

## 2.4. DC Circuits & Kirchhoff's Laws

**Imagine you're designing a camera flash. What components would you need to quickly store and release a large amount of electrical energy, and how would you control the timing?**

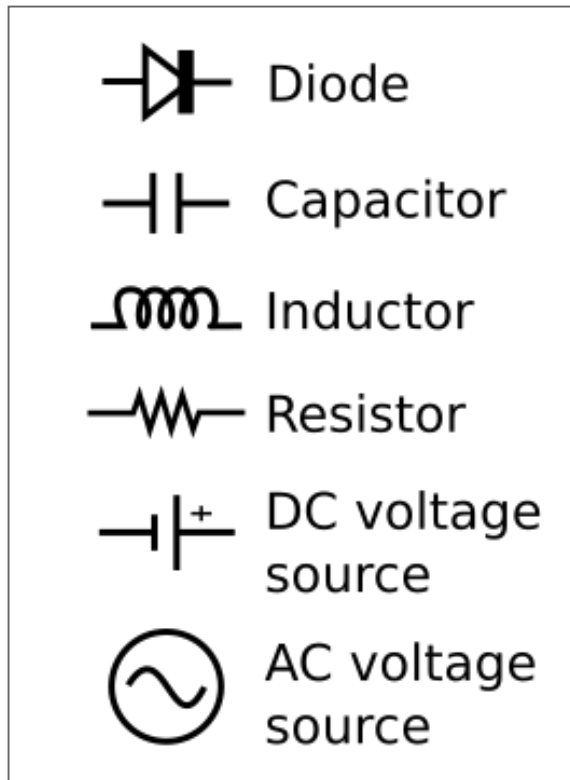
- need to design a circuit with at least
  - voltage source
  - capacitor
  - resistor
  - switch



## Circuits 101

- **Electric circuit:** Elements (batteries, resistors, capacitors) connected by wires
- **Circuit states:**
  - Open: No current flow
  - Closed: Current flow
  - Short: Excessive current (hazard)
- **Voltage source (V):** Provides potential difference, drives current (I)
- **Ground:** Reference potential (e.g., Earth)
- **Voltage drop:** Potential difference across an element
- **Element connections:** Series or parallel
- **Equivalent circuits:** Simplification by combining elements into e.g. an effective resistance

## Circuits 101 (cont'd)



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## Open-circuit voltage of a DC source

- **Source:** Energy conversion to electrical potential
- **Open-circuit voltage**  $V_0$ : Voltage without current flow
- **Internal resistance**  $R_{int}$ : Real sources have internal resistance
- **Voltage with current:**

$$V = V_0 - IR_{int}$$

- **Non-constant**  $R_{int}$ : Leads to non-linear current-voltage characteristics

## Measuring Voltages and Currents

e136 & e128

- **Ammeter:** Measures current (series connection)
- **Voltmeter:** Measures voltage (parallel connection)
- **Ohmmeter:** Measures resistance
- **Multimeter:** Combines ammeter, voltmeter, ohmmeter
- **Internal resistance:**
  - Voltmeter: High (limits current)
  - Ammeter: Low (limits voltage drop)
- **Simultaneous measurement:** Configuration choice depends on resistor and device internal resistances

## Resistors in series & parallel

e141

- **Series resistors:**

- equivalent resistance:  $R_{eq} = \sum R_i$
- voltage drops add up
- **interpretation for equivalent resistor:** increase effective length

- **Parallel Resistors:**

- equivalent resistance:  $\frac{1}{R_{eq}} = \sum \frac{1}{R_i}$
- current splits
- net resistance is smaller than the smallest individual resistance
- **interpretation for equivalent resistor:** increase effective cross-sectional area

## Capacitors in series & parallel

e123

- **Parallel Capacitors:**

- equivalent capacitance:  $C_{eq} = \sum C_i$
- voltage is the same
- total charge adds up
- **interpretation for equivalent capacitor:** increase effective plate area

- **Series Capacitors:**

- equivalent capacitance:  $\frac{1}{C_{eq}} = \sum \frac{1}{C_i}$
- charge is the same
- voltage drops add up
- net capacitance is smaller than the smallest individual capacitance

- **interpretation for equivalent capacitor:** increase effective plate distance



## Kirchhoff's Rules

- **Junction rule**

$$\sum_i I_i = 0 \quad \Leftrightarrow \quad \sum_j I_{in,j} = \sum_k I_{out,k}$$

- $\rightarrow$  **current conservation**

- **Loop rule**

$$\sum_i V_i = 0$$

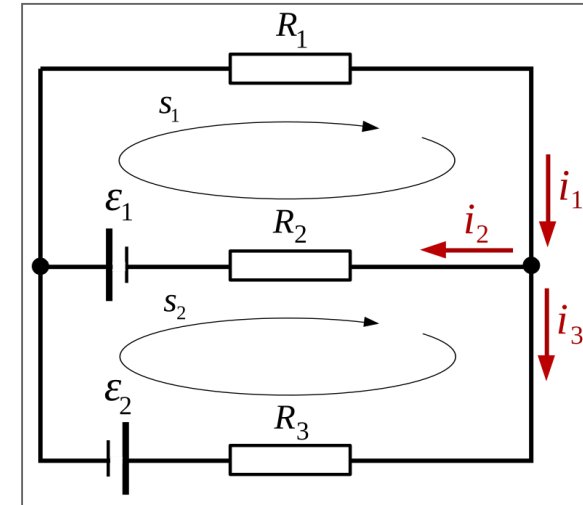
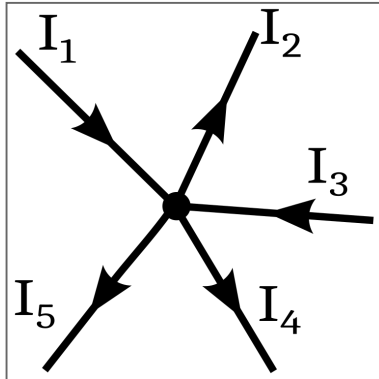
- $\rightarrow$  **energy conservation**

- **Circuit analysis steps:**

1. Label currents
2. Identify unknowns
3. Apply junction rule

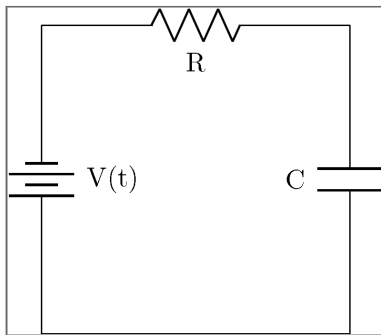
4. Apply loop rule
5. Solve equations
6. Vector/matrix form of equation

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## RC-circuit

- fundamental circuit for:
  - creating precise time delays → camera flash (charging of a capacitor determines the flash duration)
  - audio filtering → smooths out unwanted fluctuations
  - simple oscillators → periodic waveforms



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## RC-circuit: Charging

- **Circuit:** Resistor, capacitor, voltage source in series
- **Kirchhoff's loop rule:**

$$V_0 = IR + \frac{Q}{C}$$

- **Differential equation:** ( $I = \frac{dQ}{dt}$ )

$$V_0 = R \frac{dQ}{dt} + \frac{Q}{C}$$

$$\frac{dt}{RC} = \frac{dQ}{V_0 C - Q}$$

$$\frac{1}{RC} \int_0^t dt = \int_0^Q \frac{dQ}{V_0 C - Q}$$

## RC-circuit: Charging (cont'd)

- **Differential equation:** ( $I = \frac{dQ}{dt}$ )

$$\frac{1}{RC} \int_0^t dt = \int_0^Q \frac{dQ}{V_0 C - Q}$$

- **Solution:**

$$Q(t) = Q_0(1 - e^{-t/RC})$$

$$V_C(t) = V_0(1 - e^{-t/RC})$$

$$I(t) = \frac{V_0}{R} e^{-t/RC}$$

- $\rightarrow$  **Decaying current** and **increasing charge & voltage** over time
- **Time constant ( $\tau = RC$ ):**
  - Time for  $V_C$  to reach 63% of  $V_0$

- Time for  $I$  to decay to 37% of initial value
- Charging is considered complete after  $5 \tau$

## RC-circuit: Discharging

- **Circuit:** Capacitor and resistor in series; **no voltage source**
- **Kirchhoff's Loop Rule:**

$$IR = \frac{Q}{C}$$

- **Differential Equation:**

$$-\frac{dQ}{dt}R = \frac{Q}{C}$$

$$\frac{dQ}{Q} = -\frac{dt}{RC}$$



$$\int_{Q_0}^Q \frac{1}{Q} dQ = -\frac{1}{RC} \int_0^t dt$$

## RC-circuit: Discharging (cont'd)

- **Differential Equation:**

$$\int_{Q_0}^Q \frac{1}{Q} dQ = -\frac{1}{RC} \int_0^t dt$$

- **Solution:**

$$Q(t) = Q_0 e^{-t/RC}$$

$$V_C(t) = V_0 e^{-t/RC}$$

$$I(t) = I_0 e^{-t/RC}$$

- **→ Decaying voltage and current over time**

RC-circuit: Periodically switching

Script simulation RC-circuit

el11

- **Sawtooth Voltage:** Created by periodic charging and discharging
- **Practical Implementation:** Voltage source, capacitor, two resistors, and a tube
- **Charging Loop:** Capacitor charges through one resistor
- **Discharging Loop:** Tube conducts at breakdown voltage, discharging capacitor through the other resistor
- **Repeat Cycle:** Sawtooth waveform generated
- **Application:** Heart pacemaker, (music) , etc.