# Electronics for Physicists

## *Analog Electronics*

*Chapter 1; Lecture 02*

**Frank Simon**
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26.10.2023

Karlsruhe Institute of Technology

***KIT, Winter 2023/24***

Institute for Data Processing and Electronics

*Chapter 1*

# Basics

*Part 1*

- Charge, Current & Voltage
- Resistors
- Voltage- & Current Sources
- Capacitors

*Overview*

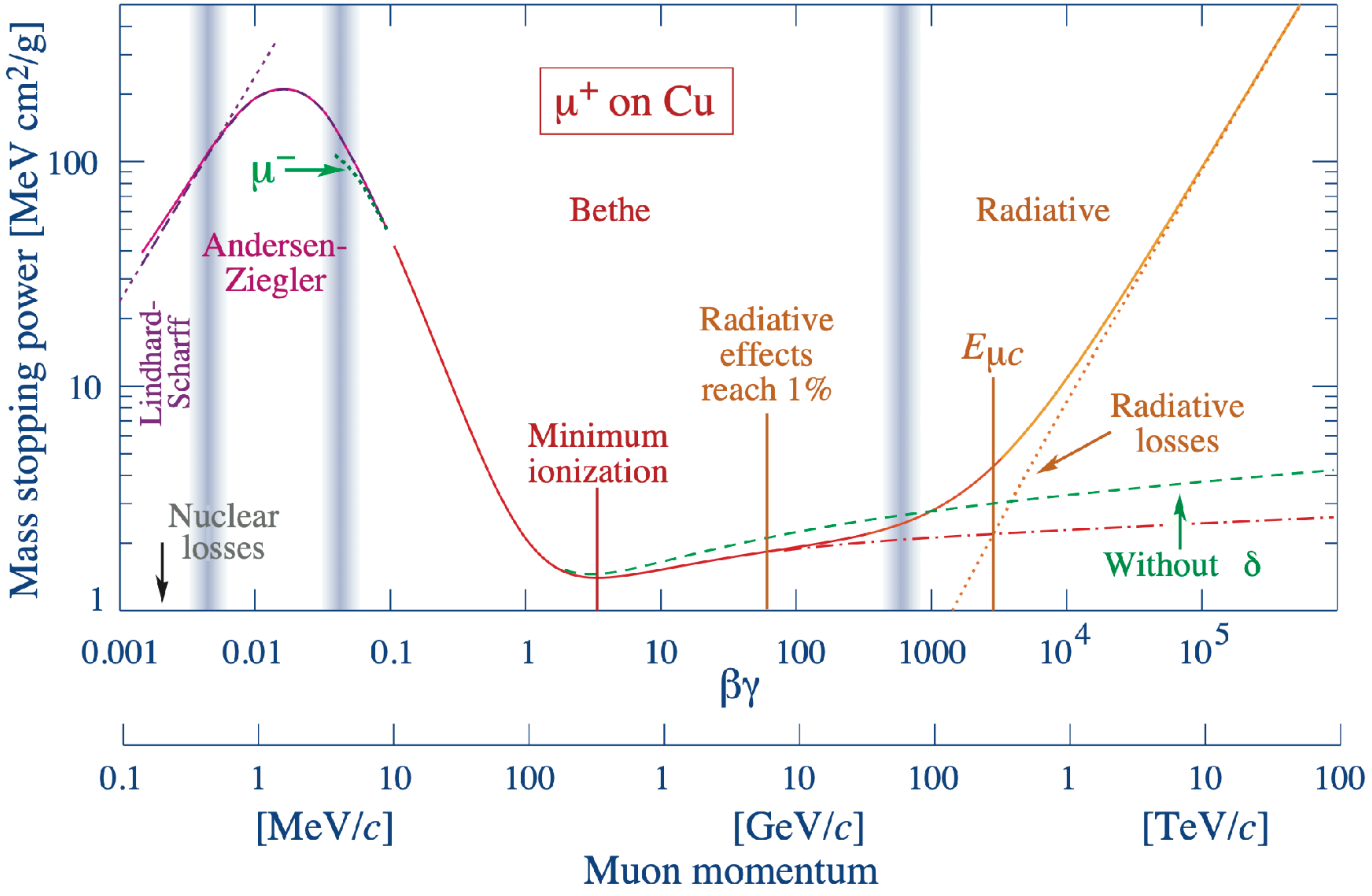
1. **Basics**
2. Circuits with R, C, L with Alternating Current
3. Diodes
4. Operational Amplifiers
5. Transistors - Basics
6. 2-Transistor Circuits
7. Field Effect Eransistors
8. Additional Topics
   - Filters
   - Voltage Regulators
   - Noise

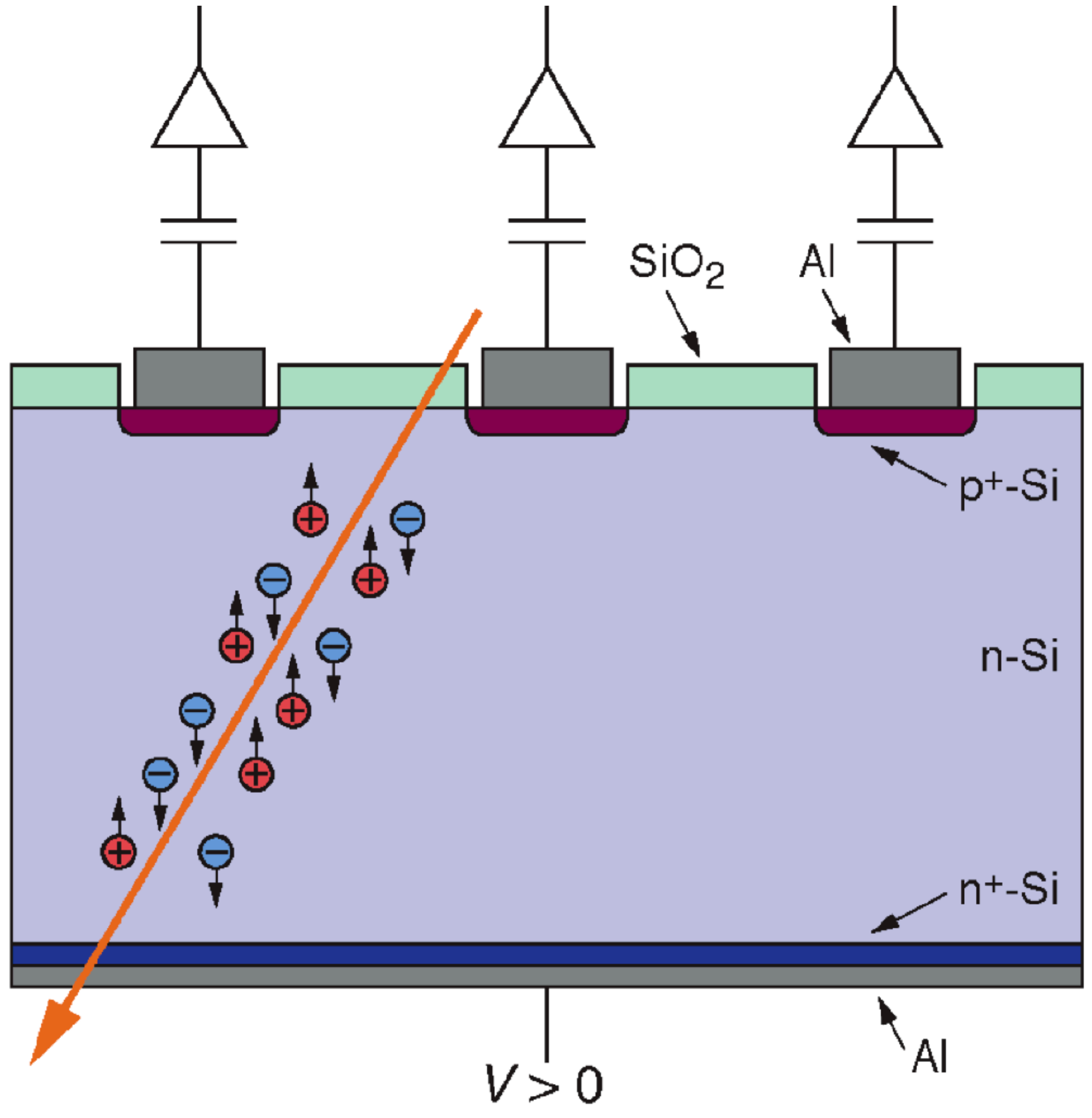
# Electric Charge

*Elektrische Ladung*

- Electric charge: unit Coulomb [C]
  - 1 C = 6.241 x $10^{18}$ $e^-$ (for most “practical” cases: A very “large” unit)
  - 1 fC = $10^{-15}$ C = ~ 6000 $e^-$

Concrete example: Ionisation in particle detectors




In Silicon: 3.6 eV / $e^-$-hole pair; ~ 80 $e^-$ per $\mu$m for MIPs

For 300 $\mu$m ~ 4 fC

# Current

*Strom*

- Current = moving charge: charge / time *Strom*

$$I = \frac{dQ}{dt}$$

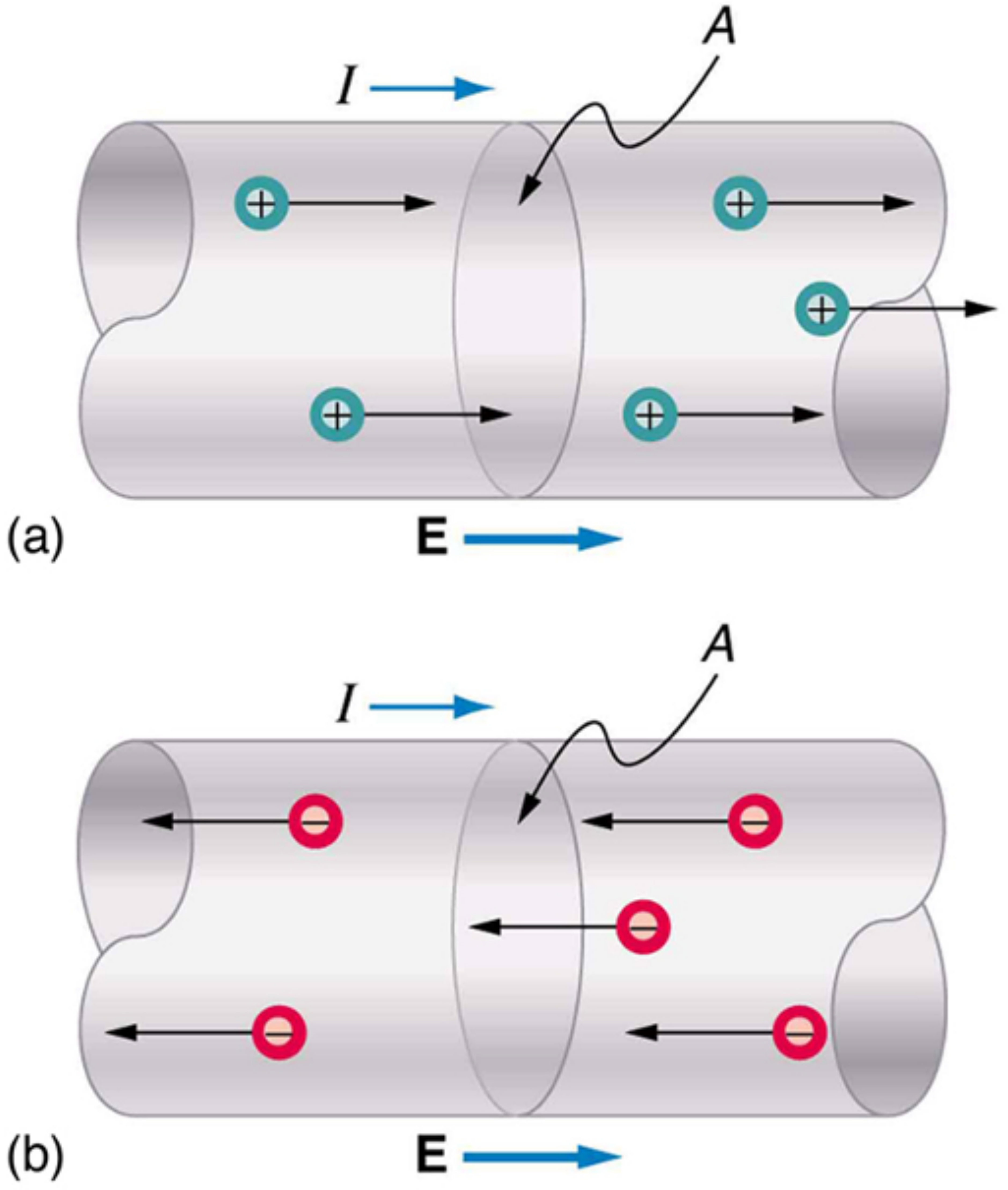
I: current in Ampere [A] = [C/s]

Q: charge in C

t: time in seconds [s]

Convention: current flow from higher (+) to lower (-) potential.

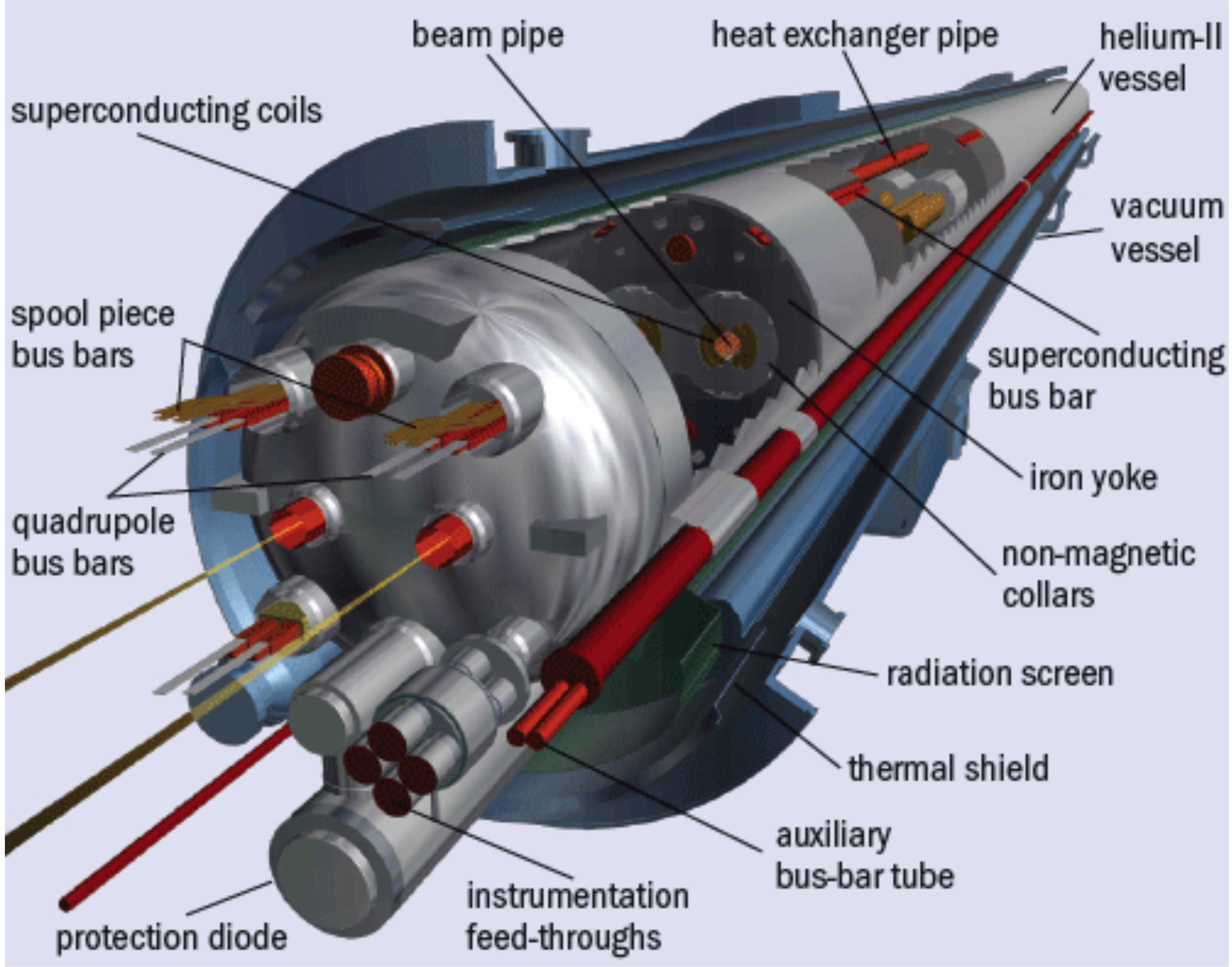
For metallic conductors: flow of electrons, opposite to the conventional direction of current flow.



# Current

*Practical Examples*

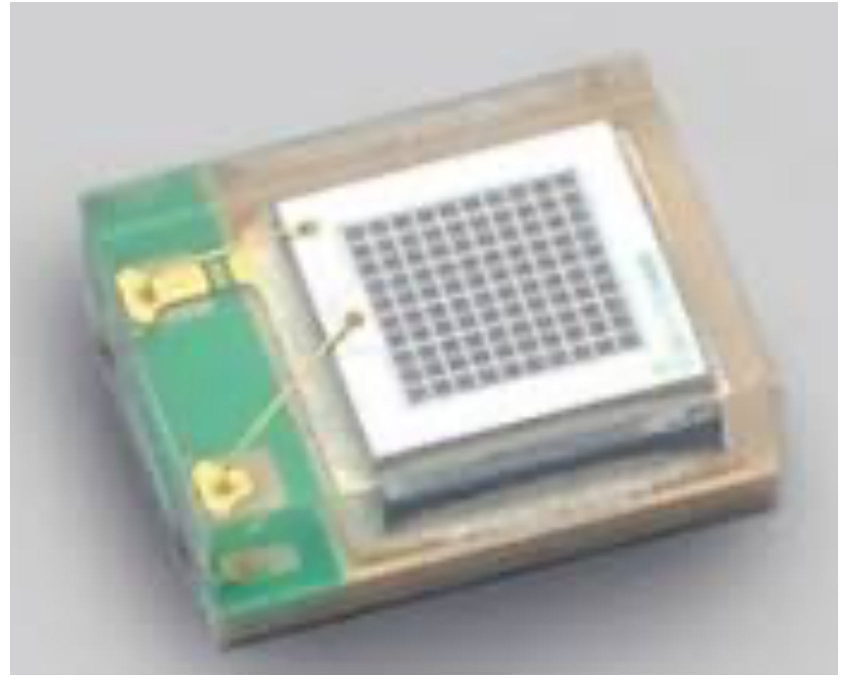
- LHC magnets



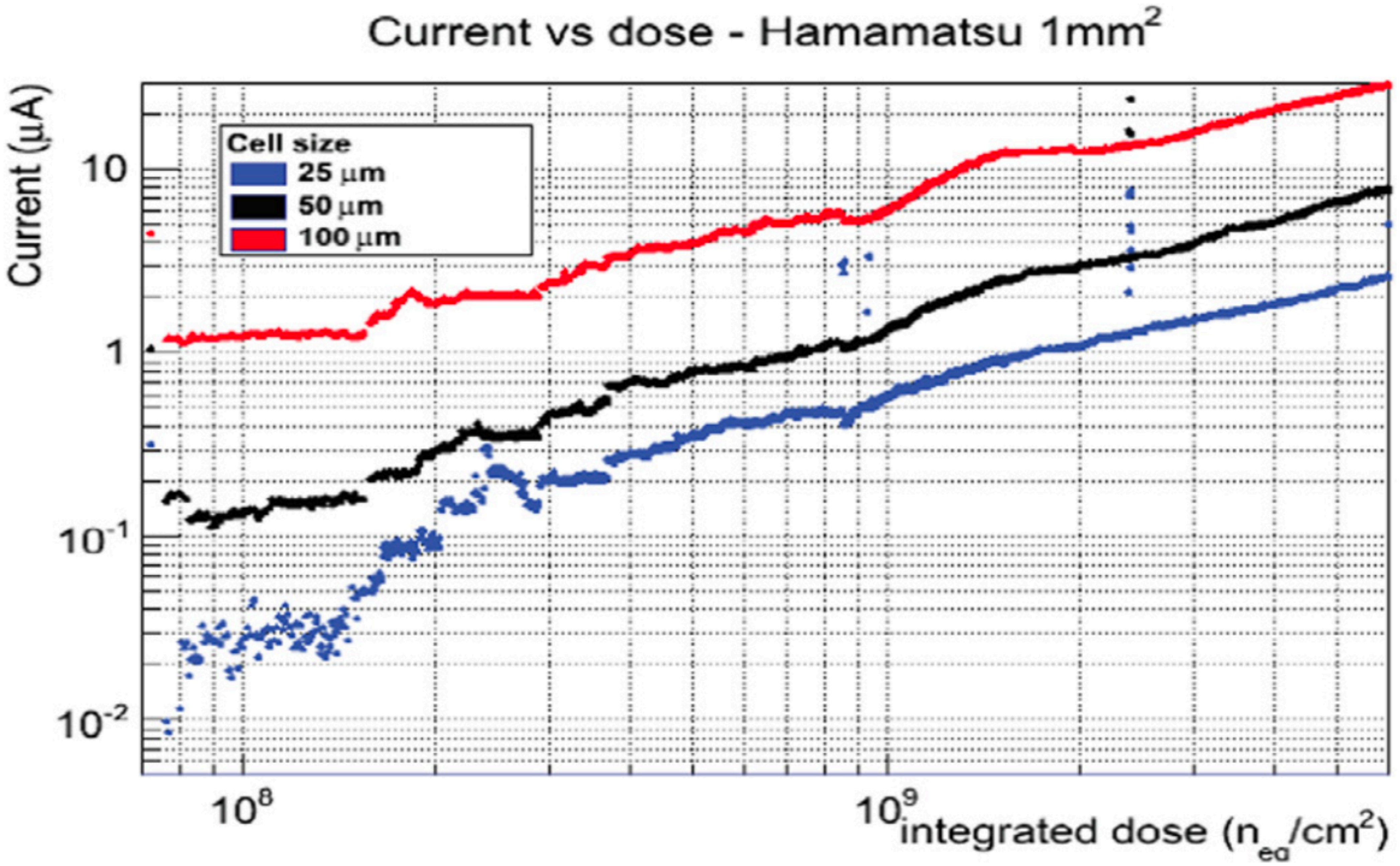

magnetic field up to 8.3 T

current up to 12 kA for

7 TeV beam energy



- leakage current in SiPMs: nA - $\mu$A



# Voltage

*Spannung*

- Voltage, oder potential difference:
  Energy W that has to be invested to move an electric charge q in a field  E.
  Also given by the electric field integrated over the distance of movement.

$$\frac{W}{q} = U = \int \vec{E}\, d\vec{s}$$

U: Voltage in  Volt [V]

E: electric field strength [V/m]

s: distance [m]

In typical applications: Electric fields are relevant for example in detectors, electric circuits normally only the voltage is of interest.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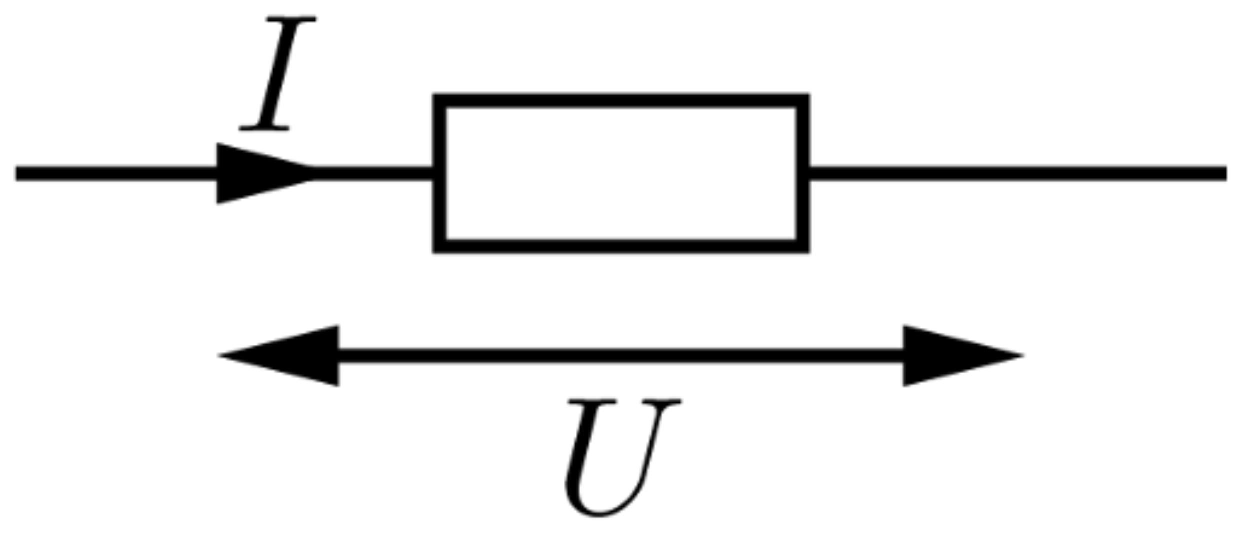
# Resistors, Ohm's Law

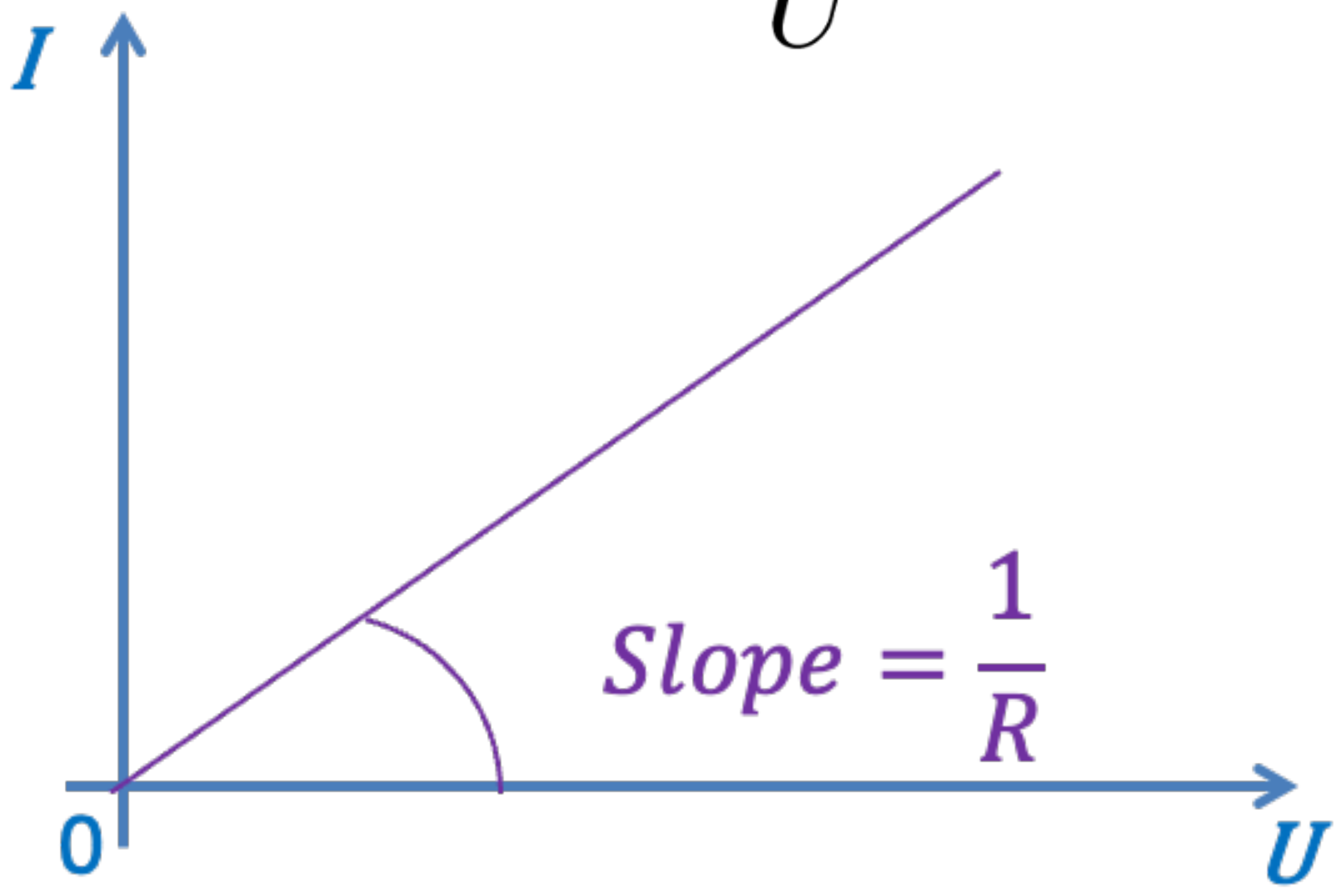
*The connection of current and voltage*

$$U = RI$$

*Widerstand*




R: resistance in Ohm [Ω = V/A]




Often used as well: *Conductance*

G = 1/R

- What Ohm's law means:
  - Voltage results in current flow
  - Current flow through a resistor results in a voltage drop across the resistor



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# Power

*Leistung*

- Power: Current and Voltage

$$P = UI = \frac{U^2}{R} = I^2R$$

P: power in Watts [W = VA]

- In our daily lives: Power as a cost factor: “energy consumption” P * t -> kWh / MWh / TWh…
- For detectors in high energy physics: power requires cooling!

# Power in Detectors

*Example: Power loss in cables*

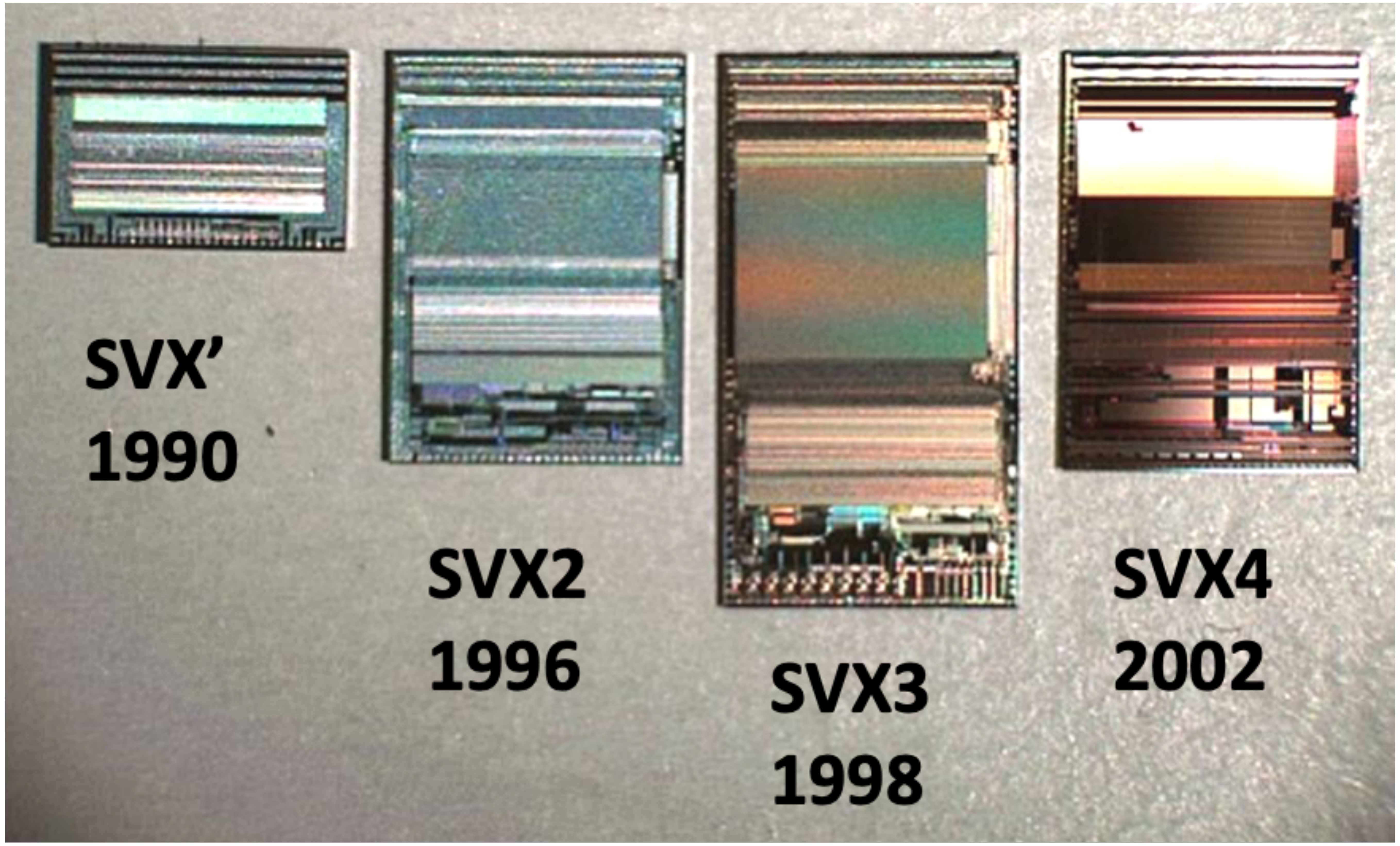
- Low voltage supply cables of the ATLAS SCT detectors

  4 Ω cable resistance for 100 m long cables; 1 A for each of the 4000 modules

  P = 4 Ω x 1 $A^2$ x 4000 = 16 kW => Pure power loss in the cables: Heating of the cables!

# Reducing Power

*Example: Frontend ASICs*



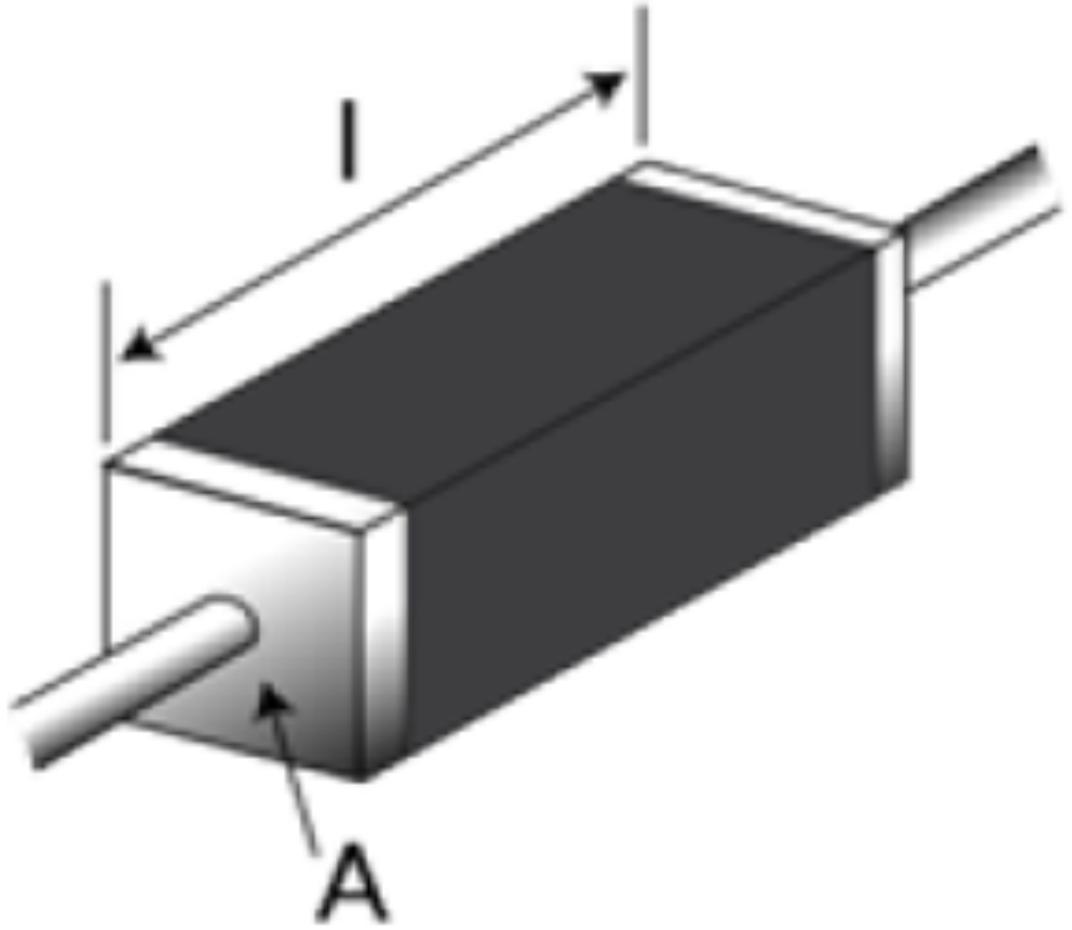

- The SVX2 ASIC was central for the discovery of the Top quark at Fermilab:
  Silicon strip, D0 Experiment;
  Further development as SVX3, 4 also for CDF
- Smaller feature size (transistor size) make ASICs smaller
- Additional functionality makes them bigger
- Smaller feature size typically means lower voltage, and with that also smaller charges: Lower power!
  (This simple logic does not apply for technologies below 65 nm)

# Specific Resistance

*Spezifischer Widerstand*

- A material property:

$$R = \rho \frac{l}{A}$$




| material | $\rho$ [$10^{-8}\,\Omega$ **m**] | Z |
|---|---|---|
| silver | 1,59 | 47 |
| copper | 1,68 | 29 |
| gold | 2,21 | 79 |
| aluminium | 2,65 | 13 |

Resistance of different metals at 20° C

R: Resistance [Ω]

ρ: specific resistance [Ωm]

A: (Cross section-) Area of resistor [m²]

l: Length of resistor [m]

➯ The resistance increases with length, reduces with larger cross section (also applies for other components, such as field effect transistors (FETs) )

➯ The material of the resistor determines the properties - also metals have a range of different values

# Specific Resistance: Consequences

*High energy physics view*

- (Power) Cables are a significant fraction of the (unwanted) material of particle detectors, in particular in tracking systems in collider experiments: The choice of the right material is of high importance.

| material | $\rho\,[10^{-8}\,\Omega\,\mathbf{m}]$ | Z |
|---|---|---|
| silver | 1,59 | 47 |
| copper | 1,68 | 29 |
| gold | 2,21 | 79 |
| aluminium | 2,65 | 13 |

Multiple scattering determined by radiation length $X_0$: ~ $A/Z^2$ in g/cm$^2$, also depends on density: ~ $1/\rho$

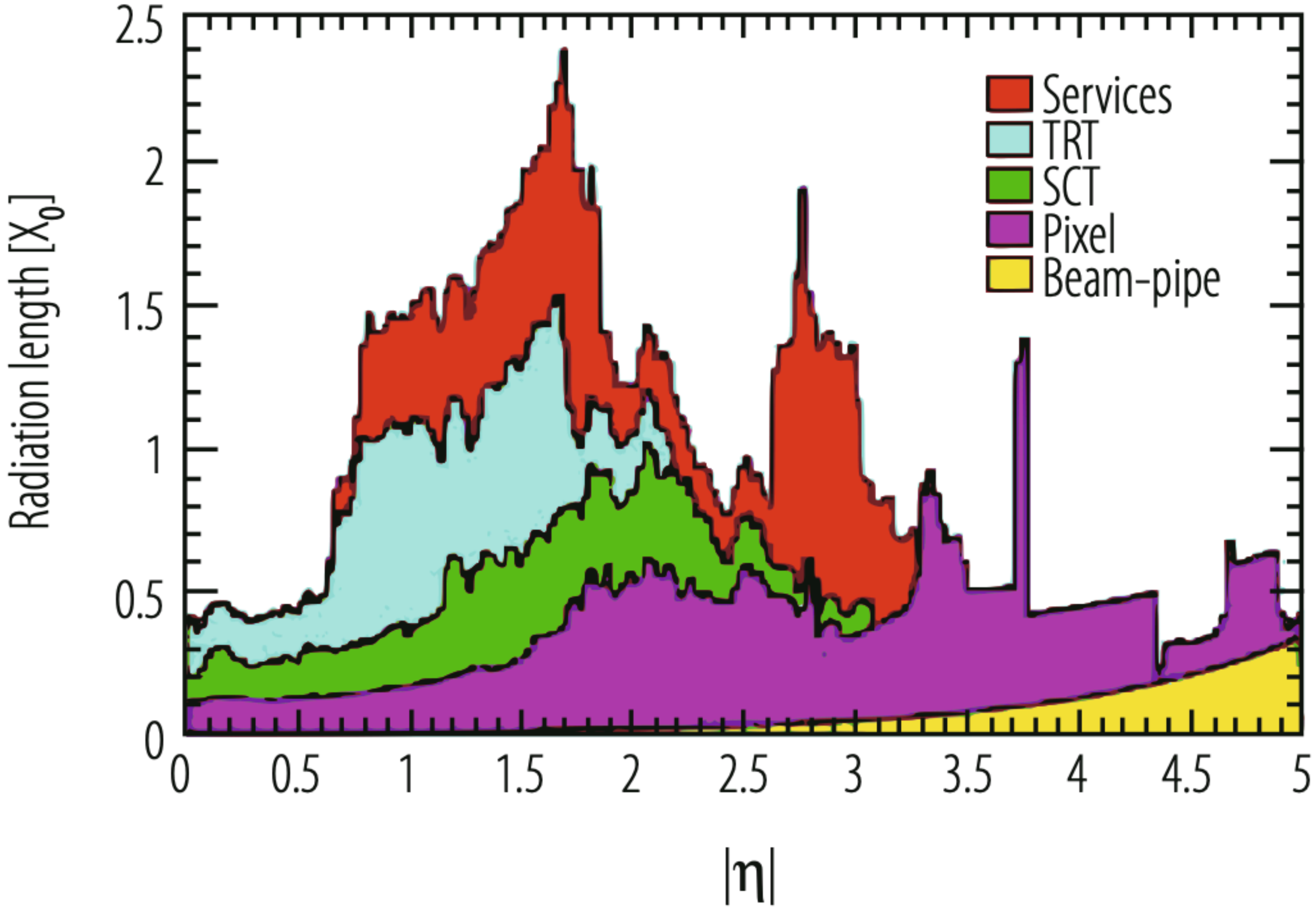
(NB: Large is good, meansL small Z, small ρ)

Copper: 14.4 mm; Aluminum: 88.9 mm

=> Despite higher specific resistance much less $X_0$ when using Al.

ATLAS tracker material:

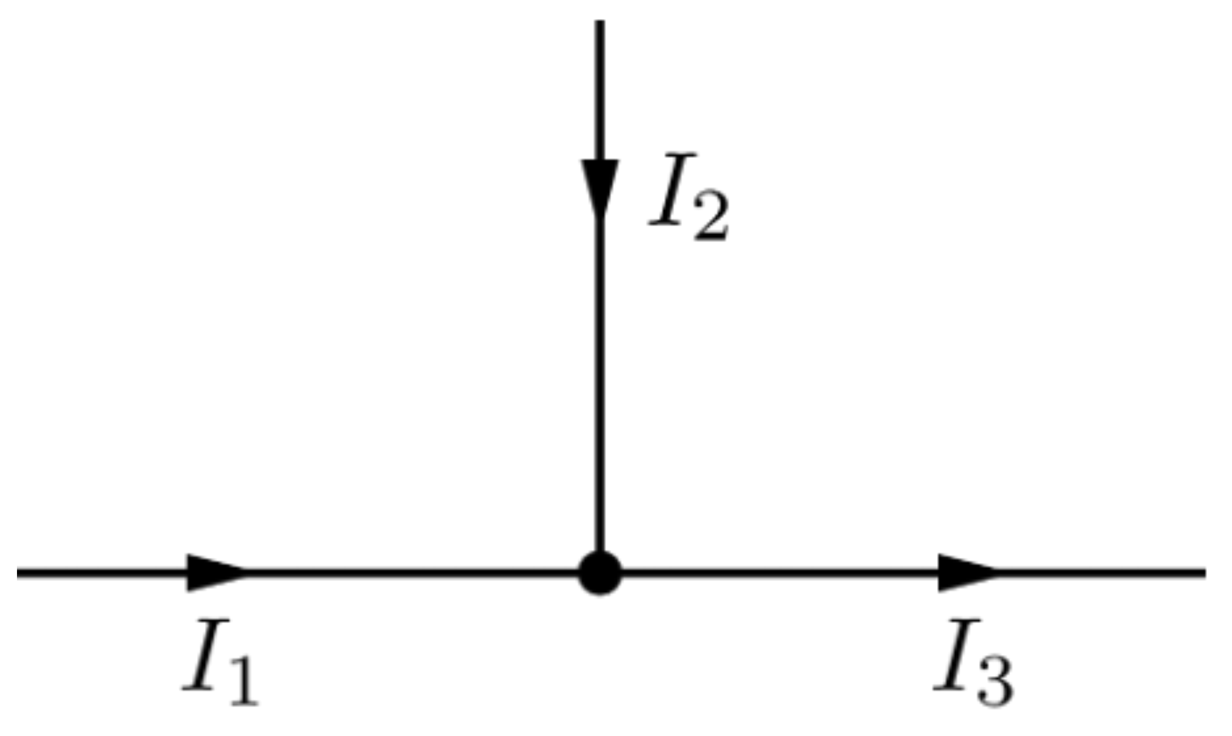
"Services": Cables beyond the detector itself (cables, cooling). Distribution of detectors include "internal" services within detector volume



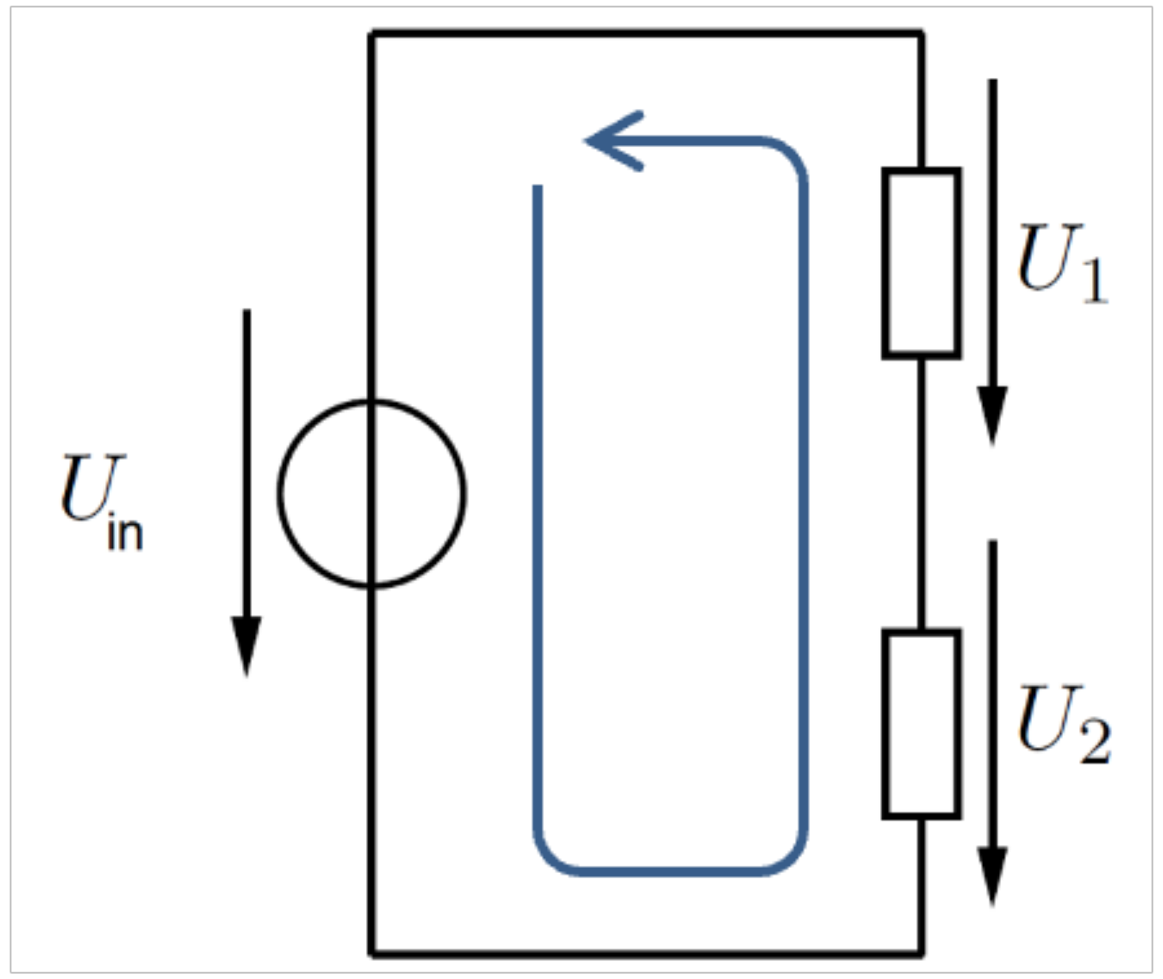
# Kirchhoff's Circuit Laws

*Kirchhoffsche Regeln*

- Follow from basic conservation laws:
  Charge, energy




$$I_1 + I_2 = I_3$$




note the direction of the arrows!

**Kirchhoff's Voltage Law KVL**

*Maschenregel / 2. Kirchhoffsches Gesetz*

$$U_{in} - U_2 - U_1 = 0$$

**Kirchhoff's Current Law KCL**

*Knotenregel / 1. Kirchhoffsches Gesetz*

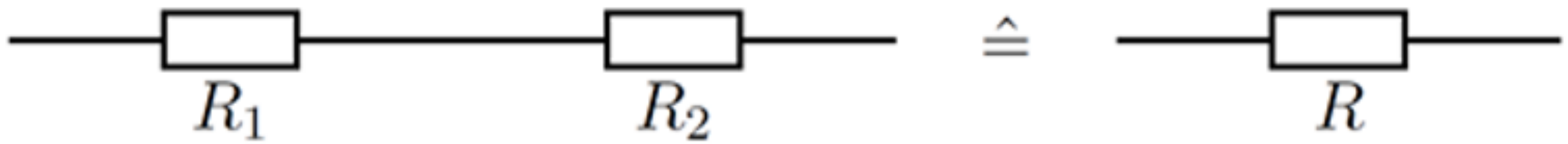
Charge conservation:
Current entering the node =
current leaving the node

Energy conservation:
The sum of all voltage drops around a loop ("Masche") is 0.
[Applies only without induction due to time-dependent magnetic fields, KVL also follows from the induction law]

# Resistor Circuits

*Parallel, Series*

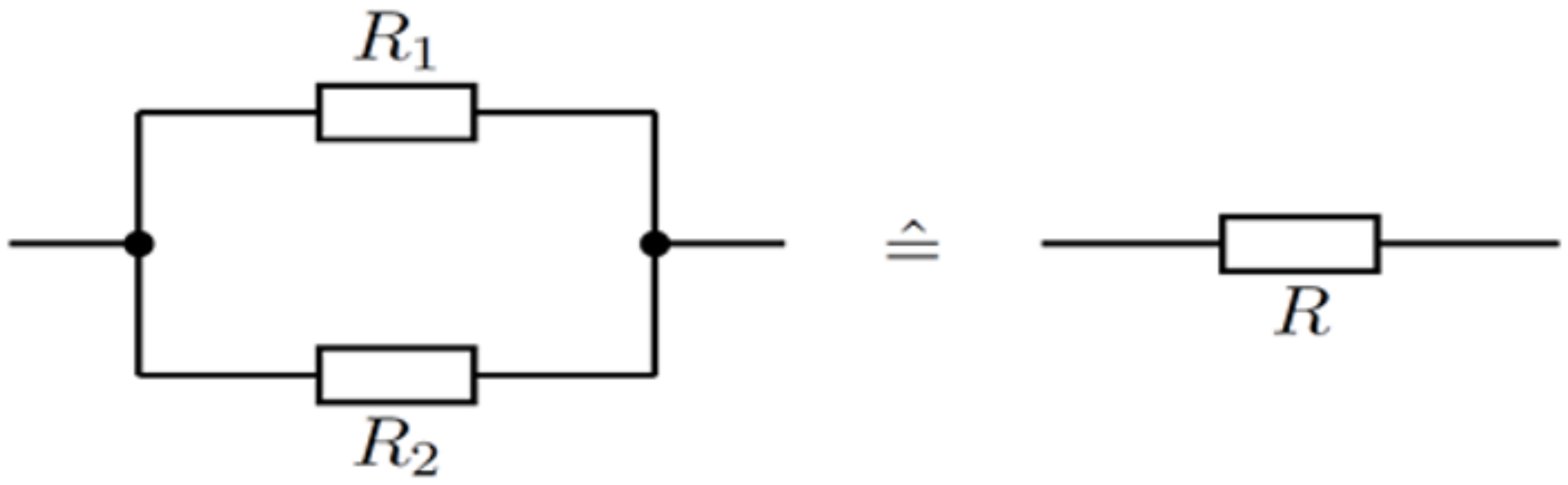
- Resistors in series (“*Reihenschaltung”*)




$$\boldsymbol{R = R_1 + R_2}$$

Same current through all resistors in series.

- Parallel resistors (“*Parallelschaltung*”)




$$R = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} = \frac{R_1\,R_2}{R_1 + R_2} = R_1 \| R_2$$

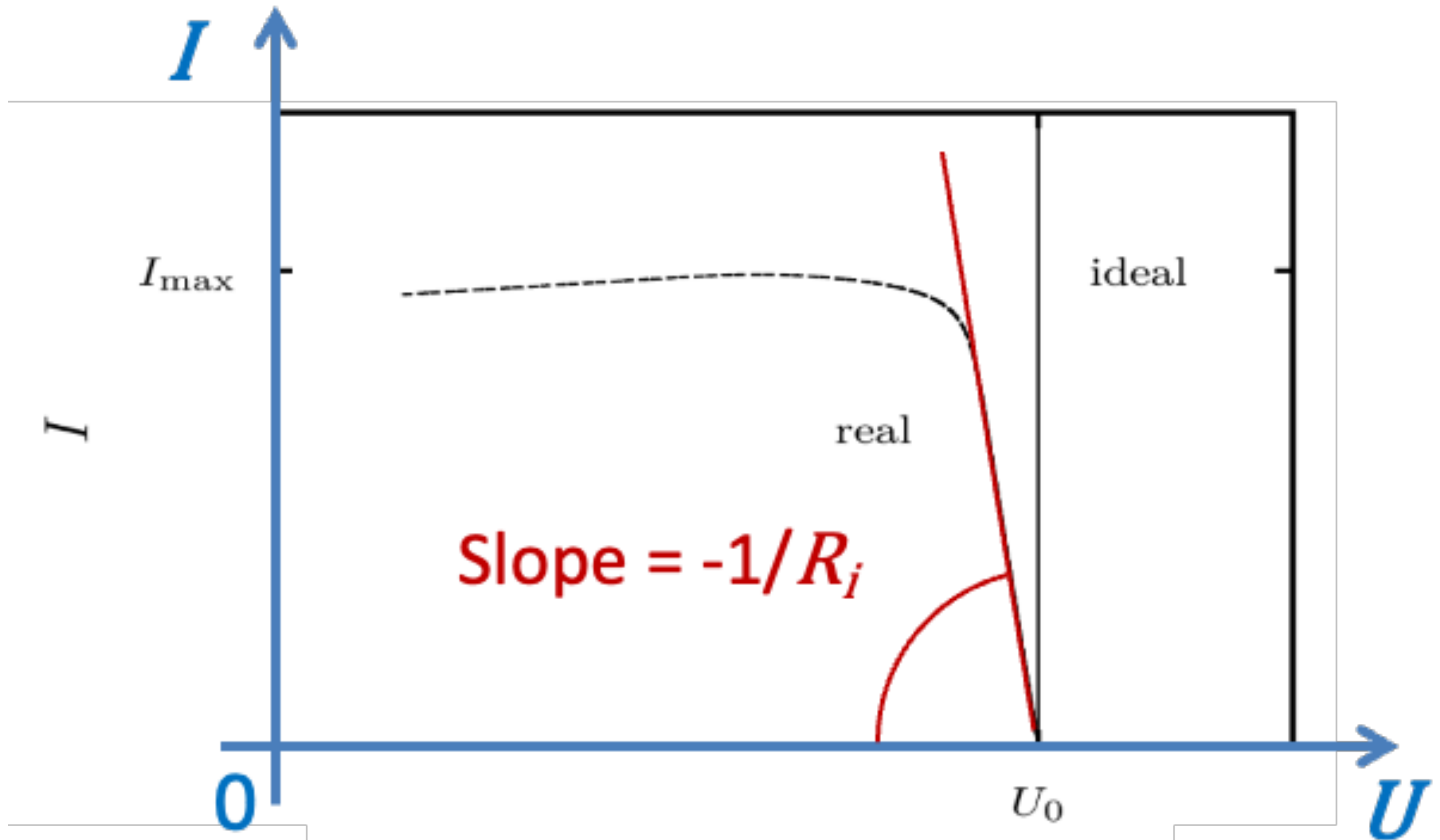
Same voltage drop across all parallel resistors.

# Voltage Sources

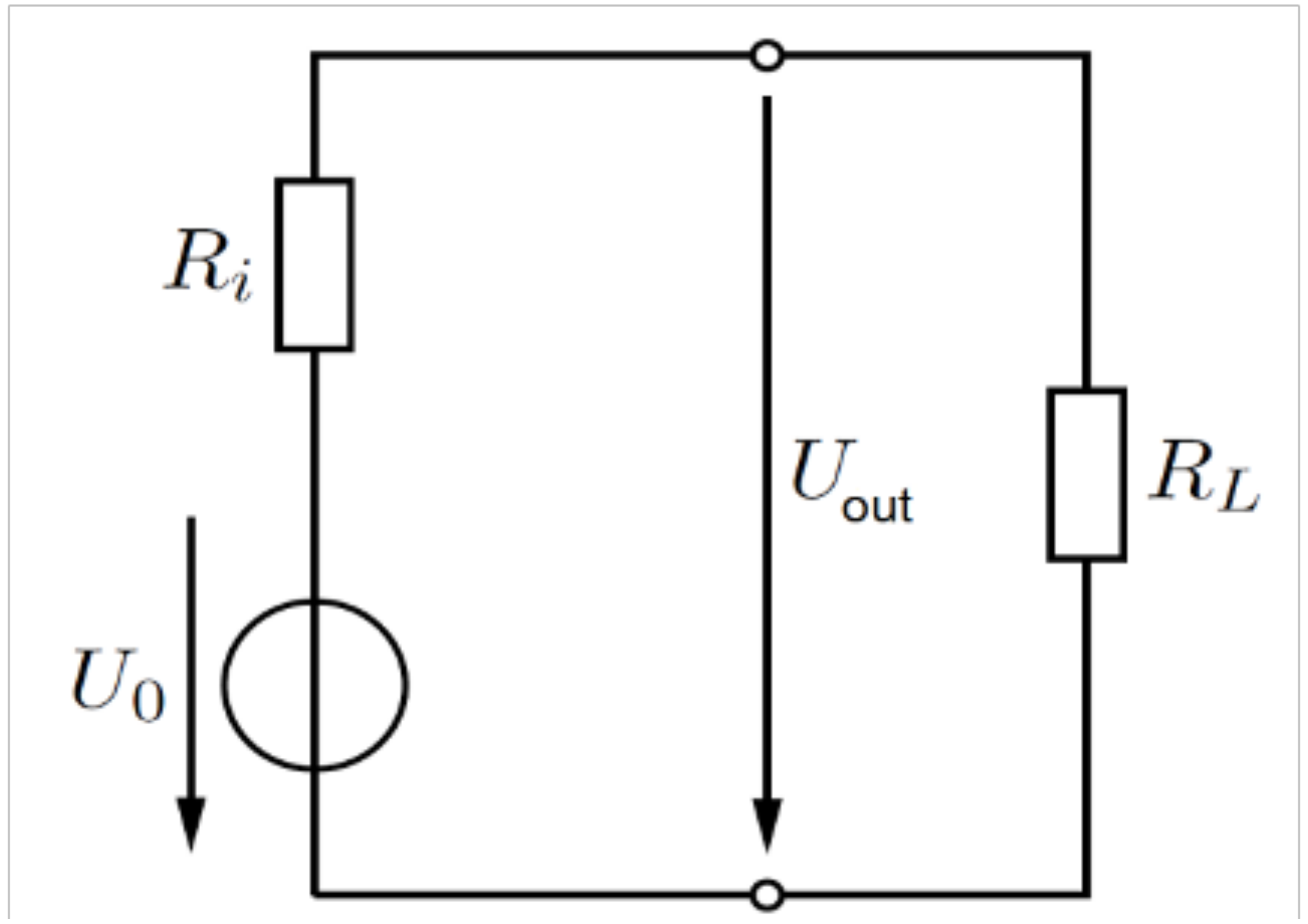
*Spannungsquellen*



- Two types of power supplies ("*Stromversorgungen*"): ***voltage sources, current sources***
- Ideal voltage source: Constant voltage, independent of load current




$$U_{out} = U_0 - I\,R_i$$




$R_i$: internal resistor

$R_L$: load resistor

lab power supply: ~$10^{-5}$ Ω

car battery: ~$10^{-2}$ Ω

(BEV battery cell: ~$10^{-3}$ Ω)

Mono-cell: 0.1 - 1 Ω

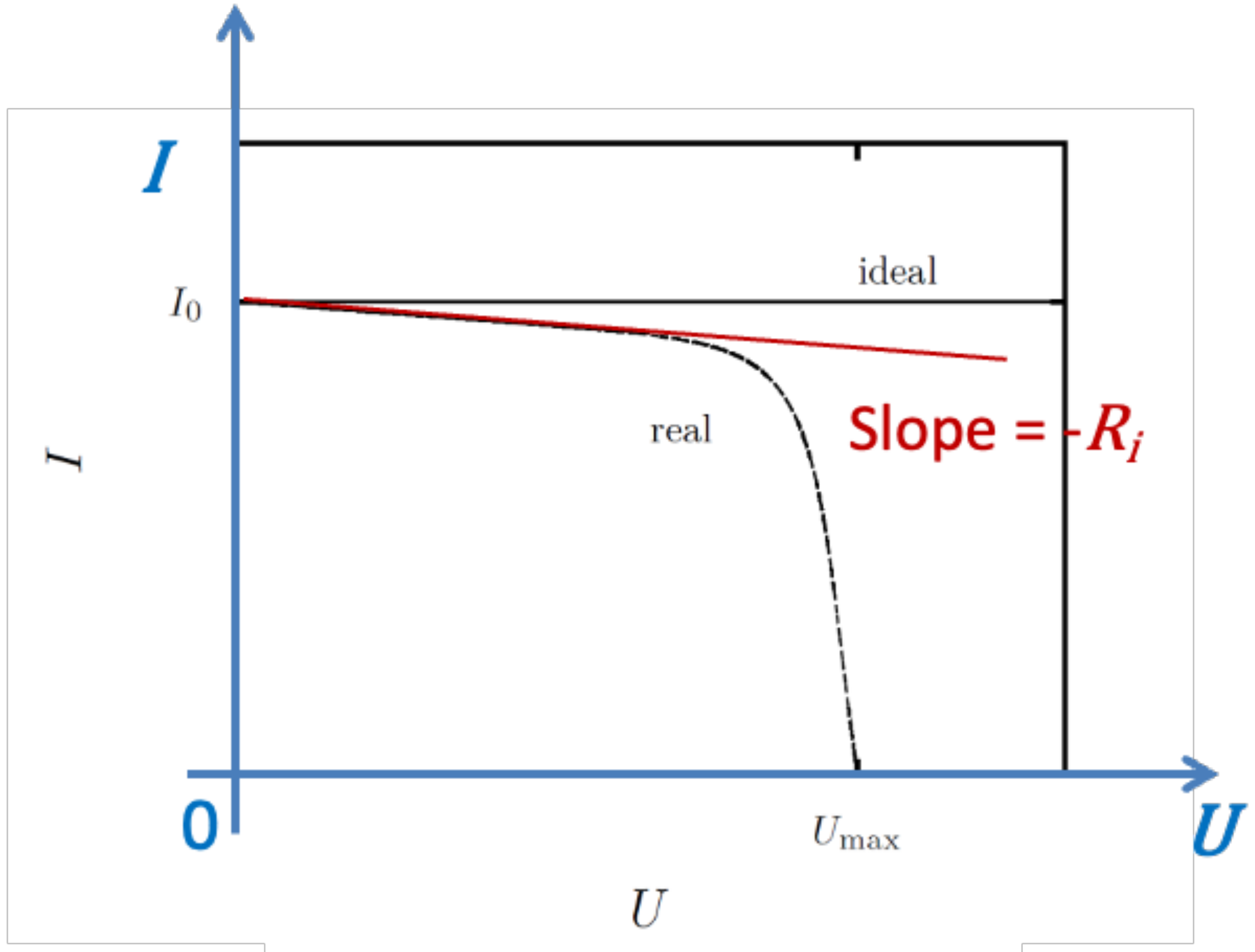
Voltage sources are best at:

- no (or small) load $R_L >> R_I$
- small load currents
- constant current

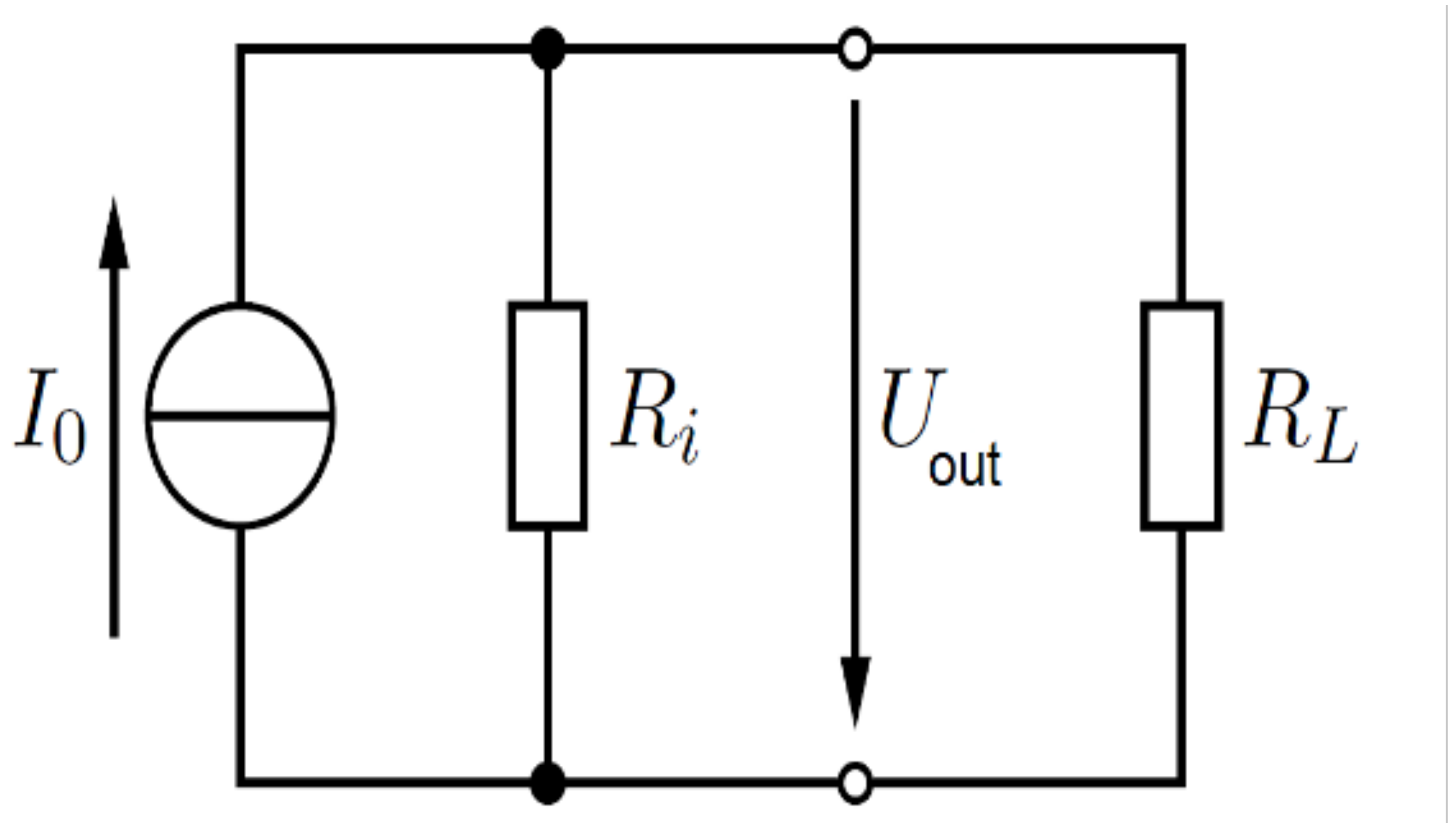
# Current Sources

*Stromquellen*

- Two types of power supplies ("*Stromversorgungen*"): ***voltage sources, current sources***
- Ideal current source: Constant current independent of voltage at the load




$$I = I_0 - \frac{U}{R_i}$$



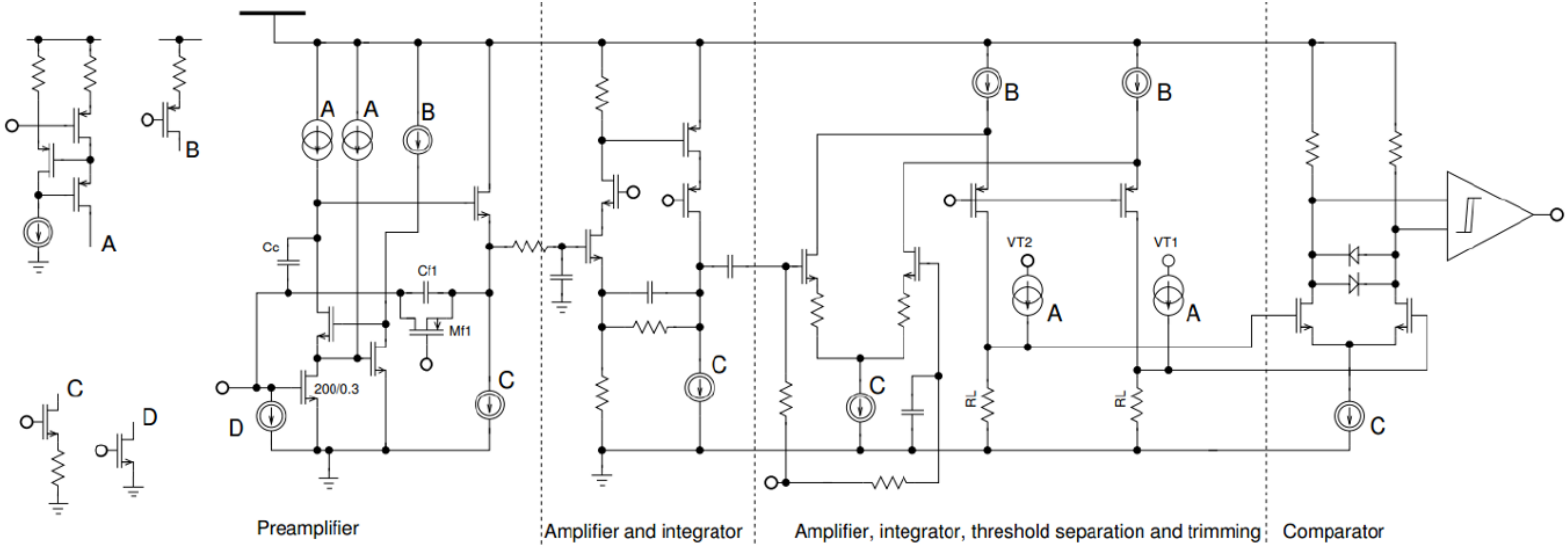

Current sources are at their best in short-circuit:

$R_L << R_i$

# Current Sources

*Nothing exotic*

- Current sources are quite common (even though we mostly "see" voltage sources in everyday life): Central elements in integrated circuits / ASICs

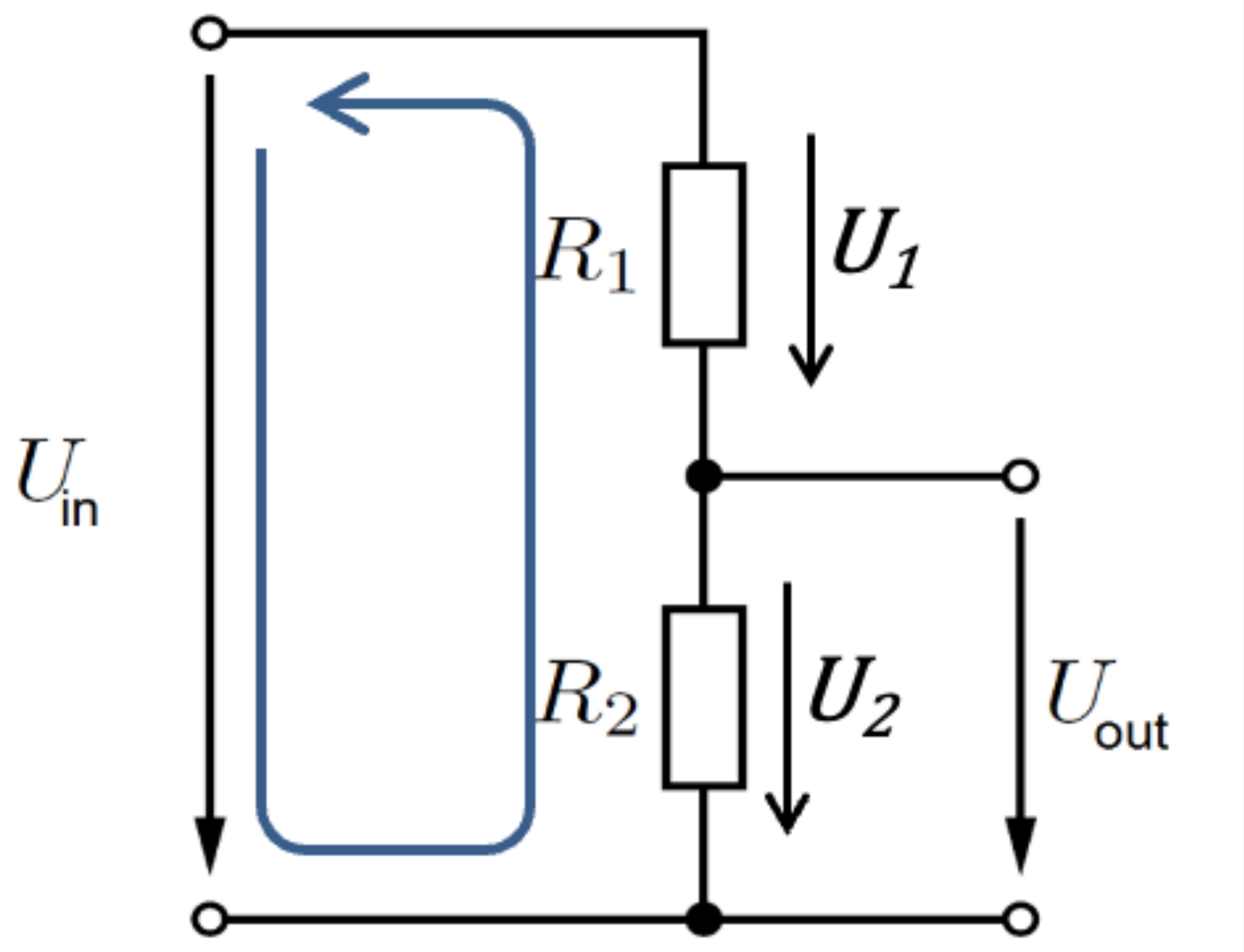



Example ABCN ATLAS silicon detector readout ASIC prototype - different current sources in operation

# Voltage Divider

*Spannungsteiler*

- Voltage dividers are some of the most common circuits




Assumption: $R_1$ adnd $R_2$ are relatively large, load currents are small

Kirchhoff's Voltage Law (KVL):

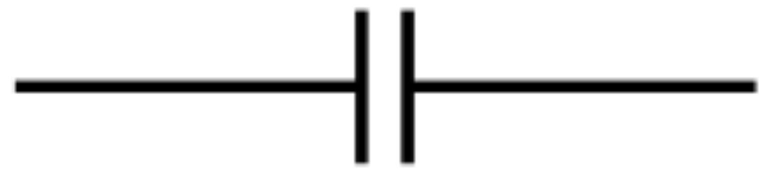
$$U_{in} = U_1 + U_2 = (R_1 + R_2)\, I \quad \text{and} \quad U_{out} = R_2\, I$$

$$U_{out} = U_{in} \frac{R_2}{R_1 + R_2}$$

# Capacitors

*Kondensatoren*

- Symbol:



$$Q = C\,U$$

C: Capacity in Farad [F = As/V]

Q: Charge [C = As]

U: Voltage [V]

Current and voltage with capacitors:

$$I = \frac{dQ}{dt} = C\,\frac{dU}{dt}$$

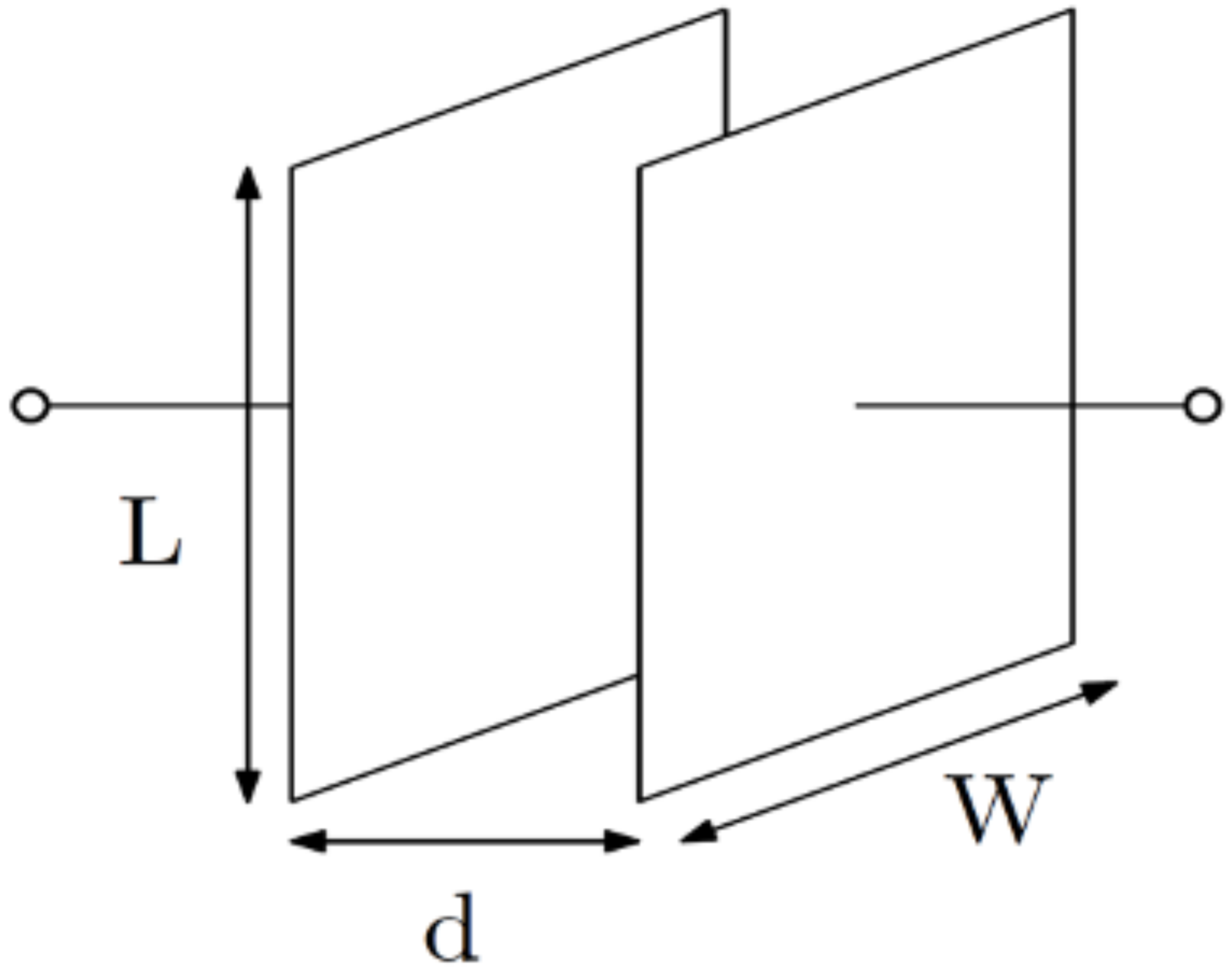



Plate capacitor

$$C = \frac{\epsilon_0\,\epsilon_r\,A}{d}$$

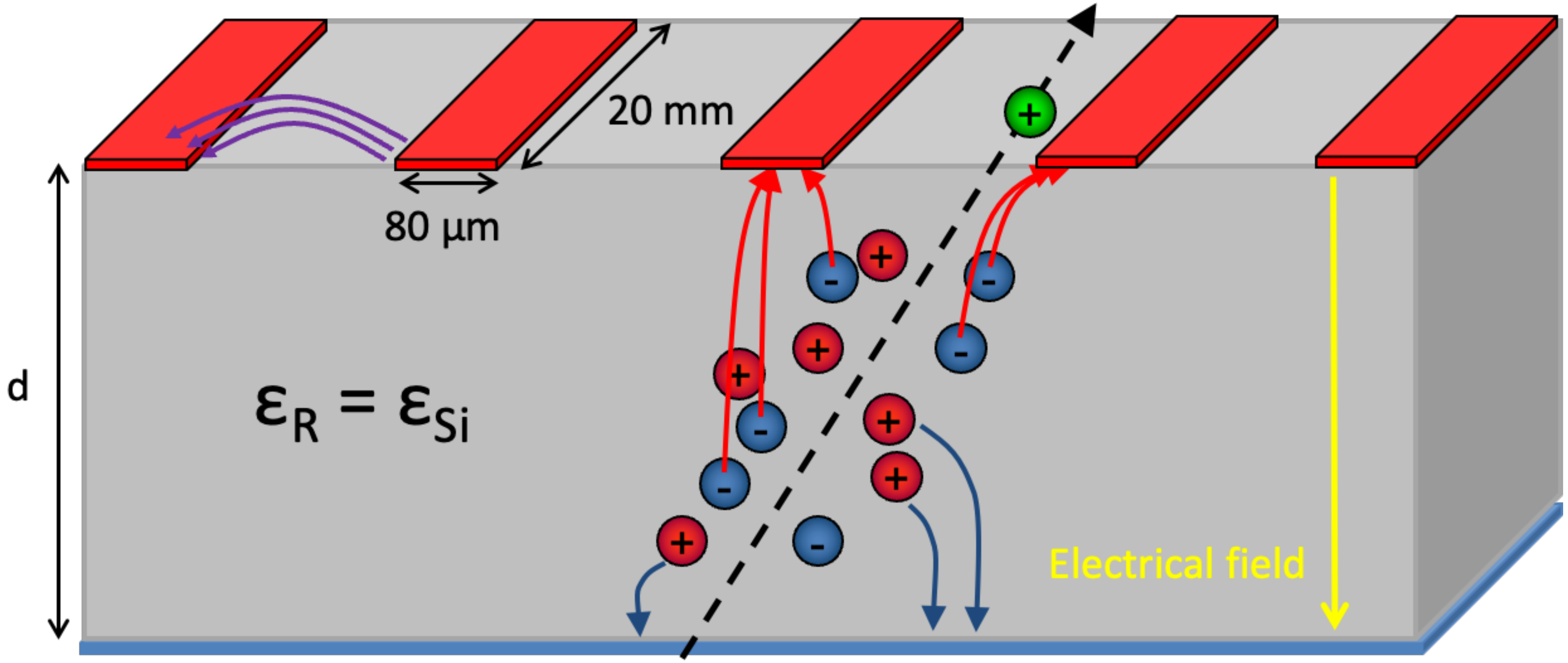
$$\epsilon_0 = 8,859\,10^{-12} \quad [\mathrm{F/m}]$$

Stored energy:

$$E = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}C\,U^2$$

# Example: Capacity of Silicon Detectors

*Silicon Strip Detectors*




$$C = \frac{\epsilon_0\, \epsilon_r\, A}{d}$$

Capacity of one strip:

A = 80 $\mu$m x 20 mm

d = 300 $\mu$m

$\varepsilon_0$ = 8.9 x $10^{-12}$ F/m and

$\varepsilon_R$ = 11.8 (Silizium)

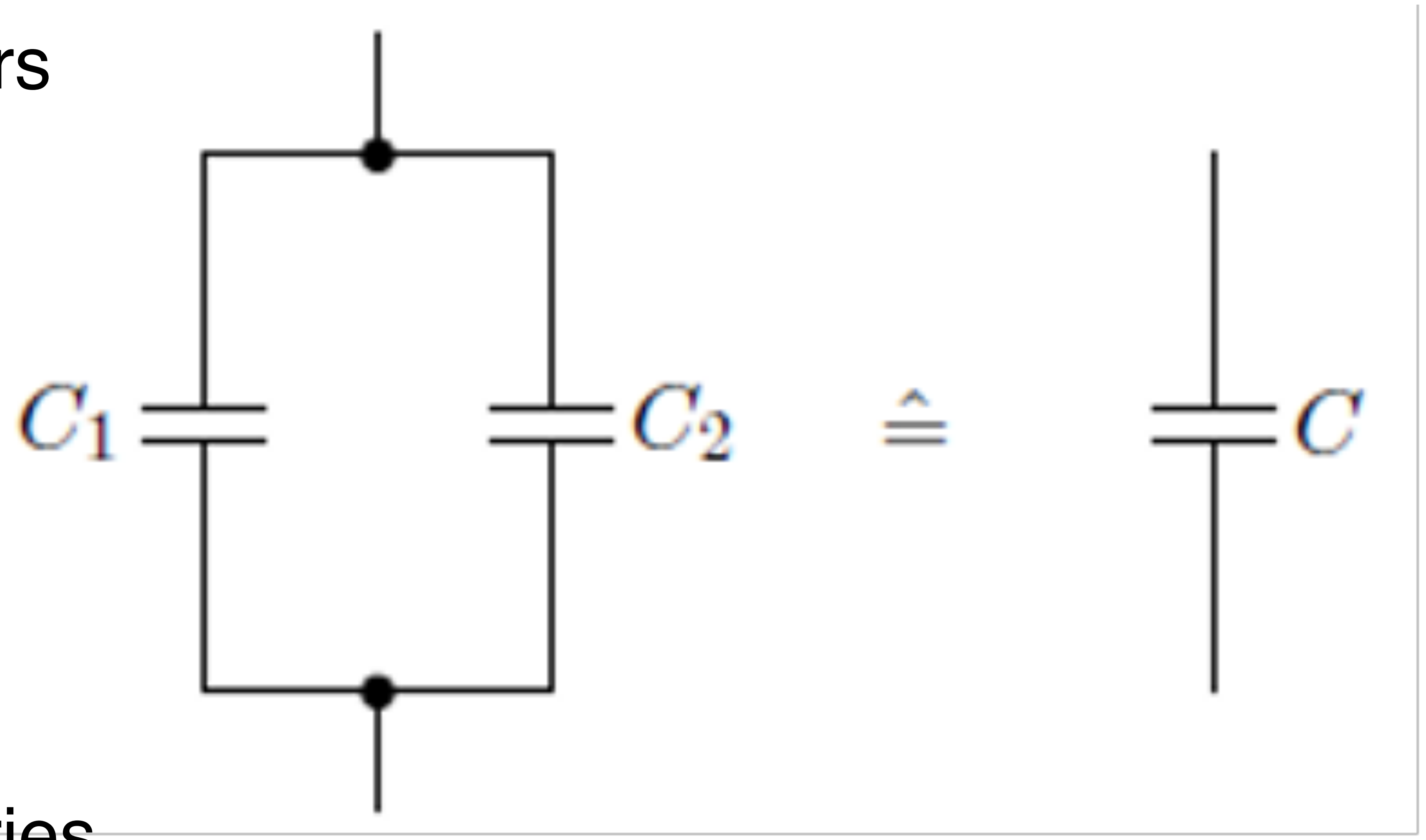
With full depletion, and neglecting neighboring strips and other effects: ~ 0.56 pF

When considering all effects (neighboring strips dominate!): 1-2 pF/cm x strip length

# Capacitors: Circuits

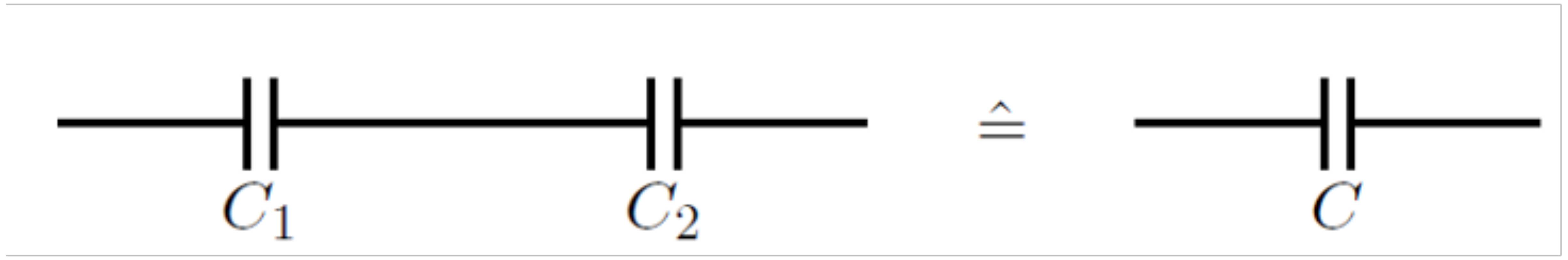
*Parallel, Series*

- Parallel capacitors




$$C = C_1 + C_2$$

- Capacitors in series




$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$$

$$C = \frac{C_1 C_2}{C_1 + C_2}$$



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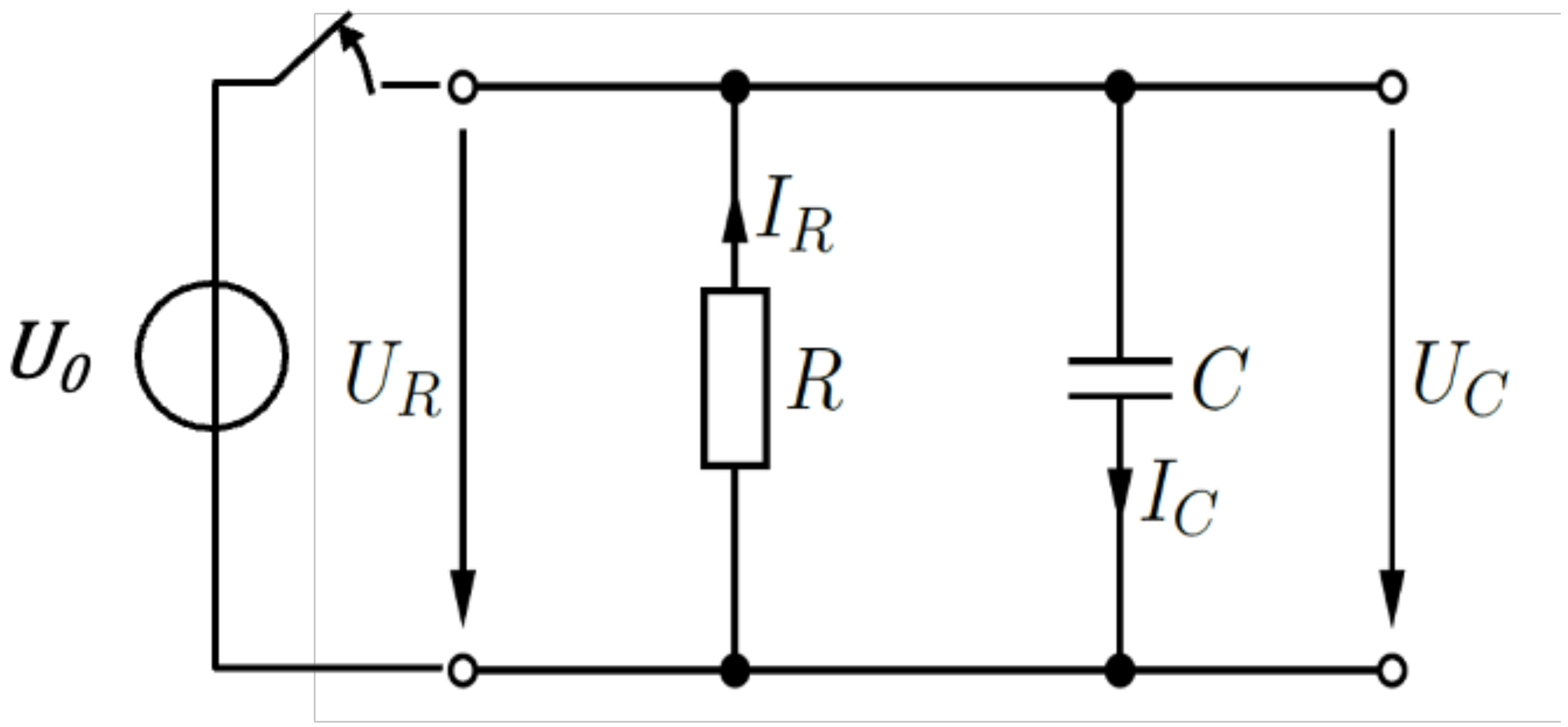
# Overview: Circuits with passive Components

*Resistor, Capacitor*

| | Series | Parallel |
|---|---|---|
| Resistor | $R = R_1 + R_2$ increases | $R = \frac{R_1 R_2}{R_1 + R_2}$ decreases |
| Capacitor | $C = \frac{C_1 C_2}{C_1 + C_2}$ decreases | $C = C_1 + C_2$ increases |

# Discharging a Capacitor

*Entladen*




For t > 0: Disconnecting the voltage source. Discharging the capacitor via R, starting from $U_C = U_0$

Kirchhoff's Current Law:

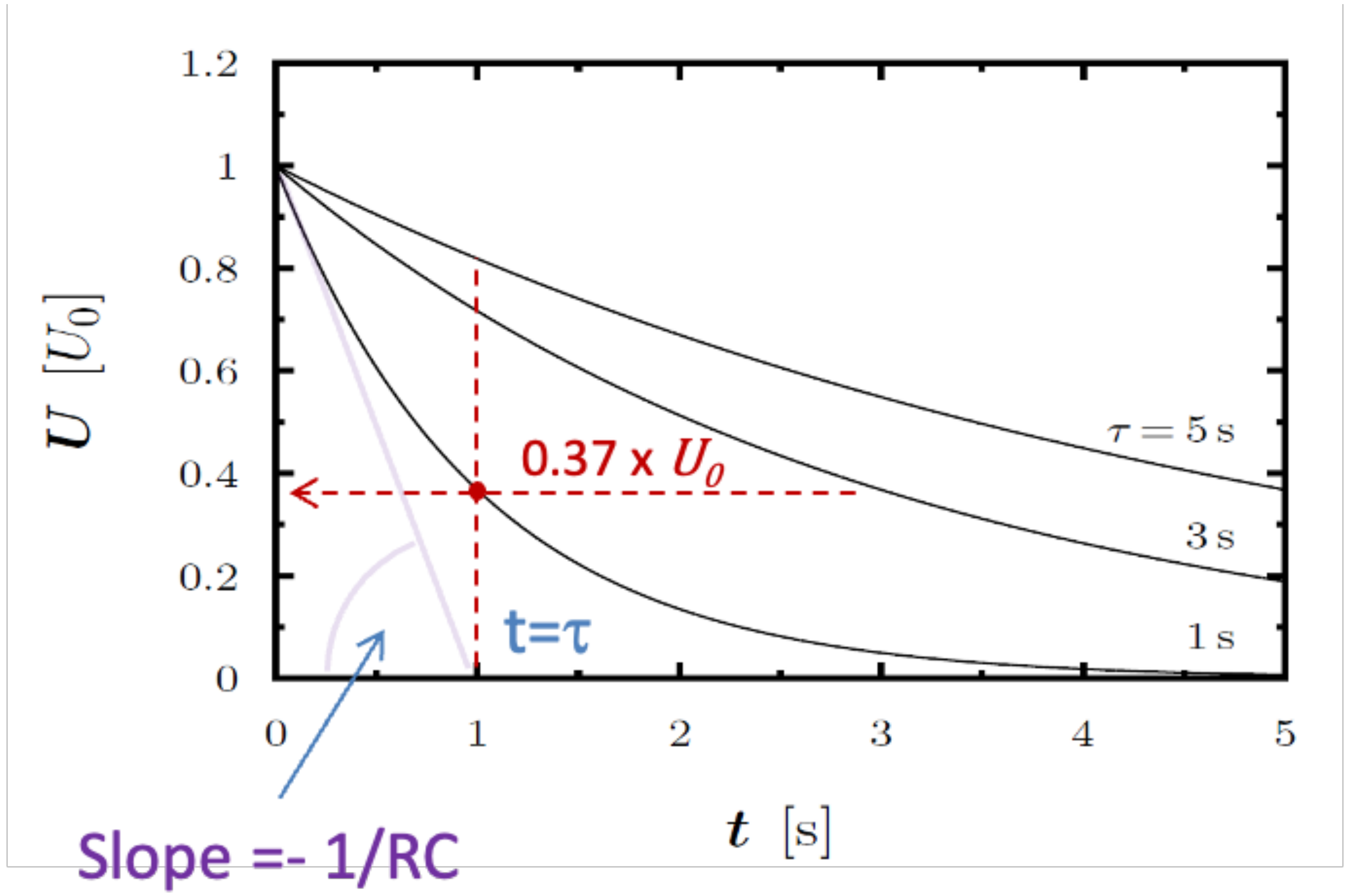
$$I_C = I_R \qquad I_C = C\frac{dU_c}{dt} = -\frac{U_C}{R}$$

Solving the differential equation

$$U_C(t) = U_0\, e^{-\frac{t}{RC}}$$

Exponential decrease with time constant

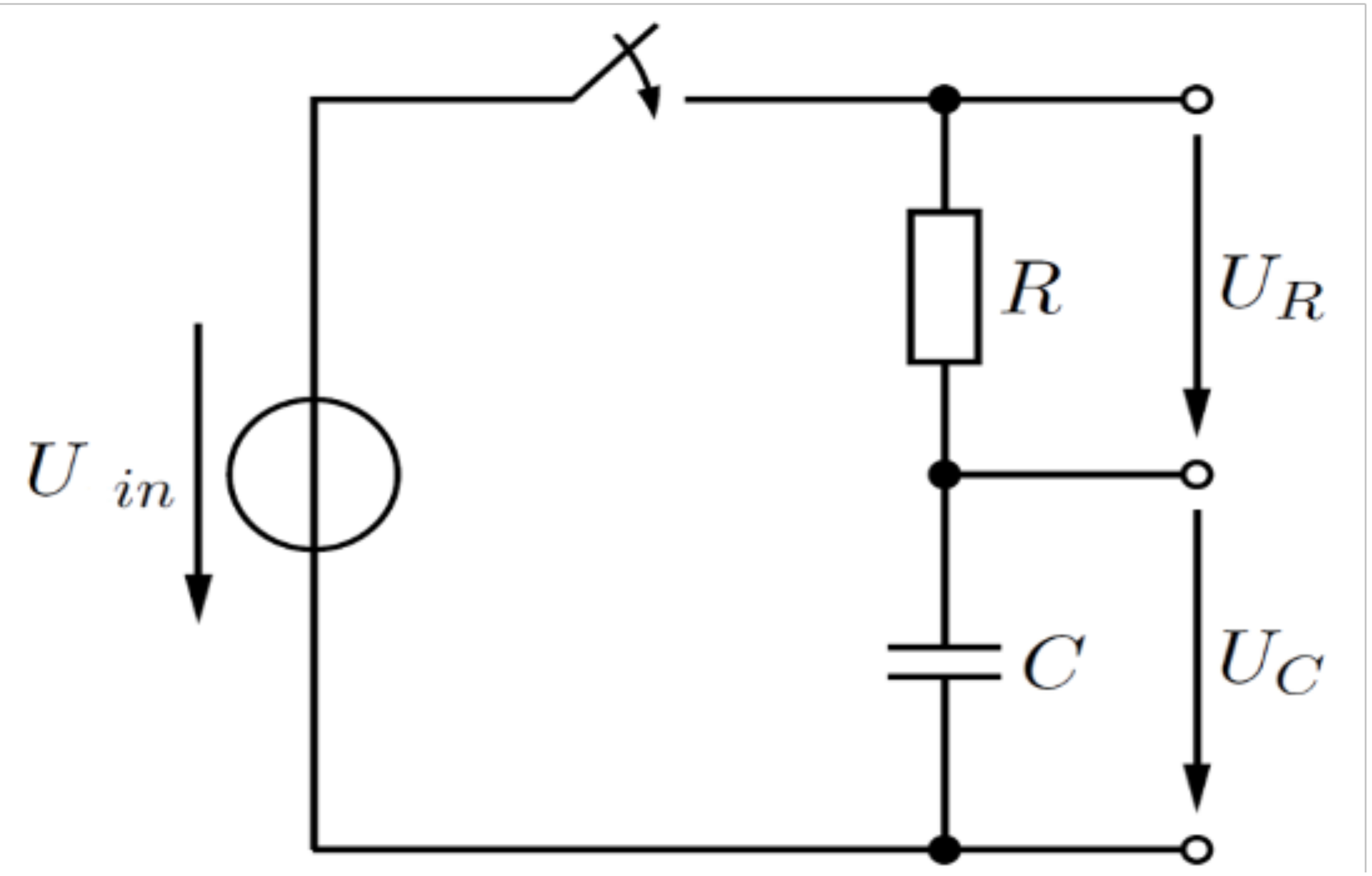
$$\tau = RC$$



# Charging a Capacitor

*with a Voltage Source*

- Charging via resistor




Large capacitor: longer charging time

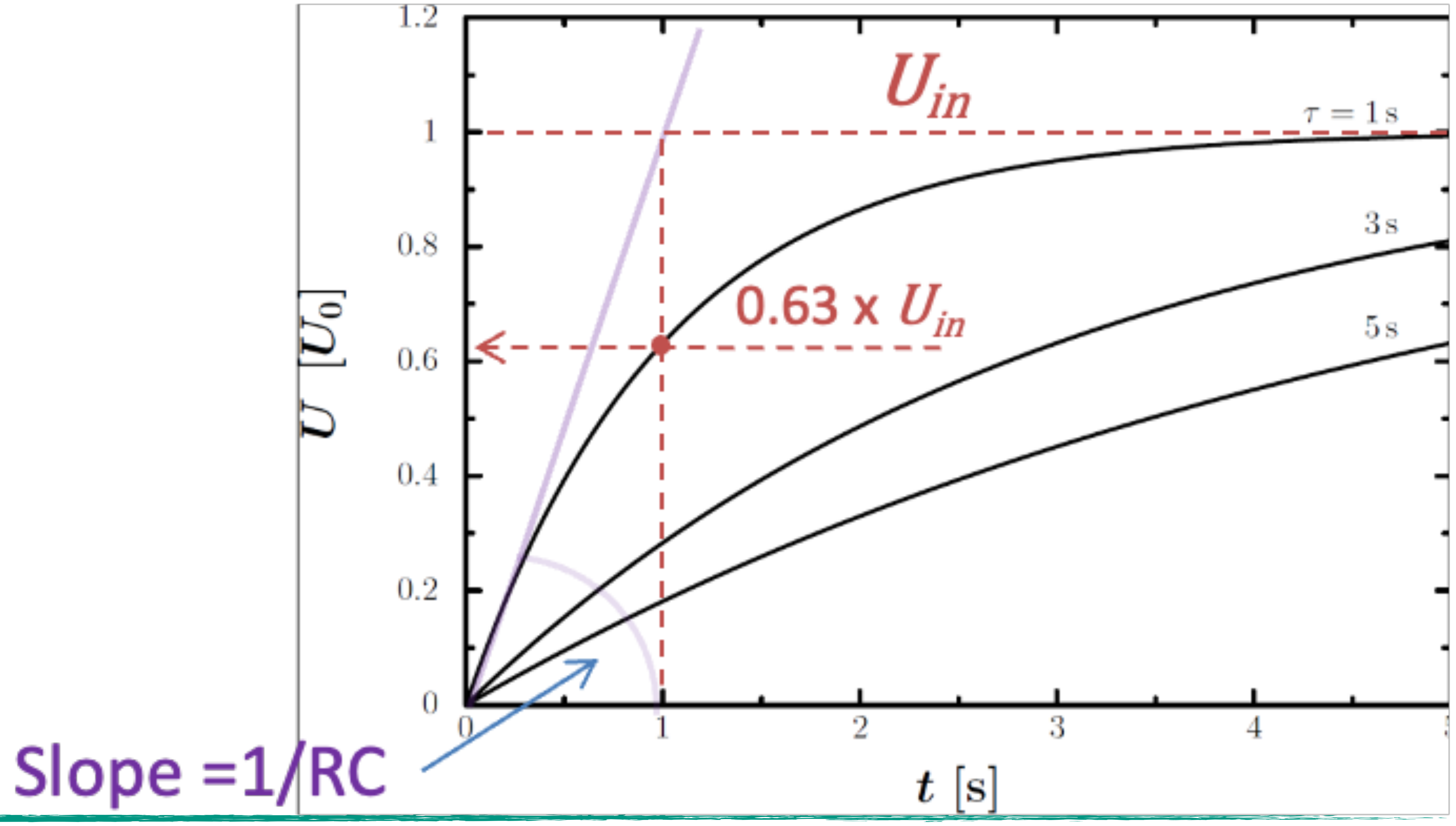
Large resistor: longer charging time

Starting point (t = 0): $U_C = 0$

"charging current": $I = U_R/R = (U_{in} - U_C)/R$

$U_C$ depend on capacitor charge: $U_C = Q_C/C$, with that depending on the integral of the current I from t=0:

$$U_C = U_{in}(1 - e^{-\frac{t}{RC}})$$





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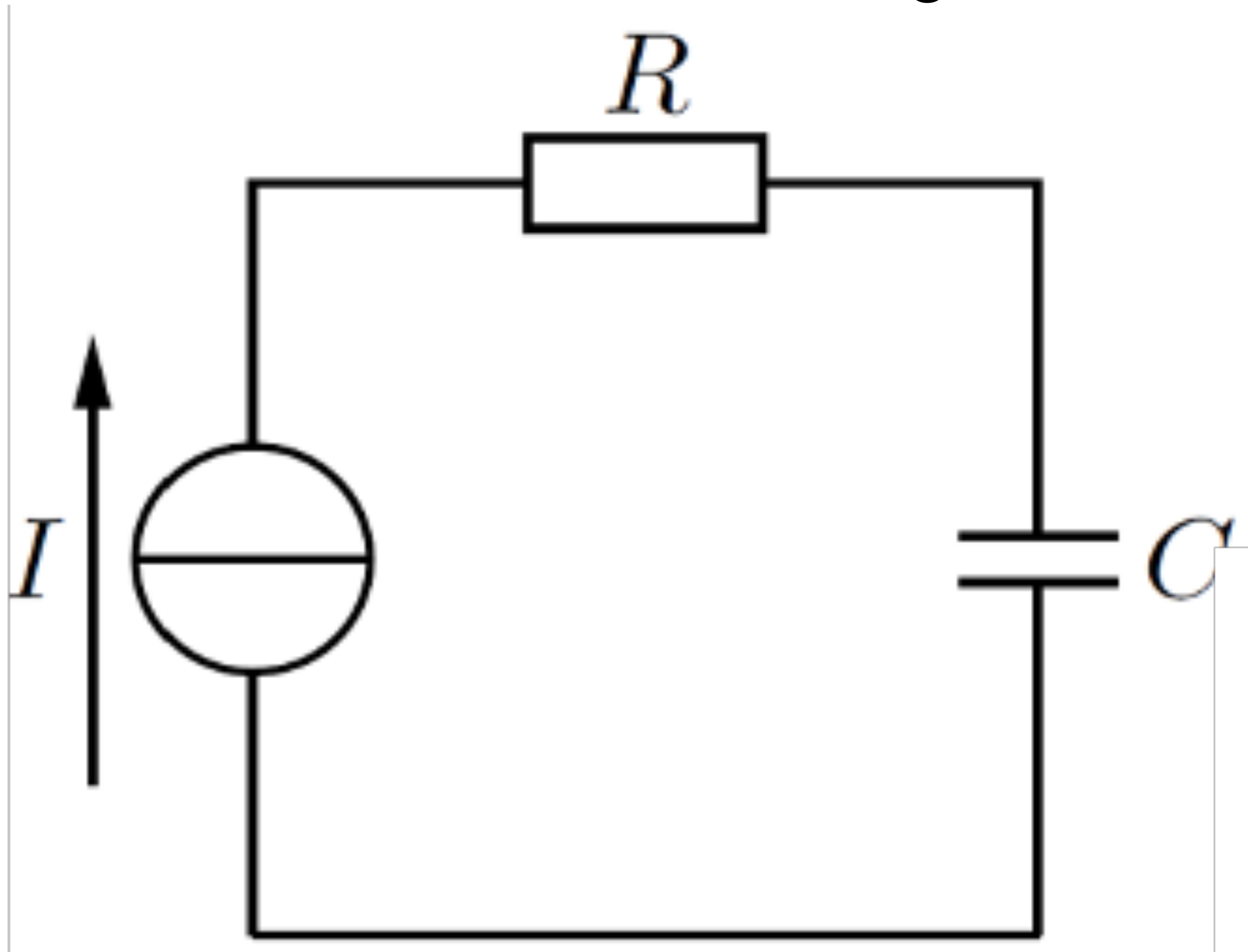
# Charging a Capacitor

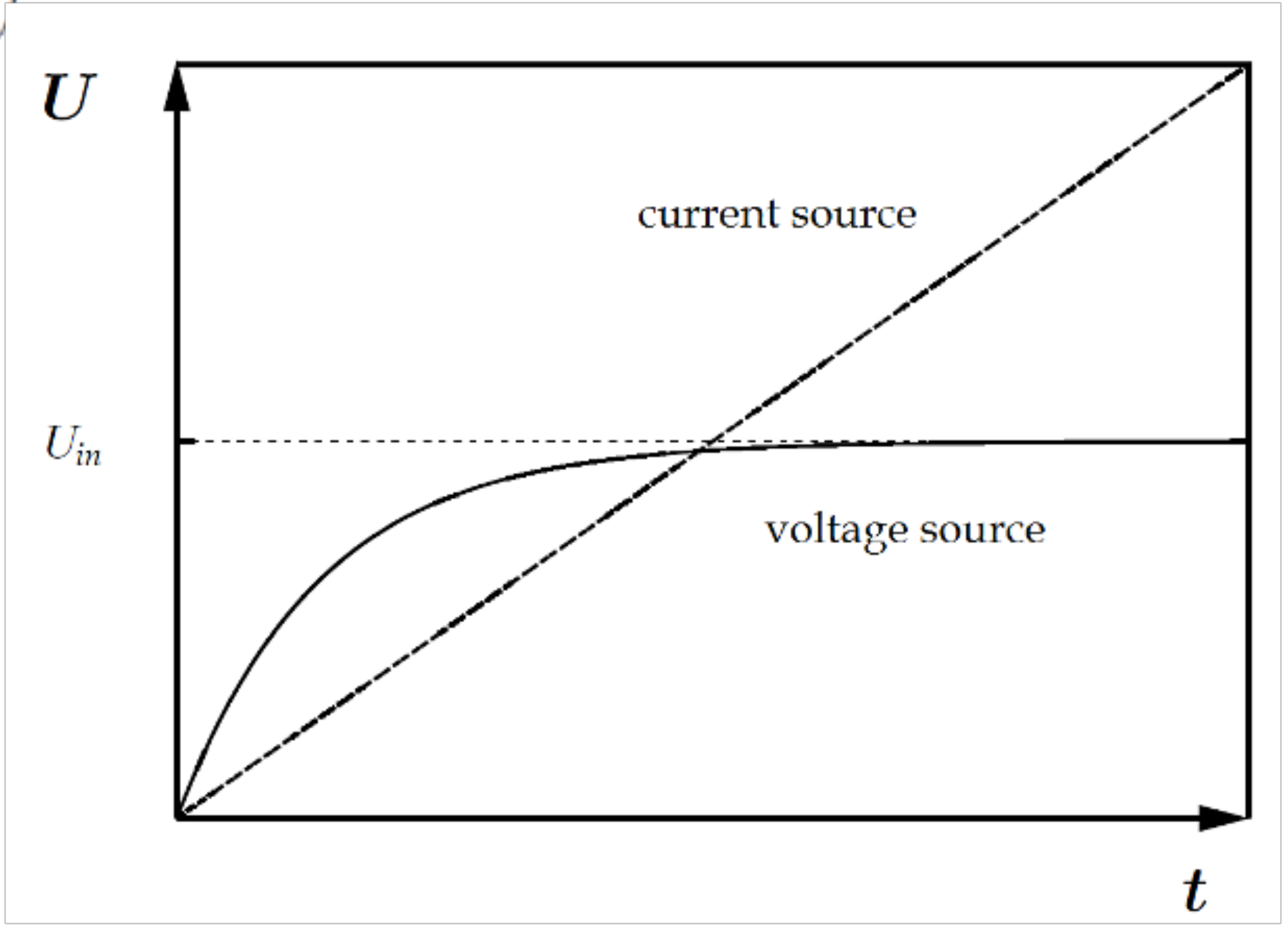
*with a Current Source*

- In contrast to the voltage source: charging current stays constant!



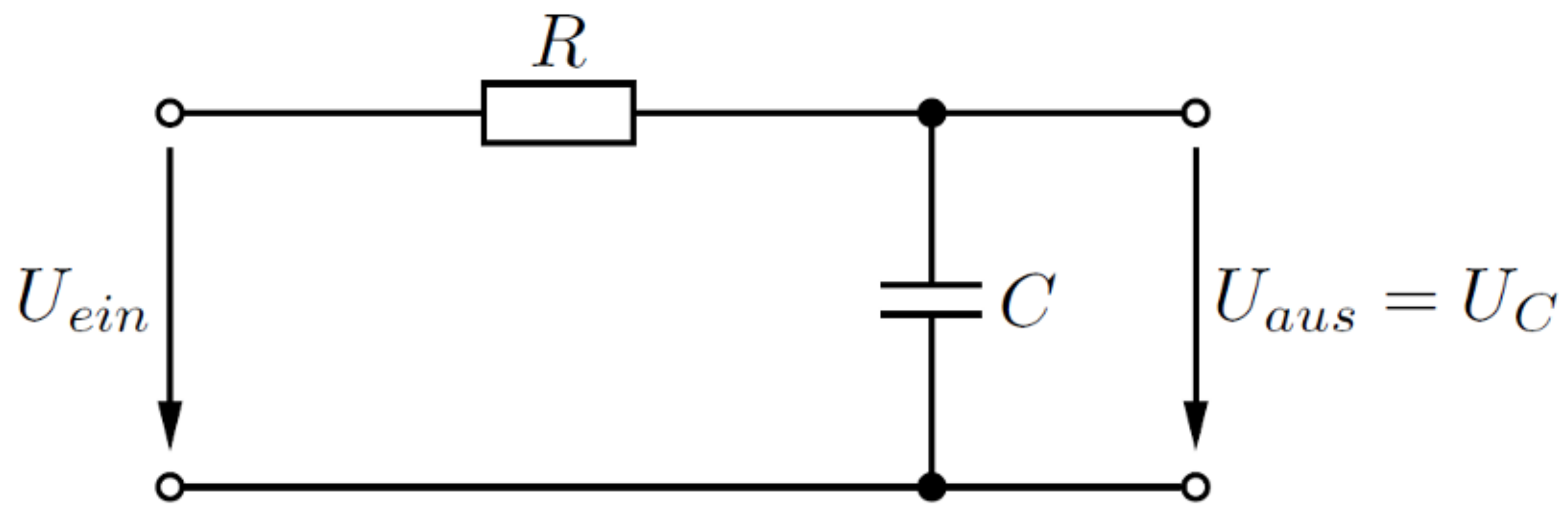

$$I = C\,\frac{dU_C}{dt} \quad \Leftrightarrow \quad U_C = \frac{1}{C}\int_0^T I\,dt = \frac{I\,T}{C}$$

Example:1 s bei C = 1 $\mu$F und I = 1 mA results in $U_C$ = 1 kV




Comparison of charging behavior with voltage and current source

- Behavior for time-dependent voltages




$$\frac{dU_C}{dt} + \cancel{\frac{U_C}{RC}} = \frac{U_{ein}}{RC}$$

First approximation: $U_C$ is small

$$U_C = U_{aus} = \frac{1}{RC}\int U_{ein}\,dt$$

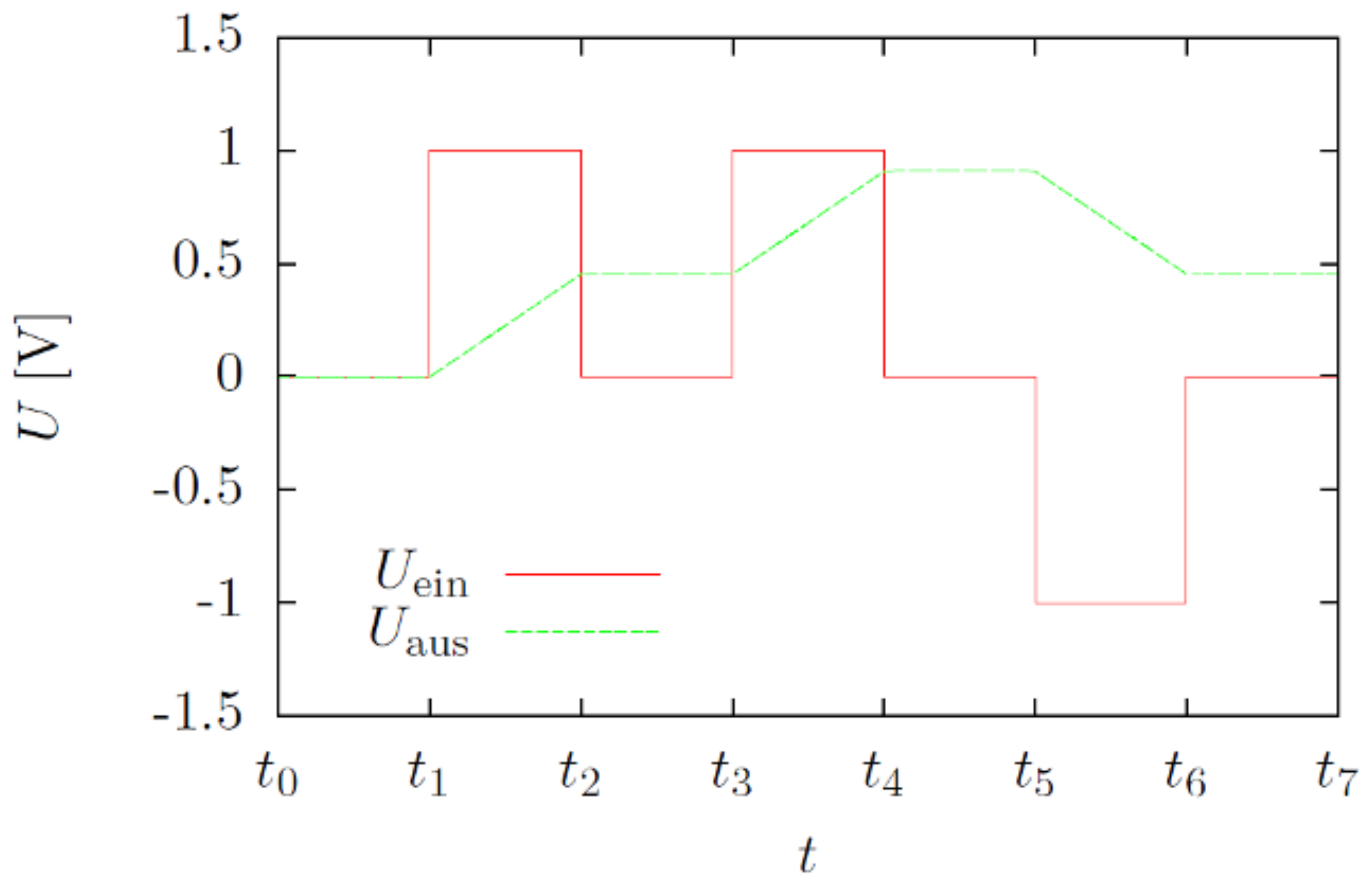
**Integrator circuit!**

Kirchhoff's Laws:

$I_C = I_R$ KCL

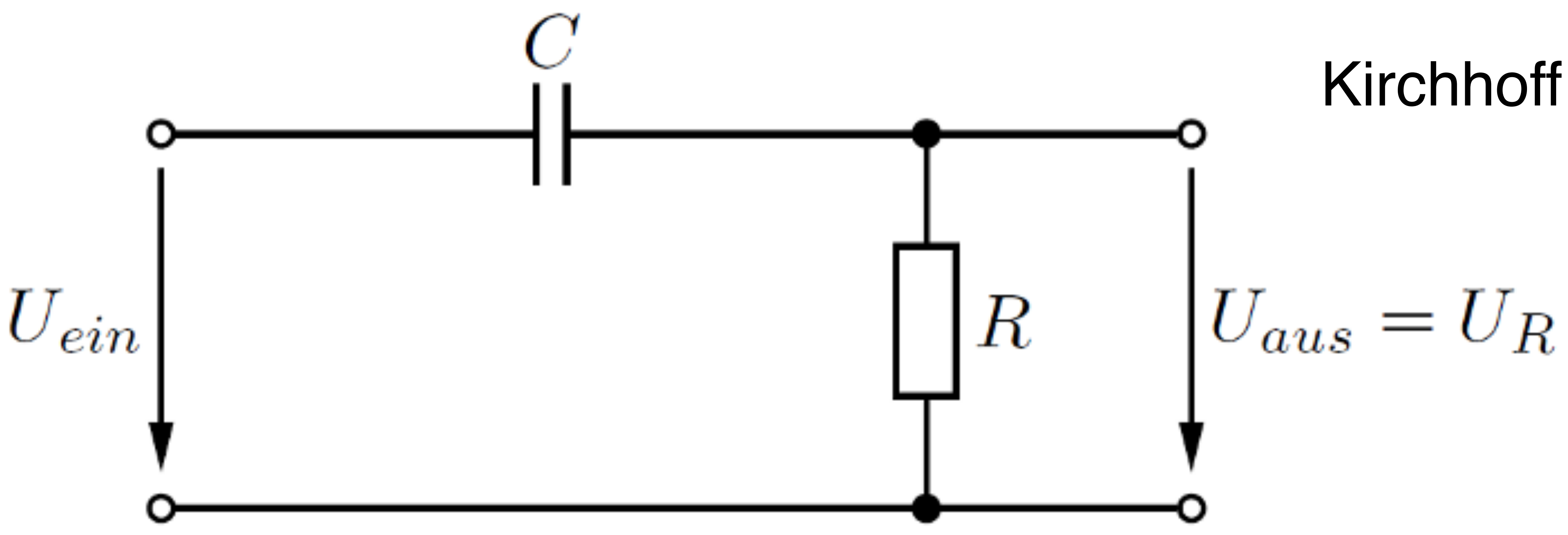
$U_{ein} - U_C - U_R = 0$ KVL

$$I_C = I_R \rightarrow C\frac{dU_C}{dt} = \frac{U_{ein} - U_C}{R}$$



# High Pass / Differentiator

*Hochpass / Differenzierer*



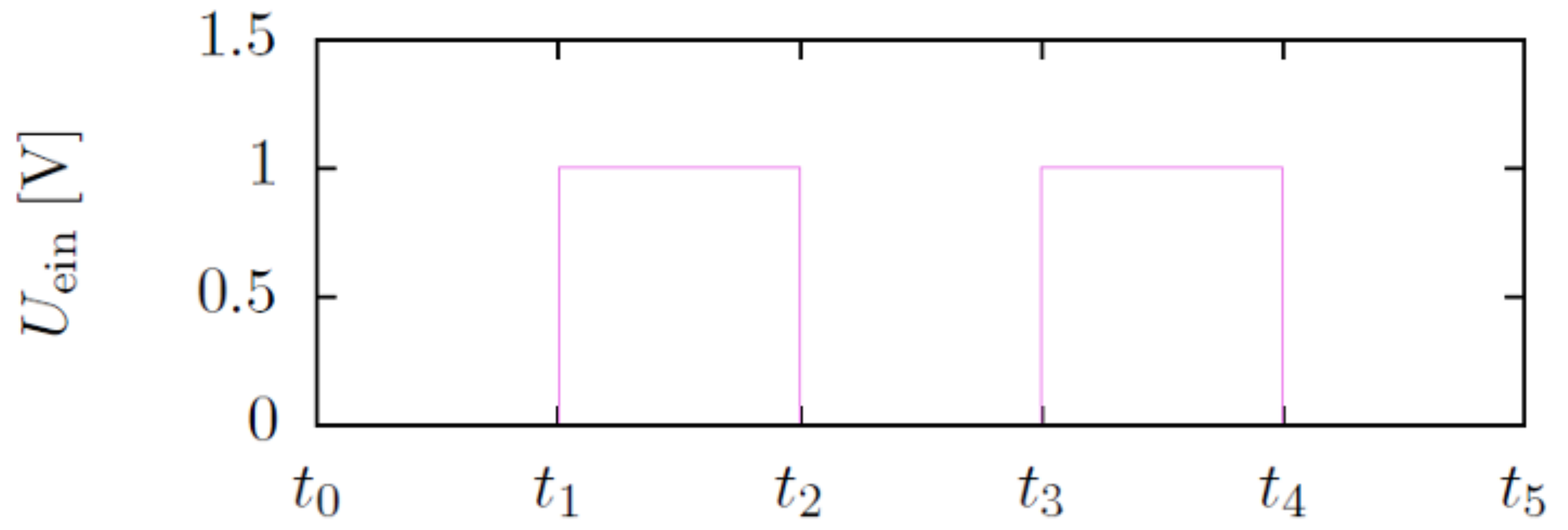

Kirchhoff: $I_C = I_R$ $\quad U_{ein} - U_C - U_R = 0$

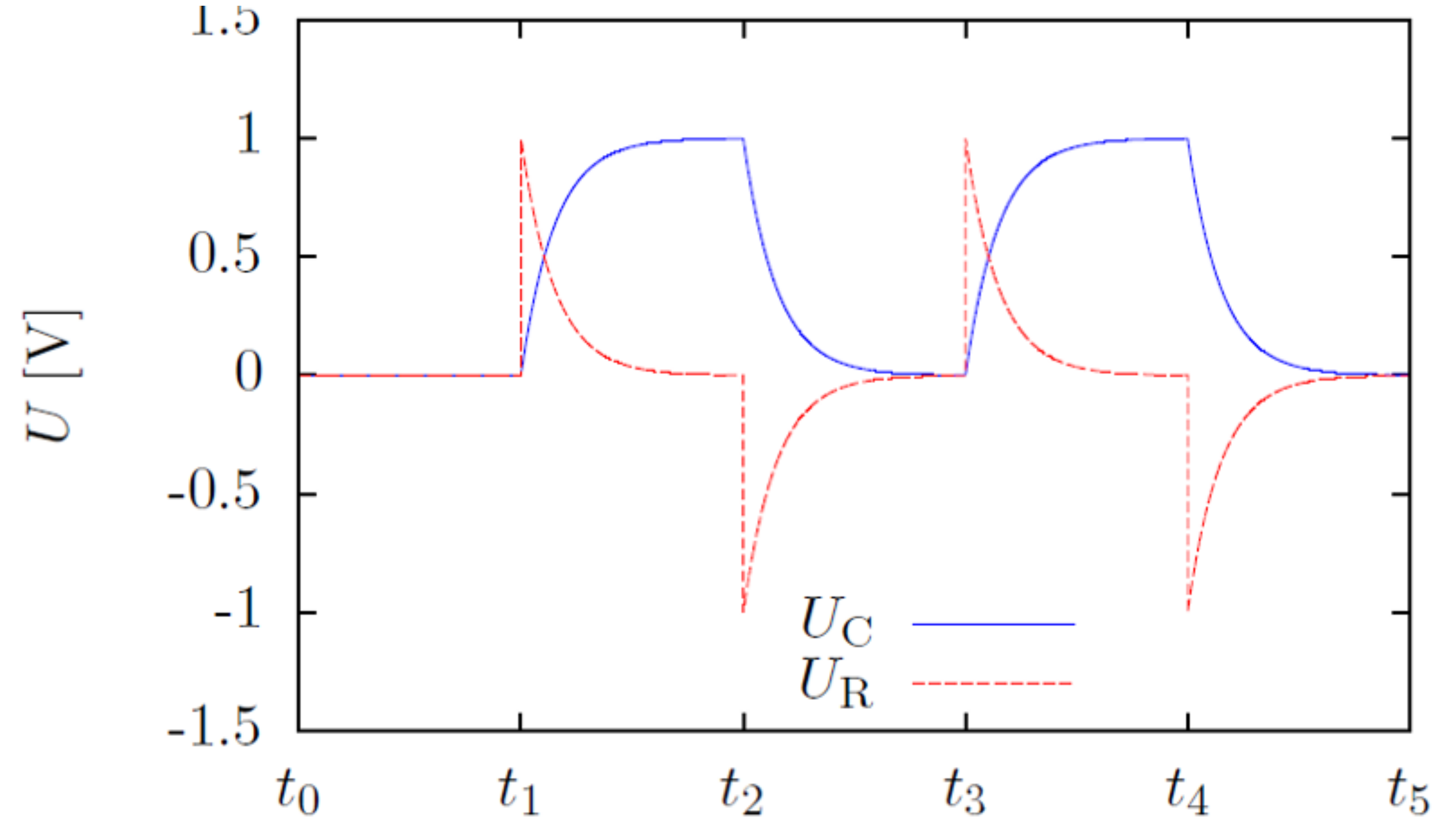
$$U_{ein} = U_C + RC\frac{dU_C}{dt}$$

$$U_{ein} - U_C = RC\frac{d(U_{ein} - U_{aus})}{dt} = U_{aus}$$

For small R: $U_{ein} - U_{aus} \sim U_{ein}$ (only small voltage drop)

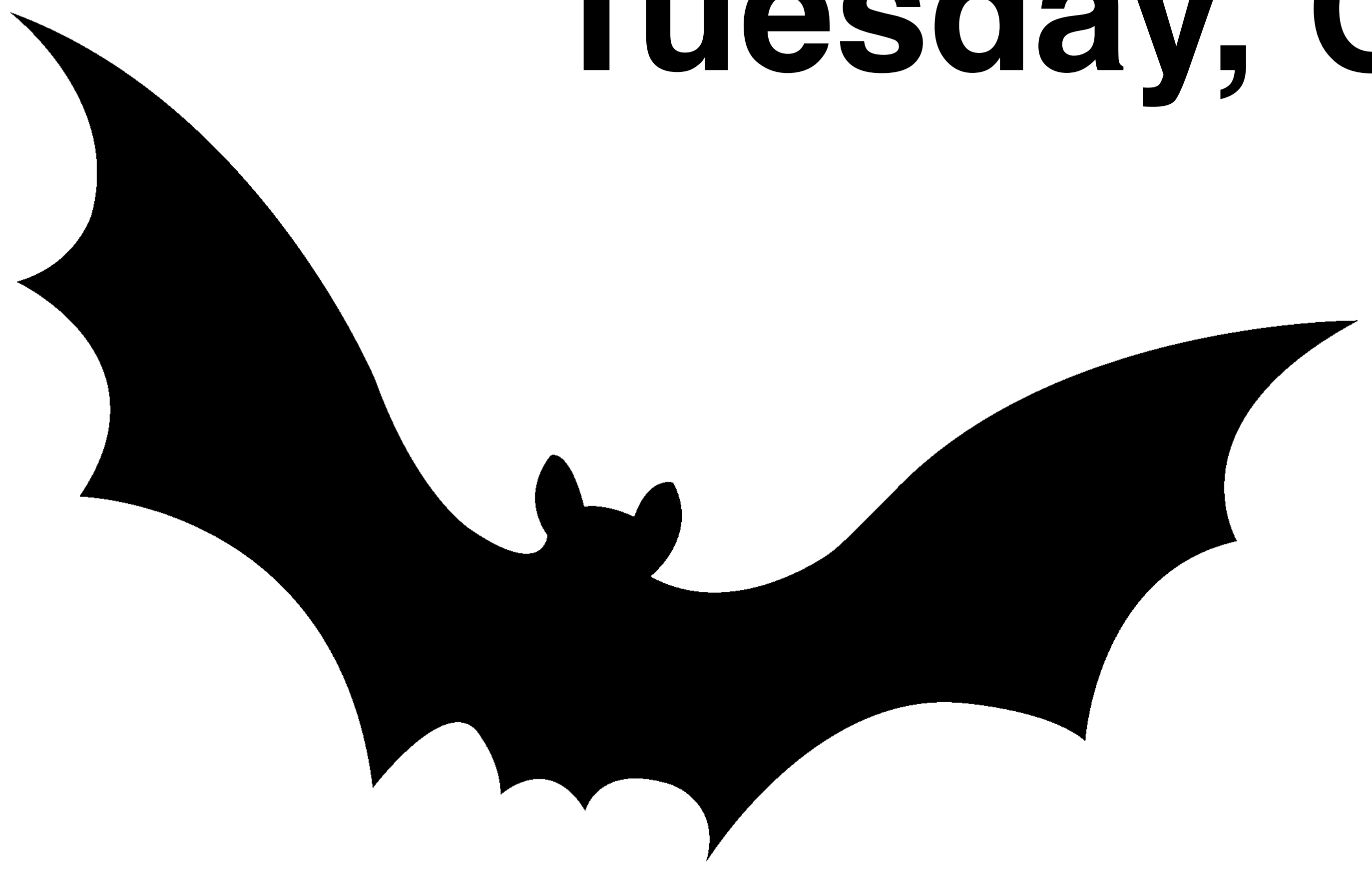
$$\boxed{U_{aus} = RC\frac{dU_{ein}}{dt}}$$



**Next Lecture: Analog 03 - Chapter 01**

**Tuesday, October 31 - same time, same place.**



# Electronics for Physicists

## *Analog Electronics*

*Chapter 1; Lecture 02*

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26.10.2023

Karlsruhe Institute of Technology

***KIT, Winter 2023/24***

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