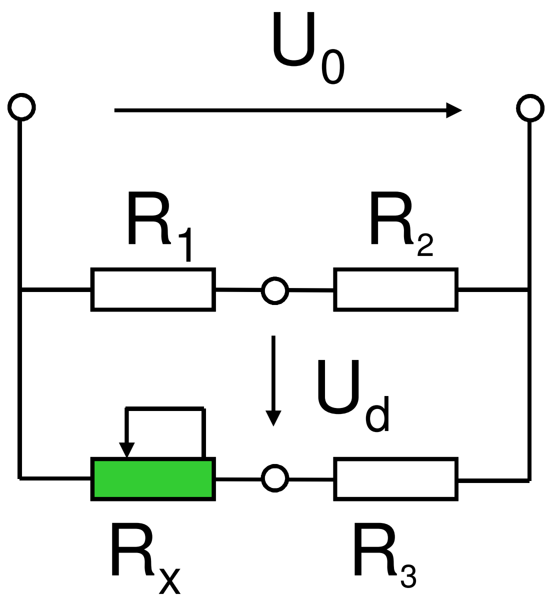
Proportional to supply voltage

5.2 Measurement of Resistances

Wheatstone-Bridge

$$U_d = U_0\left(\frac{R_2}{R_1+R_2} - \frac{R_3}{R_3+R_x}\right)$$

$$= \frac{R_2 \cdot R_x - R_1 \cdot R_3}{(R_1+R_2)\cdot(R_3+R_x)}$$



$$R_1 = R_2 = R_3 = R_0$$

$$R_x = R_0 + \Delta R$$

$$U_d = \frac{R_0 \cdot (R_0 + \Delta R) - R_0 \cdot R_0}{(R_0 + R_0)\cdot(R_0 + R_0 + \Delta R)} U_0$$

$$= \frac{\Delta R}{4R_0 + 2\Delta R} U_0 \approx \frac{\Delta R}{4R_0} U_0$$

$$\boxed{U_d \approx \frac{\Delta R}{4R_0} U_0}$$

5.2 Measurement of Resistances

1/4-, 1/2- and Fullbridge

U_d near a certain working point

$$U_d = U_0 \frac{R_2 R_3 - R_1 R_4}{(R_1 + R_2)(R_3 + R_4)}$$

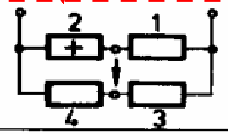
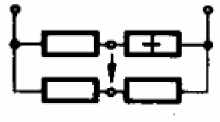
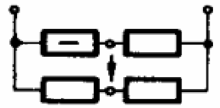
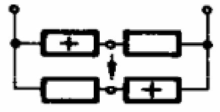
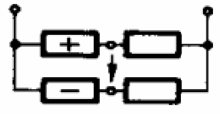
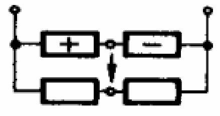
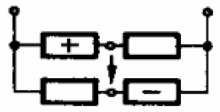
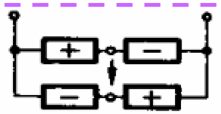
For small ΔR

$$U_d = \frac{U_0}{4}\left(\frac{\Delta R_2}{R_2} - \frac{\Delta R_1}{R_1} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right)$$

[+] → $R_0+\Delta R$
[-] → $R_0-\Delta R$
[ ] → R_0

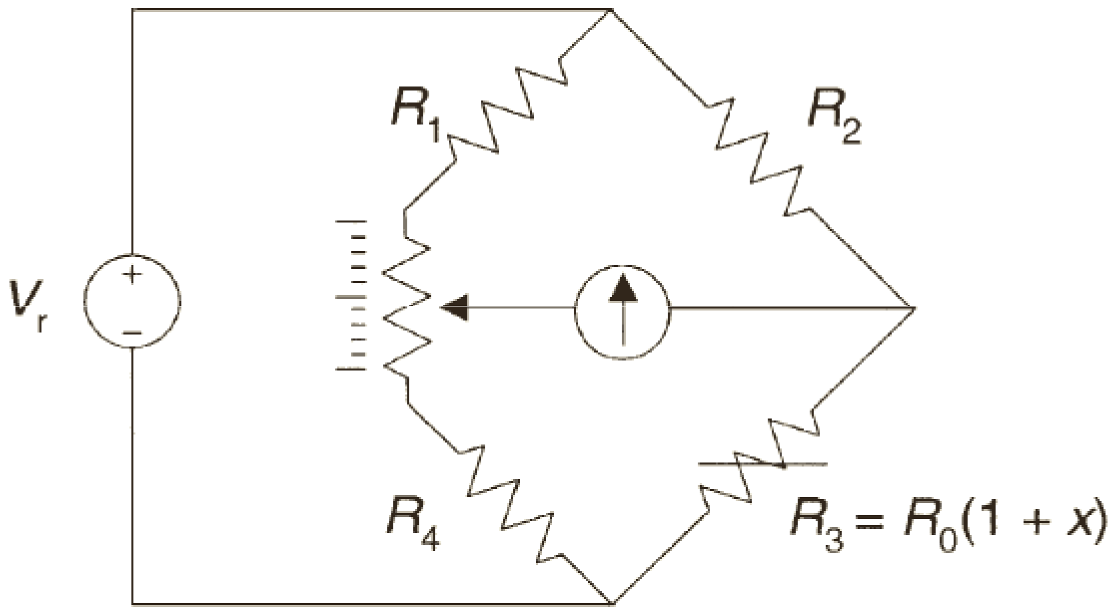
[Schrüfer]

¼-brücke (rows a–c), ½-brücke (rows d–g), Fullbridge (row h)

		U_0– gespeist	I_0– gespeist
a		$U_d \approx +\frac{U_0}{4}\frac{\Delta R}{R_0}$	$U_d \approx \frac{I_0}{4}\Delta R$
b		$U_d \approx -\frac{U_0}{4}\frac{\Delta R}{R_0}$	$U_d \approx -\frac{I_0}{4}\Delta R$
c		$U_d \approx -\frac{U_0}{4}\frac{\Delta R}{R_0}$	$U_d \approx -\frac{I_0}{4}\Delta R$
d		$U_d \approx \frac{U_0}{2}\frac{\Delta R}{R_0}$	$U_d = \frac{I_0}{2}\Delta R$
e		$U_d \approx \frac{U_0}{2}\frac{\Delta R}{R_0}$	$U_d = \frac{I_0}{2}\Delta R$
f		$U_d = \frac{U_0}{2}\frac{\Delta R}{R_0}$	$U_d = \frac{I_0}{2}\Delta R$
g		$U_d \approx -\frac{U_0}{4}\left(\frac{\Delta R}{R_0}\right)^2$	$U_d = -\frac{I_0}{4}\frac{\Delta R}{R_0}\Delta R$
h		$U_d = U_0\frac{\Delta R}{R_0}$	$U_d = I_0 \Delta R$

5.2 Measurement of Resistances

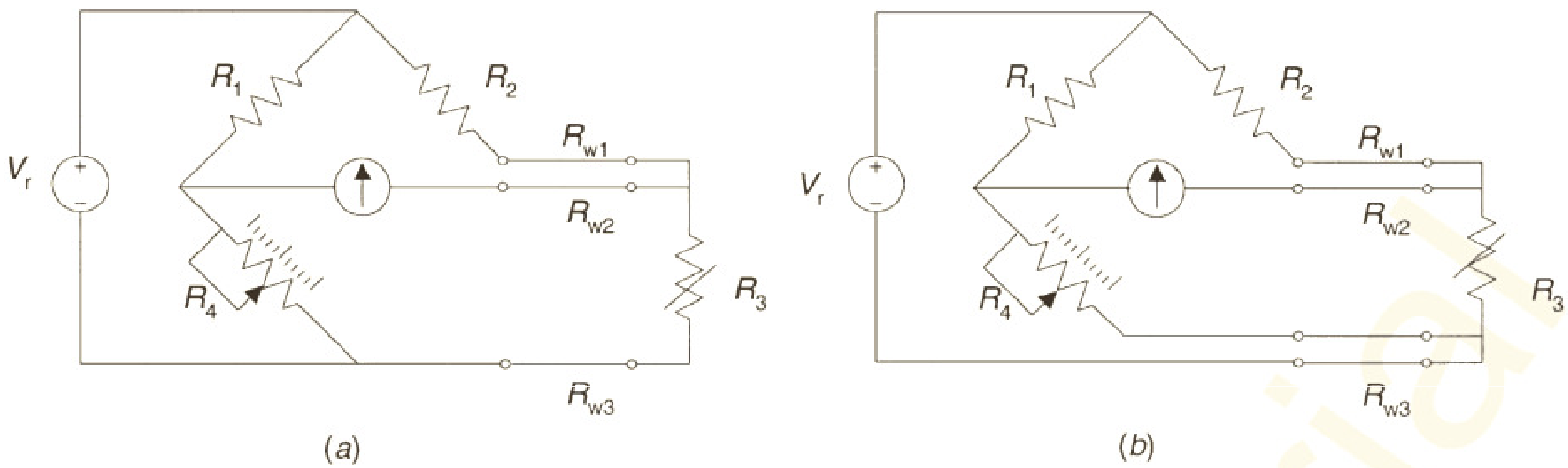
Fullbridge



- Reduction of the effect of contact resistance

5.2 Measurement of Resistances

Fullbridge with 3 wires and 4 wires contacting

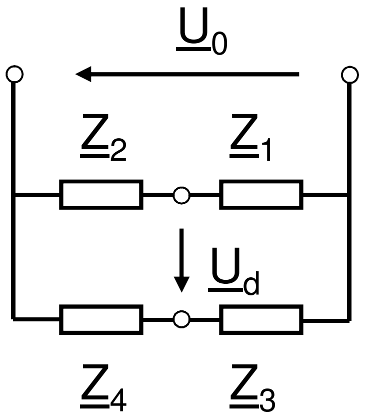


Deviation: $\varepsilon = \Delta R_3 / R_3$

$$\varepsilon = \frac{R_4 R_2 / R_1 - R_3}{R_3} = \frac{R_w}{R_3}\left(1 - \frac{R_4}{R_1}\right)$$

$R_3 >> R_W$

Alternating current bridge



$$\underline{U}_d = \left(\frac{\underline{Z}_2}{\underline{Z}_1 + \underline{Z}_2} - \frac{\underline{Z}_4}{\underline{Z}_4 + \underline{Z}_3} \right) \cdot \underline{U}_0$$

Adjustment for für: $\underline{Z}_1 \underline{Z}_4 = \underline{Z}_3 \underline{Z}_2$

With $\underline{Z}_k = Z_k \, e^{j\varphi_k}$

$$Z_1 \, e^{j\varphi_1} \; Z_4 \, e^{j\varphi_4} = Z_3 \, e^{j\varphi_3} \; Z_2 \, e^{j\varphi_2}$$

$$Z_1 \, Z_4 e^{j(\varphi_1 + \varphi_4)} = Z_3 \, Z_2 \, e^{j(\varphi_3 + \varphi_2)}$$

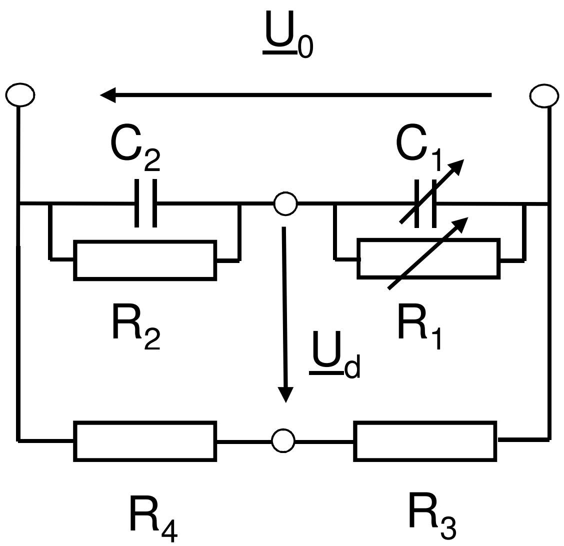
Necessary conditions for adjustment:

1. Phase condition $\varphi_1 + \varphi_4 = \varphi_3 + \varphi_2$

2. Modulus condition $Z_1 \, Z_4 = Z_3 \, Z_2$!

5.3.1 AC-Current-Bridge

Capacitance bridge by Wien
(measurement of lossy capacitances)



R_2, C_2 are unknownt

R_1, C_1 are modifiable

Condition for adjustment

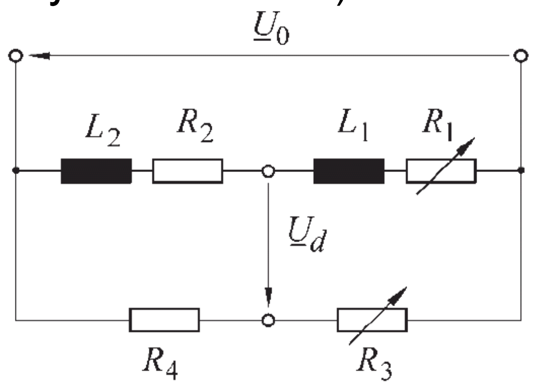
$$\frac{\dfrac{R_2}{j\omega C_2}}{R_2 + \dfrac{1}{j\omega C_2}} R_3 = \frac{\dfrac{R_1}{j\omega C_1}}{R_1 + \dfrac{1}{j\omega C_1}} R_4$$

$$R_2 = \frac{R_4}{R_3} R_1$$

$$C_2 = \frac{R_3}{R_4} C_1$$

5.3.1 AC-Current-Bridge

Inductivity-Bridge by Maxwell
(Measurement of lossy Inductivities)

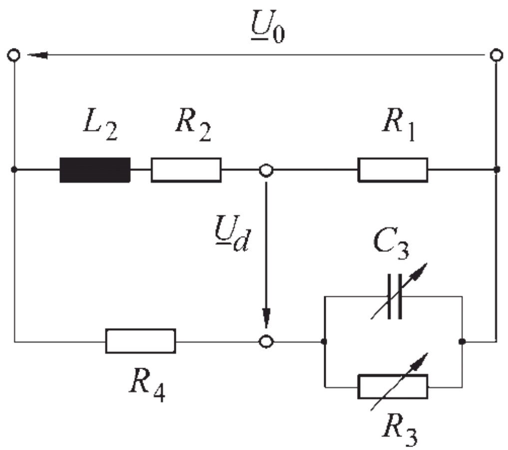


L_2, R_2 are unknown

$$L_2 = \frac{L_1\,R_4}{R_3}$$

$$R_2 = \frac{R_4}{R_3}\,R_1$$

Inductivity-Bridge by Maxwell-Wien
(Measurement of lossy Inductivities)

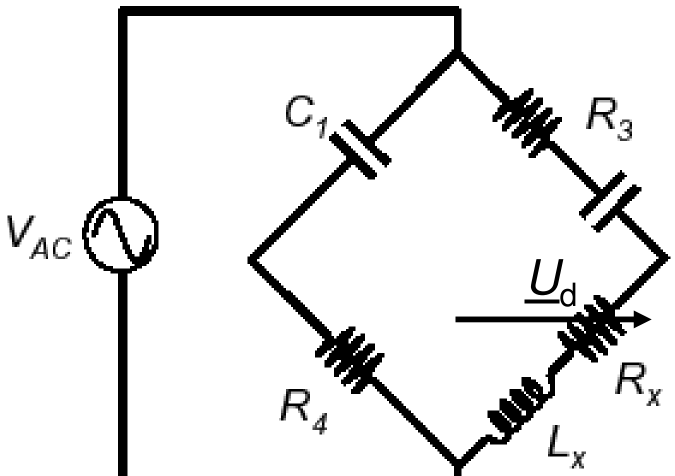


L_2, R_2 are unknown

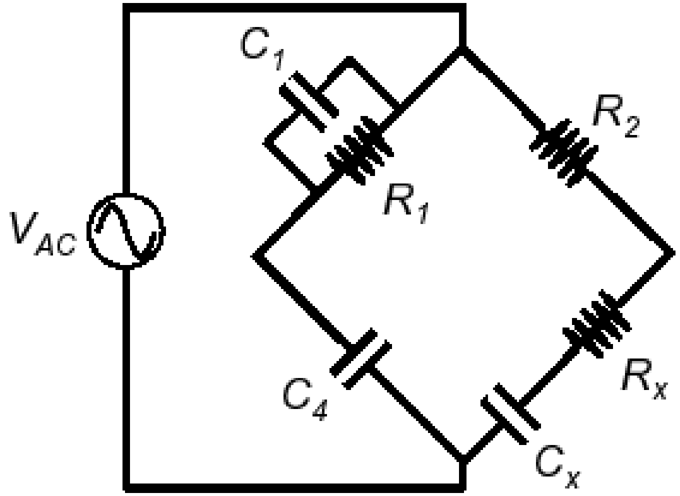
$$L_2 = R_1\,R_4\,C_3$$

$$R_2 = \frac{R_1\,R_4}{R_3}$$

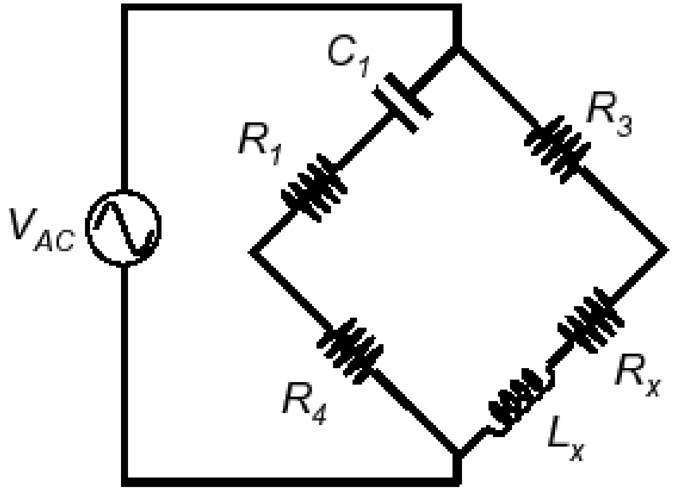
5.3.1 AC-Current-Bridge



Owen



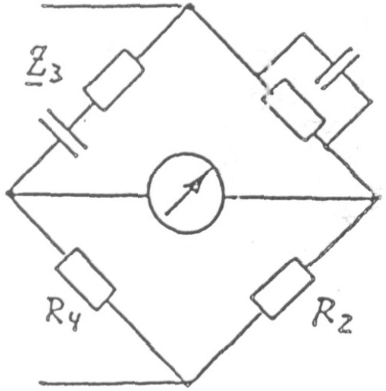
Schering

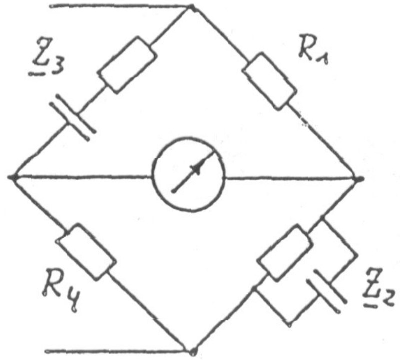


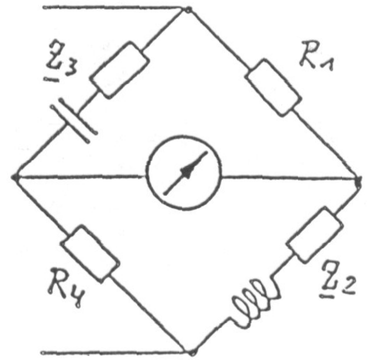
Hay

5.3.1 AC-Current-Bridge

Checking the phase condition



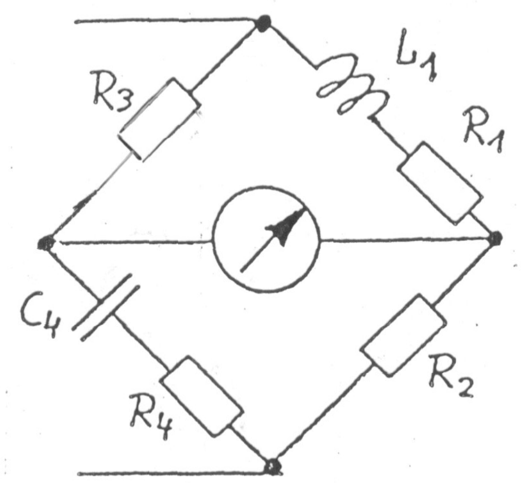




$\varphi_3 < 0 \quad \varphi < 0$	$\varphi_3 < 0 \quad \varphi_1 = 0$	$\varphi_3 < 0 \quad \varphi_1 = 0$
$\varphi_4 = 0 \quad \varphi_2 = 0$	$\varphi_4 = 0 \quad \varphi_2 < 0$	$\varphi_4 = 0 \quad \varphi_2 > 0$
$\varphi + \varphi_4 < 0$	$\varphi_1 + \varphi_4 = 0$	$\varphi_1 + \varphi_4 = 0$
$\varphi_3 + \varphi_2 < 0$	$\varphi_3 + \varphi_2 < 0$	$\varphi_3 + \varphi_2$ beliebig
Adjustment is possible	Adjustment is not possible	Adjustment is possible

The judgement of the modulus condition is in the special case necessary !

5.3.1 AC-Current-Bridge
Frequency dependence of the adjustment



$$\underline{Z}_1 = R_1 + j\,\omega\,L_1$$

$$\underline{Z}_2 = R_2$$

$$\underline{Z}_3 = R_3$$

$$\underline{Z}_4 = R_4 - j\frac{1}{\omega\,C_4}$$

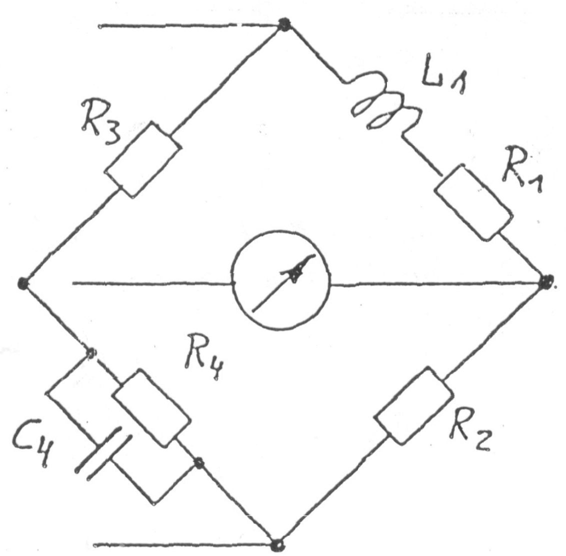
$$\underline{Z}_1\,\underline{Z}_4 = \underline{Z}_3\,\underline{Z}_2 \quad \triangleright \quad (R_1 + j\omega L_1)\left(R_4 - j\frac{1}{\omega\,C_4}\right) = R_3\,R_2$$

$$\triangleright \quad R_1\,R_4 + \frac{L_1}{C_4} = R_3\,R_2$$

$$\frac{R_1}{\omega\,C_4} = \omega\,L_1\,R_4$$

Frequency dependent adjustment

5.3.1 AC-Current-Bridge
Frequency dependence of the adjustment



$$\underline{Z}_1 = R_1 + j\,\omega L_1$$

$$\underline{Z}_2 = R_2$$

$$\underline{Z}_3 = R_3$$

$$\underline{Z}_4 = \frac{1}{\frac{1}{R_4} + j\omega C_4}$$

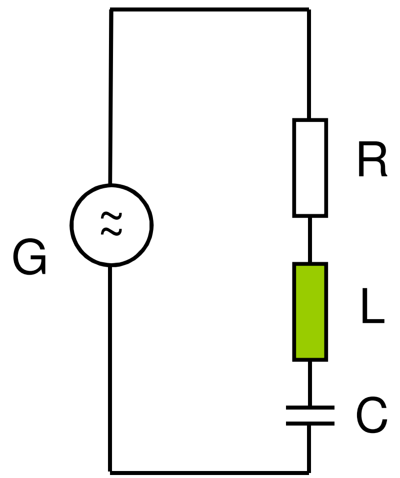
$$\underline{Z}_1\,\underline{Z}_4 = \underline{Z}_3\,\underline{Z}_2$$

$$R_3 R_2 = R_1 R_4$$

$$C_4 = \frac{L_1}{R_2 R_3}$$

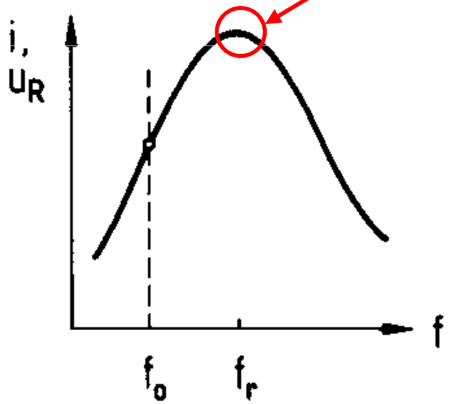
Frequency independent adjustment!

5.3.2 Measurement with Oscillators



$$Z = R + jX = R + j\left(\omega L - \frac{1}{\omega C}\right)$$

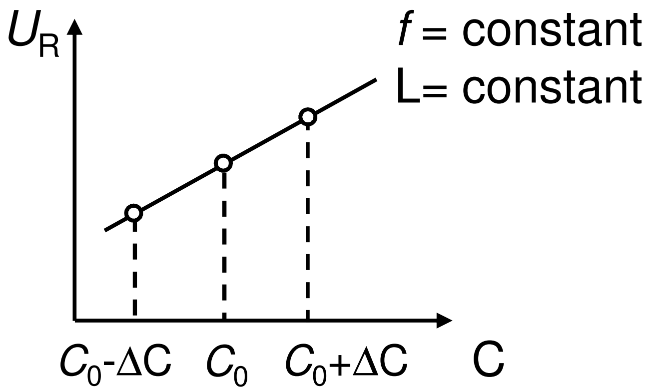
Resonance frequency:



$$\omega_r L = \frac{1}{\omega_r C} \qquad f_r = \frac{1}{2\pi}\frac{1}{\sqrt{LC}}$$

⇒ L or C measurement

Example

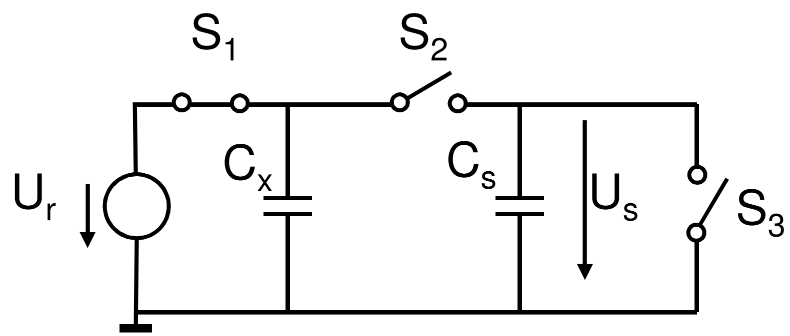


5.3.3 Charge-Transfer Method for Measurment of Capacitances

Signal preprocessing for capacitive sensors, which are suitable for monolitic Integration!

S_1 closed
→ C_x is charged to U_r

S_1 openned and S_2 closed
→ C_s is charged to U_s

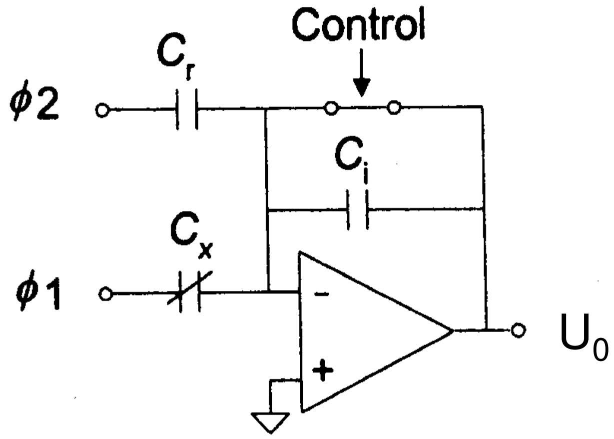


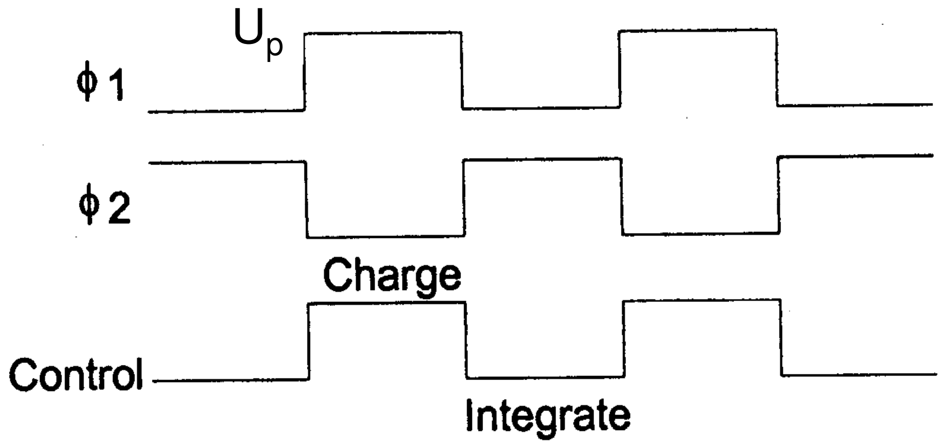
$C_x << C_s$

$$U_s = U_r \cdot \frac{C_x}{C_x + C_s} \approx U_r \cdot \frac{C_x}{C_s}$$

$$C_x = C_s \cdot \frac{U_s}{U_r}$$

5.3.3 Charge-Transfer Method for Measurement of Capacitances





Voltages Φ1 und Φ2 are switched together with the Relai "Control"

During Φ1 is switched on U_p :
- Relay "Control" is closed
- The (-)-Input of the OPV is on ground
- The capacitance C_x is loaded

During Φ2 is switched on U_p :
- The Relay "Control" is opened
- It flows a current from C_x over C_i

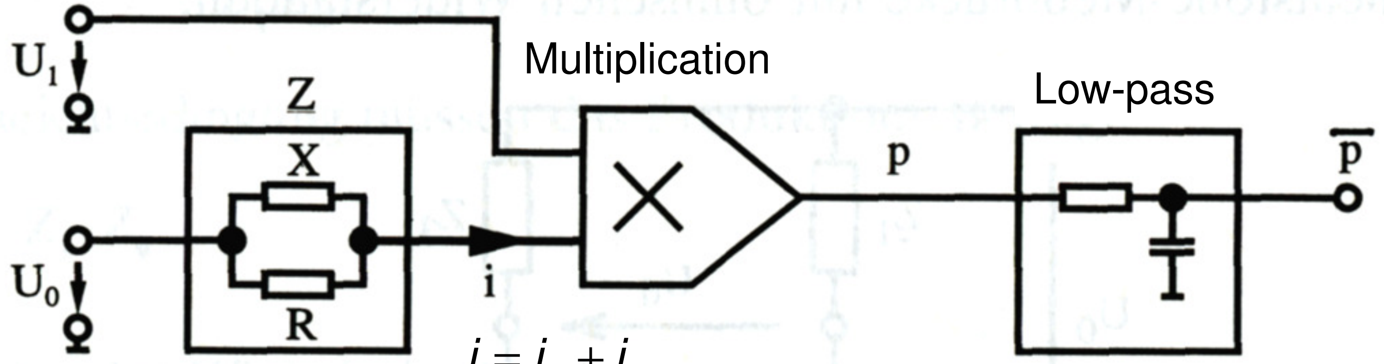
$$U_0 = U_p \cdot \frac{C_x - C_r}{C_i}$$

5.3.3 Power Measurement Method

$$u_1 = \hat{u}_1 \sin(\omega t + \varphi)$$

φ selectable

$$u_0 = \hat{u}_0 \sin(\omega t)$$



$i = i_x + i_R$

Case 1: $\varphi = 0°$

$$p = \left\{ \frac{\hat{u}_0}{R} \sin(\omega t) + \hat{u}_0\ \omega C \cos(\omega t) \right\} \hat{u}_1 \sin(\omega t)$$

$$= \frac{\hat{u}_1 \hat{u}_0}{R} \sin^2(\omega t) + \hat{u}_0 \hat{u}_1\ \omega C \cos(\omega t)\sin(\omega t)$$

$$= \frac{\hat{u}_1 \hat{u}_0}{2R} - \frac{\hat{u}_1 \hat{u}_0}{2R} \cos(2\omega t) + \frac{\hat{u}_0 \hat{u}_1}{2}\ \omega C \sin(2\omega t)$$

$$\sin(x)\cos(y) = \frac{1}{2}\left(\sin(x-y) + \sin(x+y)\right)$$

$$\sin^2(x) = \frac{1}{2}\left(1 - \cos(2x)\right)$$

$$\overline{p} = \frac{1}{T}\int_0^T p_w(t)\, dt = \frac{\hat{u}_0 \hat{u}_1}{2R}$$

Measurement of active power

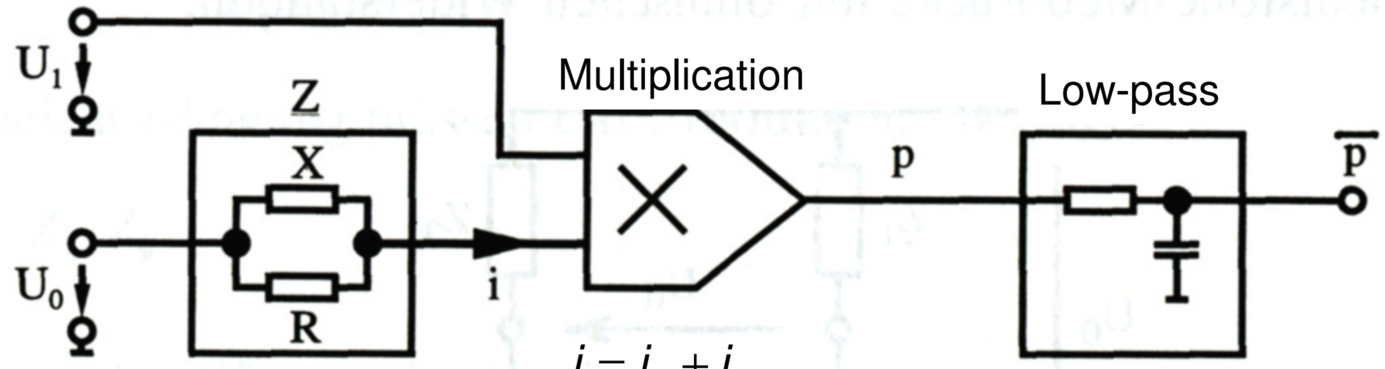
$\varphi = 0°$ $\quad \overline{p_w} = \dfrac{\hat{u}_0\, \hat{u}_1}{2R}$ ▶ R

5.3.3 Power Measurement Method

$u_1 = \hat{u}_1 \sin(\omega t + \varphi)$

φ selectable

$u_0 = \hat{u}_0 \sin(\omega t)$



$i = i_x + i_R$

Case 2: $\varphi = 90°$

$$\sin(x)\cos(y) = \frac{1}{2}\left(\sin(x-y) + \sin(x+y)\right)$$

$$\sin^2(x) = \frac{1}{2}\left(1 - \cos(2x)\right)$$

$$\cos^2(x) = \frac{1}{2}\left(1 + \cos(2x)\right)$$

$$p = \left\{ \frac{\hat{u}_0}{R} \sin(\omega t) + \hat{u}_0 \ \omega C \cos(\omega t) \right\} \hat{u}_1 \cos(\omega t)$$

$$= \frac{\hat{u}_1 \hat{u}_0}{R} \sin(\omega t)\cos(\omega t) + \hat{u}_0 \hat{u}_1 \ \omega C \cos^2(\omega t)$$

$$= \frac{\hat{u}_1 \hat{u}_0}{2R} \sin(2\omega t) + \frac{\hat{u}_0 \hat{u}_1}{2} \ \omega C \left(1 + \cos(2\omega t)\right)$$

$$\overline{p} = \frac{1}{T} \int_0^T p_w(t)\, dt = \frac{\hat{u}_0 \hat{u}_1}{2} \omega C$$

Measurement of the idle power

$\varphi = 90°$ $\quad \overline{p_B} = \omega C \dfrac{\hat{u}_0 \hat{u}_1}{2}$ ▷ X

5.4 Computer-based Data Acquisition-Overview

Problem

Manual transfer of the measurement results

- Processing?
- Saving?
- Tranfer?

Solution: Computer-based Data Acquisition

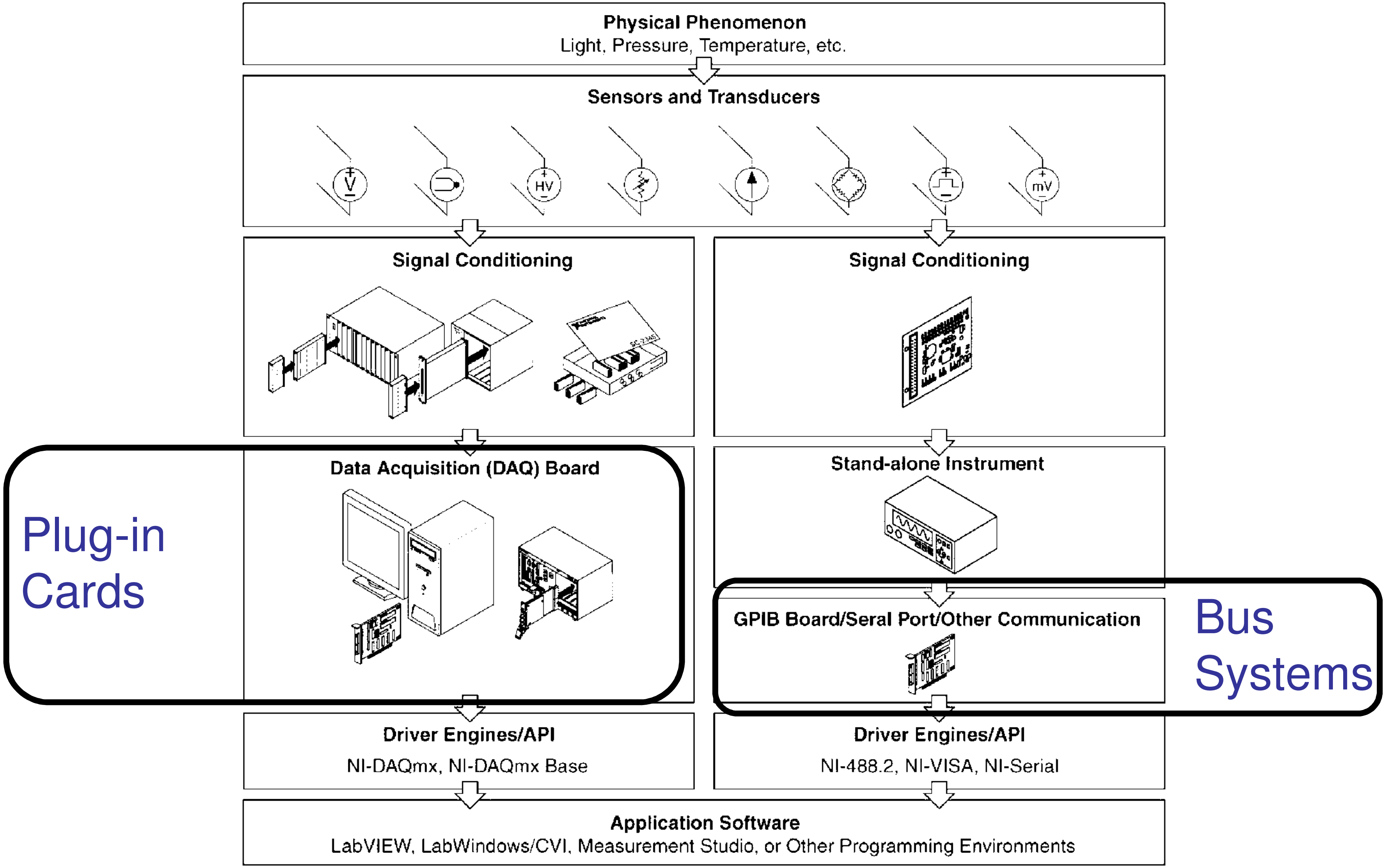
<u>Advantages</u>

- Automation
- Fast Acquisition (Nyquist-Criterion)
- Fast Data Transfer
- Big Memory
- Signal Processing

<u>Concepts</u>

- Connection to a PC
  → Bus Systems
- Integration in a PC
  → Plug-in Cards

5.4 Computer-based Data Acquisition-Overview



5.4 Computer-based Data Acquisition
Bus Systems

<u>Advantages</u>

- Combination of inhomogeneous Architectures
- Special Measurement Devices can be used

Ofen used communication networks

- GPIB
- RS232, RS xyz
- CAN
- Ethernet
- USB

Example: GPIB
parallel 8-Bit, untill 15 devices
Device has a coded Adress (1-15)

5.4 Computer-based Data Acquisition
Bus Systems – Use over Driver Libraries

Use of GPIB in MATLAB

```
voltmeter = gpib('ni',0,1);
fopen(voltmeter)
fprintf(voltmeter,'measure:volt')
```
→ Start a Measurement

```
fprintf(voltmeter,,read?')
```
→ Interrogation of the Measurement Value

```
data = fscanf(voltmeter)
fclose(voltmeter)
```
→ Read-out of the data buffer

Further commands according to the instruction set of the measurement Device

Command	Description
:CONFigure:<function>	Places the Model 2000 in a "one-shot" measurement mode for the specified function.
:FETCh?	Requests the latest reading without triggering.
:READ?	Performs an :ABORt, :INITiate, and a :FETCh?.
MEASure[:<function>]?	Performs an :ABORt, :CONFigure:<function>, and a :READ?.

:CONFigure:<function>

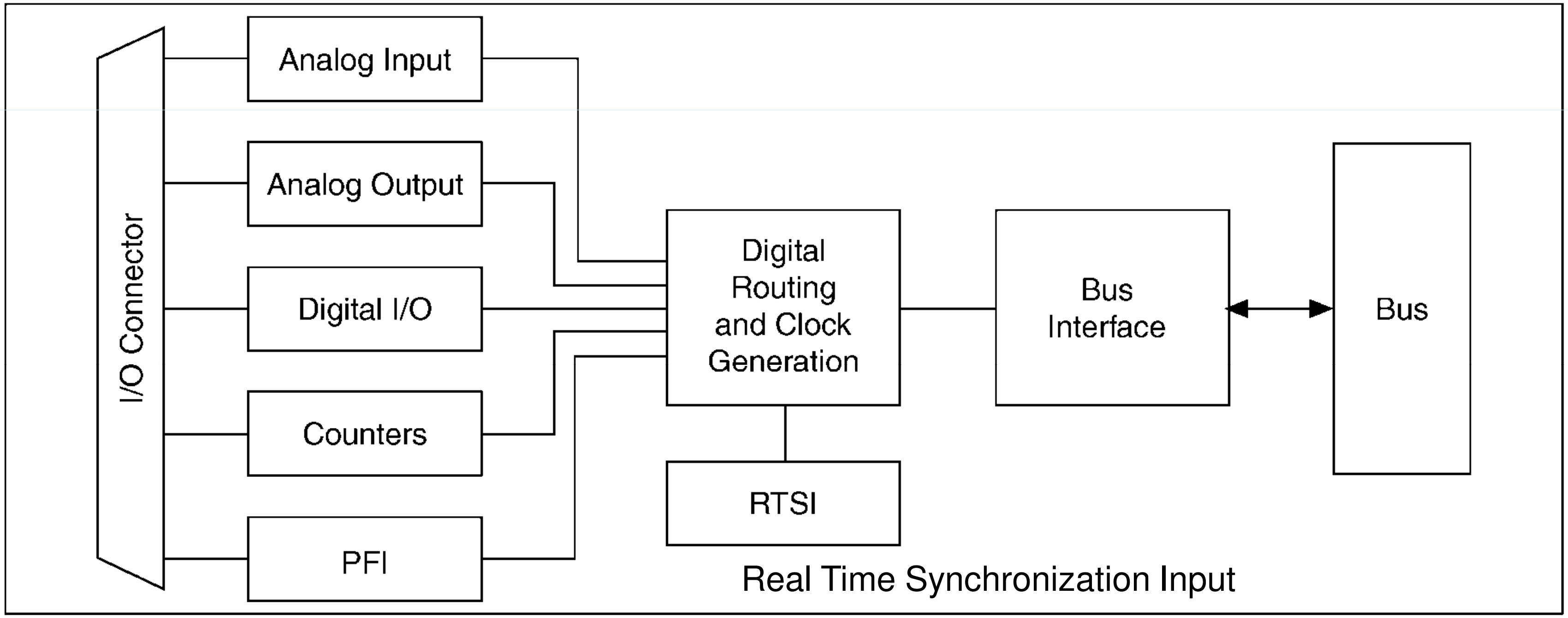
<function> =		
	CURRent:AC	AC current
	CURRent[:DC]	DC current
	VOLTage:AC	AC voltage
	VOLTage[:DC]	DC voltage
	RESistance	2-wire resistance
	FRESistance	4-wire resistance
	PERiod	Period
	FREQuency	Frequency
	TEMPerature	Temperature
	DIODe	Diode testing
	CONTinuity	Continuity test

5.4 Computer-based Data Acquisition
Plug-in Cards

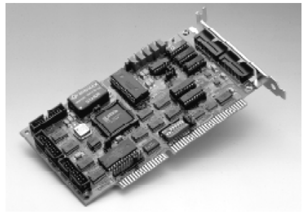
Advantages
- Low Costs
- Universal Use

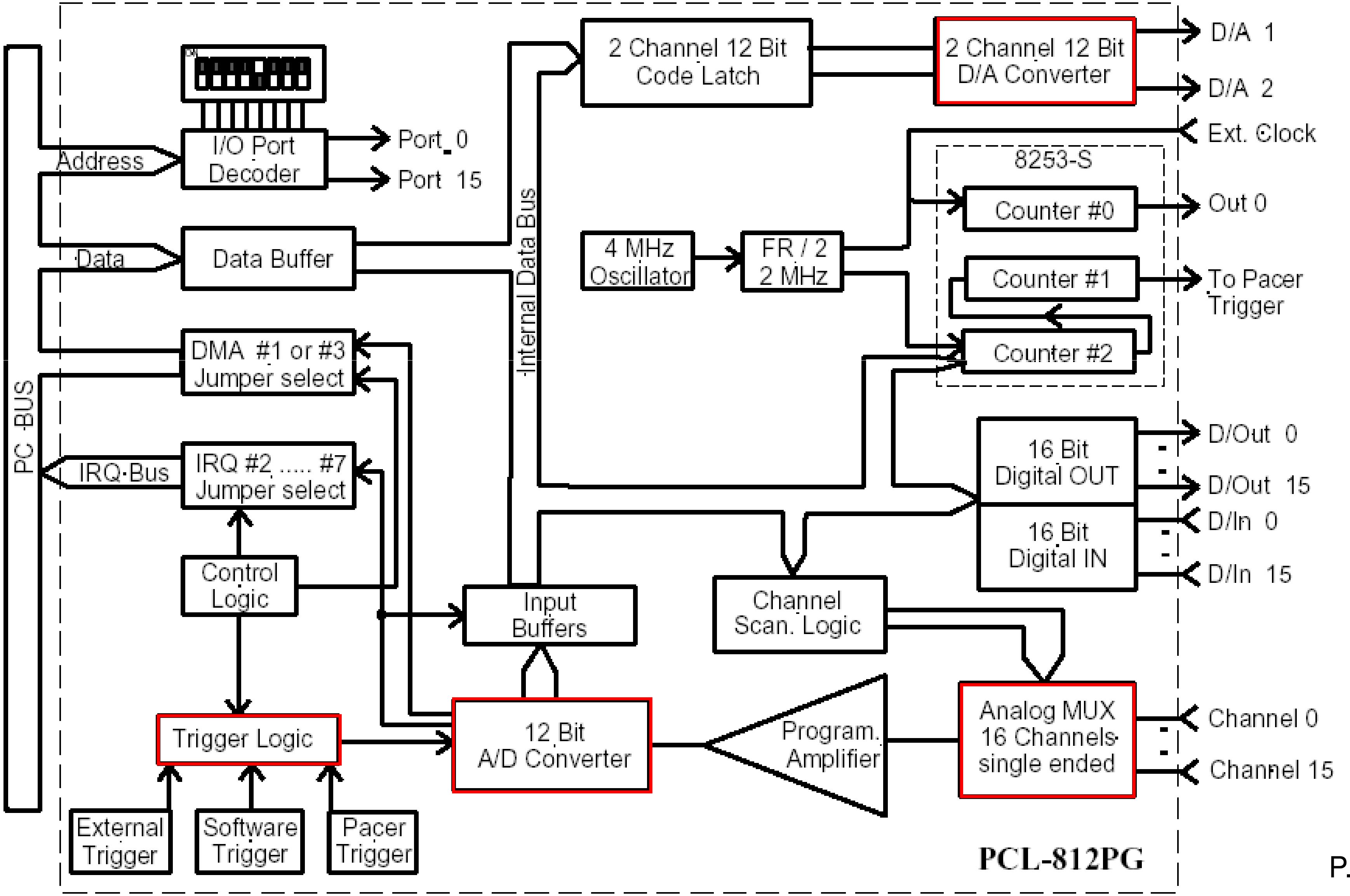
Applications:
- Multi functional Data Acquisition
- Signal Generators
- Image Acquisition and Processing

Example: National Instruments M-Series Multi Functional Plug-in Card



5.4 Computer-based Data Acquisition
Example of a Plug-in Card





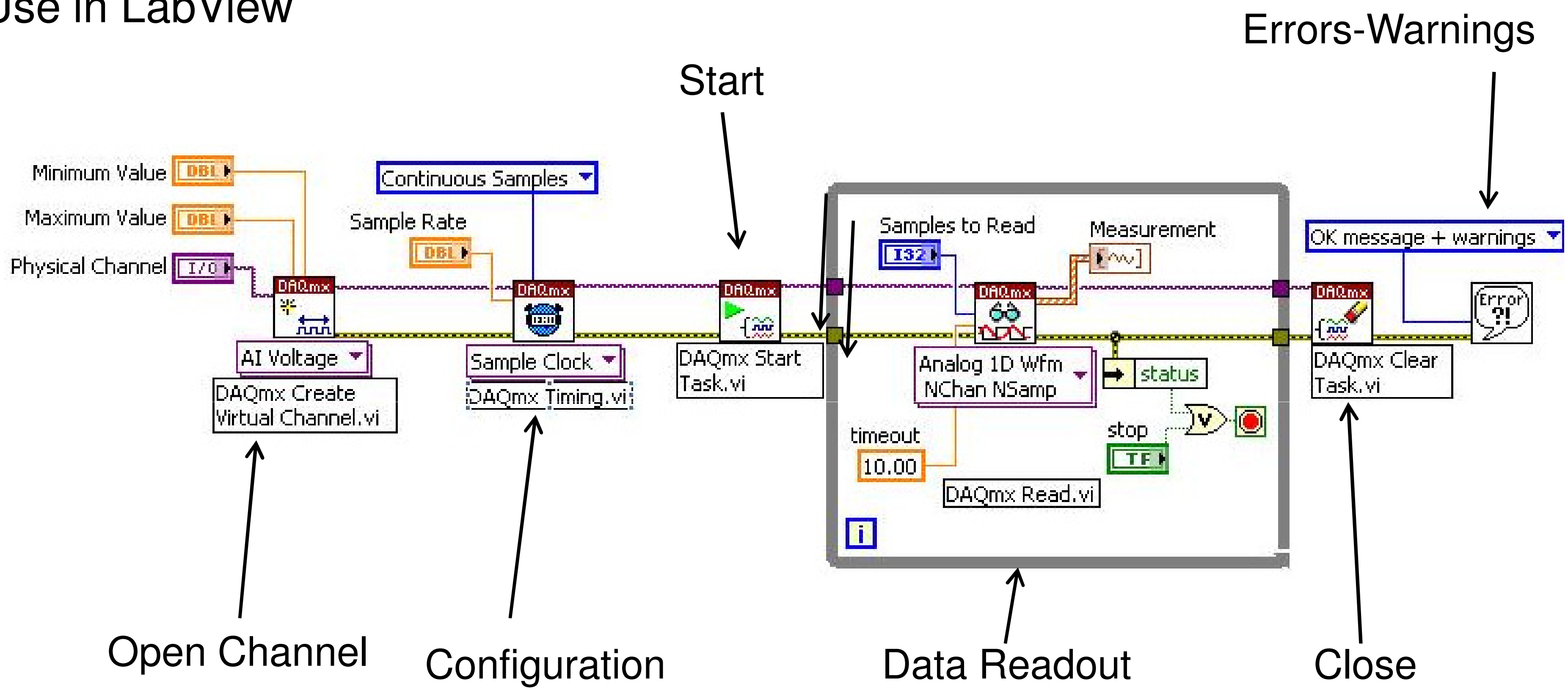
Use in C

```c
#include <NIDAQmx.h>
…
DAQmxCreateTask(taskHandle);
…
DAQmxStartTask(taskHandle);
…
DAQmxReadAnalog(taskHandle,…,data);
…
DAQmxStopTask(taskHandle);
```

- `#include <NIDAQmx.h>` ← Function library of the card
- `DAQmxCreateTask(taskHandle);` ← Pointer on the data sector of the card
- `DAQmxReadAnalog(taskHandle,…,data);` ← Depositing the data in a variable

5.4 Computer-based Data Acquisition
Plug-in Cards– Use of Driver Library

Use in LabView



5.4 Computer-based Data Acquisition
Evaluation Software

Examles for Software

- MATLAB
- C / C++
- Visual Basic
- Excel

} Use of hardware over driver bibliothek

Further Software for Data Evaluation

- Maple
- Mathematica
- Maxima (open source)

} Symbolic

- Scilab (open source)
- Octave (open source)

} Numeric

Example: Differentiation in Maxima

```
(%i1) diff(x^3,x,2);
(%o1) 6 x
```

Example Statistic in Octave

```
octave-3.0.1.exe:3> x=rand(1,5)
x =

   0.12758   0.80826   0.99206   0.82528   0.78898

octave-3.0.1.exe:4> std(x)
ans =  0.33464
```

5.4 Computer-based Data Acquisition
Special Software

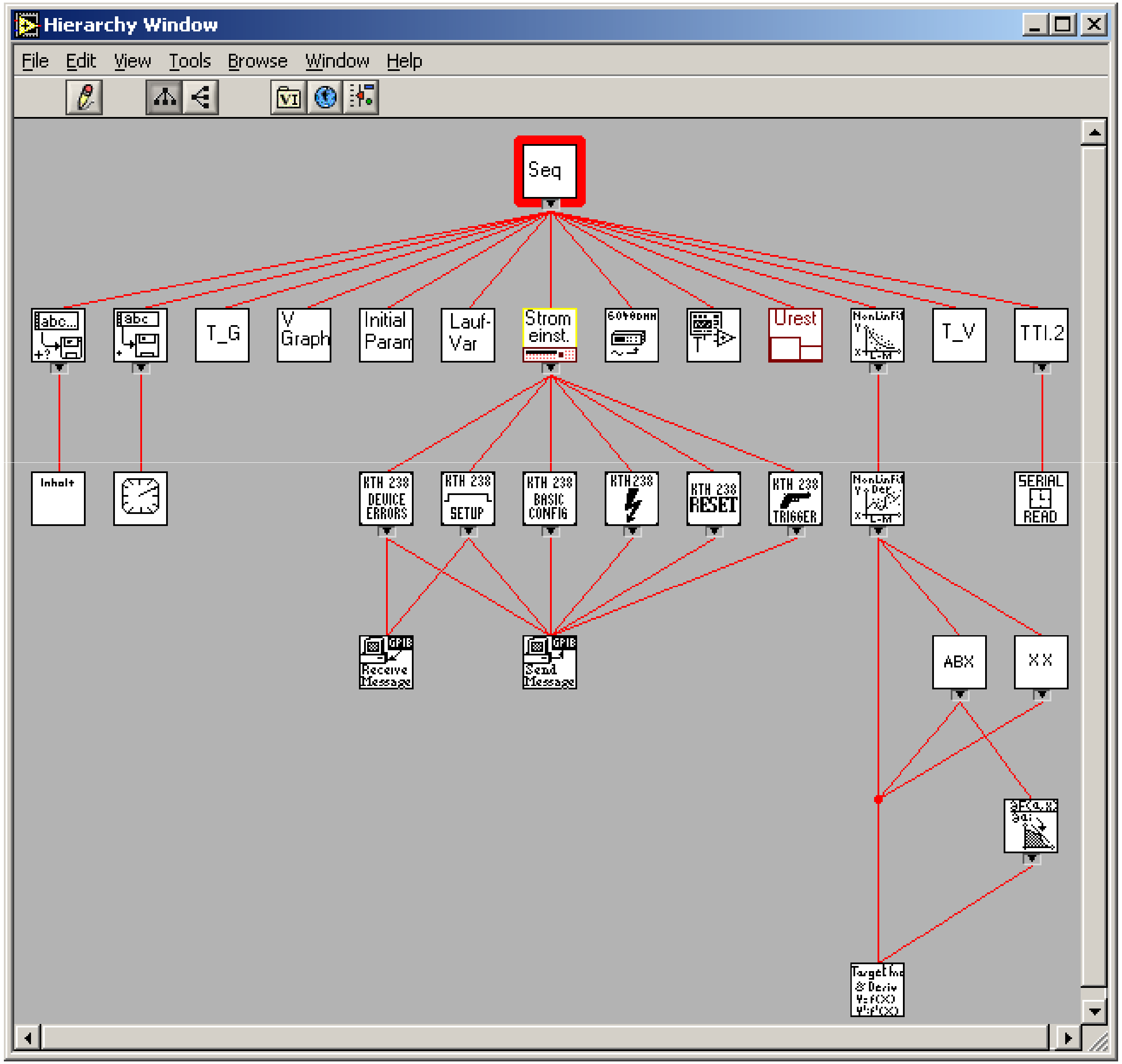
Softwarepa-ket	Lieferant	Merkmale
DASYLab	Datalog Mönchengladbach	Grafisch interaktives Paket auf Windows-Basis Schaltpläne für Meß- und Steueraufgaben, Interaktive Erstellung Funktionsmodule für Messen, Steuern, Analyse Visualisierung am Bildschirm während des Ablaufs Treiber für gängige Meßwerterfassungskarten Übernahme von Ergebnisse in andere Windowsprogramme
ARGUS / NT	Sorcus Düsseldorf	Echtzeitfähige Standardsoftware zum Messen, Prüfen, Überwachen unter Windows NT, 95 und 98 Umfangreiche Meß-, Auswerte- und Analysefunktionen
LABVIEW	National Instruments	Grafische Programmiersprache auf der Basis von C zum Aufbau von Meßwert-erfassungs- und Steuerungssystemen mit grafischer Bedienungsoberfläche
DIADEM	Gesellschaft für Strukturanalyse GfS Aachen	PC-Werkstatt unter Windows mit Geräten aus Software zur one-line und off-line Bearbeitung technischer Daten Konzeptionell mit DASYLab und ARGUS vergleichbar Umfangreiche Treiber-Bibliothek Autosequenzen für den automatischen Ablauf wiederkehrender Sequenzen
FlexPro	Weisang GmbH Menden	Dokumentieren, analysieren und archivieren (Windows) Datenbanken für umfangreiche Meßdateien Importfilter für unterschiedliche Datenformate Script-Sprache zur Erstellung von Formeln Darstellung in 2D-, 3-D-Diagrammen, Tabellen

VEE Agilent Messdatenerfassung

⋮

5.4 Computer-based Data Acquisition
Labview: User Interface

5.4 Computer-based Data Acquisition
Labview: Program Hierarchy



5.4 Computer-based Data Acquisition

Program