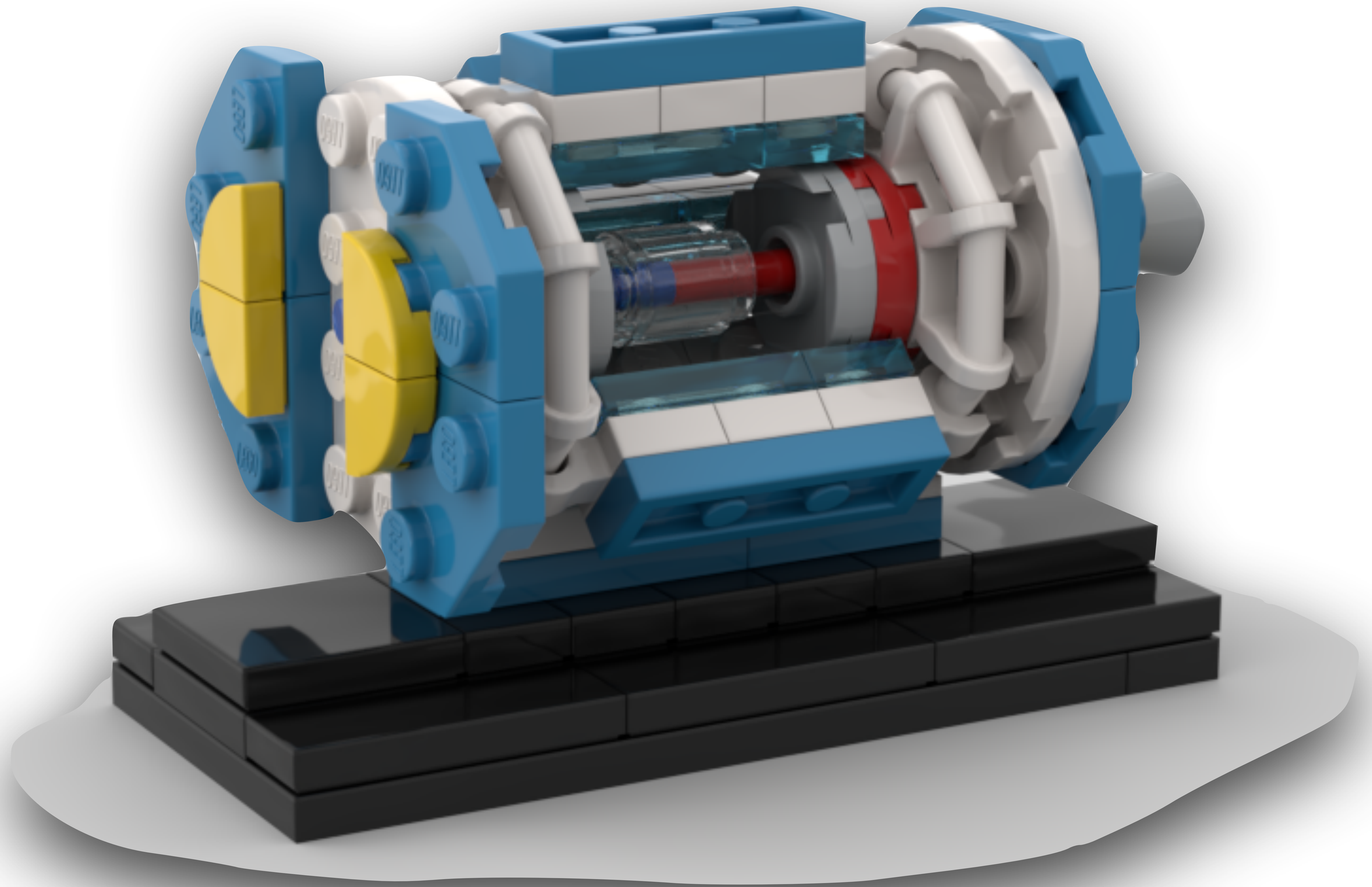
Belle II Academy · Hardware

Build Your Own Particle Detector

Sebastian Laudage, Ilias Tsaklidis

05.05.2026



NETZWERK TEILCHENWELT

https://www.belle2.de/belle-2-and-you/belle-2-materialien

Sebastian Laudage

- Physics background

B.Sc. Physics + M.Sc. Astrophysics in Bonn

- PhD project

DIY particle detectors for schools · FASER-ν

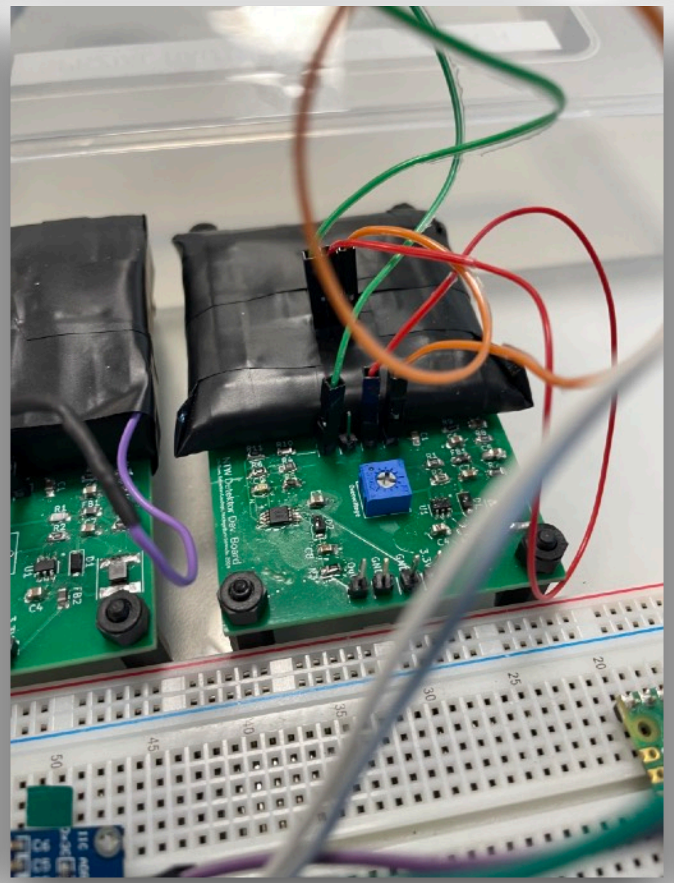
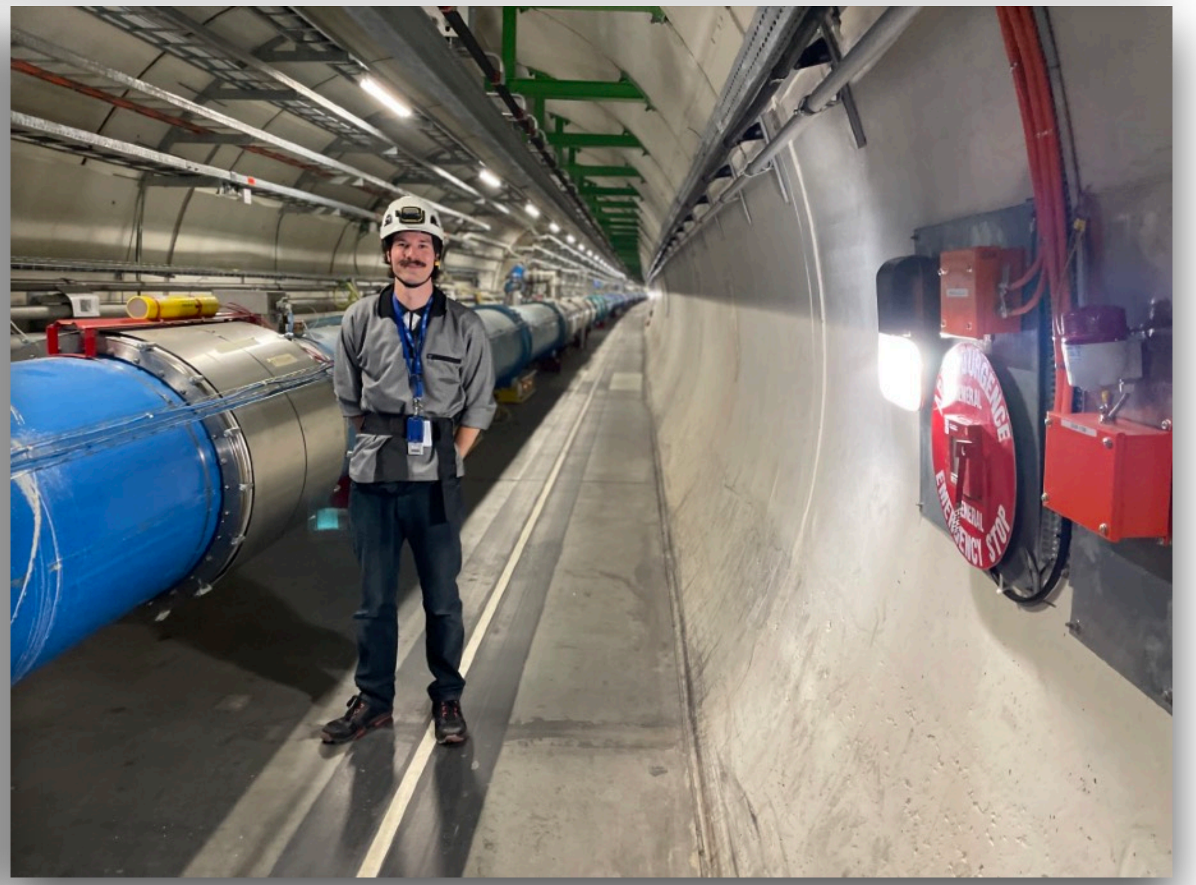
- Outreach activities

Netzwerk Teilchenwelt · BL4S

- Beyond work

Music · guitar · electronics · kayaking



Raise your hand if..

…you are currently doing a Master's.

Raise your hand if..

…you are currently doing a PhD.

Raise your hand if..

…you mainly work on data analysis or software development.

Raise your hand if..

…you mainly work on hardware.

Raise your hand if..

…your last electronics lecture was more than two years ago.

Raise your hand if..

…you have used LTspice or similar circuit simulation software before.

Raise your hand if..

…you have built a „DIY Particle Detector“ before.

Hardware Session

Hardware I	Tuesday, 11:00–12:30	Introduction & theory
Hardware II	Wednesday, 09:00–10:30	Circuit simulation in LTspice
Hardware III	Wednesday, 11:00–12:30	Soldering basics
Hardware IV	Wednesday, 13:45–15:15	Hands-on detector building
Hardware V	Wednesday, 15:45–18:00	Testing · Debugging · Measuring

Practical Skills

Signal Conditioning
Processing signals from the sensor to the data logger

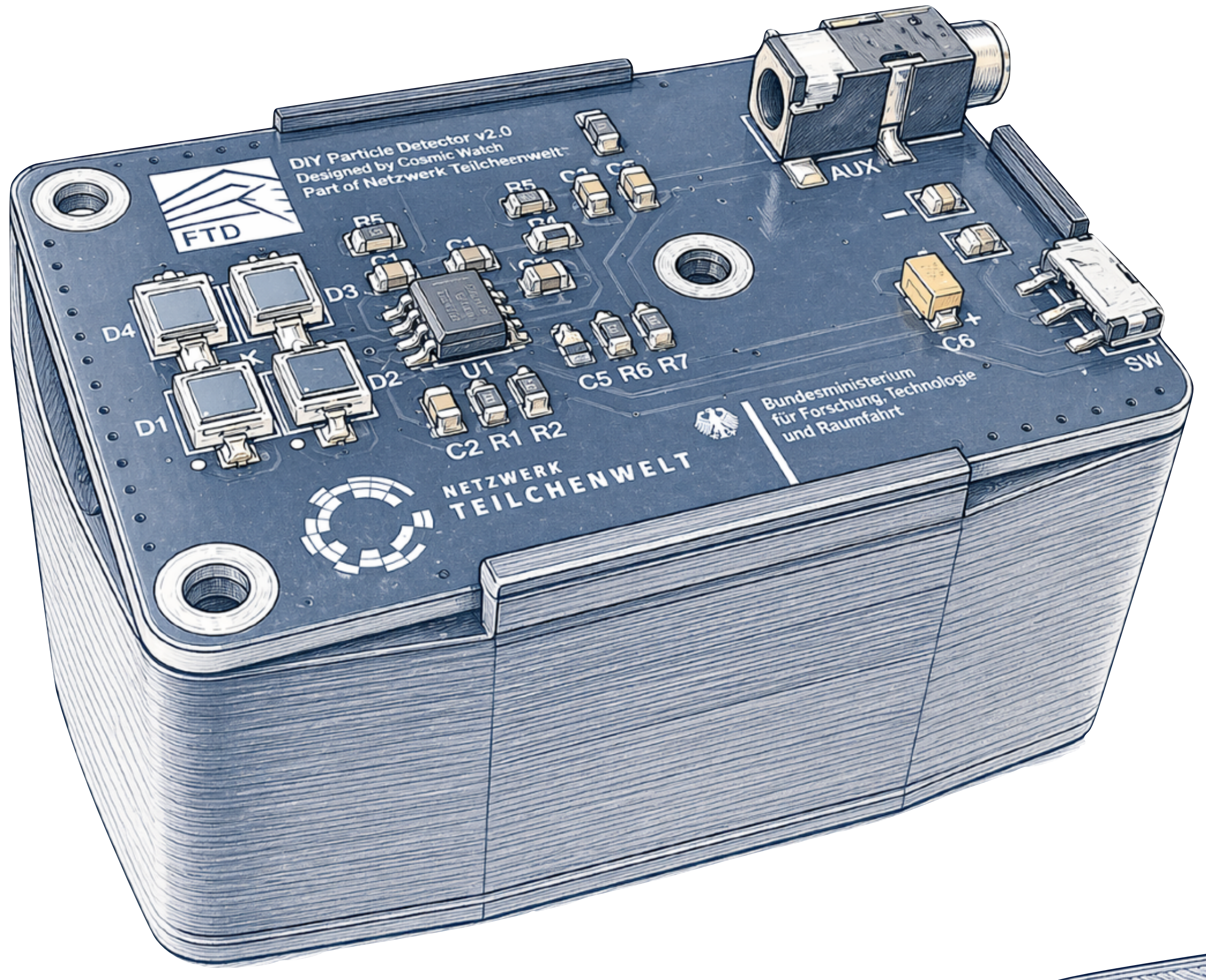
Circuit simulation
Use LTspice to simulate and understand circuits

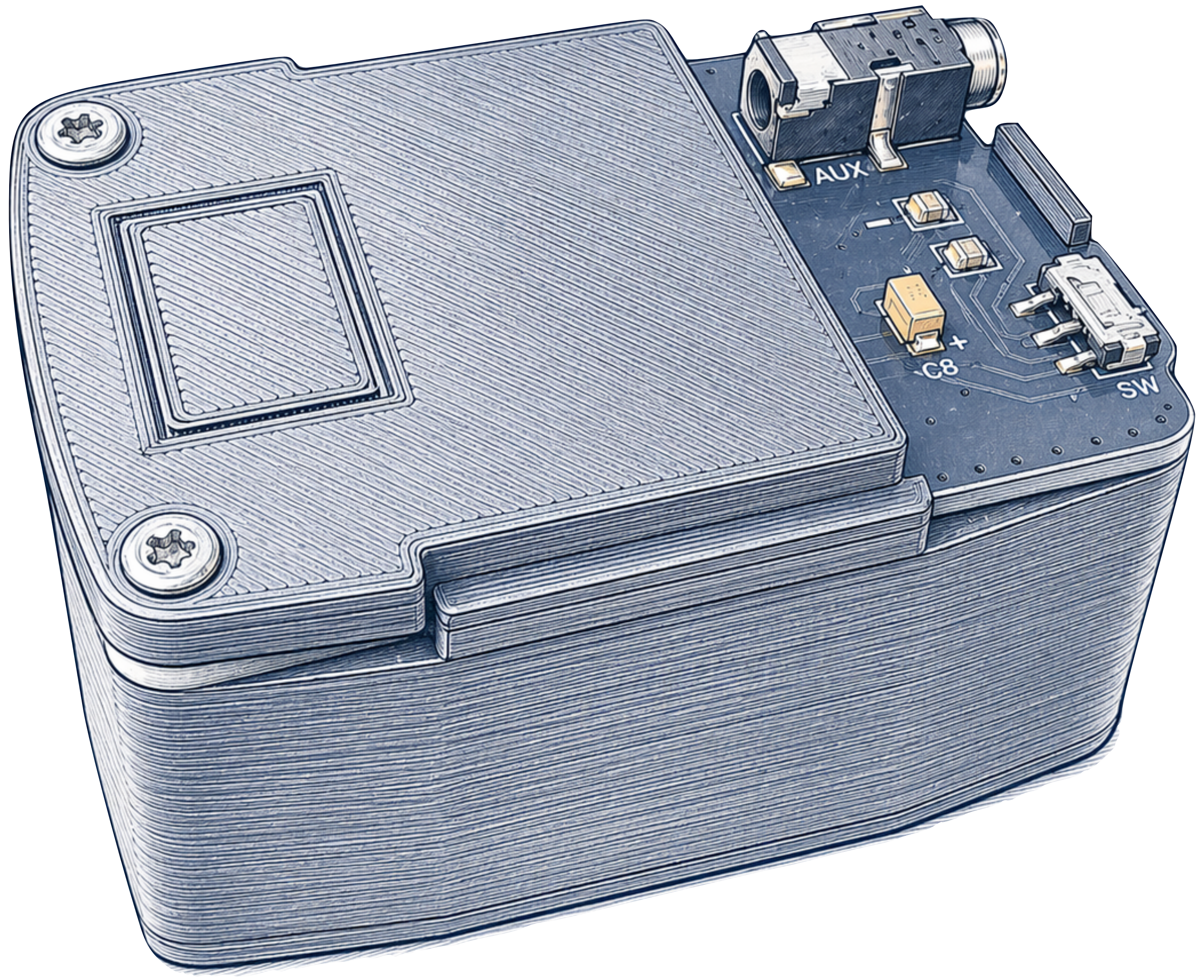
Soldering
Practice handling and soldering electronic components

Detector assembly & Troubleshooting
Assemble the detector step by step and troubleshoot issues

DIY Particle Detector SMD

- Pocket particle detector
    - Cost: ~15 €
    - Build time: ~2 h
    - Beginner-friendly design
- Based on low-cost silicon PIN diodes
- Measures ionizing radiation
    - natural background
    - radioactive sources
- Bachelor thesis (Rojin Aksu, 2025)





Disclaimer: This is a brand new design

- Things might go wrong
- Feedback and questions are wanted!!

DIY Detector History

1986


Besonders praktisch:

Radioaktivitätsmesser im Miniformat

Strahlungs-Meßgerät mit Zählrohr- oder Pin-Dioden-Detektor

Ein handliches, stets einsatzbereites Radioaktivitäts-Meßgerät, das auch hohen Anforderungen entspricht und genaue, reproduzierbare Meßwerte liefert, läßt sich auf kleinstem Raum verwirklichen. Anstelle des derzeit schwer erhältlichen Zählrohres kann man hier auch wesentlich preisgünstigere Halbleiter-Sensoren einsetzen.

Becker, J. Radioaktivitätsmesser im Miniformat. Funkschau 1986, 21, 63–69.

German amateur radio operator magazin

2011

Fig. 1. Pocket Geiger (Type 4) and its PCB.

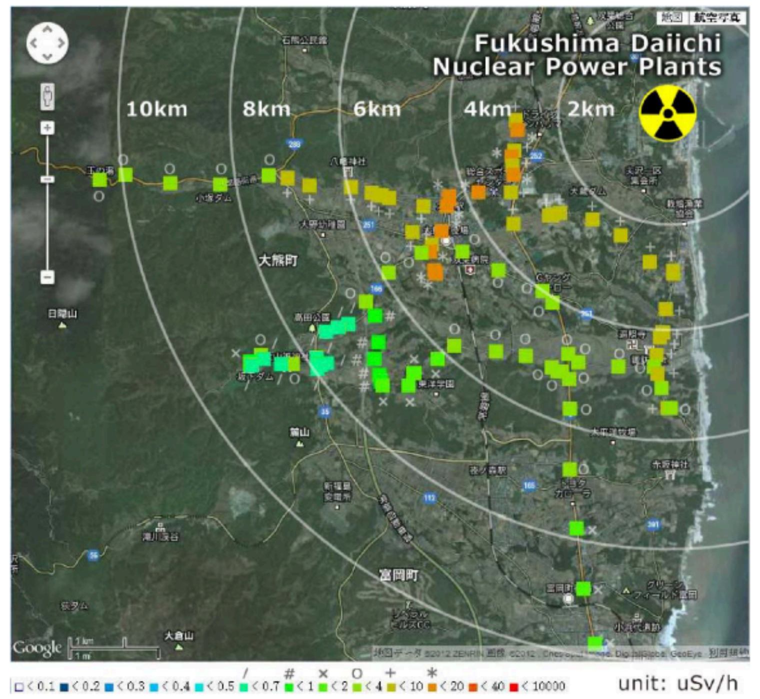
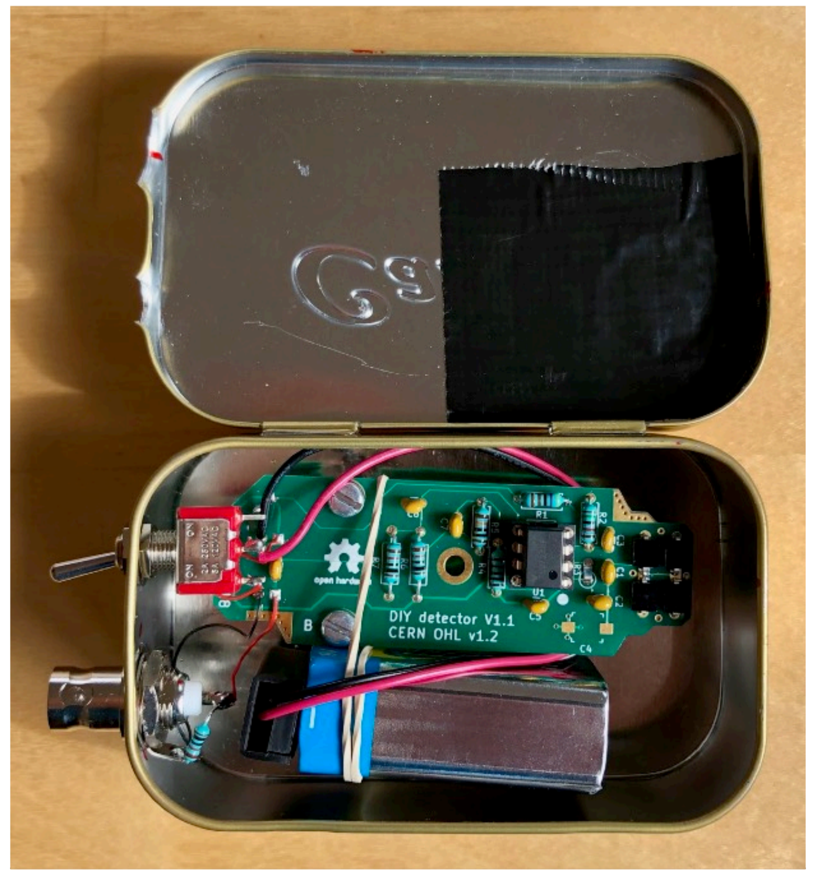


Fig. 10. Visualization of radiation levels around Fukushima Daiichi Nuclear Power Plants.

Ishigaki, Y.; Matsumoto, Y.; Ichimiya, R.; Tanaka, K. Development of Mobile Radiation Monitoring System Utilizing Smartphone and Its Field Tests in Fukushima 2011

Advanced design by Tokyo hacker community

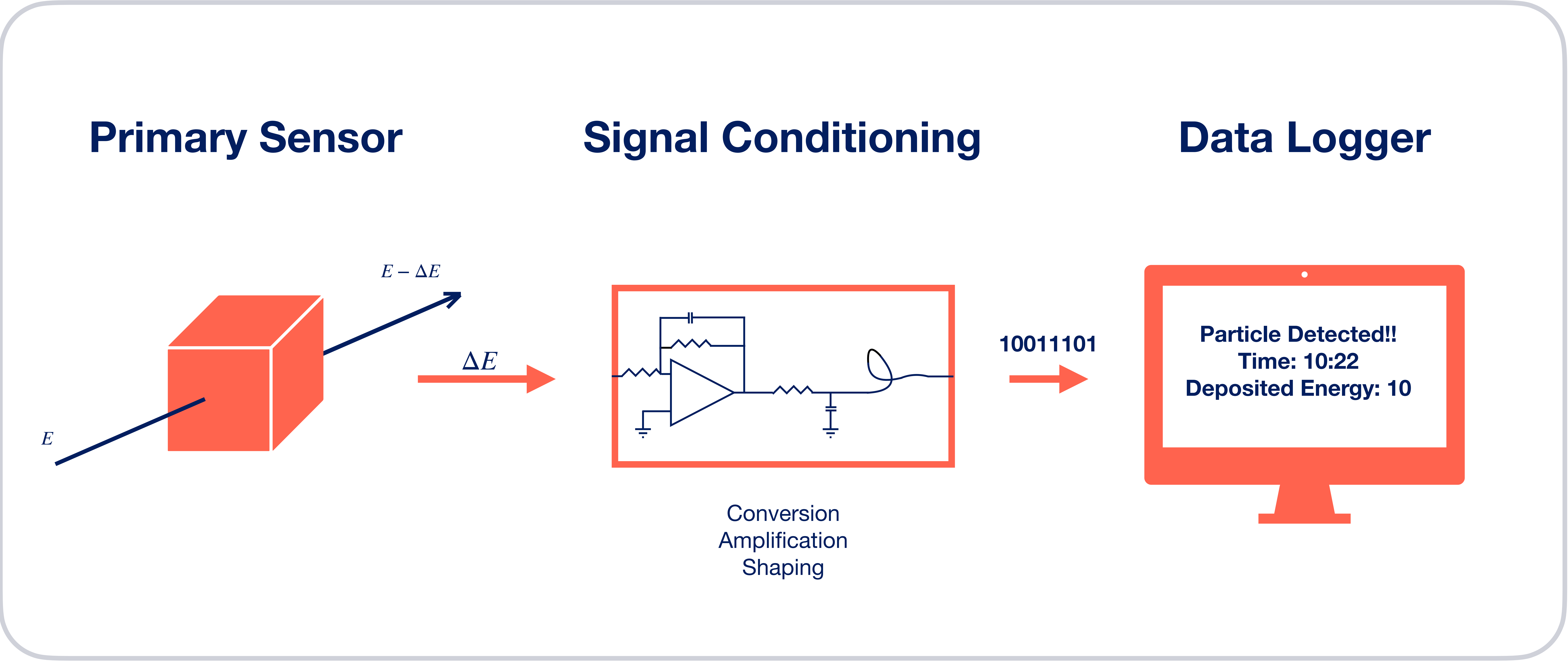
2018



https://github.com/ozel/DIY_particle_detector

First educational design by Oliver Keller

(Silicon-)
Detector Physics Basics



Primary Sensor

4x BPW34

- Commercially used Silicon Photodiodes: BPW34
- PIN structure
- Typically used as light sensors
- Price ~0.2€
- 7x7 mm^2 silicon per diode
- Simultaneous readout
- Total active area:

$7x7x4\ mm^2 = 196\ mm^2$

Primary Sensor

4x BPW34

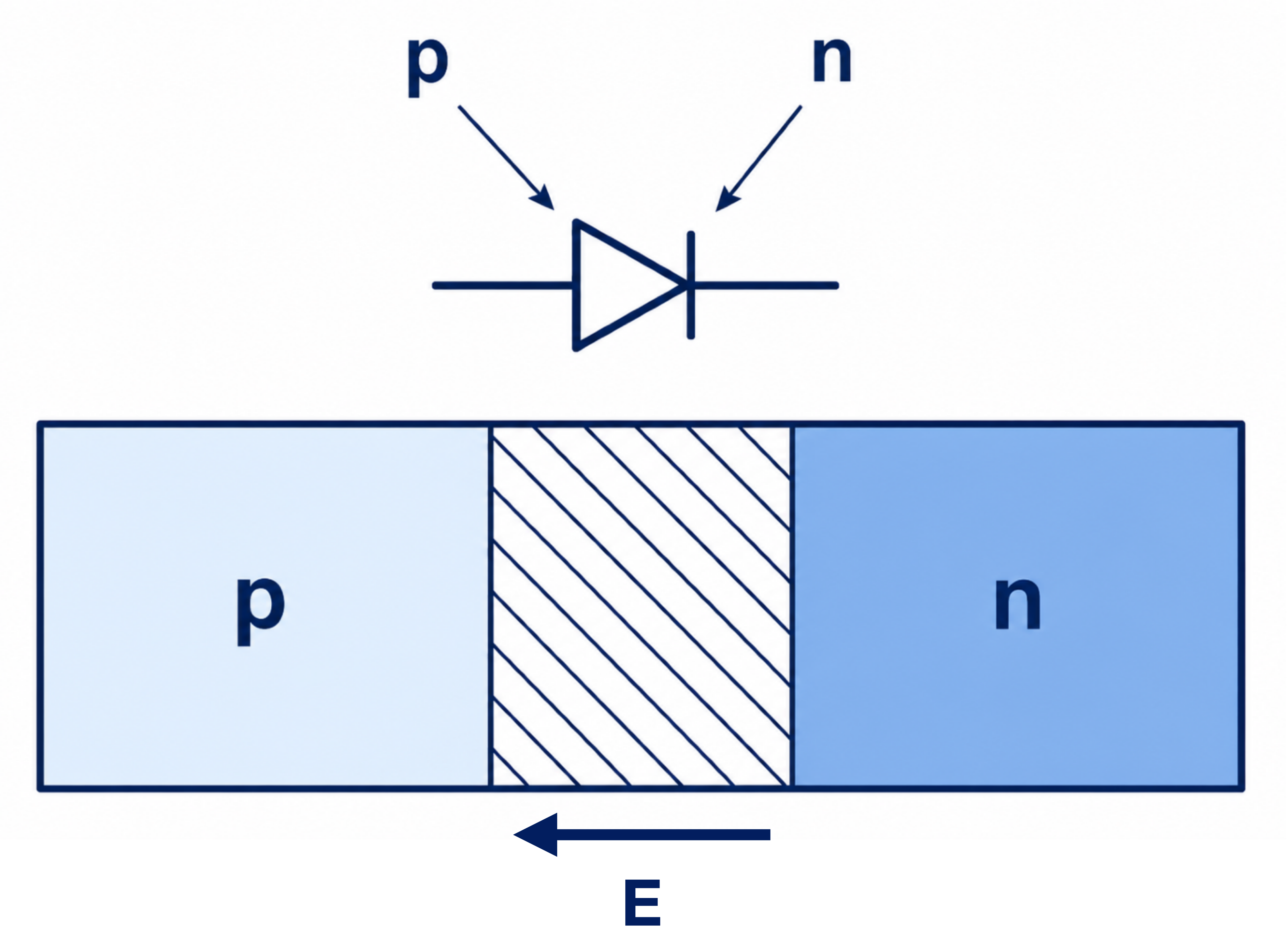
<=>

PXD Belle II

Primary Sensor

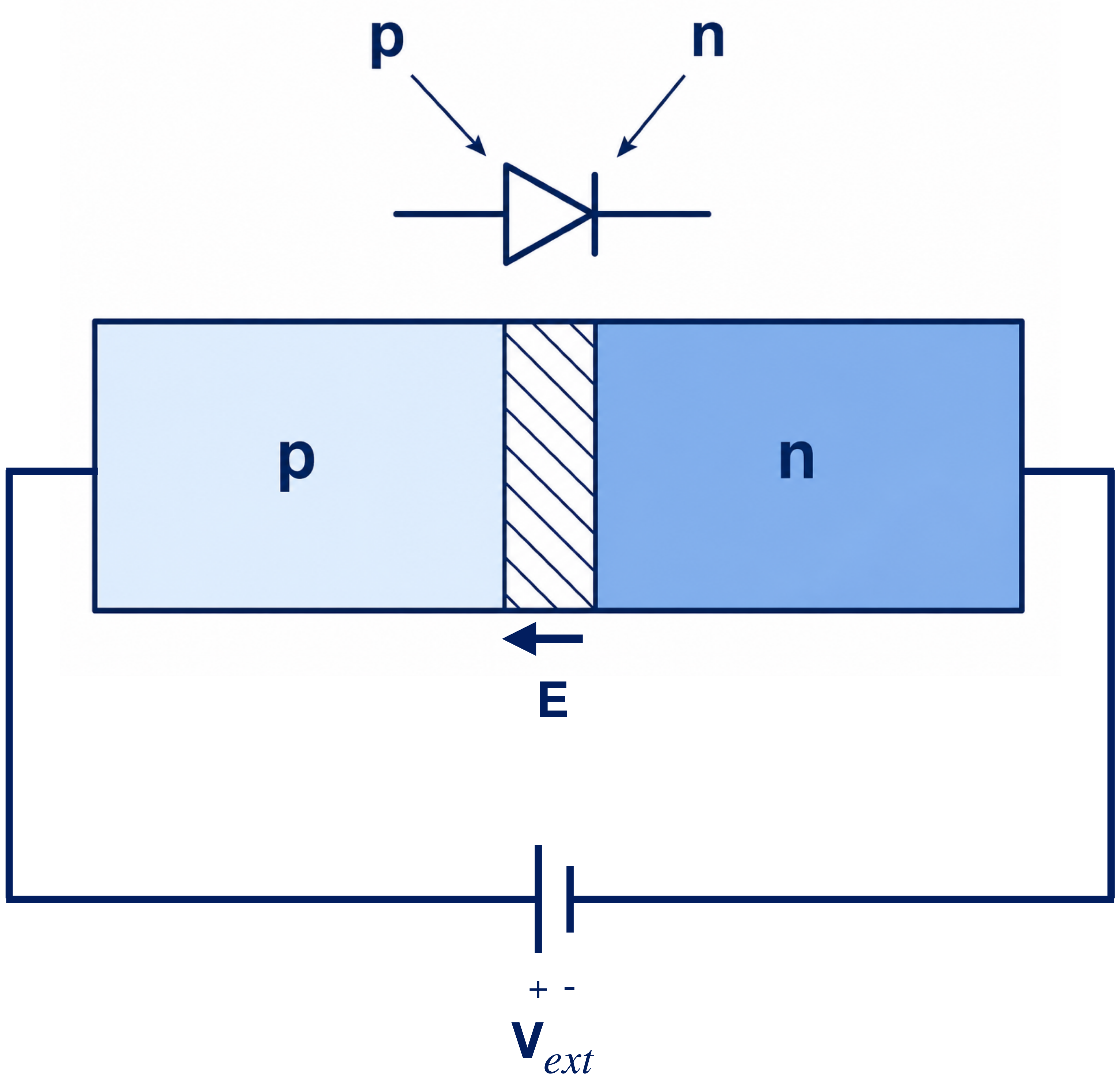
PN-Diodes review

- Basic electronic component made from **semiconductors**
- Junction of p- and n-doped region
- **Depletion region** (insulator) from recombination of electrons and holes
- No conduction across the depletion region



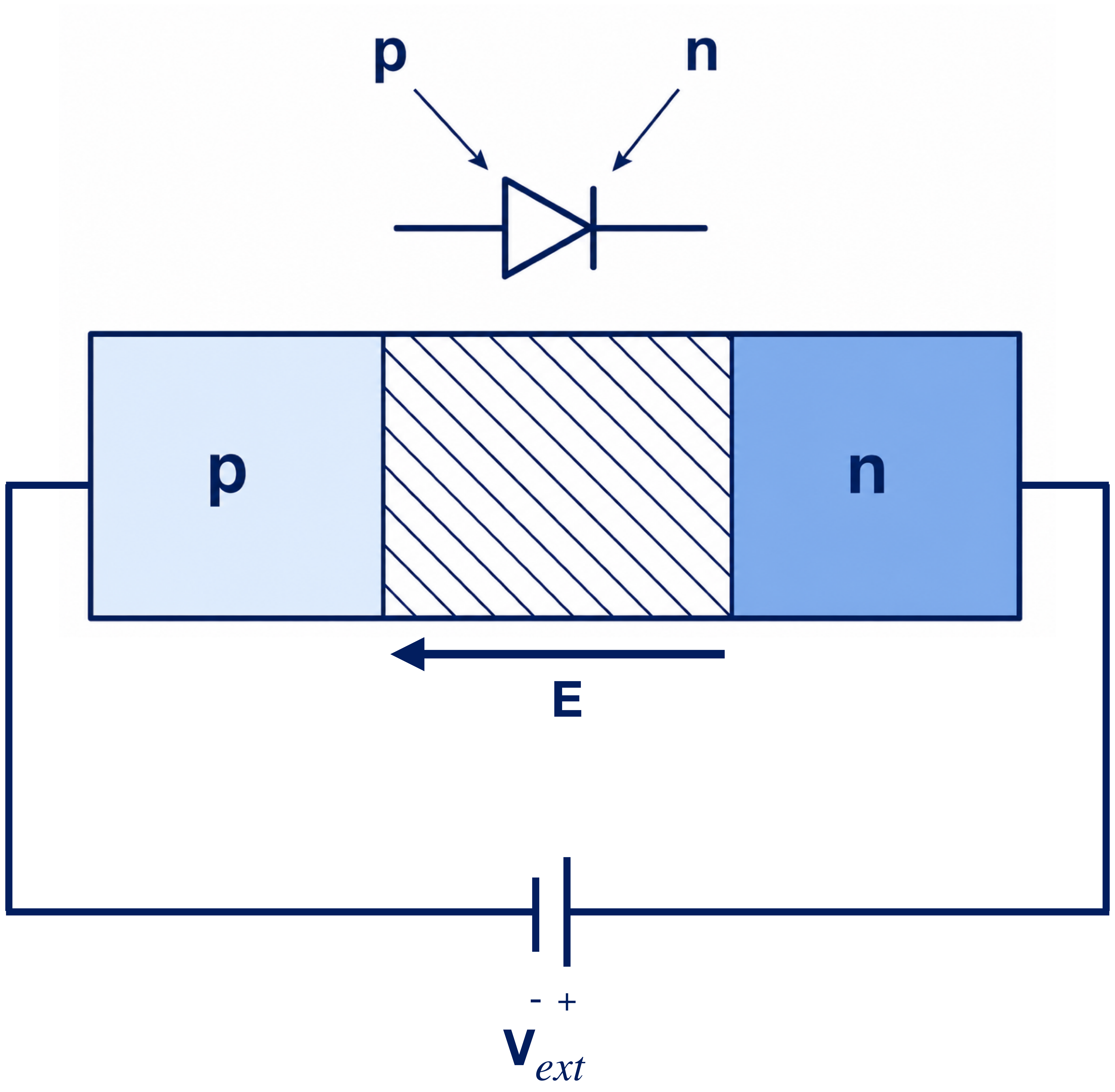
Primary Sensor

Forward Bias



Primary Sensor

Reverse Bias



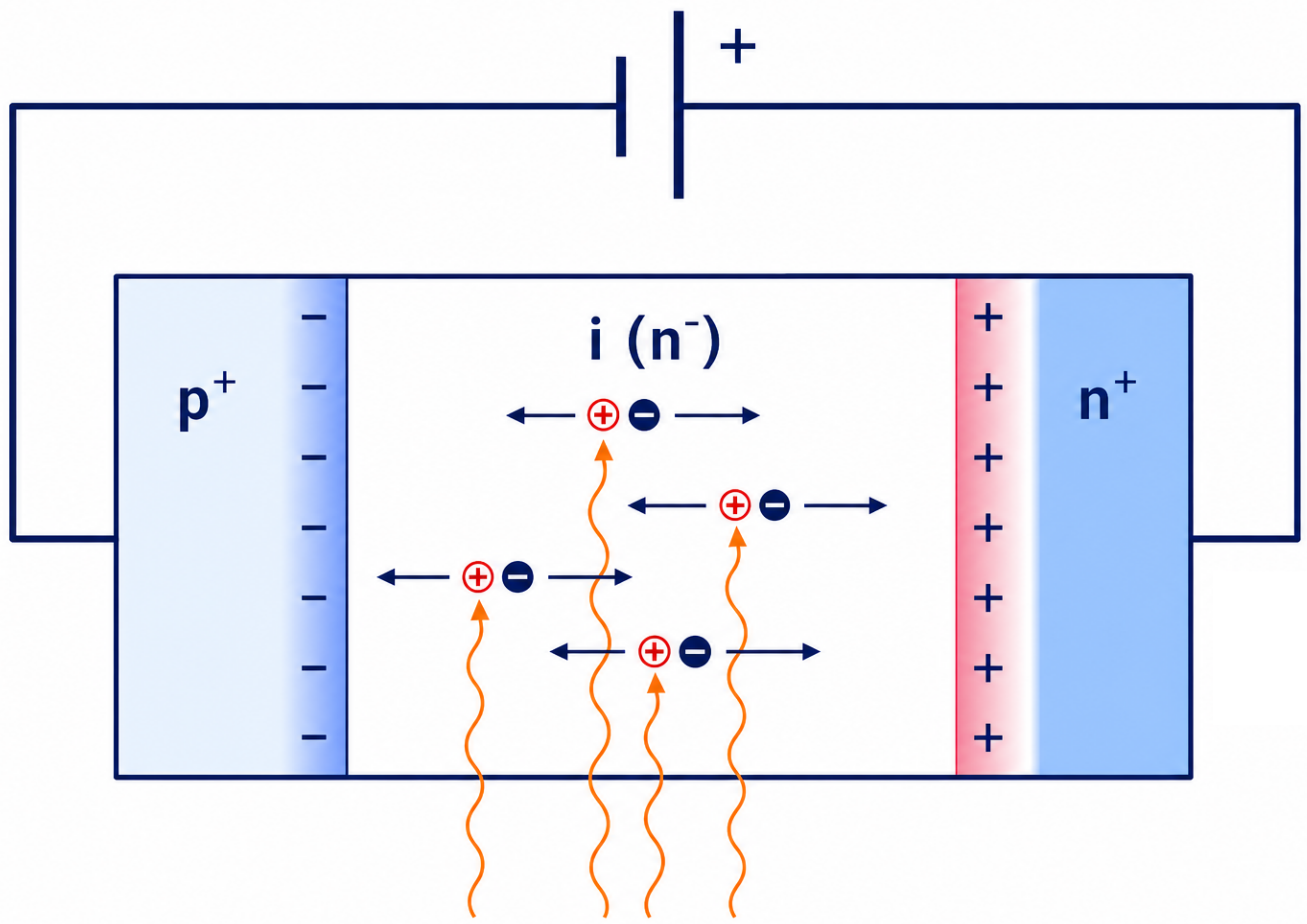
Primary Sensor

Particle detection

- Depleted volume ≈ sensitive volume
- Ionizing radiation → electron–hole pairs
- Electric field collects charge carriers
- Current pulse measurable

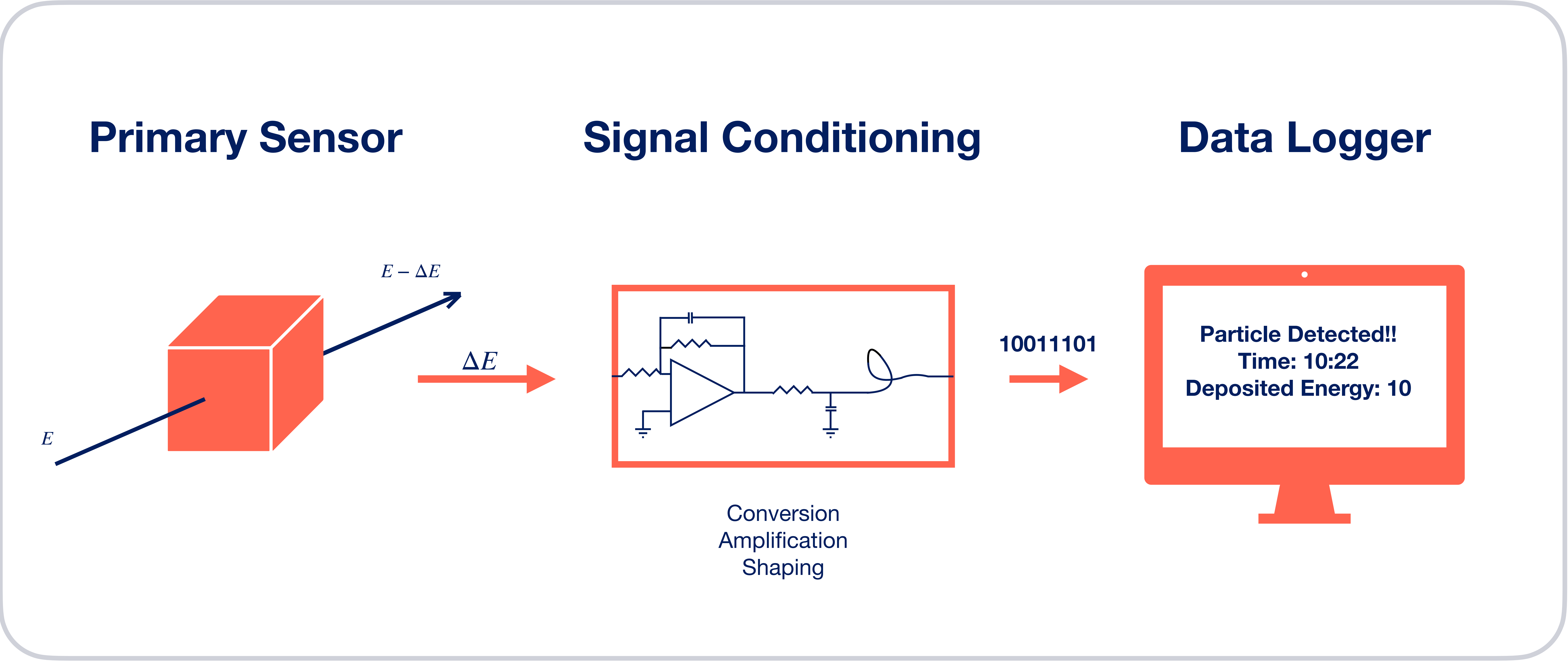
PIN-Diodes review

- Undoped or weakly doped „intrinsic“ layer
- Larger depletion regions possible
  => larger sensitive volume

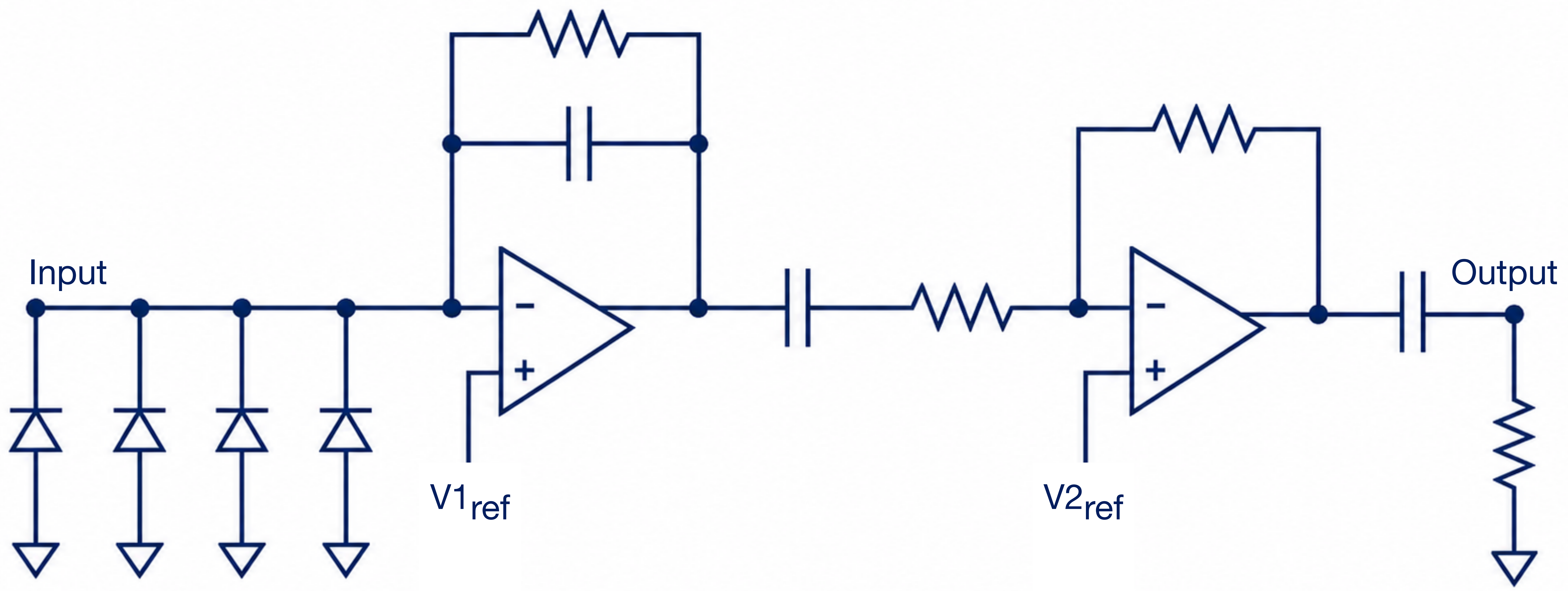


PIN-Diode

(Silicon-)
Detector Physics Basics



Signal Conditioning



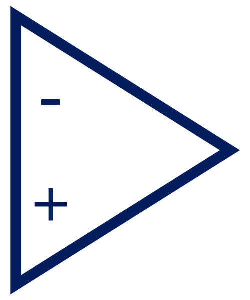
Signal Conditioning

Heuristic Definition: Everything is a resistor..

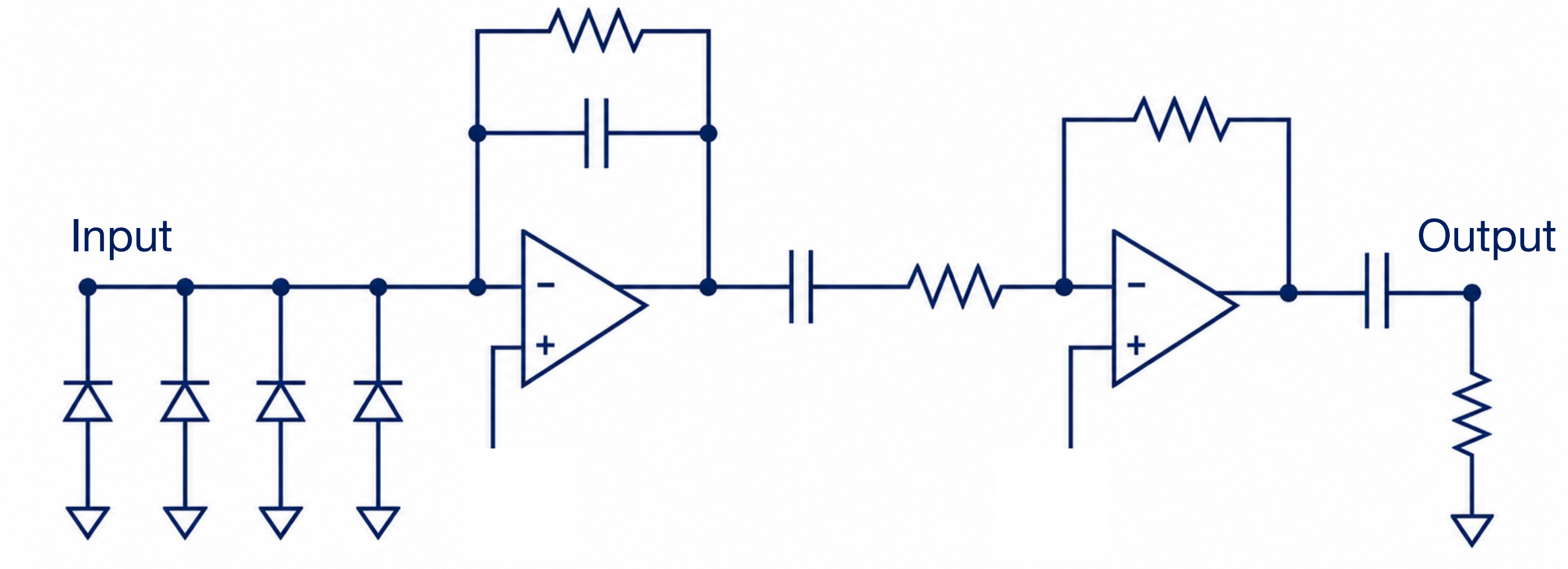
A **resistor** resists current flow

A **capacitor** resists steady current flow

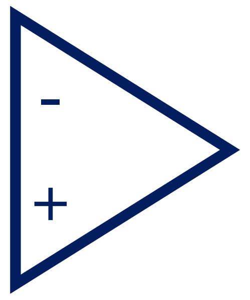
A **diode** strongly resists current flow



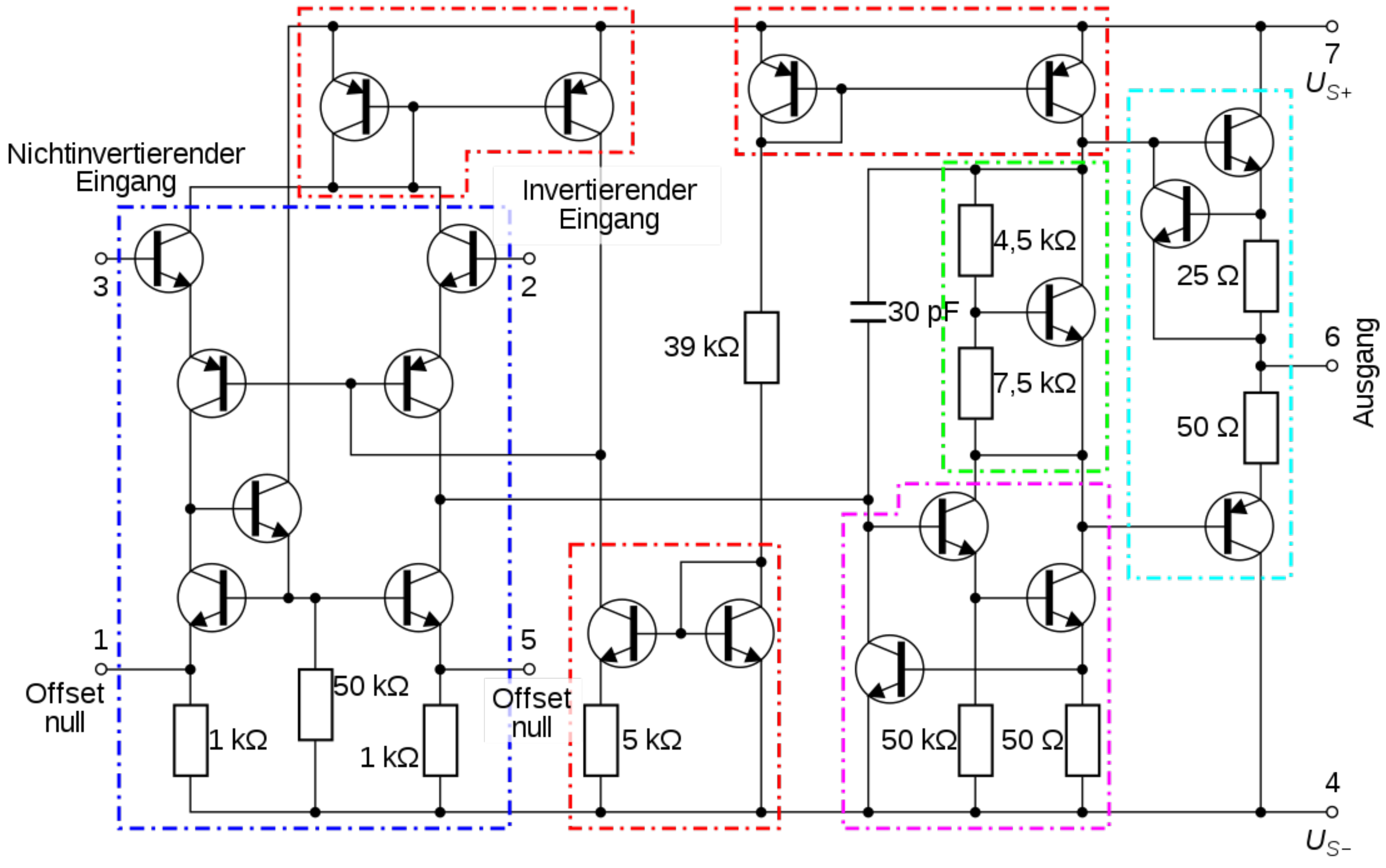
An Operational Amplifier..



Signal Conditioning

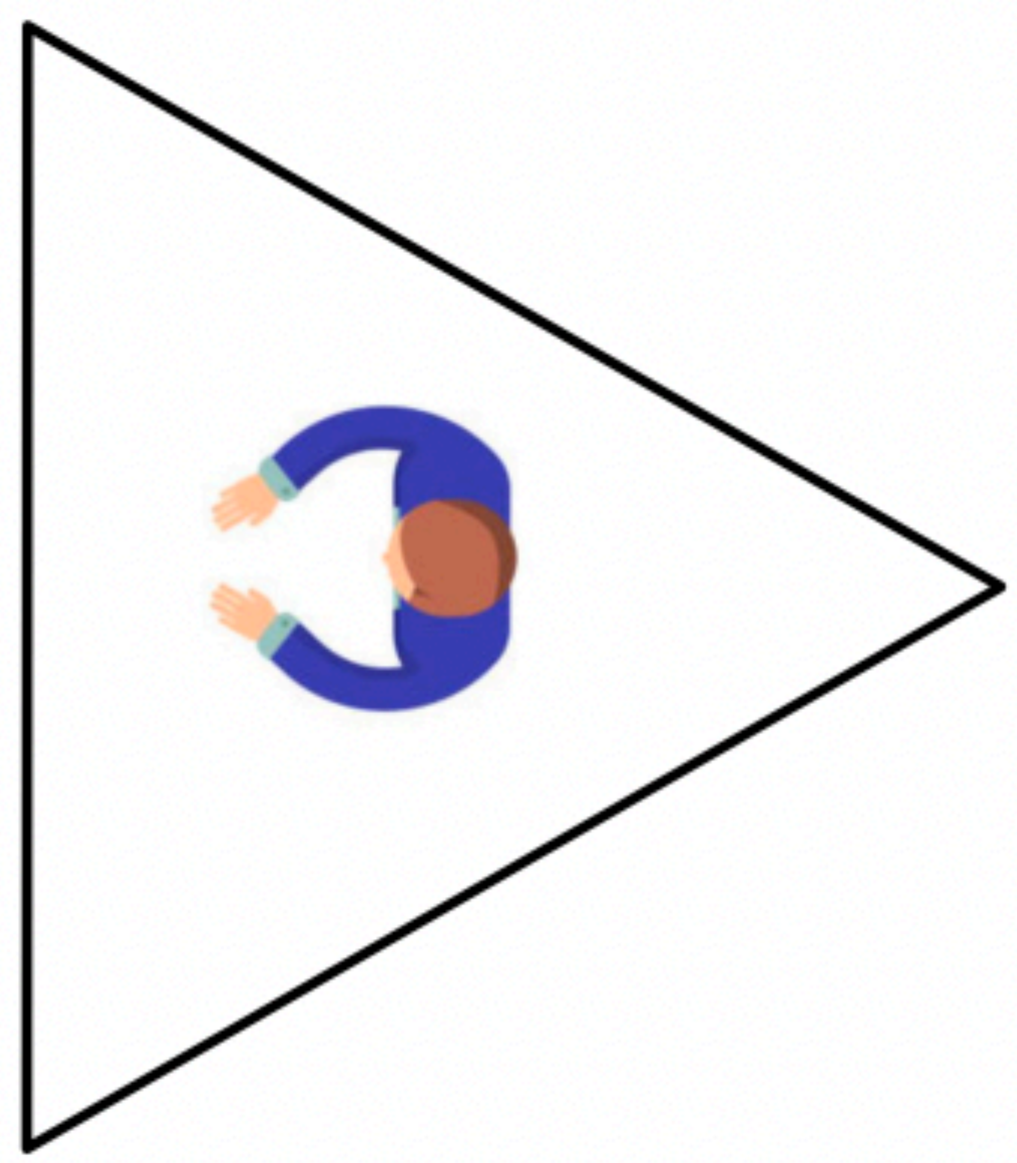


An Operational Amplifier =



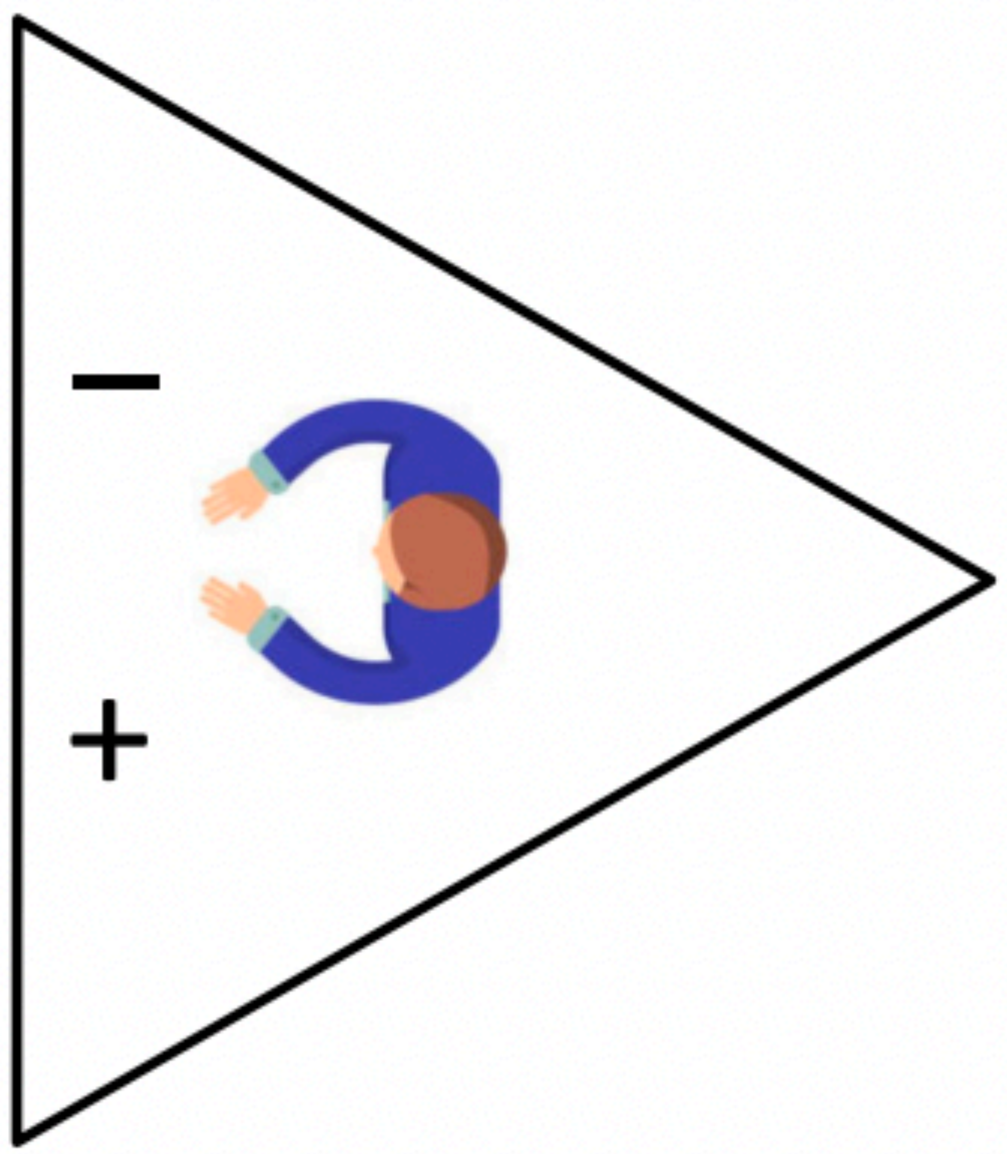
Signal Conditioning

A bed time story: Inside a litte triangle lives a tiny little person called Dr. OpAmp..



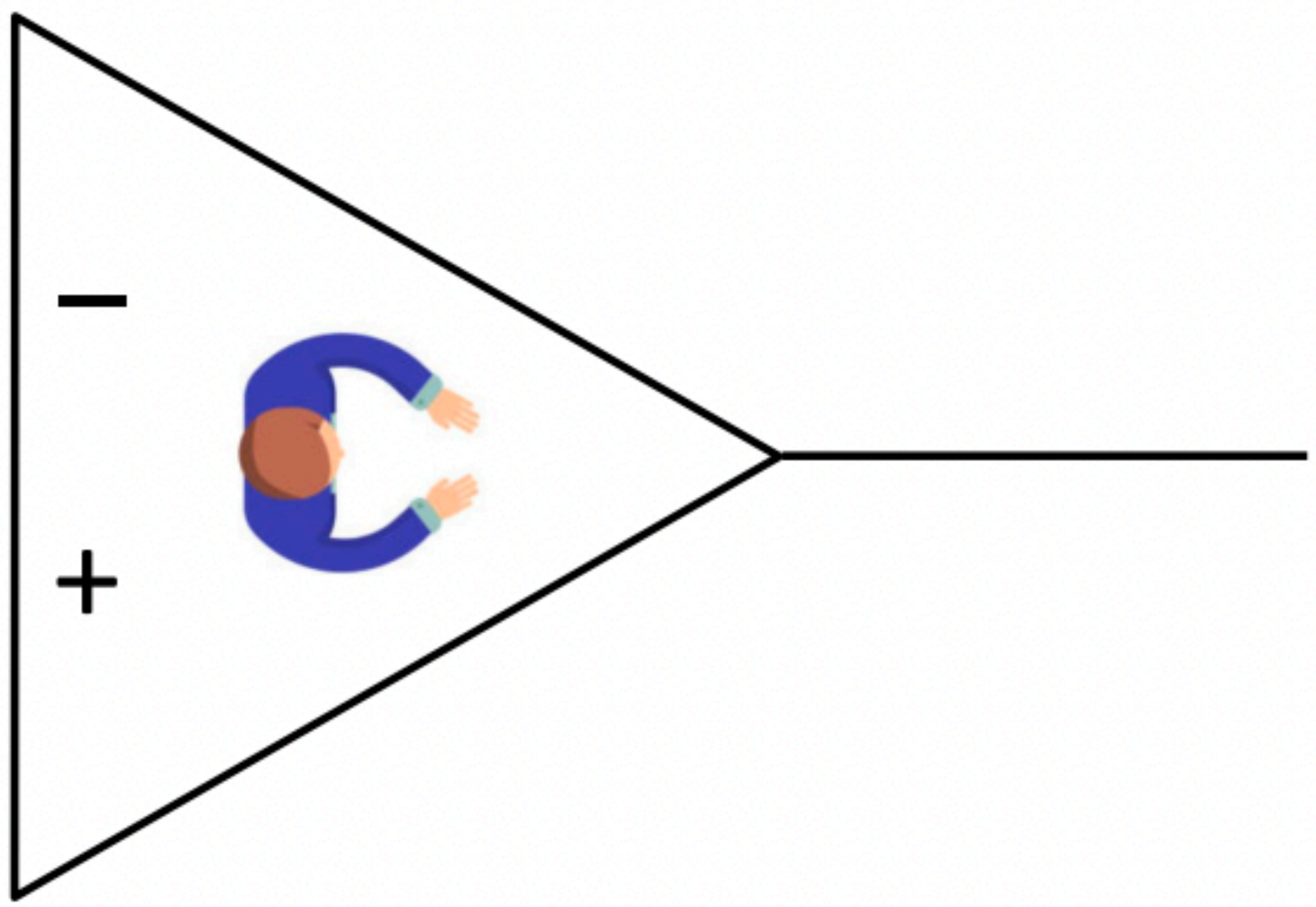
Signal Conditioning

Dr. OpAmp is constantly monitoring two inputs, which are labeled the + (non-inverting) and - (inverting)



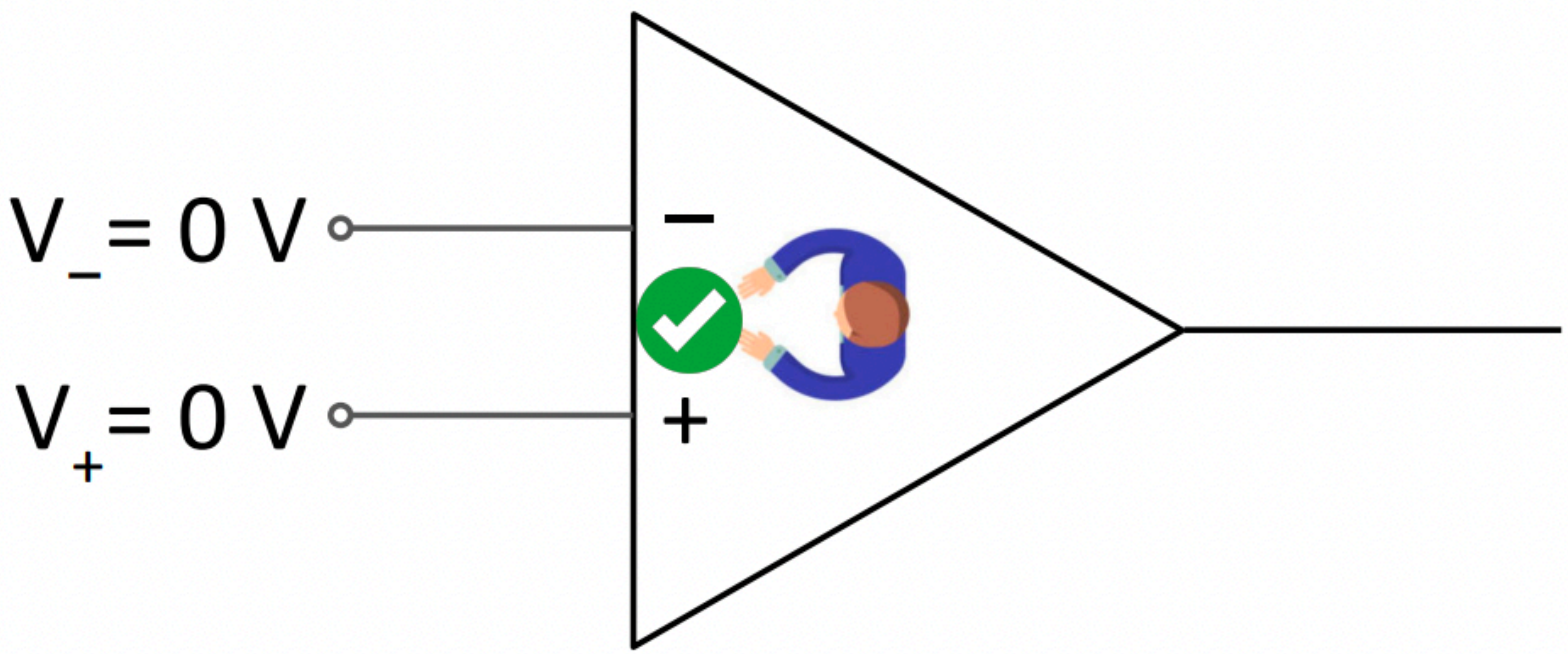
Signal Conditioning

They can control one output „however“ he wants…



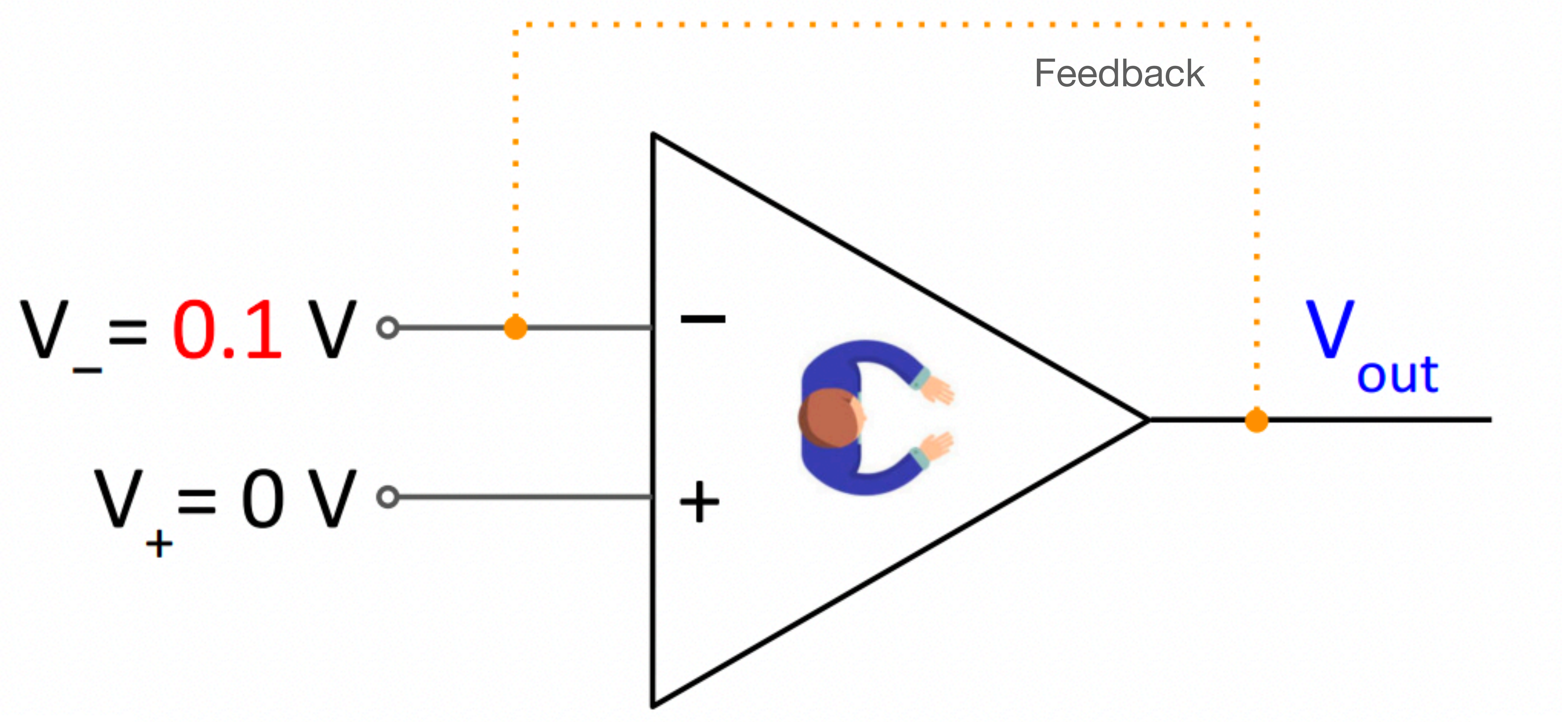
Signal Conditioning

Their job is to make sure that the **voltage difference** between the two inputs is always **zero**…



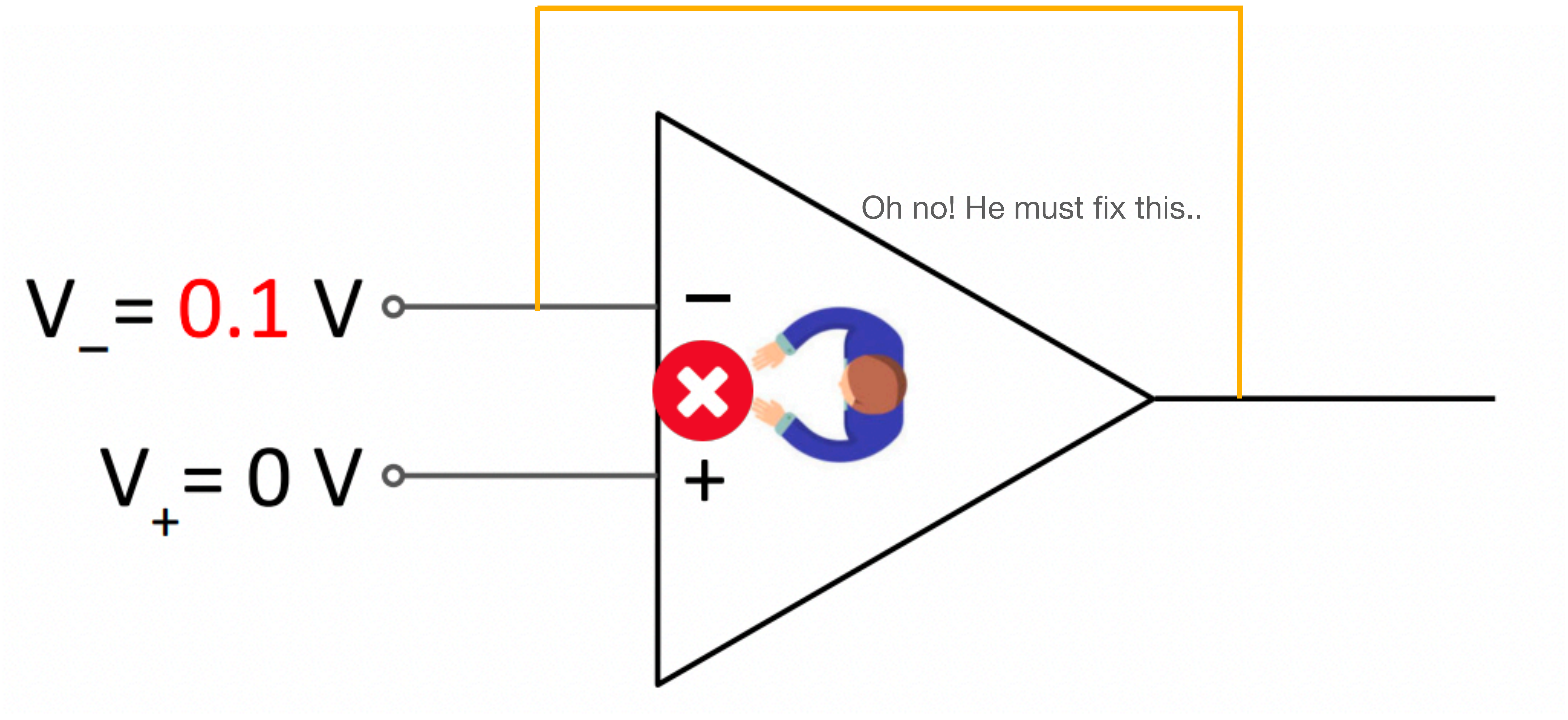
Signal Conditioning

..they were told by their boss that there is a **connection** between the output and the **inverting input..**



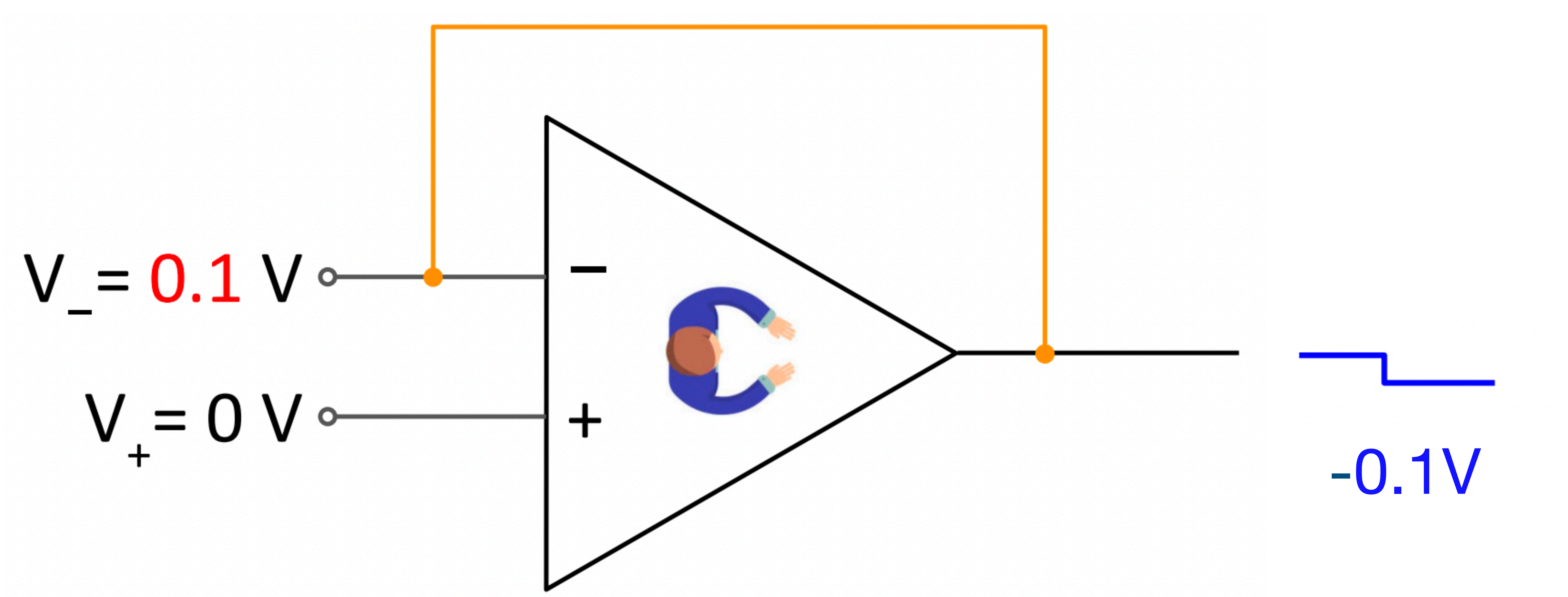
Signal Conditioning

..lets mess with them and send **0.1V** to the **inverting input**..



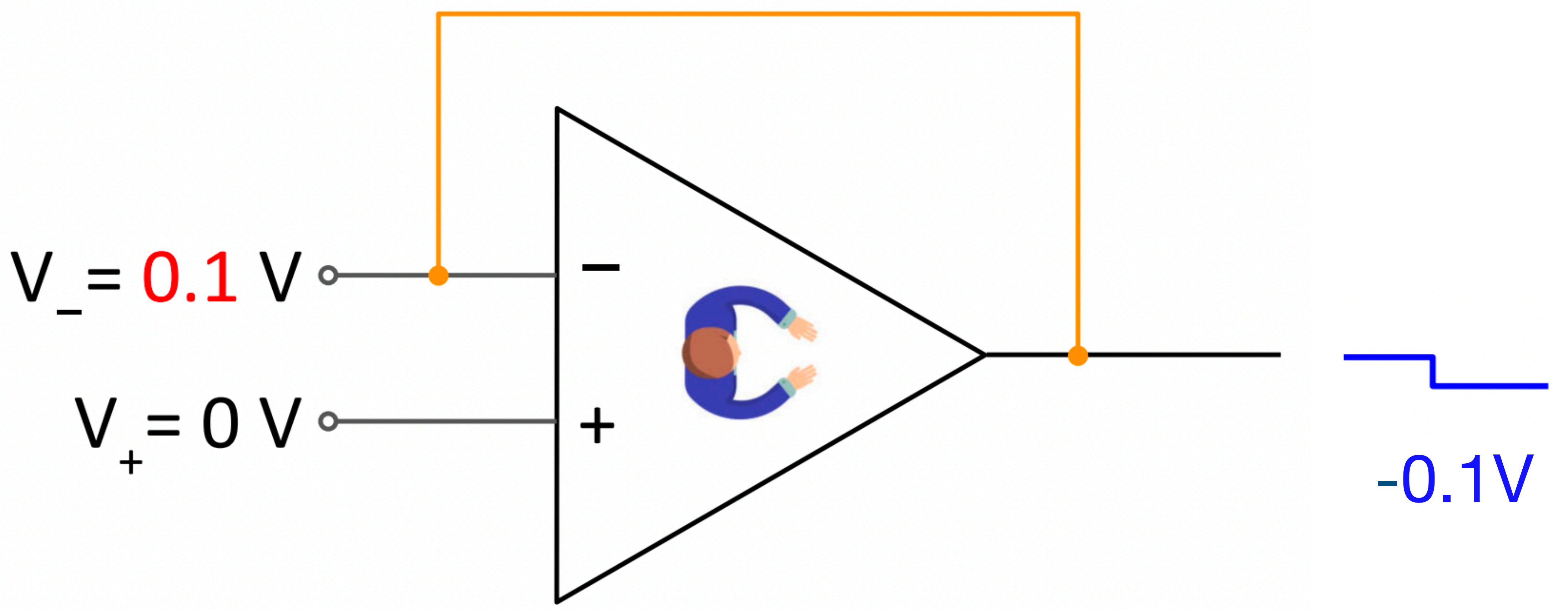
Signal Conditioning

..they can instantly fix the problem by sending out -0.1V in the feedback loop..



Signal Conditioning

This device is turning 0.1V into -0.1V..



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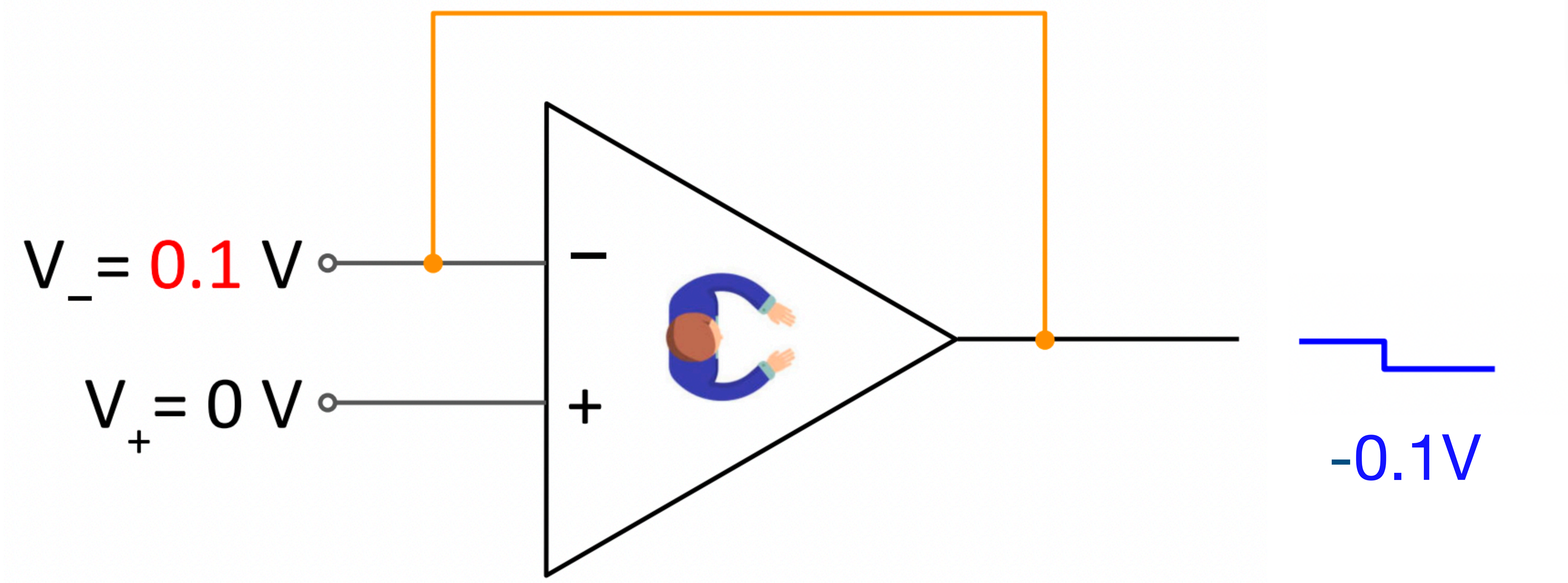
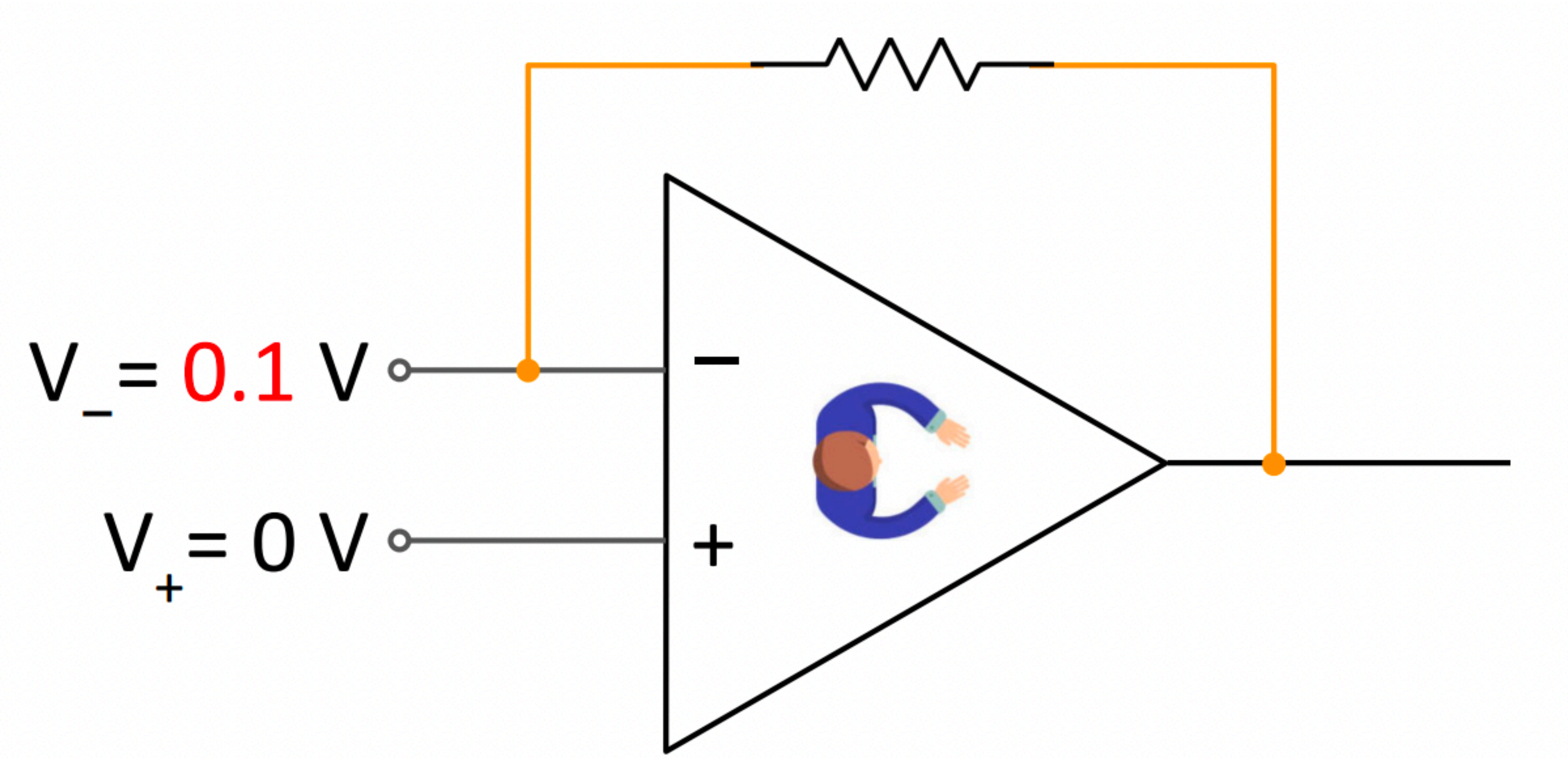


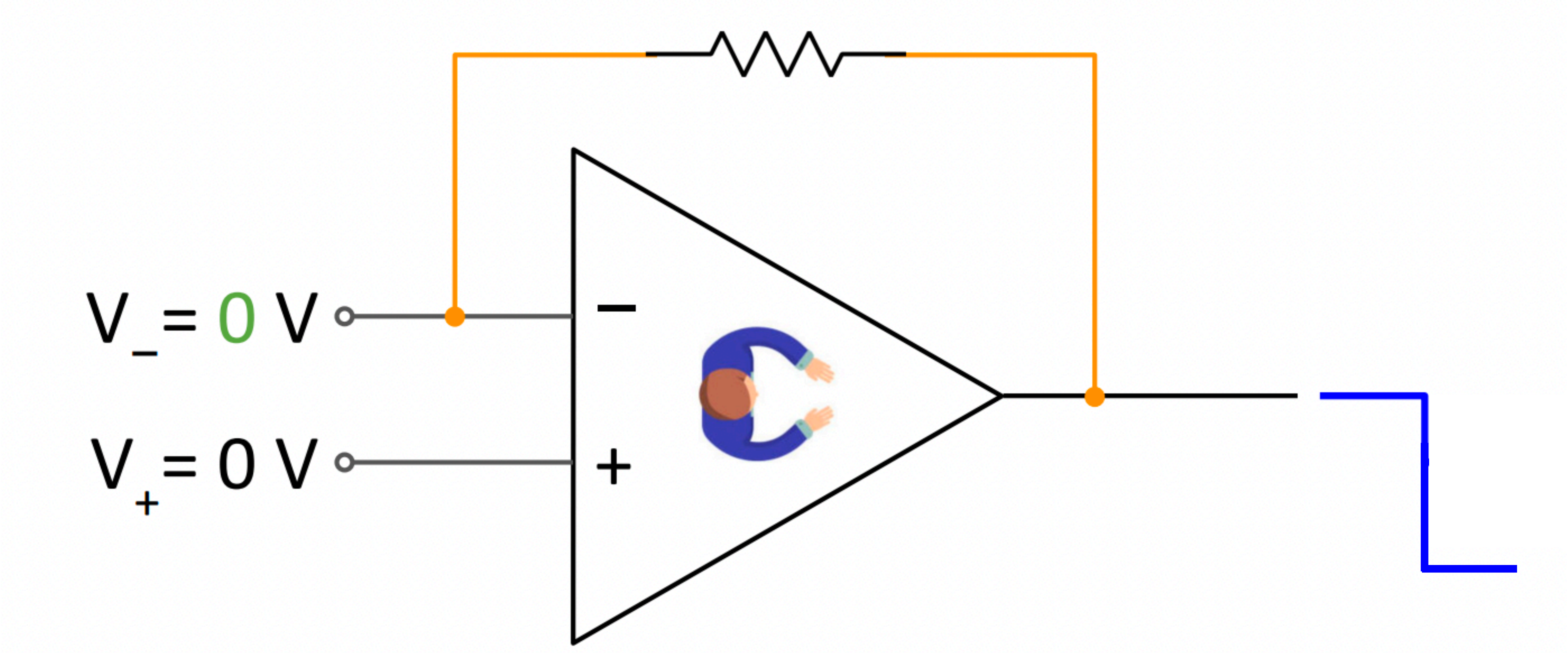
Signal Conditioning

Okay let's exploit their assumption by putting a resistor in the feedback loop..



Signal Conditioning

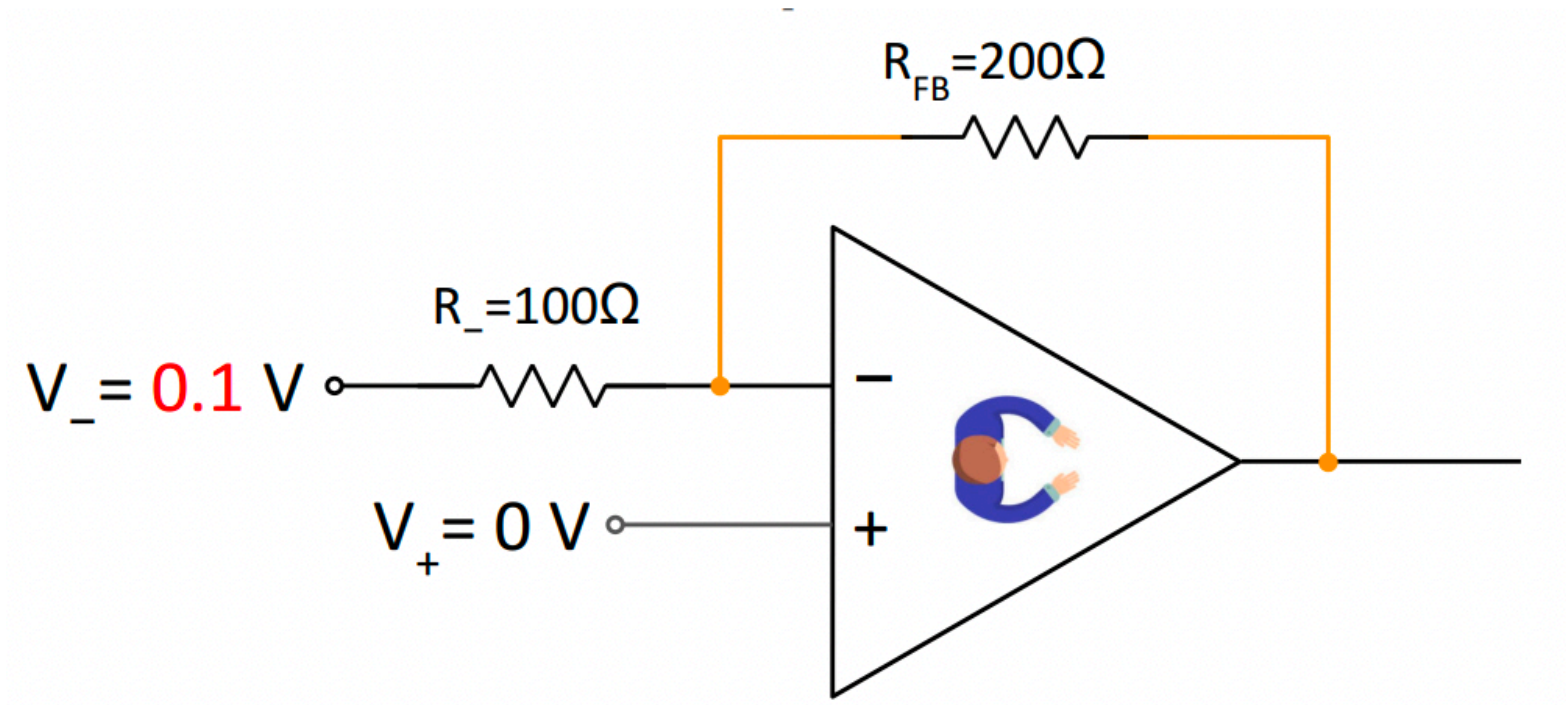
They has to work harder and send out more voltage to correct the same problem..



We created an **inverting amplifier**..

Signal Conditioning

But wait.. the input has no restiance while the feedback loop has resistance so Dr. OpAmp can never win this fight.. Lets add a resistor to the input!



What signal will we see at the output now?

Signal Conditioning

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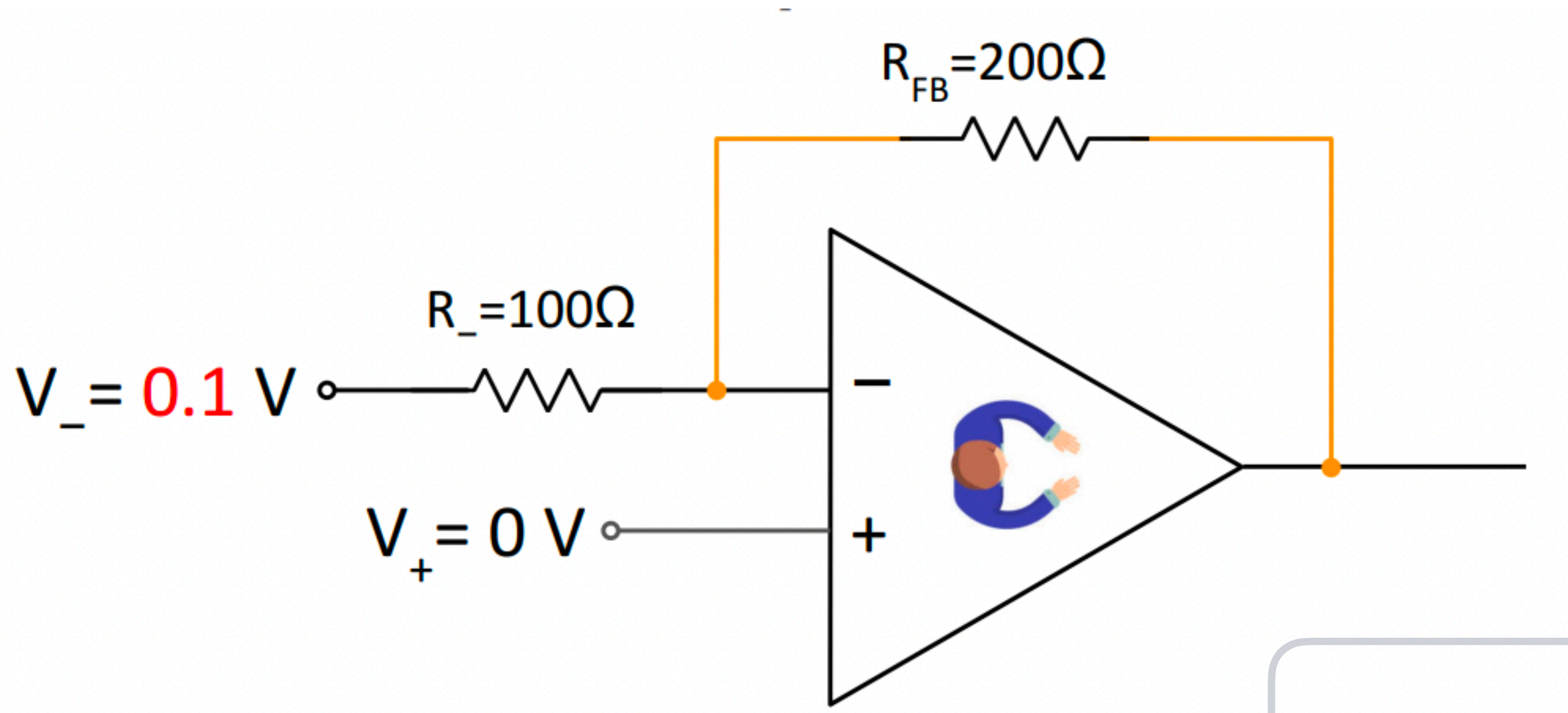


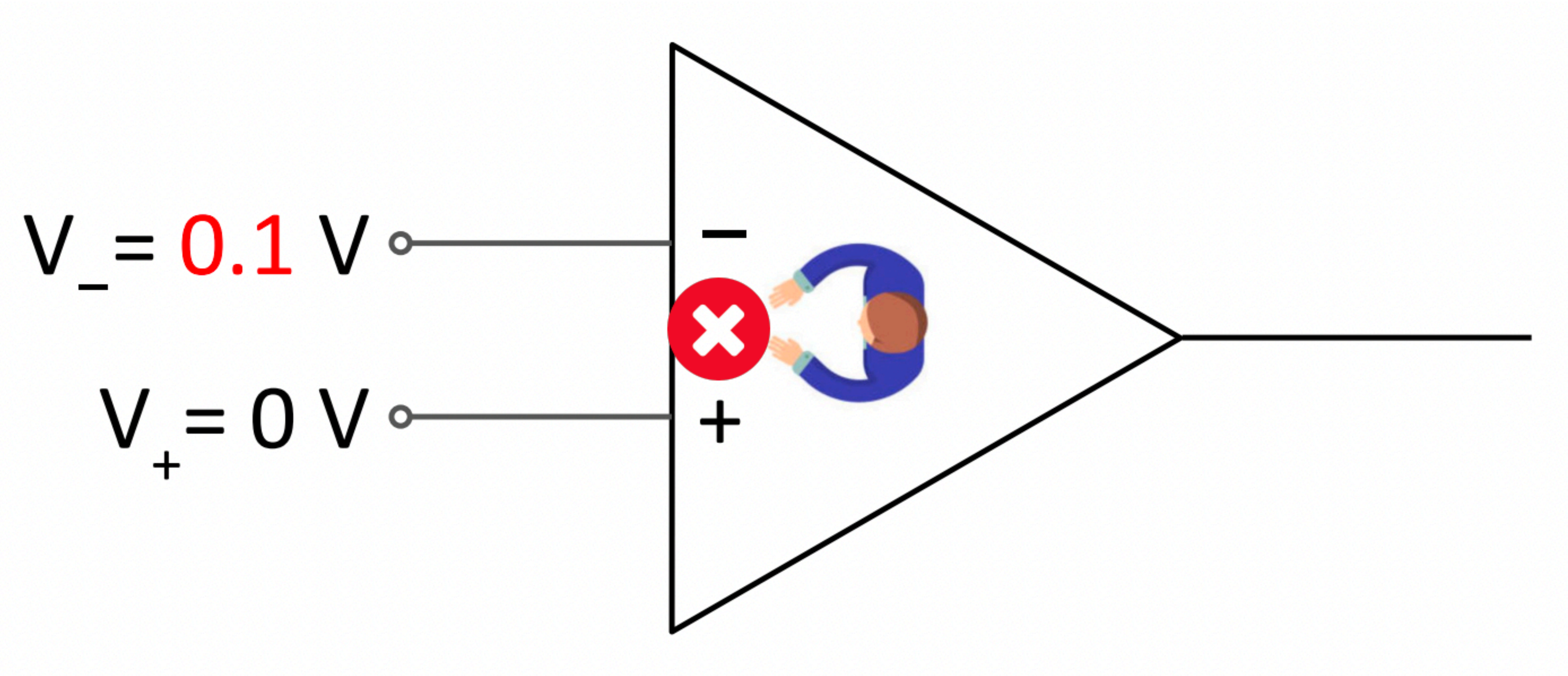
V = -0.2V

Inverting Amplifier: $U_{out} = -\frac{R_F}{R_{in}} U_{in}$

What signal will we see at the output now?

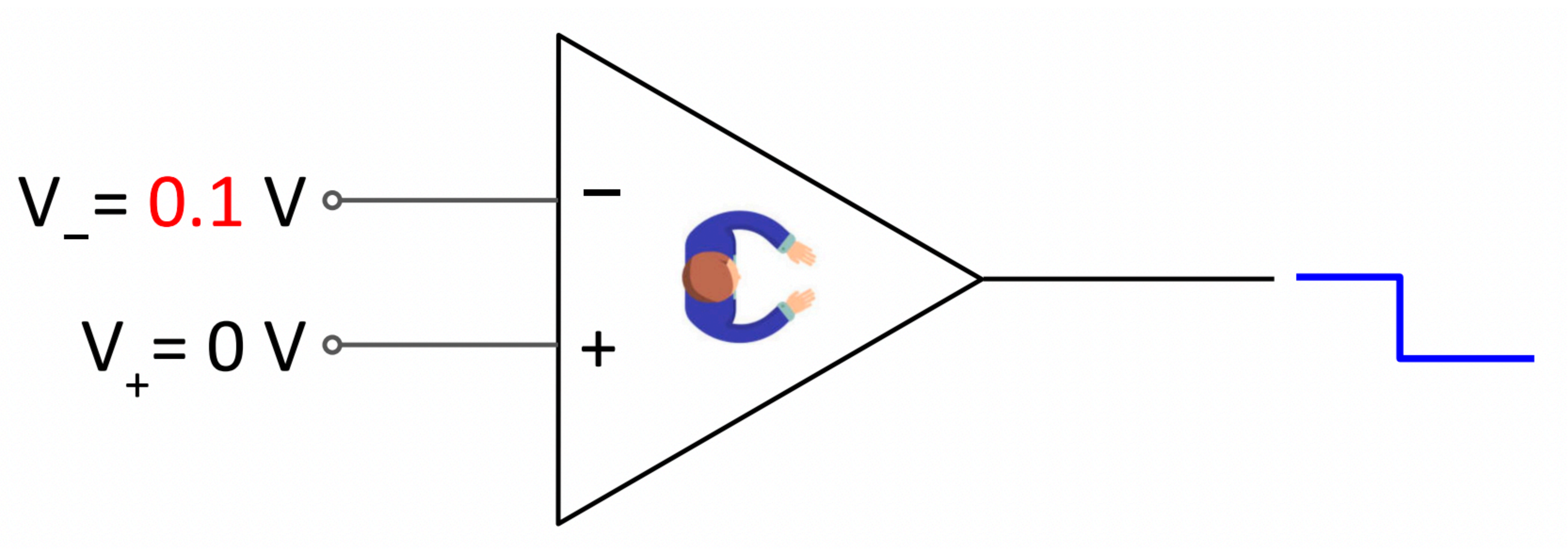
Signal Conditioning

Test: What happens if we send an input voltage of 0.1V but there is no feedback loop?



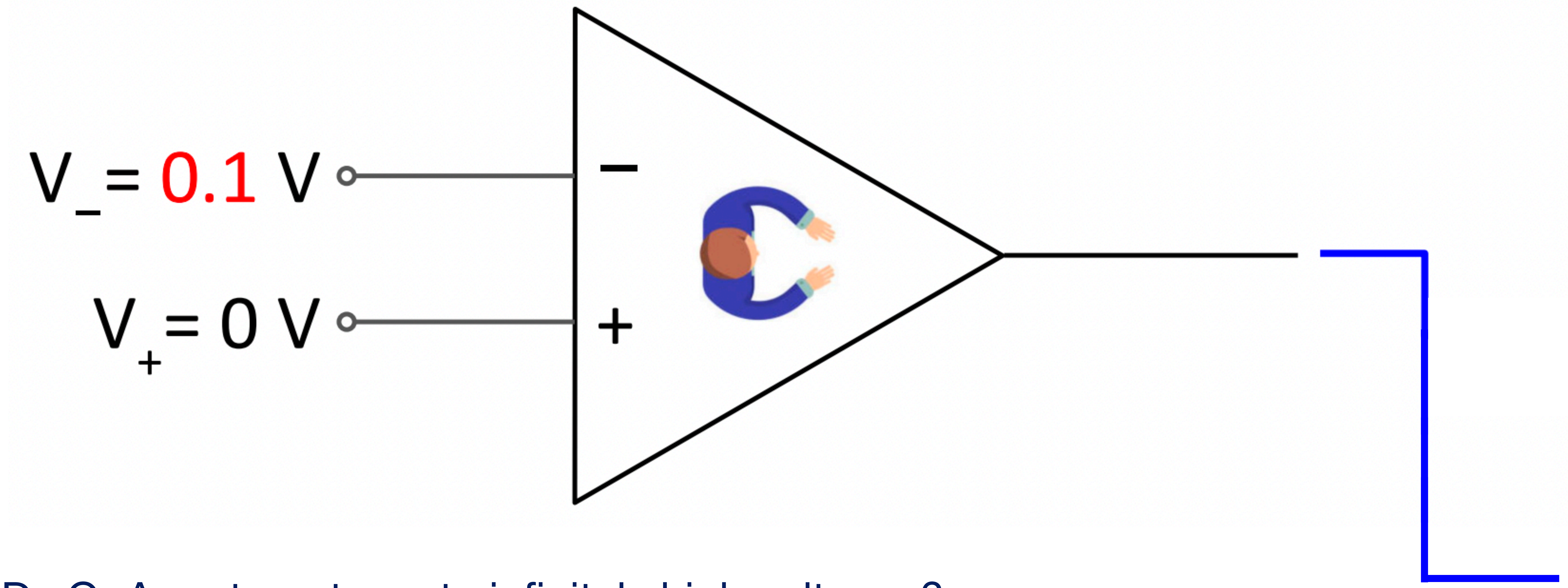
Signal Conditioning

They will still send out a negative voltage because they assume there is a feedback loop..



Signal Conditioning

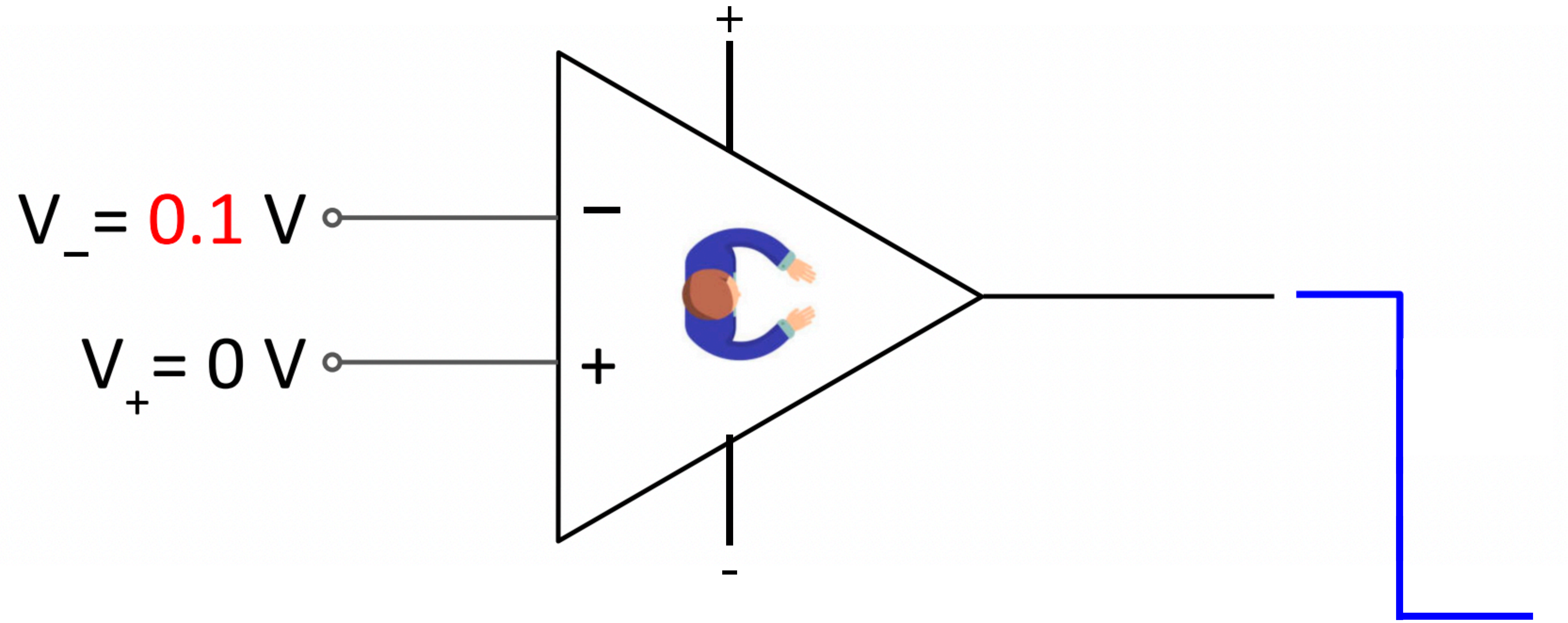
Since nothing is changing they will not stop increasing the voltage..



What limits Dr. OpAmp to not create infinitely high voltages?

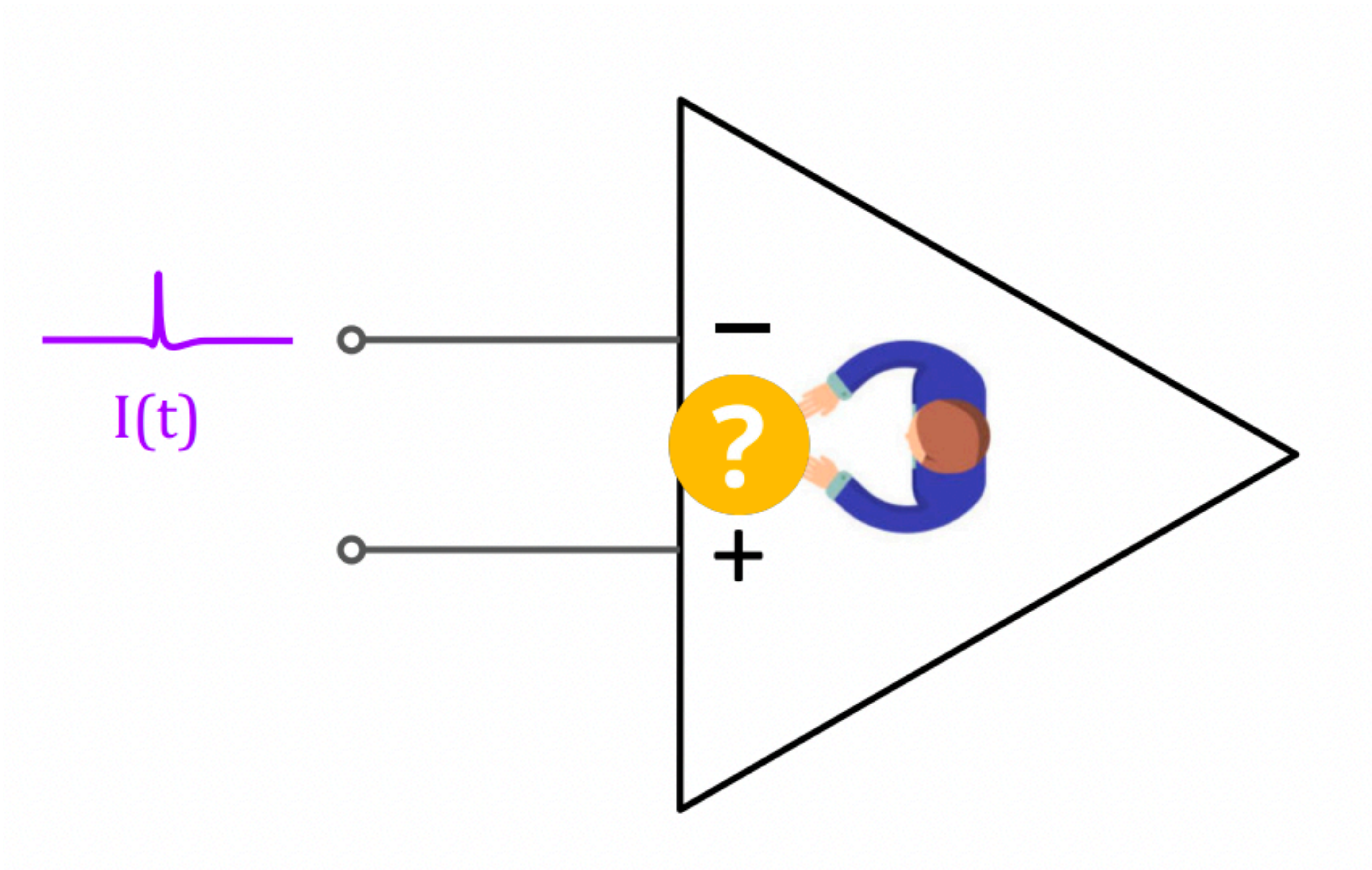
Signal Conditioning

They have an upper and a lower limit which is defined by the positive and negative power supply..



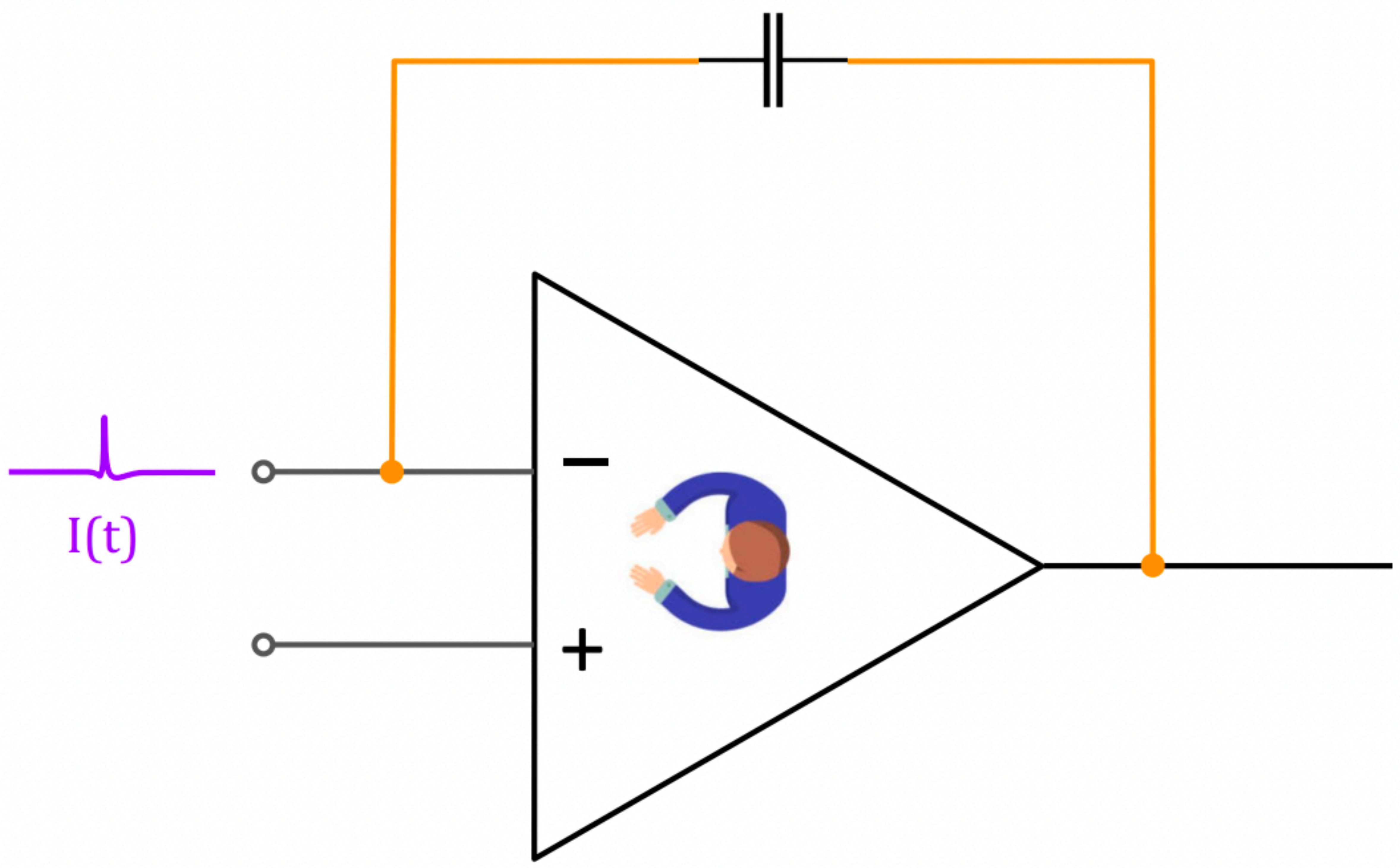
Signal Conditioning

But our **PIN-Diode** will only output a **current**, not a **voltage**.. Dr. OpAmp is only concerned with voltages..



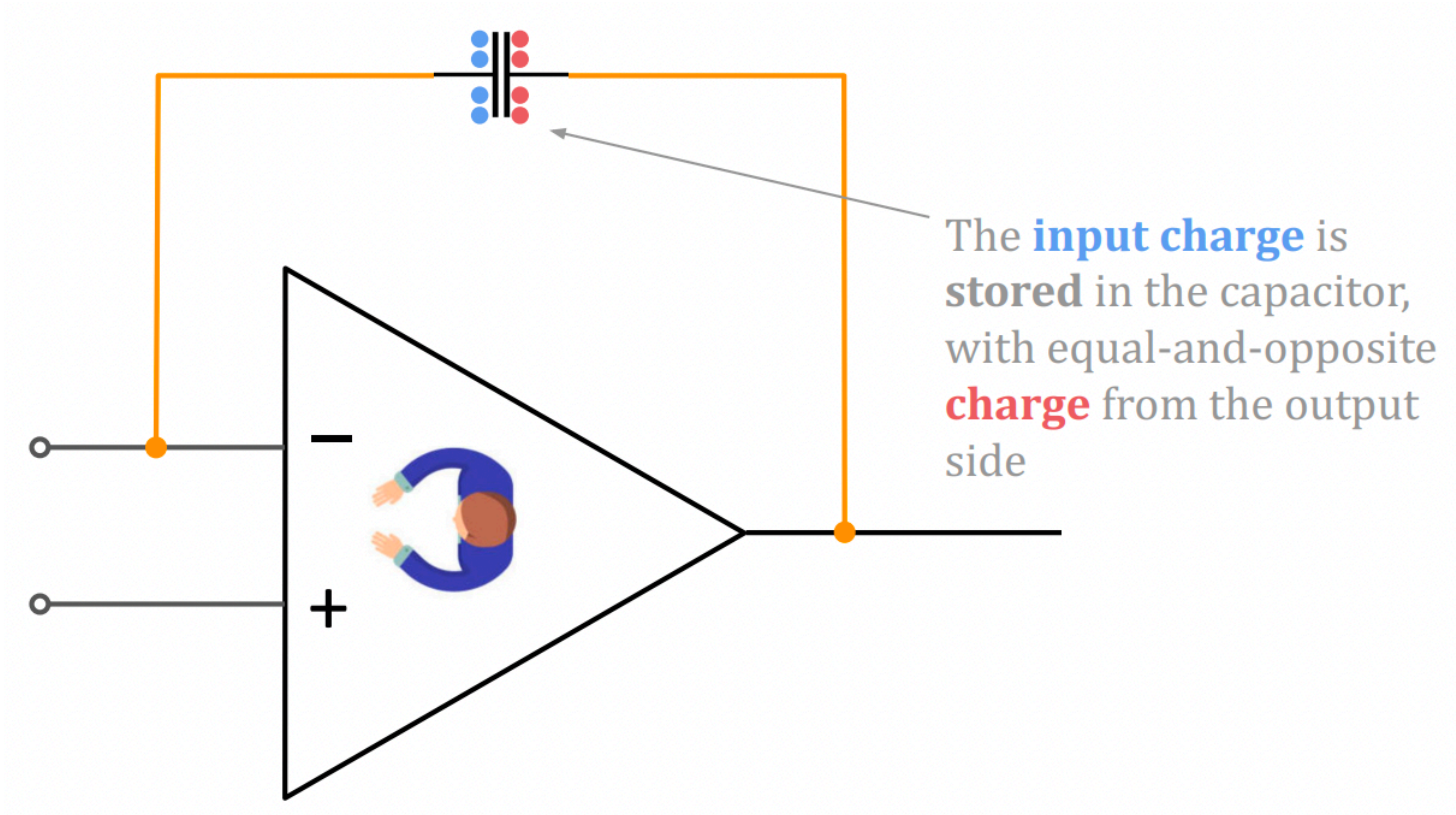
Signal Conditioning

Let’s put a capacitor here..



Signal Conditioning

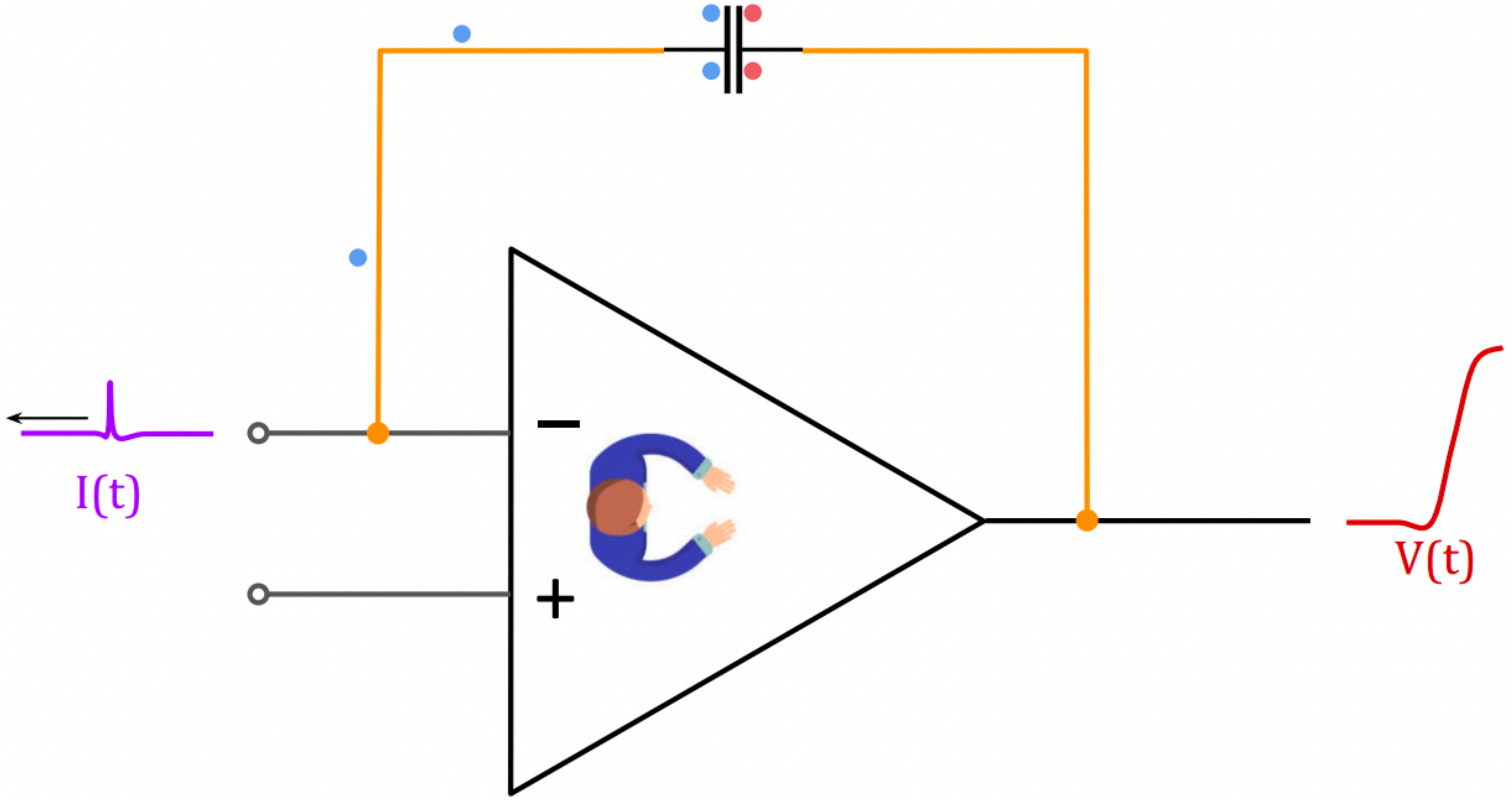
The capacitor will do capacitor things: adding charge q will lead a voltage difference of q/C across the capacitor..



So Dr. OpAmp sees a voltage proportional to the deposited charge..

Signal Conditioning

Dr. OpAmp will send out a voltage which begins to cancel the capacitors voltage, discharging the capacitor, reducing the input voltage until it is equalized..



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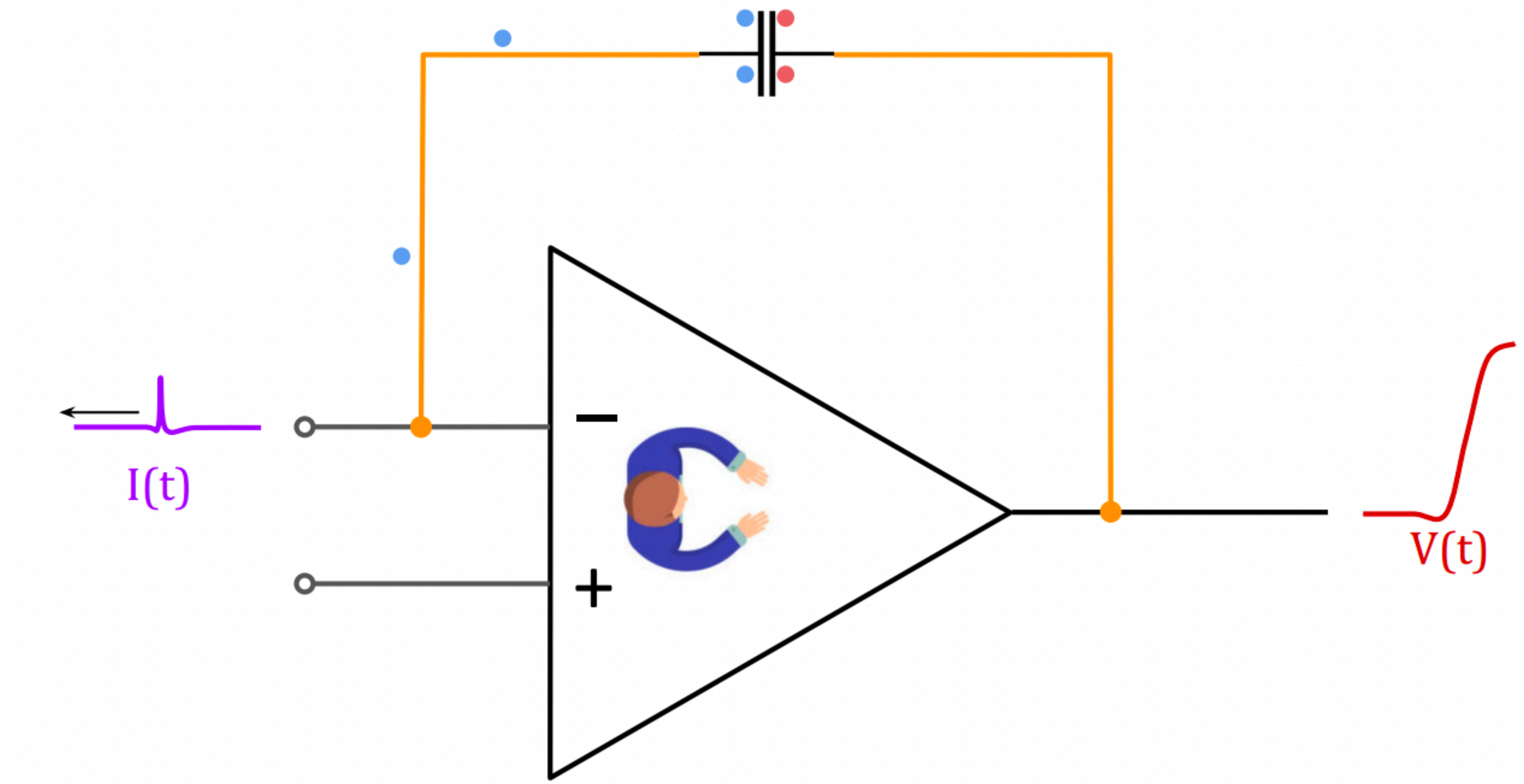
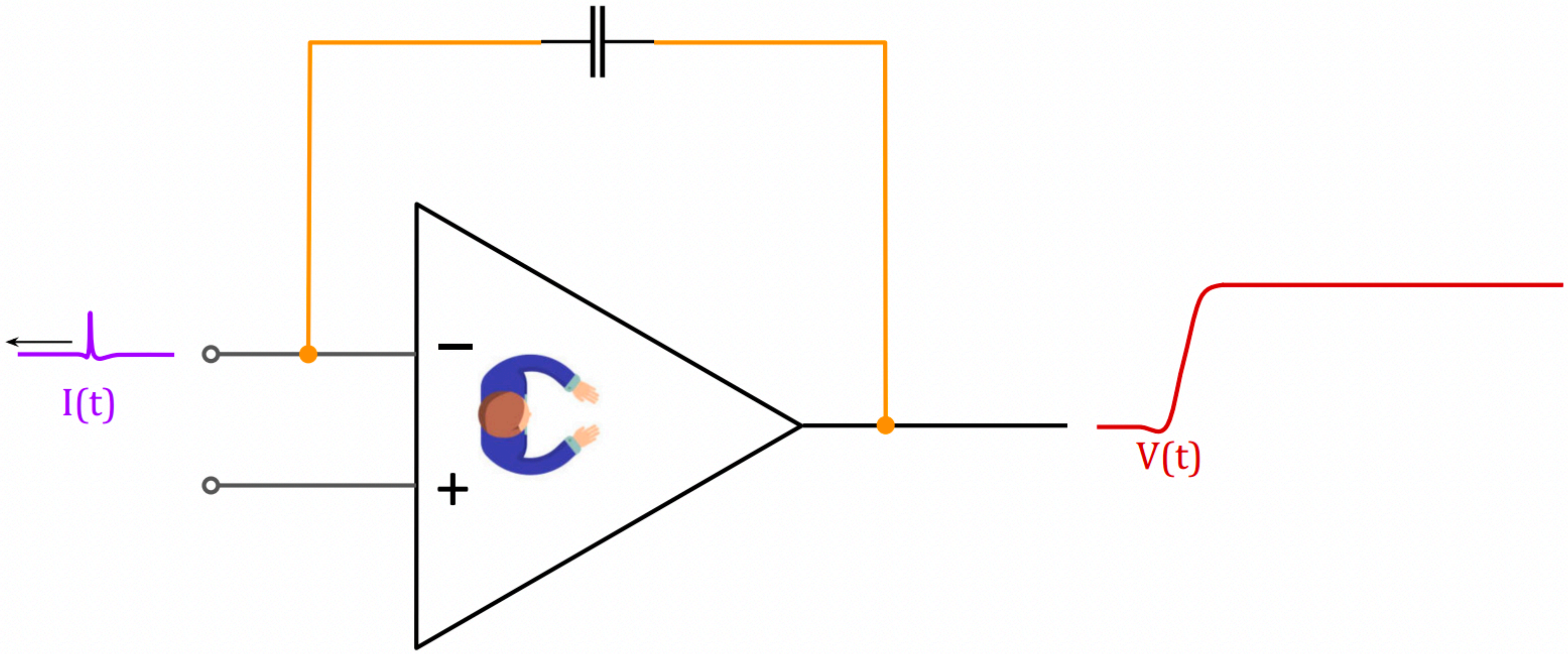


Problem: The created charge carriers cannot leave the circuit in any way. If Dr. OpAmp drops his voltage again, the capacitor will be loaded again.

Signal Conditioning

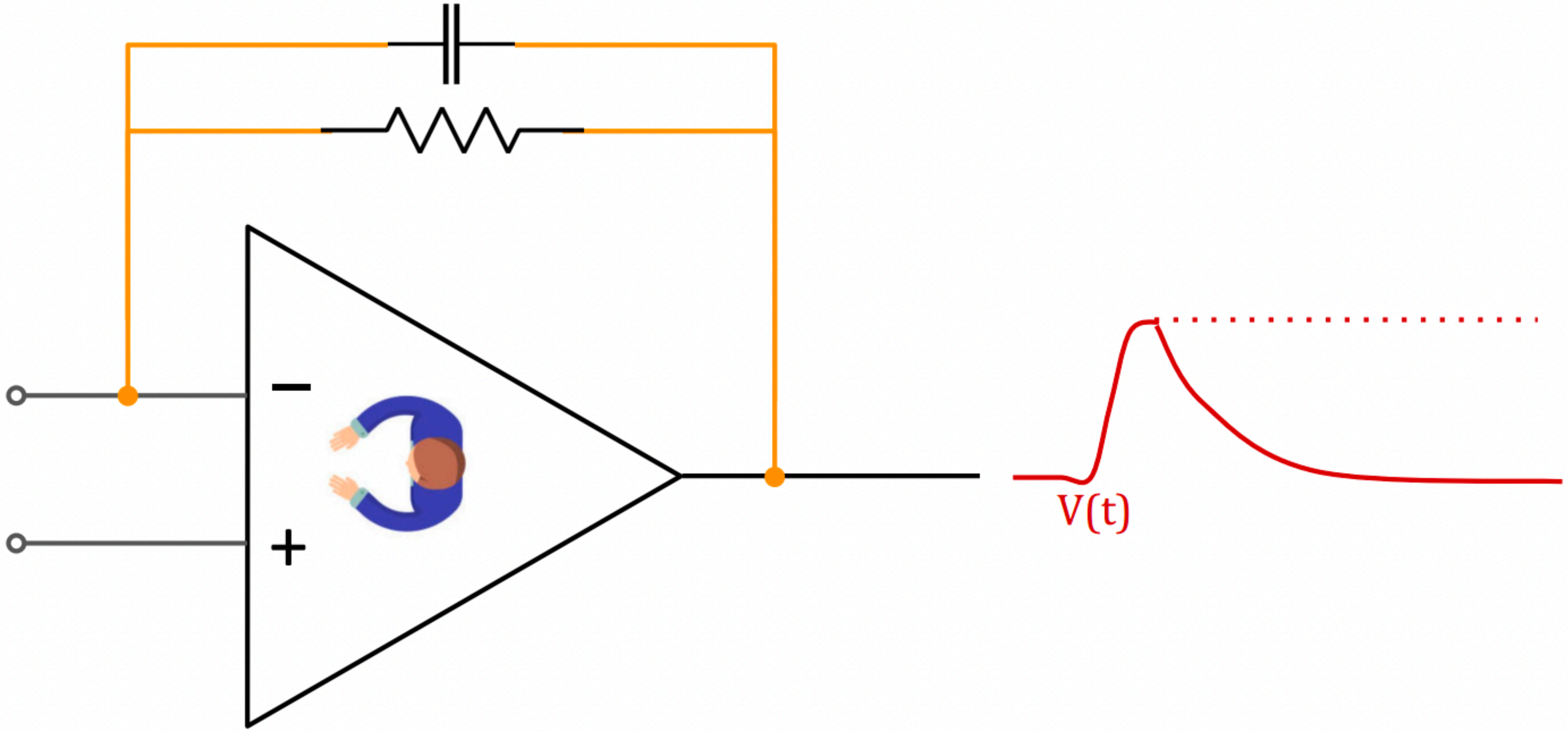
Dr. OpAmp is stuck, without removing the injected charge they can never return to normal..



How do we reset our amplifier now?

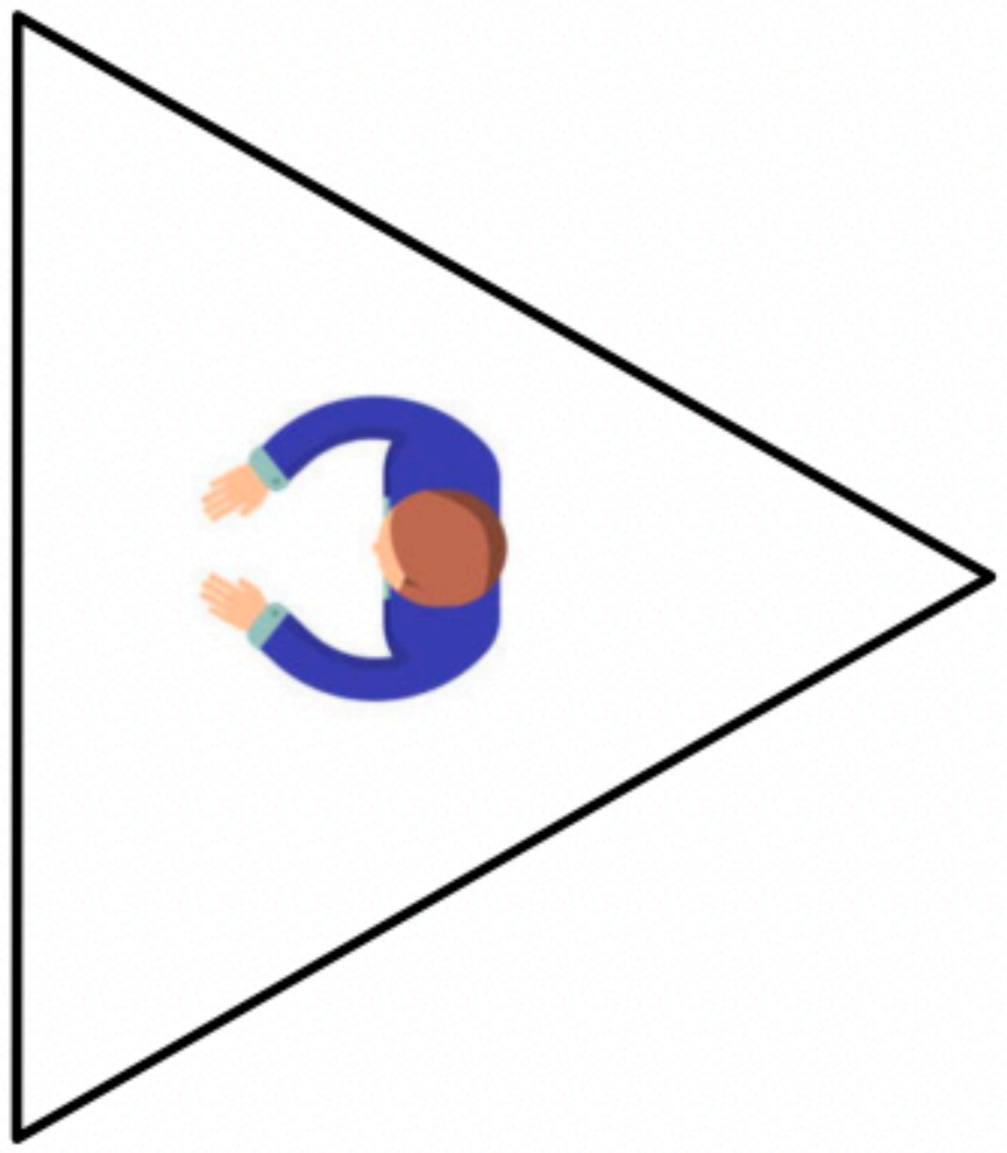
Signal Conditioning

Let's add a big resistor, allowing charge to slowly drain out of the input. Dr. OpAmp can relax and prepare for the next pulse..

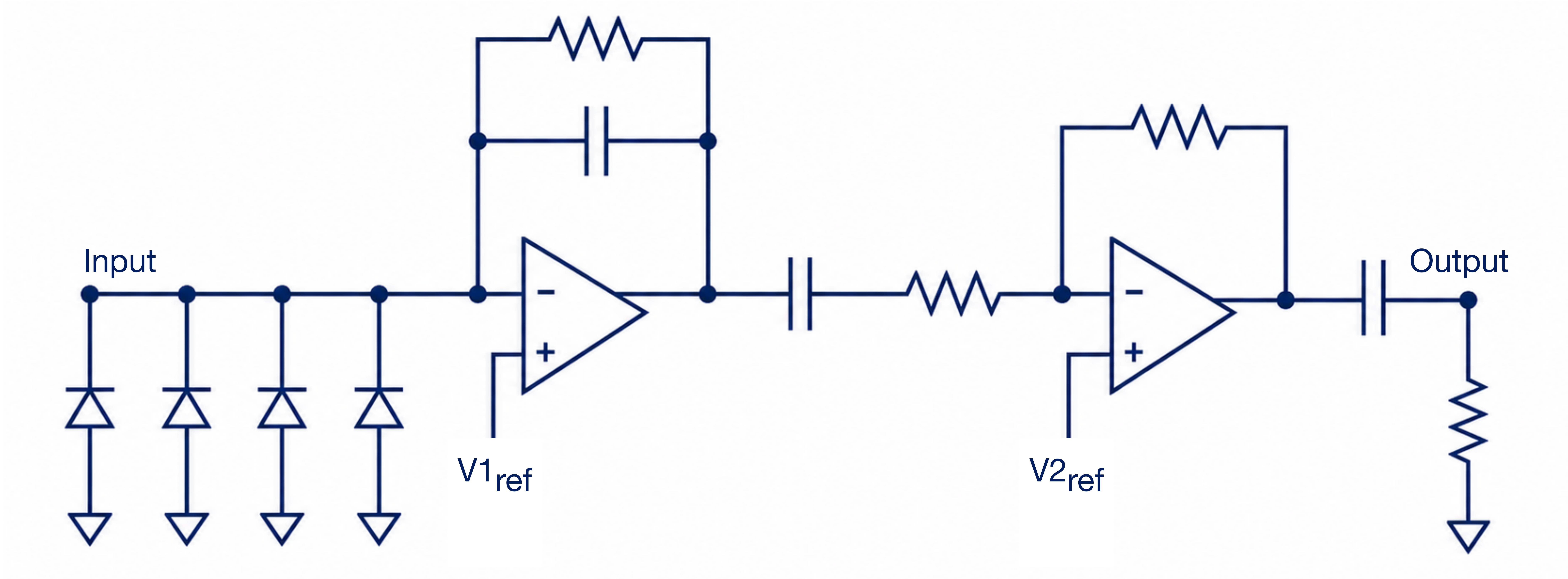


Signal Conditioning

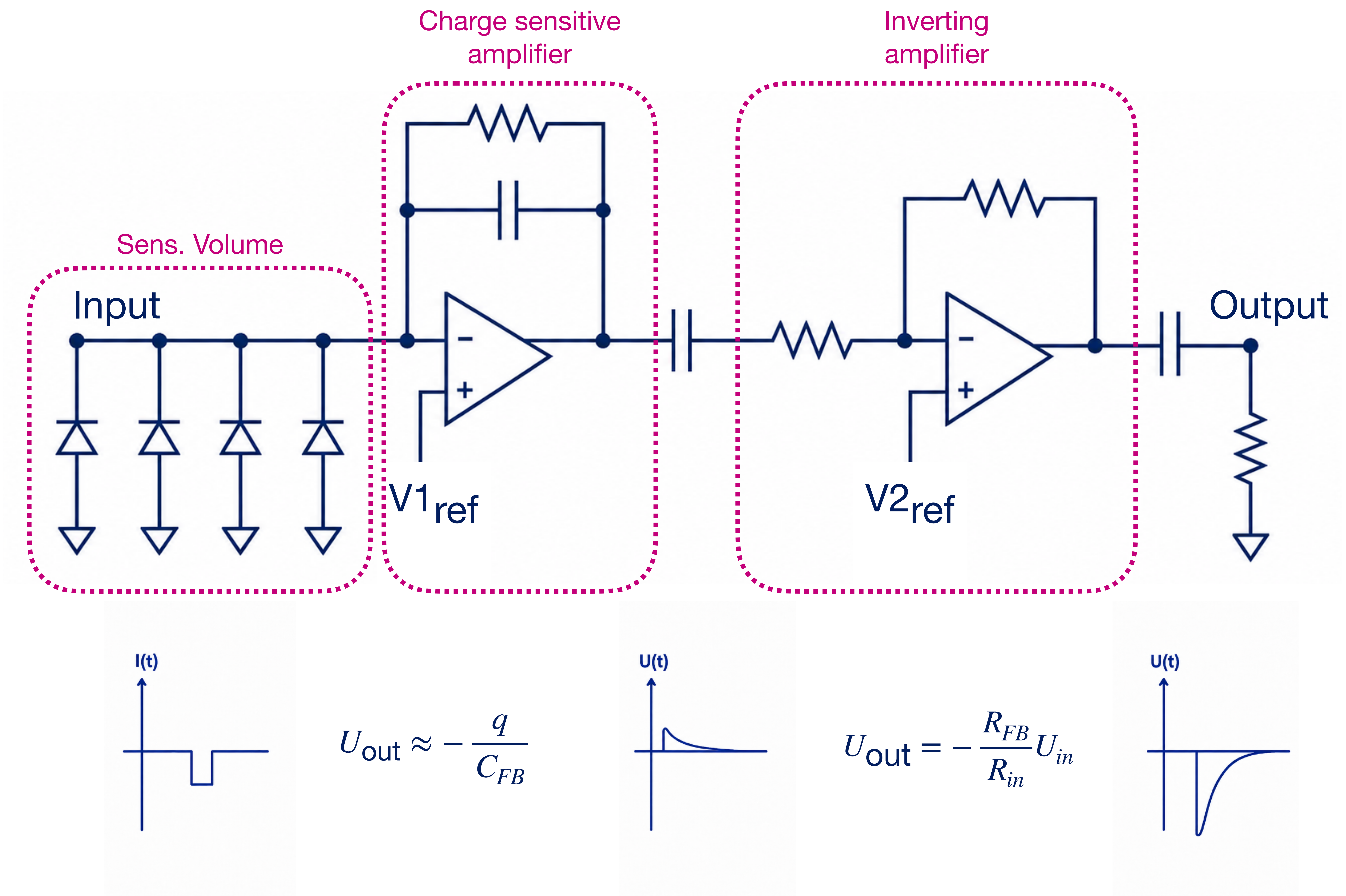
The End



Signal Conditioning



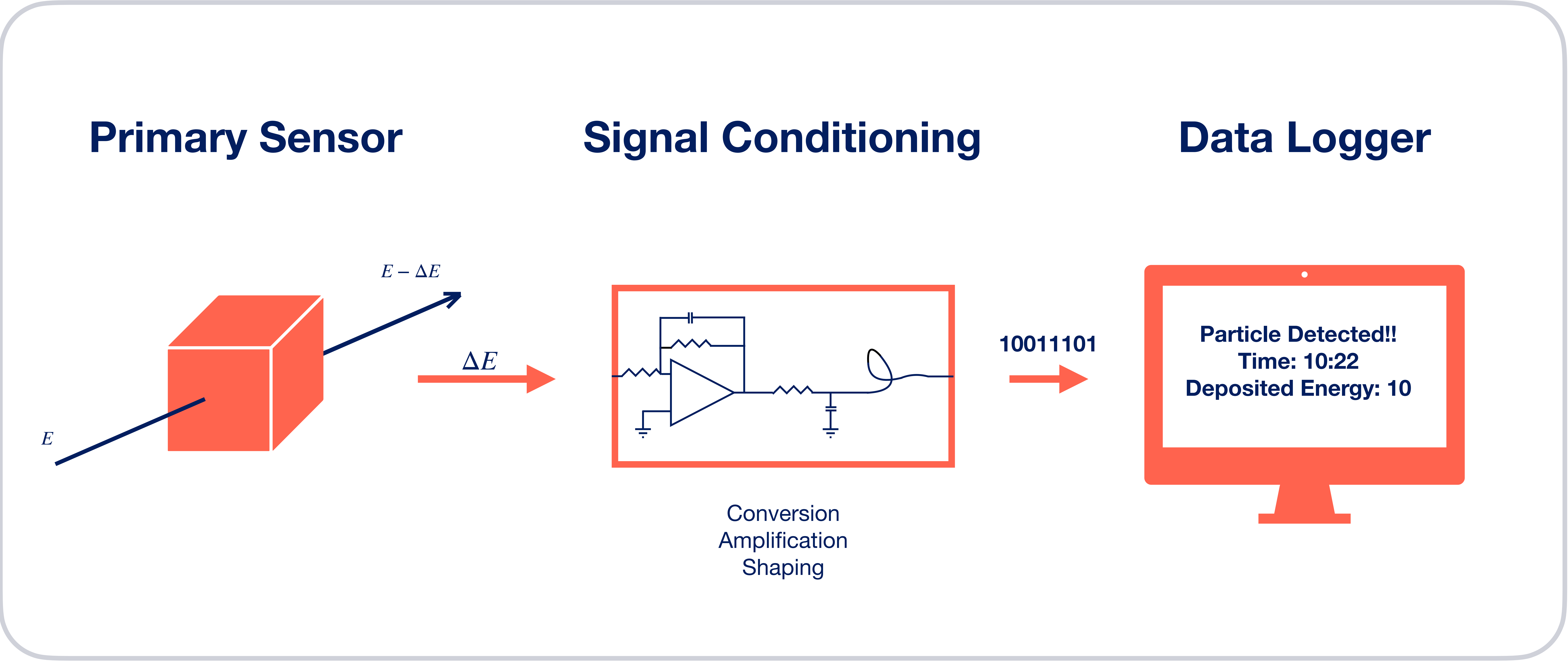
Signal Conditioning



$$U_{out} \approx -\frac{q}{C_{FB}}$$

$$U_{out} = -\frac{R_{FB}}{R_{in}}U_{in}$$

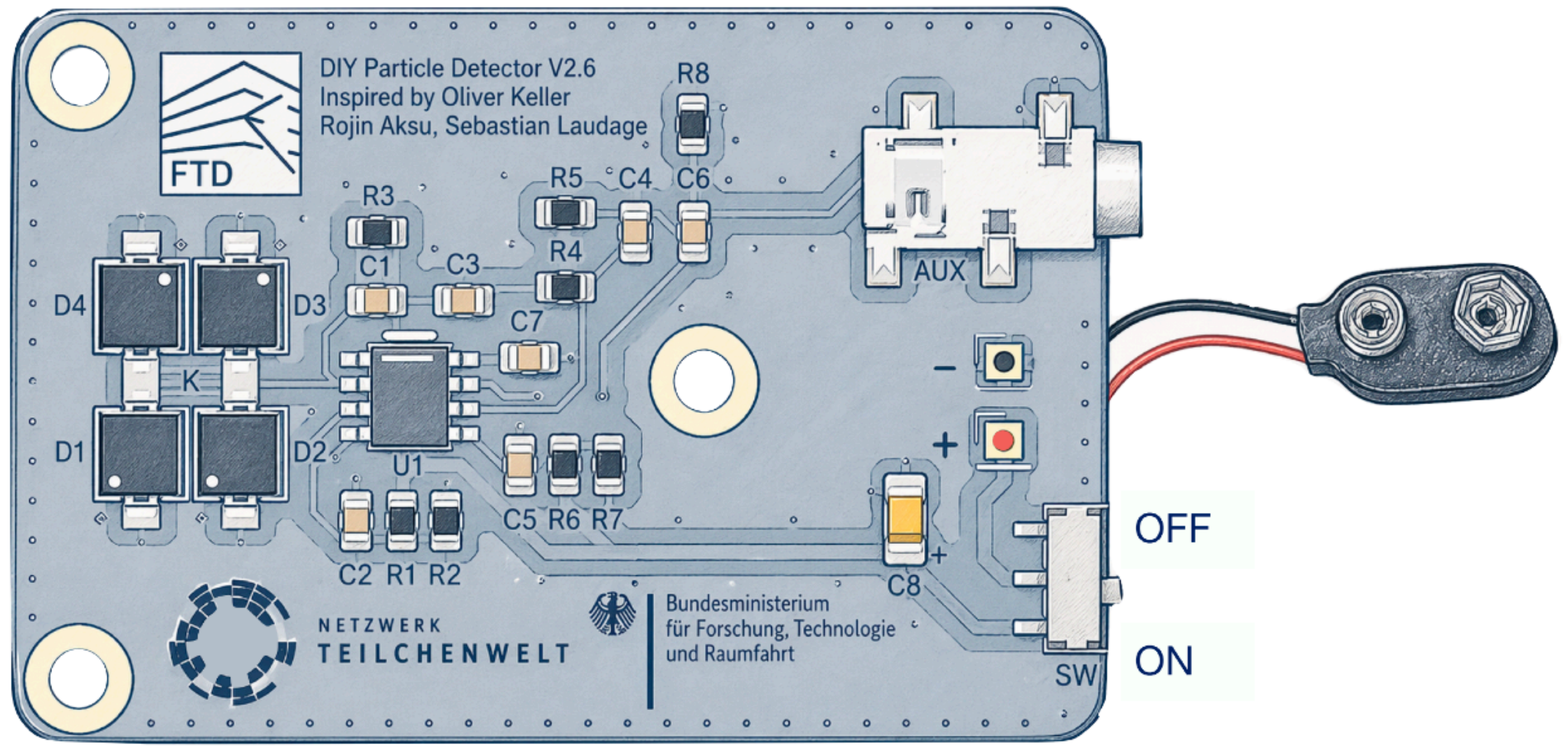
(Silicon-)
Detector Physics Basics



(Silicon-)
Detector Physics Basics

Primary Sensor

Signal Conditioning



Data Logger

Data Logger

Audio cable

+

Soundcard

Data Logger

Web based digital audio oscilloscope https://openprocessing.org/sketch/2931559

Demo

Detection Capabilities

Sensitive to:

- β radiation
- γ-ray response
- α particles only with exposed sensor

Experiments:

- Simple sample activity tests
- Coincidence of cosmics
- Radon decay measurements (balloon experiment)

Possible Samples

- Natural Background
    - Cosmic Rays
    - Atmospheric radon
    - Stones from certain regions
- Uranium glass
- Potassium carbonate
- Potassium tablets
- Low-sodium salt
- Welding rods
- Smoke detectors
- Gas mantles for camping
- European tea from 1986

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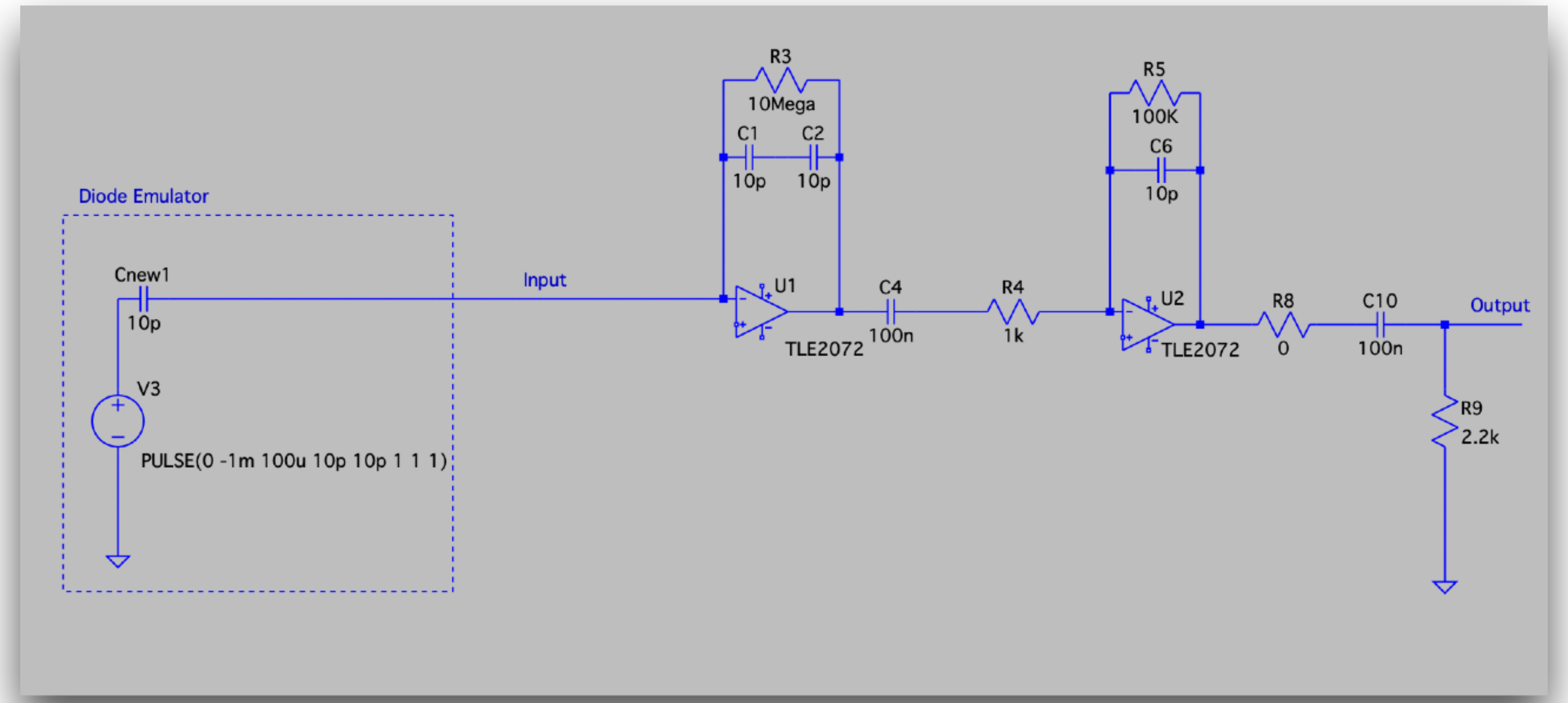
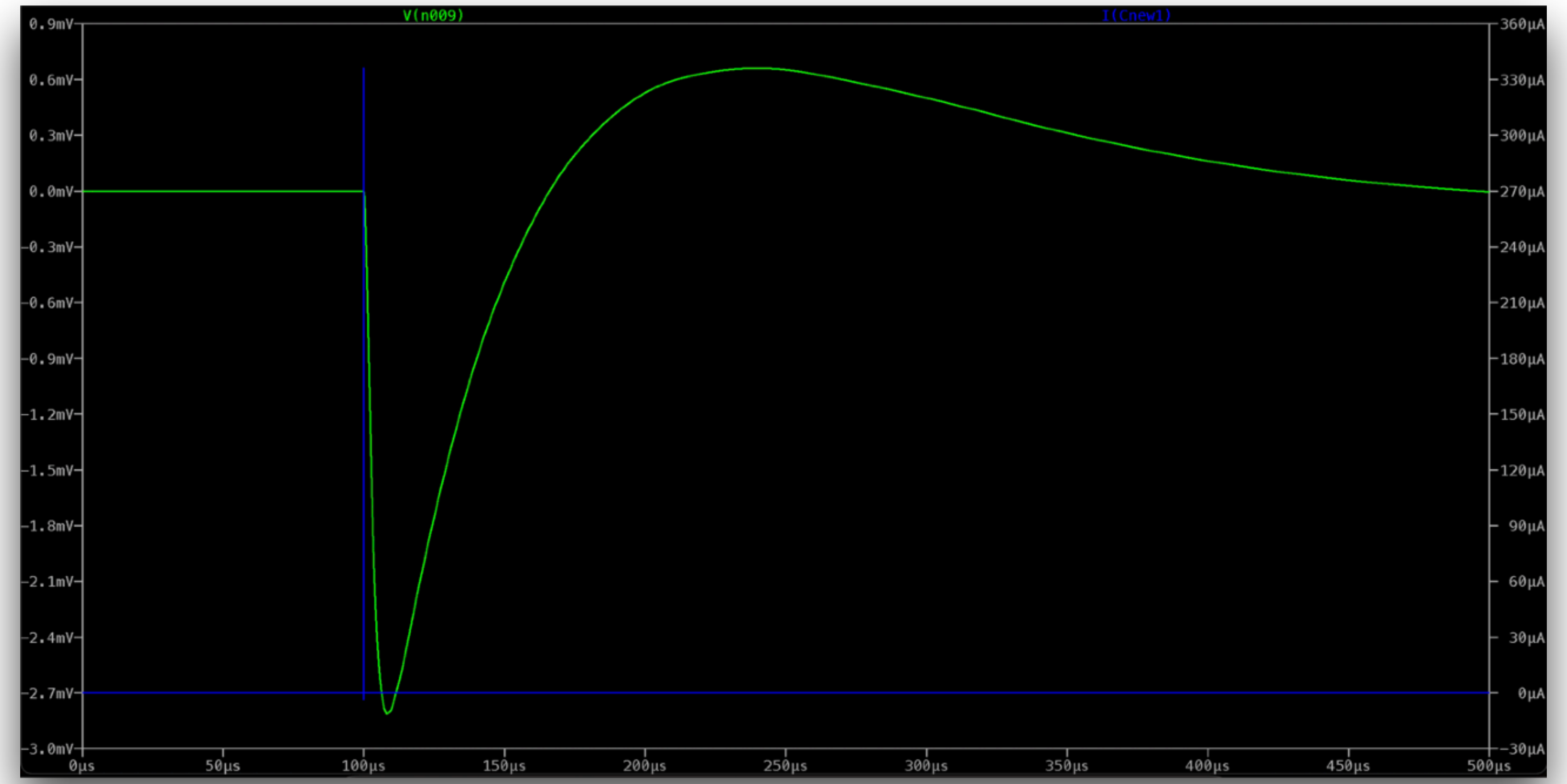
LTspice

- Free circuit simulator originally developed by Linear Technology
- Design, test and understand circuits
- Use realistic component models from manufacturers
- Simulate voltage and current behavior as a function of time and frequency

Circuit design



Signal Simulation



Install LTspice

Windows & macOS

- Official download: analog.com → LTspice
- Available for: Windows 10/11, Windows ARM64, macOS

Linux/ Ubuntu

- No native Linux version
- Use Windows version via Wine

```
sudo apt-get install wine-stable

cd /tmp/
wget https://ltspice.analog.com/
software/LTspice64.exe

wine LTspice64.exe
rm LTspice64.exe
```

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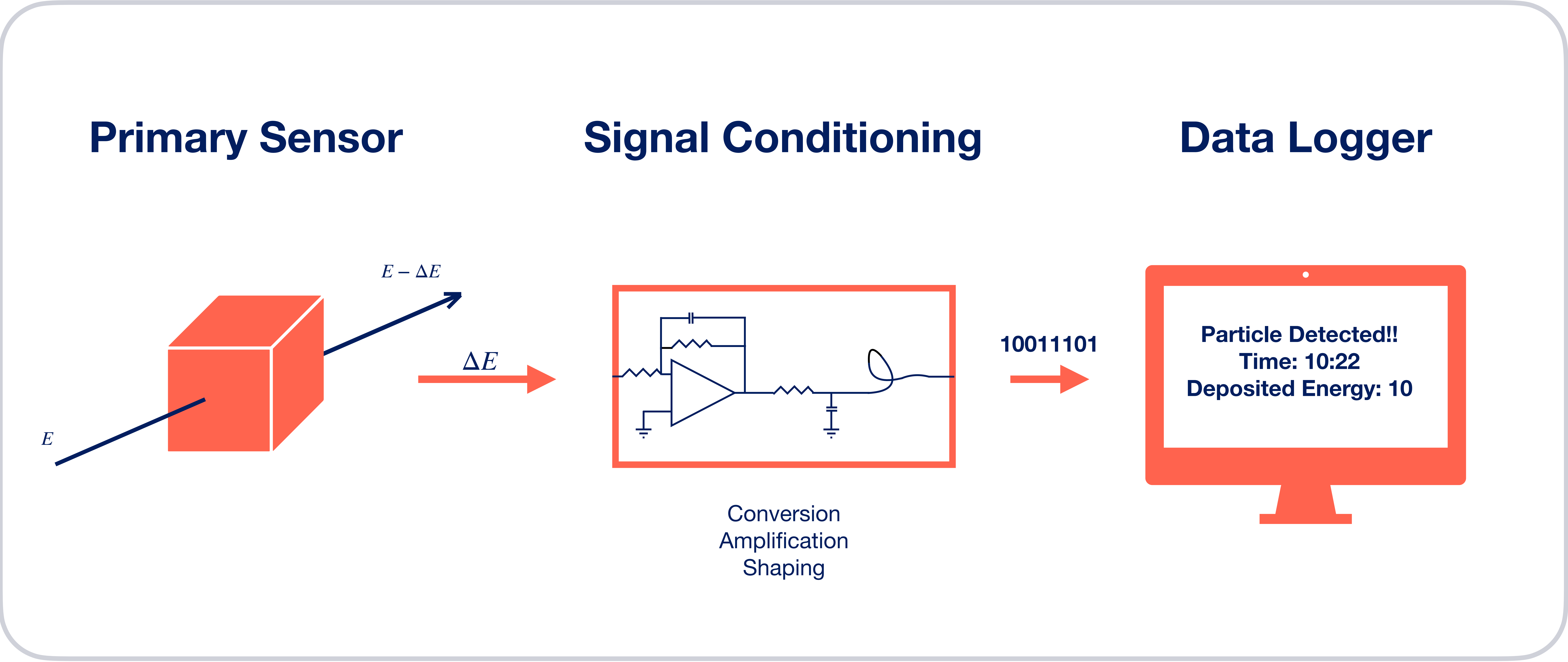
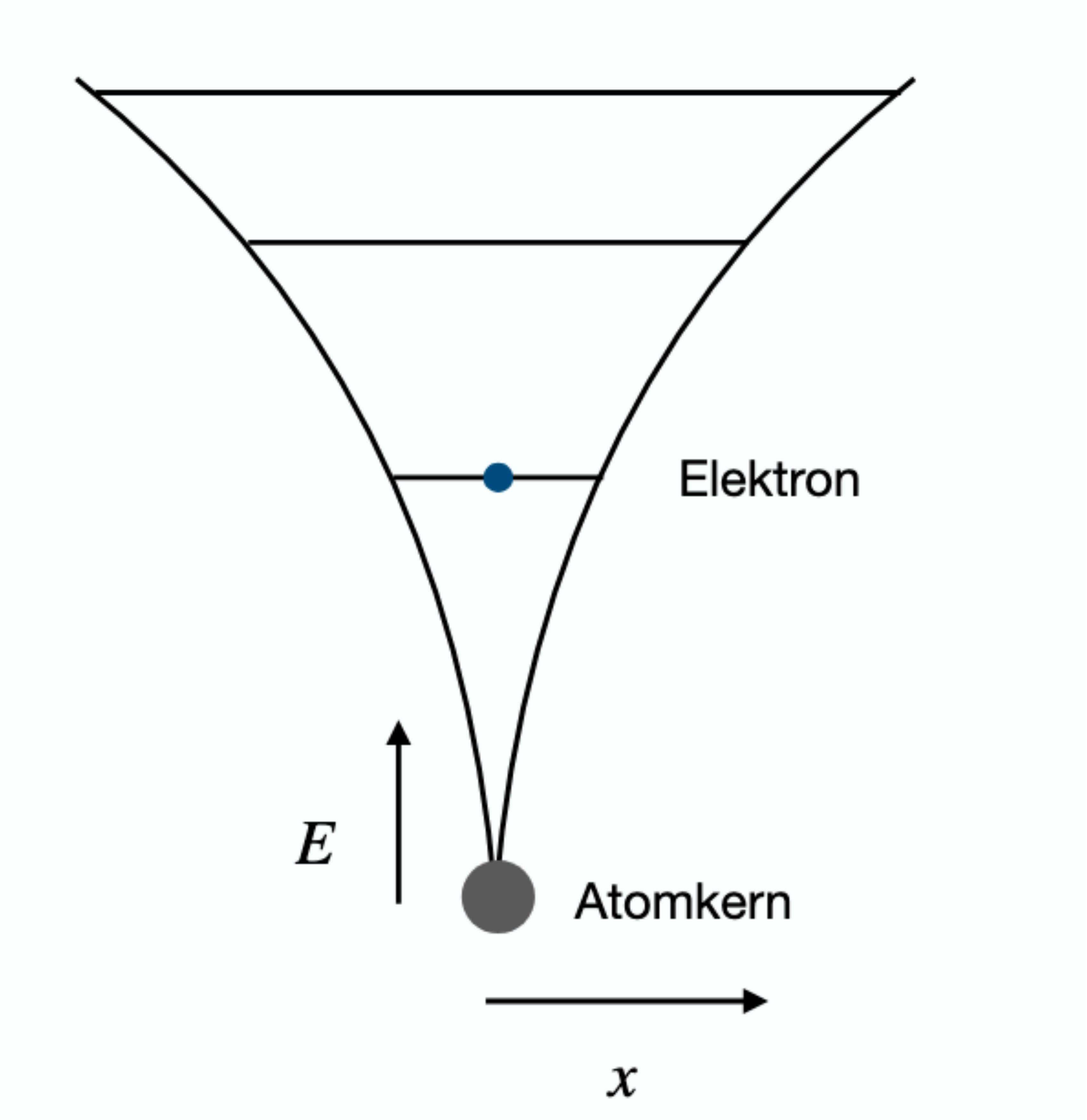
(Silicon-)
Detector Physics Basics



Detektorphysik

- **Was sind eigentlich Halbleiter?**



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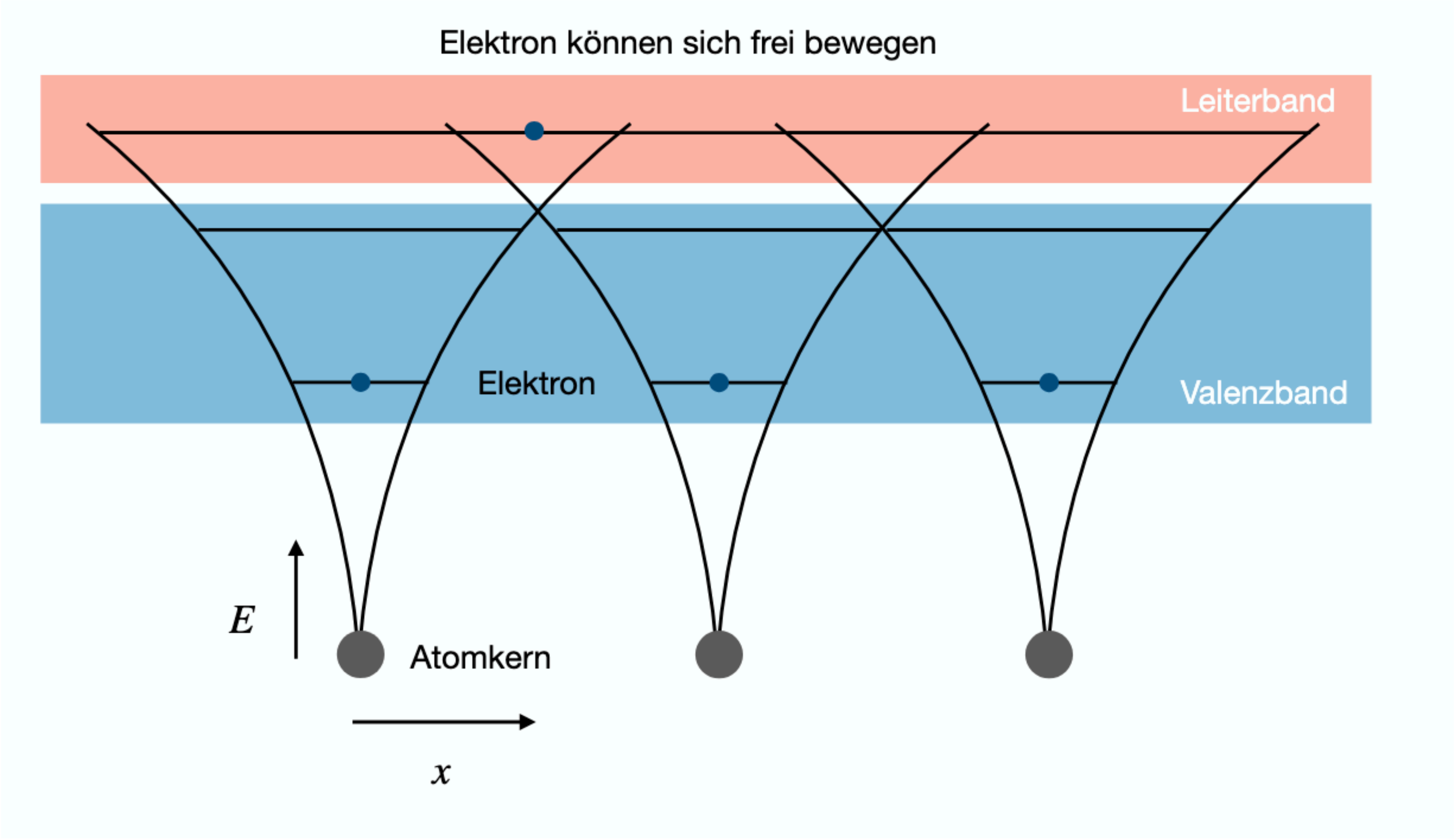

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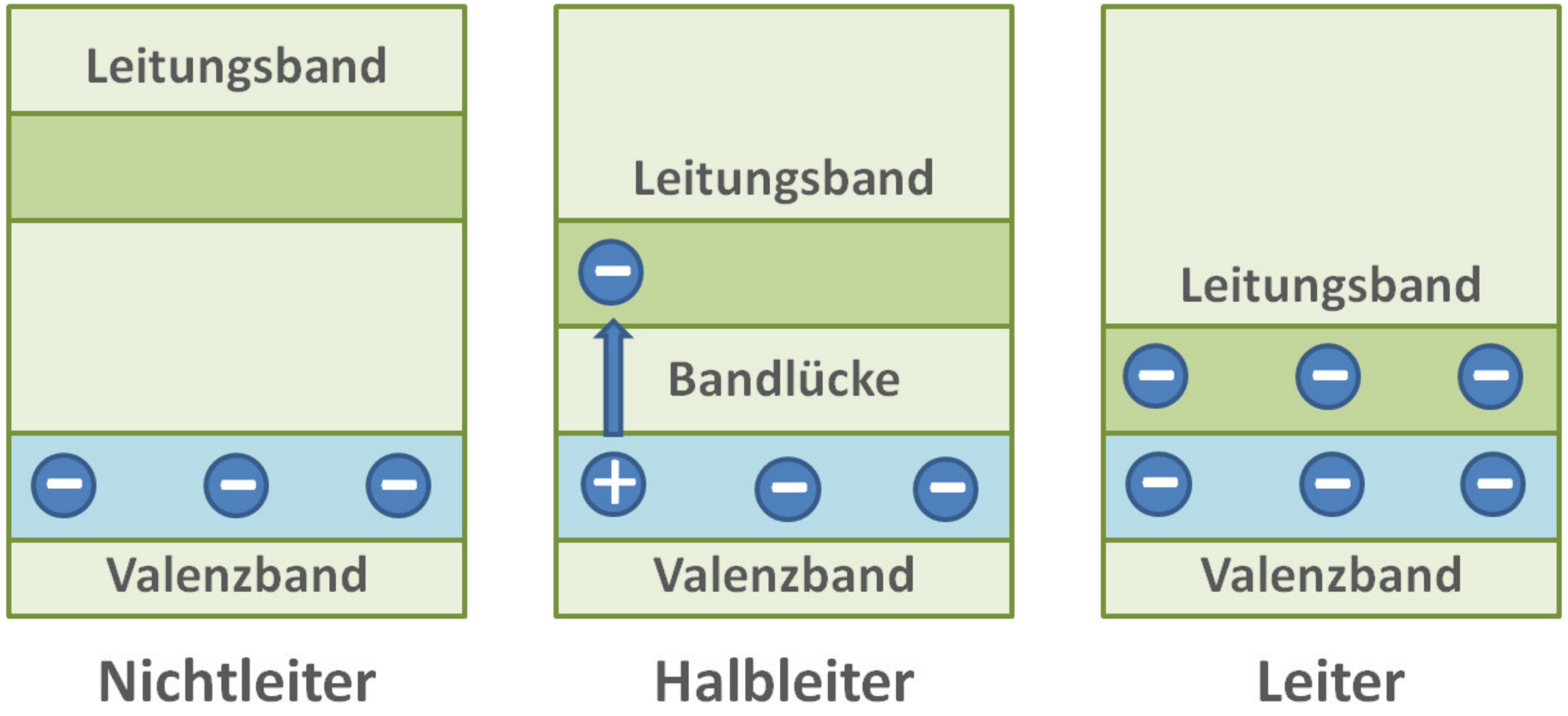
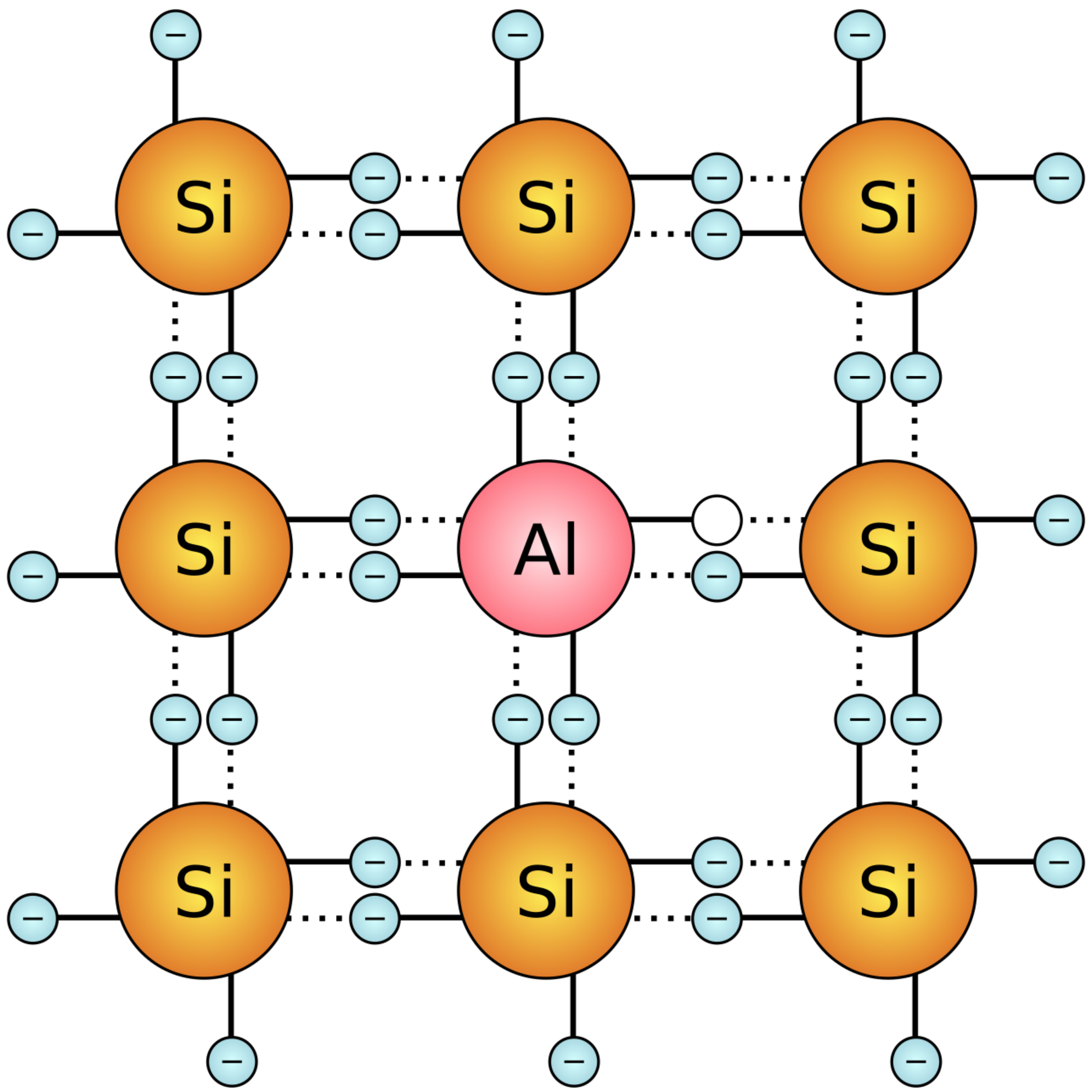
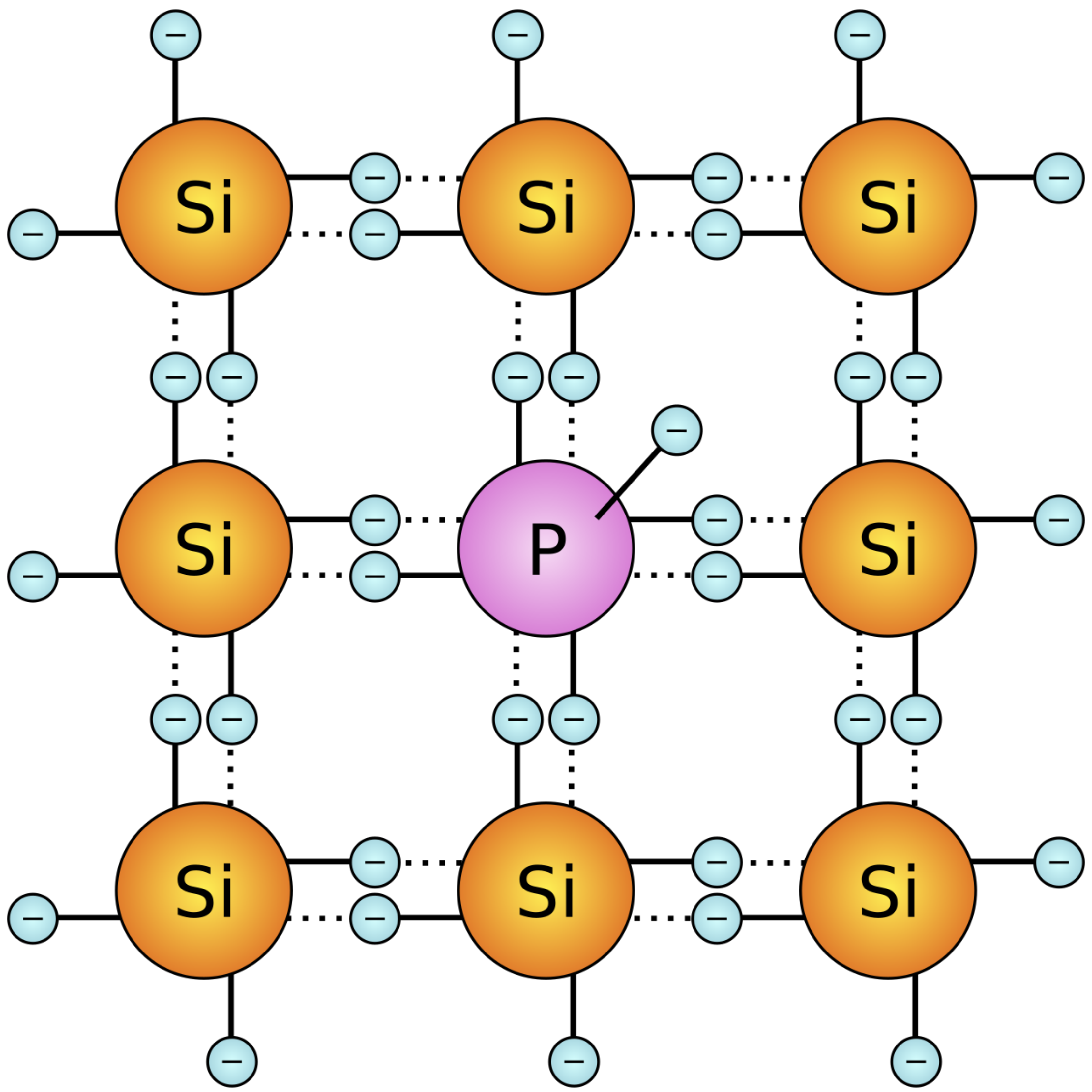


Detektorphysik

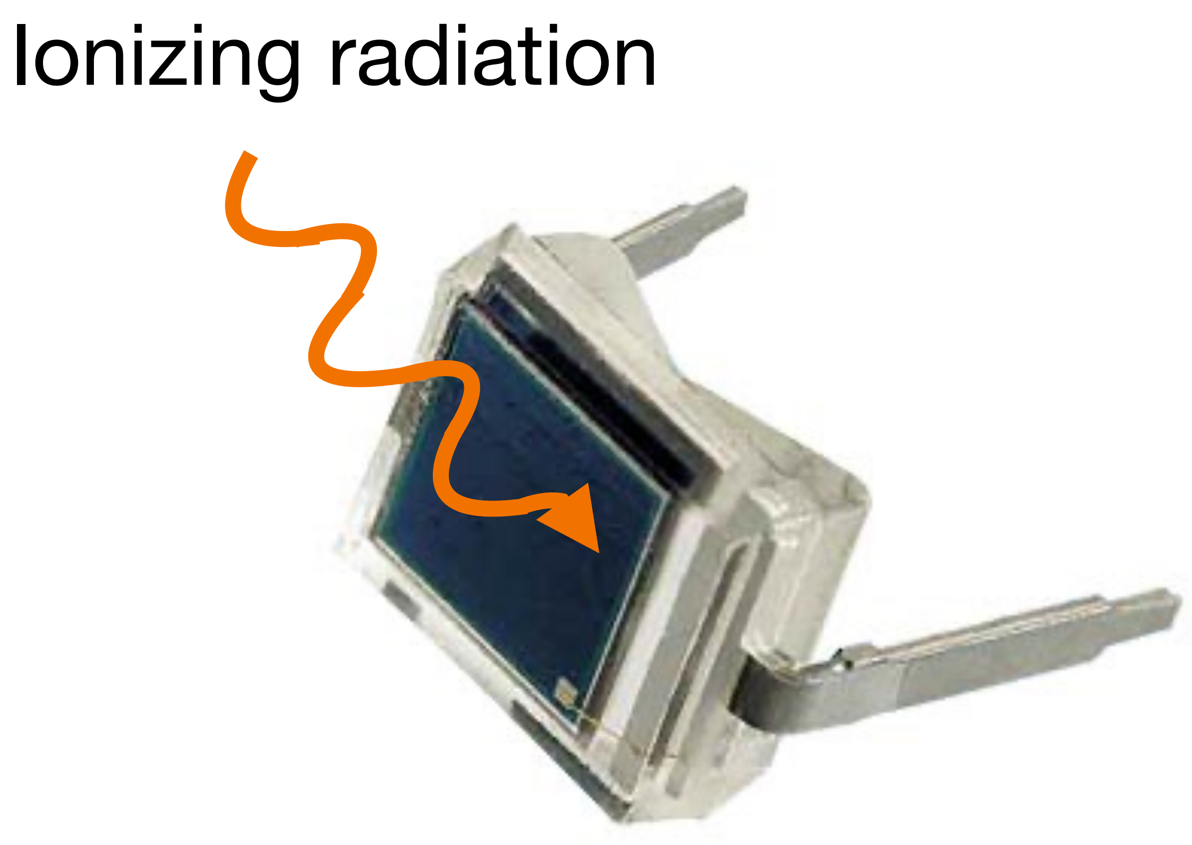


P-Dotiert



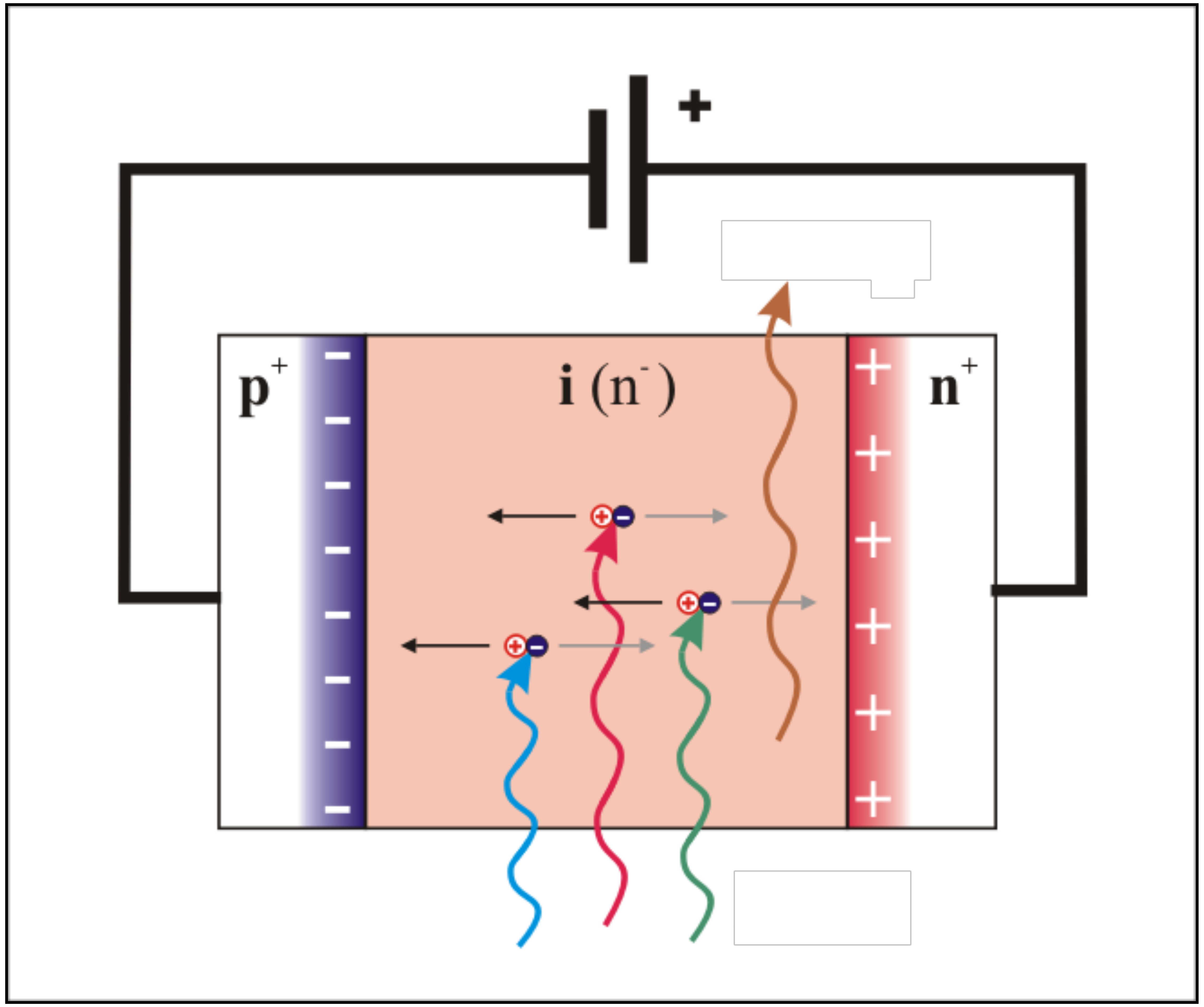
N-Dotiert

Detektorphysik

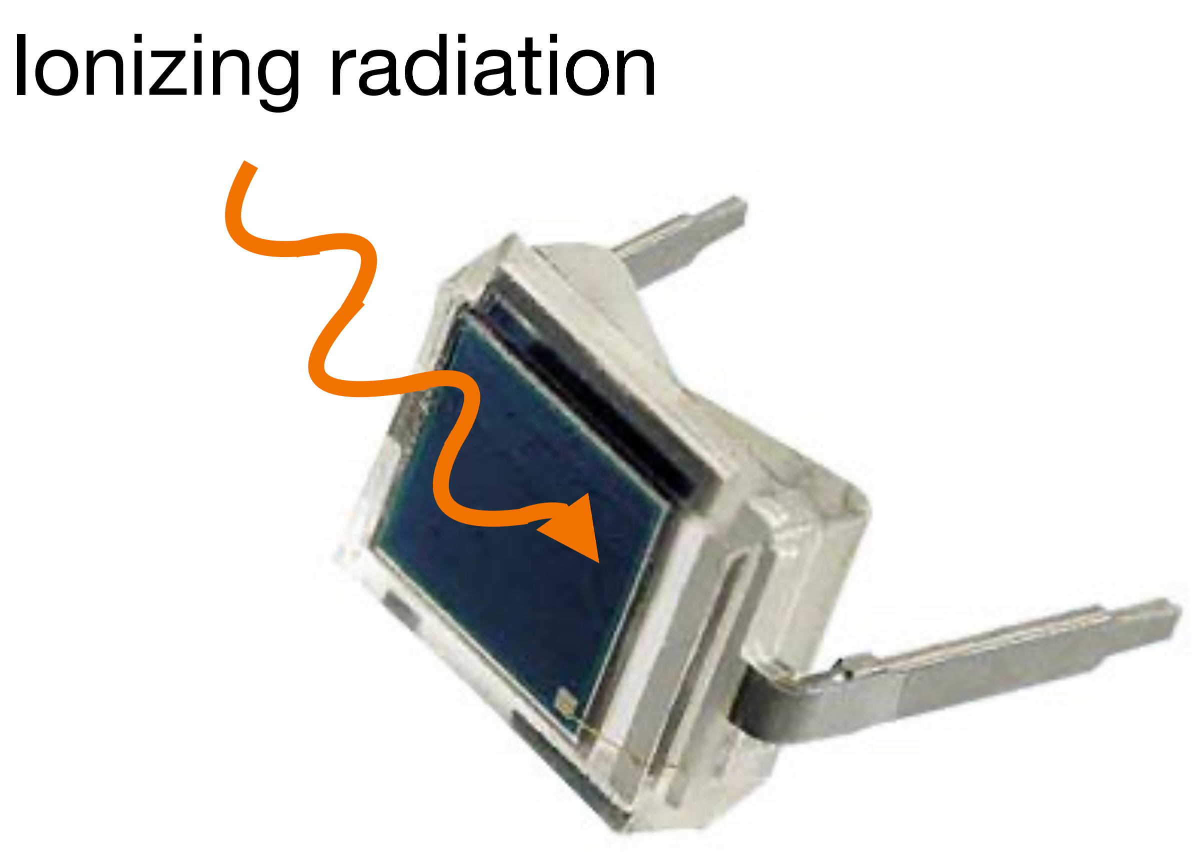


BPW34

Sensitive Fläche: ~$7mm^2$
Sensitive Tiefe: ~$50\mu m$ at 8V



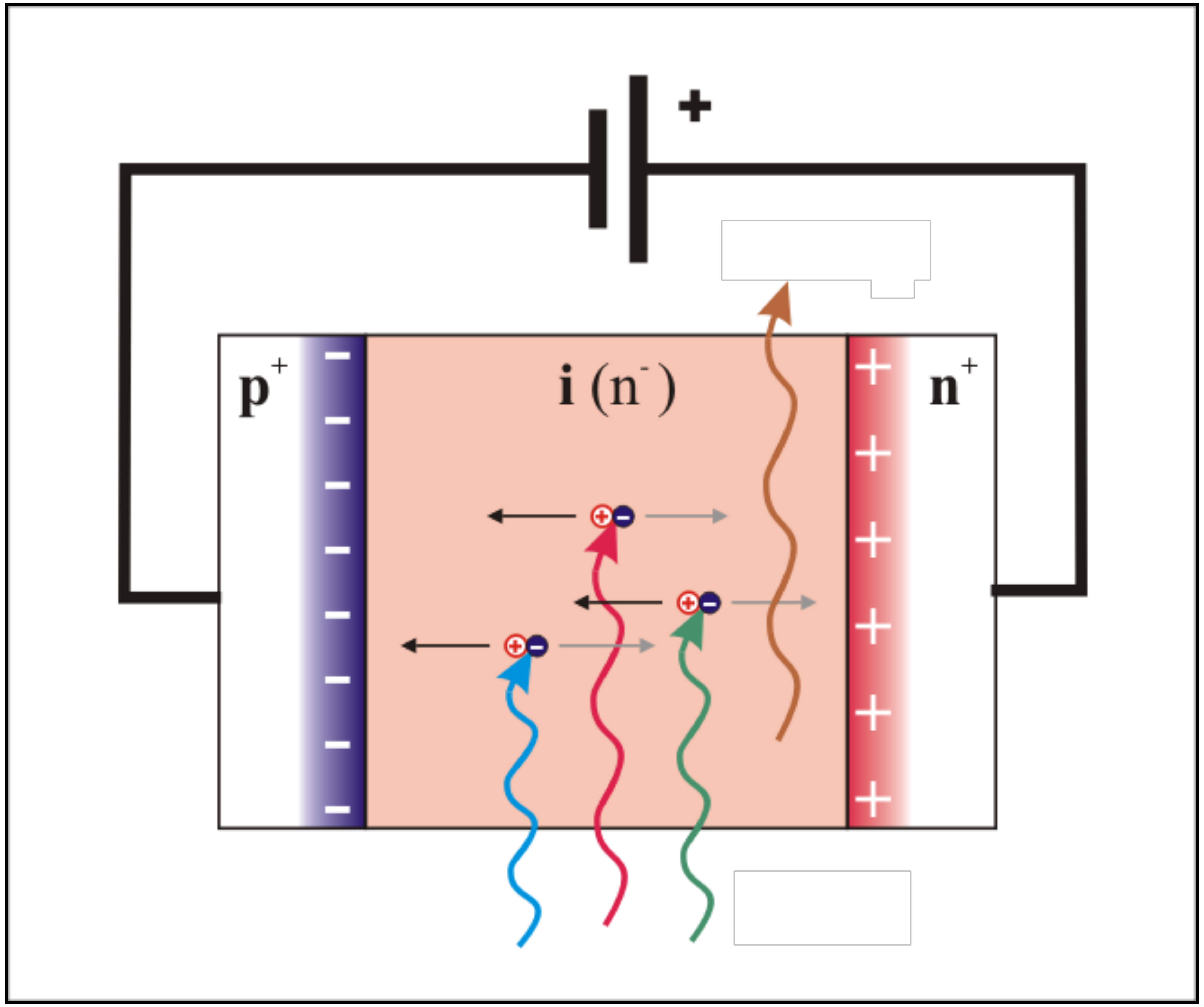
Detektorphysik



BPW34

Sensitive Fläche: ~7mm^2

Sensitive Tiefe: ~50μm at 8V

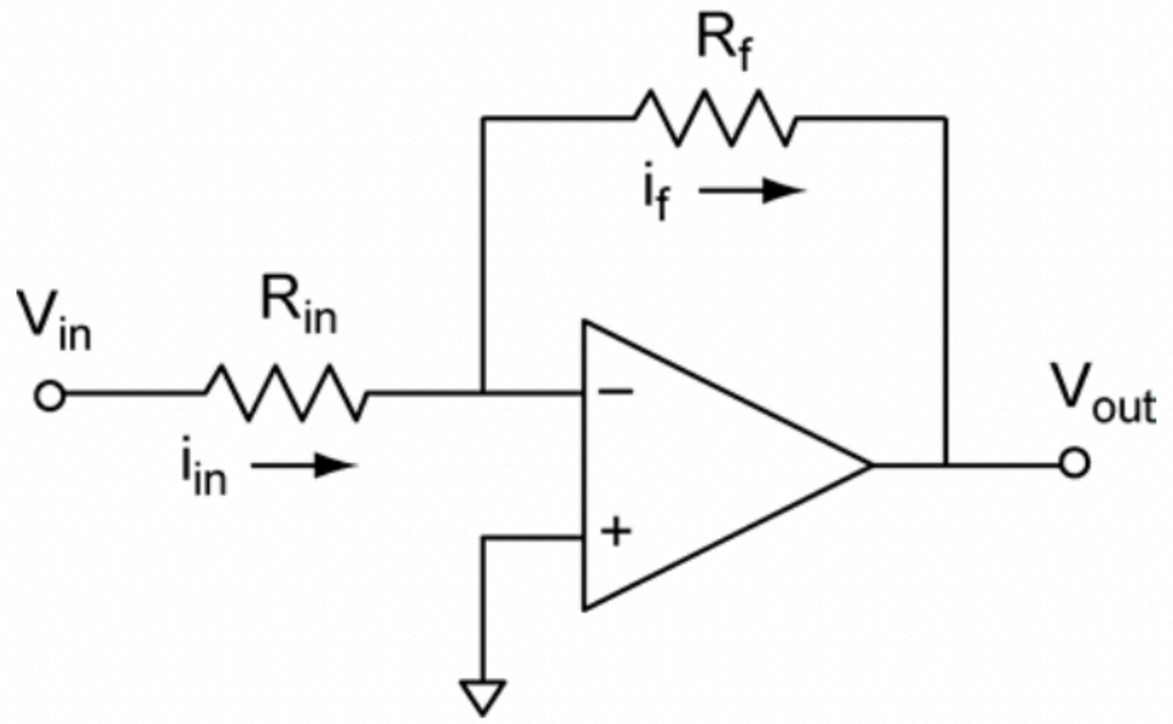


Inverting Amp

Op Amp Golden Rules (memorize these rules)

1) The op amp has infinite open-loop gain.
2) The input impedance of the +/− inputs is infinite. (The inputs are ideal voltmeters). The output impedance is zero. (The output is an ideal voltage source.)
3) No current flows into the +/− inputs of the op amp. This is really a restatement of golden rule **2**.
4) In a circuit with negative feedback, the output of the op amp will try to adjust its output so that the voltage difference between the + and − inputs is zero ($V_+ = V_-$).

Inverting Amplifier



$$V_{out} = -\frac{R_f}{R_{in}} V_{in}$$

$$A_V = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_{in}}$$

$$\frac{dV_{in}}{dI_{in}} = R_{in}$$

Analysis of the inverting amplifier starts with our op amp golden rules. From rule #4 we know that $V_- = V_+$ and that $V_- = 0$ because V_+ is connected to ground. From rule #3 we know that $I_{in} = I_f$ because no current flows into the inverting input.

$$V_- = V_+ \qquad V_+ = 0 \qquad I_{in} = I_f = I$$

Then we can find the relationship between V_{in} and V_{out} using Ohm's law (OL) and Kirchhoff's voltage law (KVL).

$$V_{in} - V_- = I_{in} R_{in} \qquad V_{in} - 0 = IR_{in} \qquad V_{in} = IR_{in} \qquad I = \frac{V_{in}}{R_{in}}$$

$$V_- - V_{out} = I_f R_f \qquad 0 - V_{out} = IR_f \qquad V_{out} = -IR_f$$

$$V_{out} = -\frac{R_f}{R_{in}} V_{in}$$

Charge sens. Amp

1.5.4. Analog front-end electronics

Charge dissipated in silicon diode detector by ionizing radiation has to be collected and transferred to measure quantities like current or voltage. It is obviously done by a transimpedance/charge amplifier (figure 9) (Keim 2018).

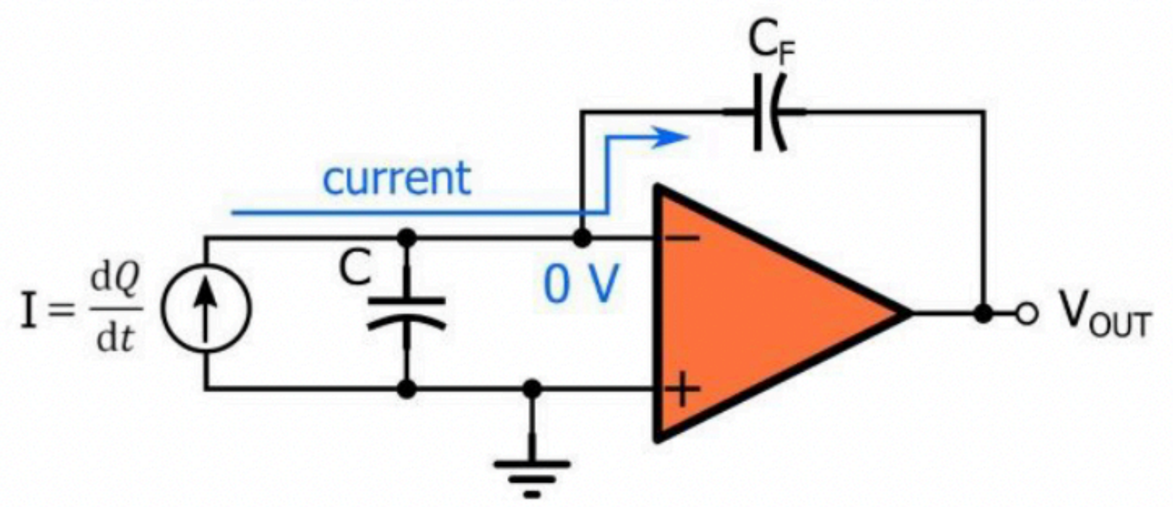


Figure 9*: Charge amplifier (Keim 2018).*

This circuit can convert charge to voltage according to

$$V_{OUT} = \frac{1}{C_F} \int -I\, dt = -\frac{Q}{C_F}.$$

Amplifier has a gain

$$A_Q = \frac{dV_{OUT}}{dQ} \approx \frac{1}{C_F}.$$

However, the circuit in figure 9 is impractical due to amplification of offset current flowing into the input of an operational amplifier. The resistor parallel to the feedback capacitor C_F has to be connected (figure 10) for discharging the C_F.

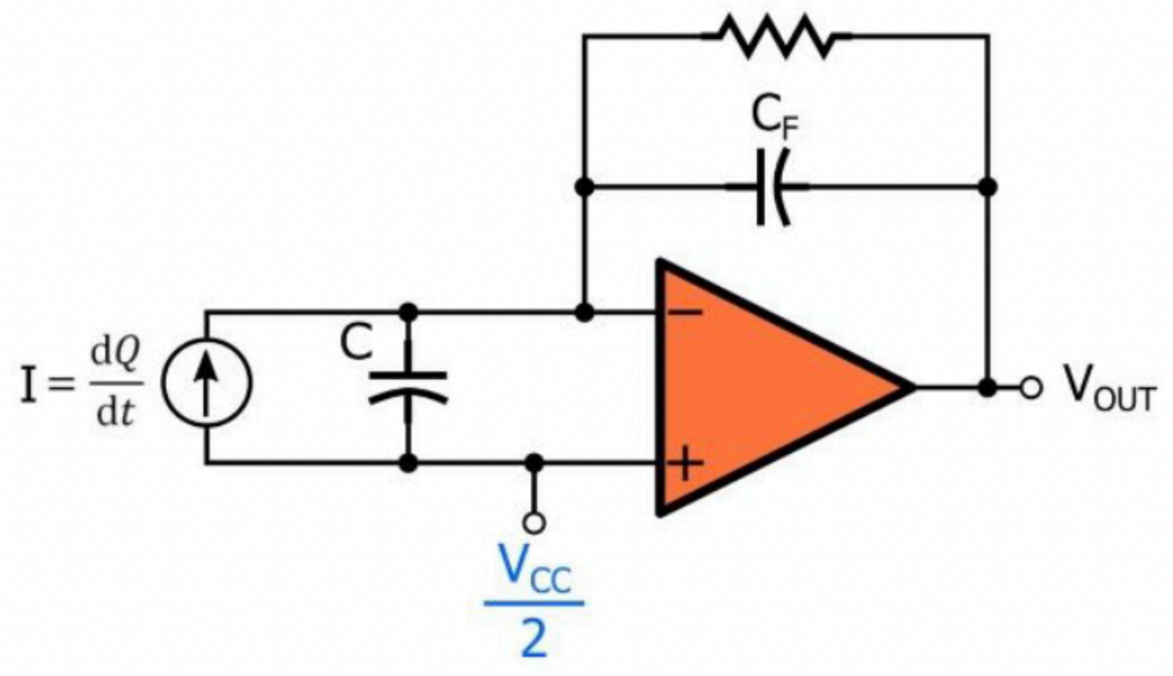
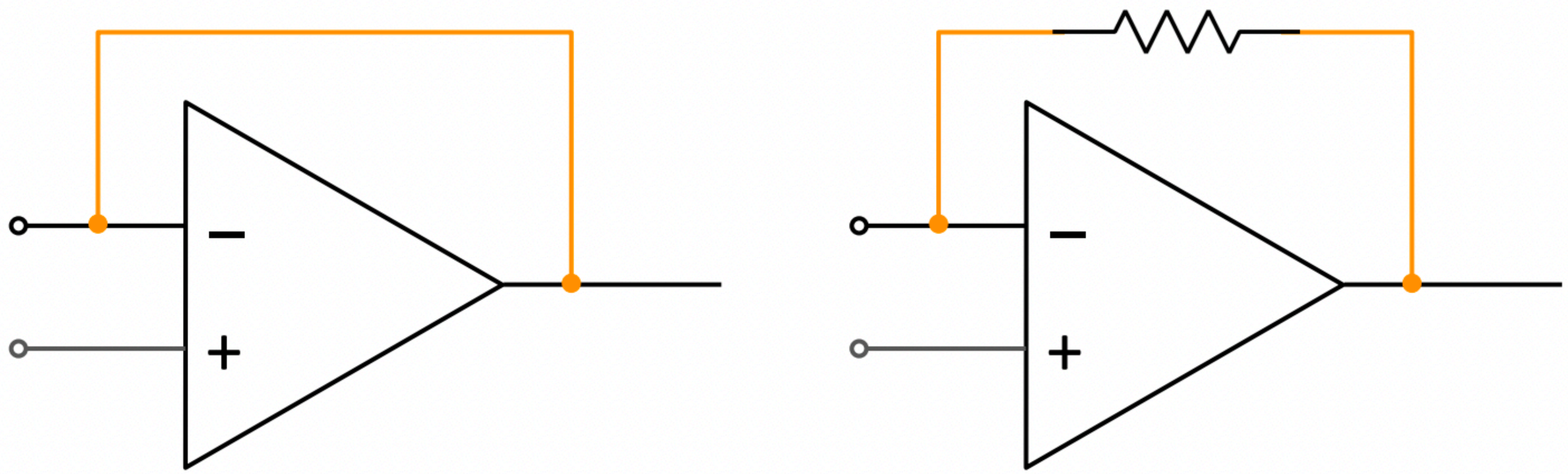


Figure 10*: Practical arrangement of charge amplifier (Keim 2018).*

Feedback Capacitor

With a feedback capacitor:

At *high frequencies* At *low frequencies*



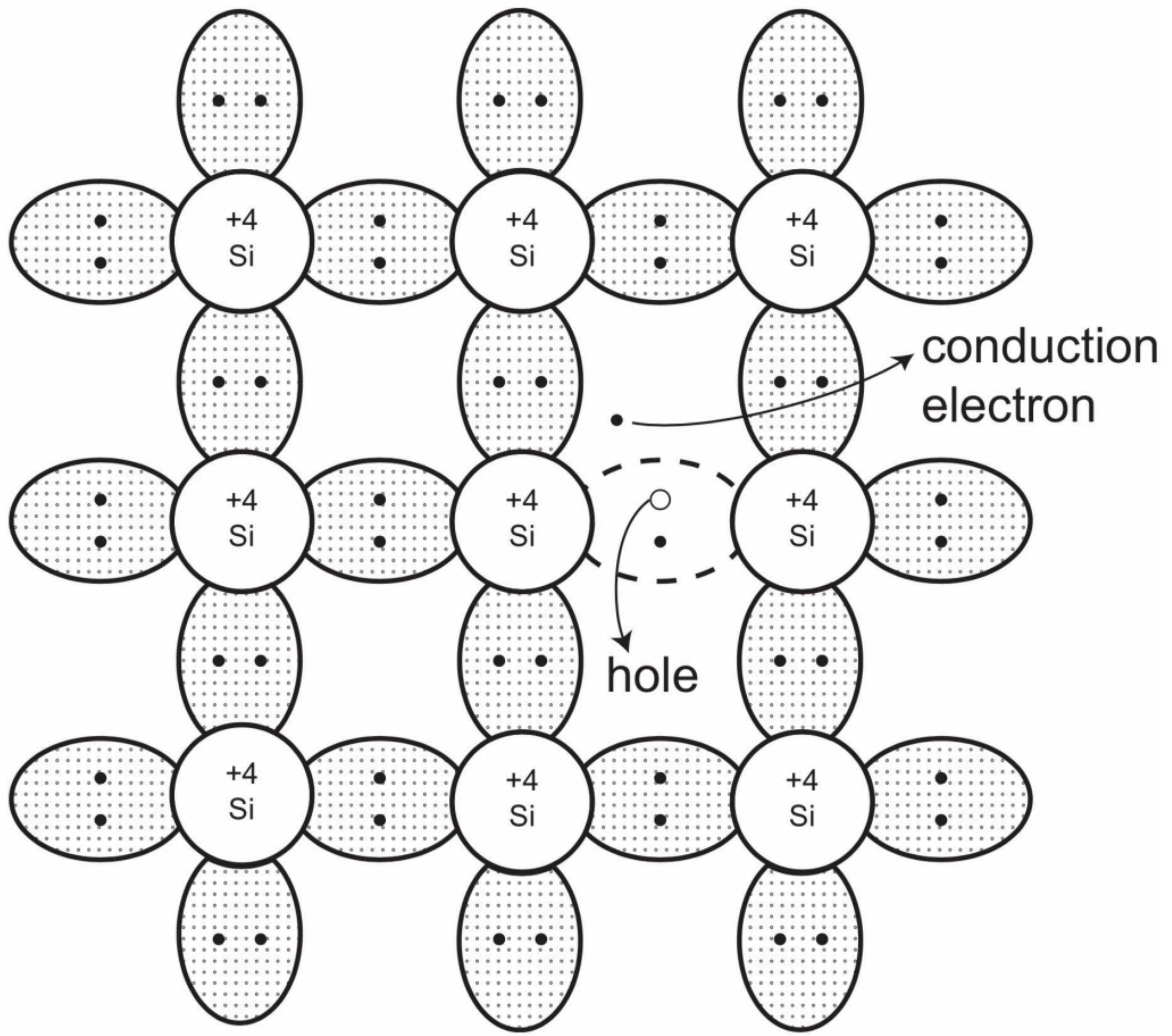
No (unity) gain for high-frequencies, max gain for low frequencies: this provides *noise filtering* (among other things!)

Capacitive Reactance: $X = \dfrac{1}{2\pi f C}$

Detector Physics

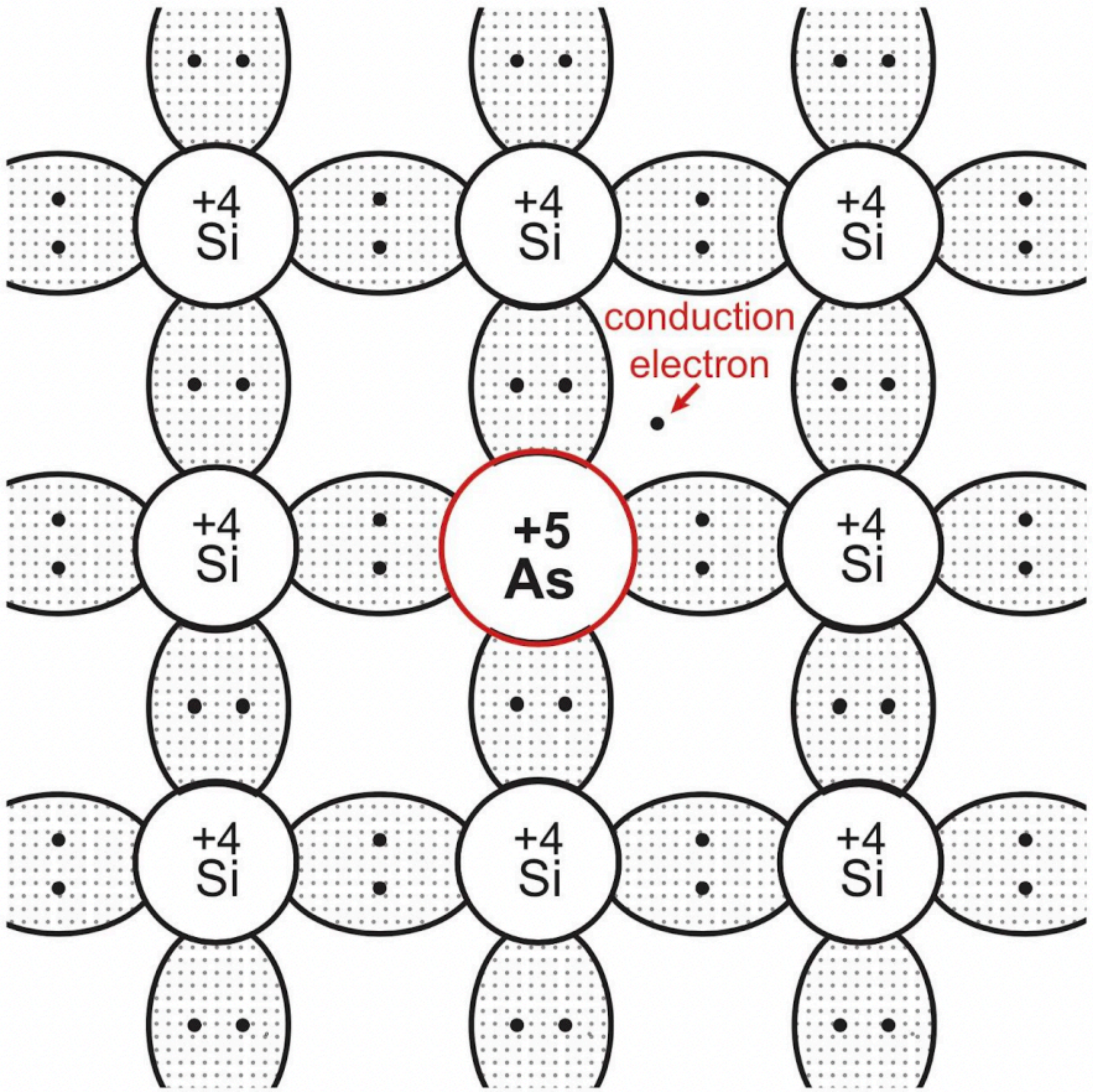
Semiconductor:

- Intrinsic semiconductors are **undoped**
- Conduction arises from movement of electrons and holes
- They have a small **band gap (1.12 eV for silicon),** small energies are needed to move electrons from the **valence band** to the **conduction band**
- **Thermal energy** can be enough for electrons to be kicked into the conduction band

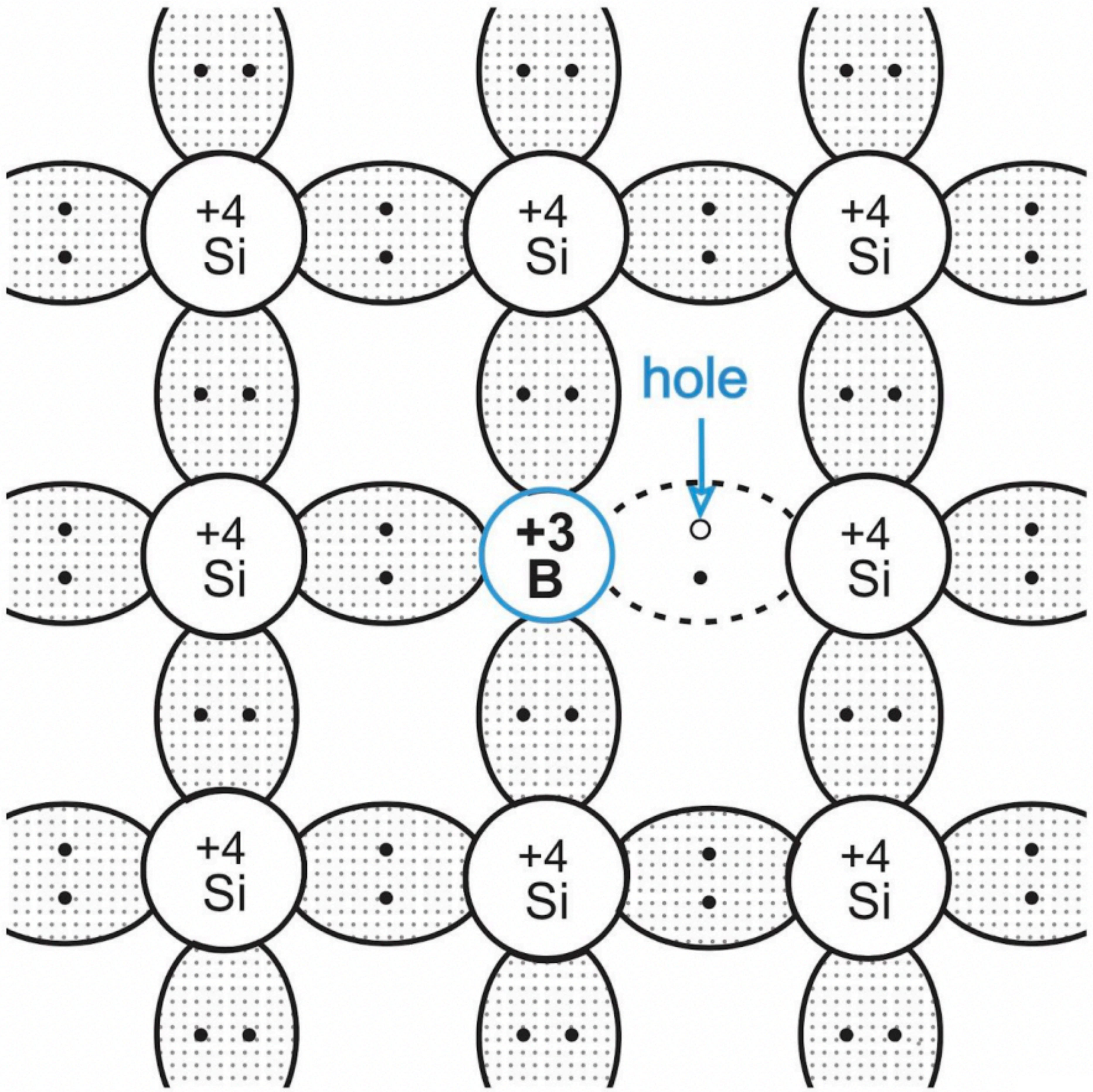


Detector Physics

Doping semiconductors can make them eager electron donors or acceptors



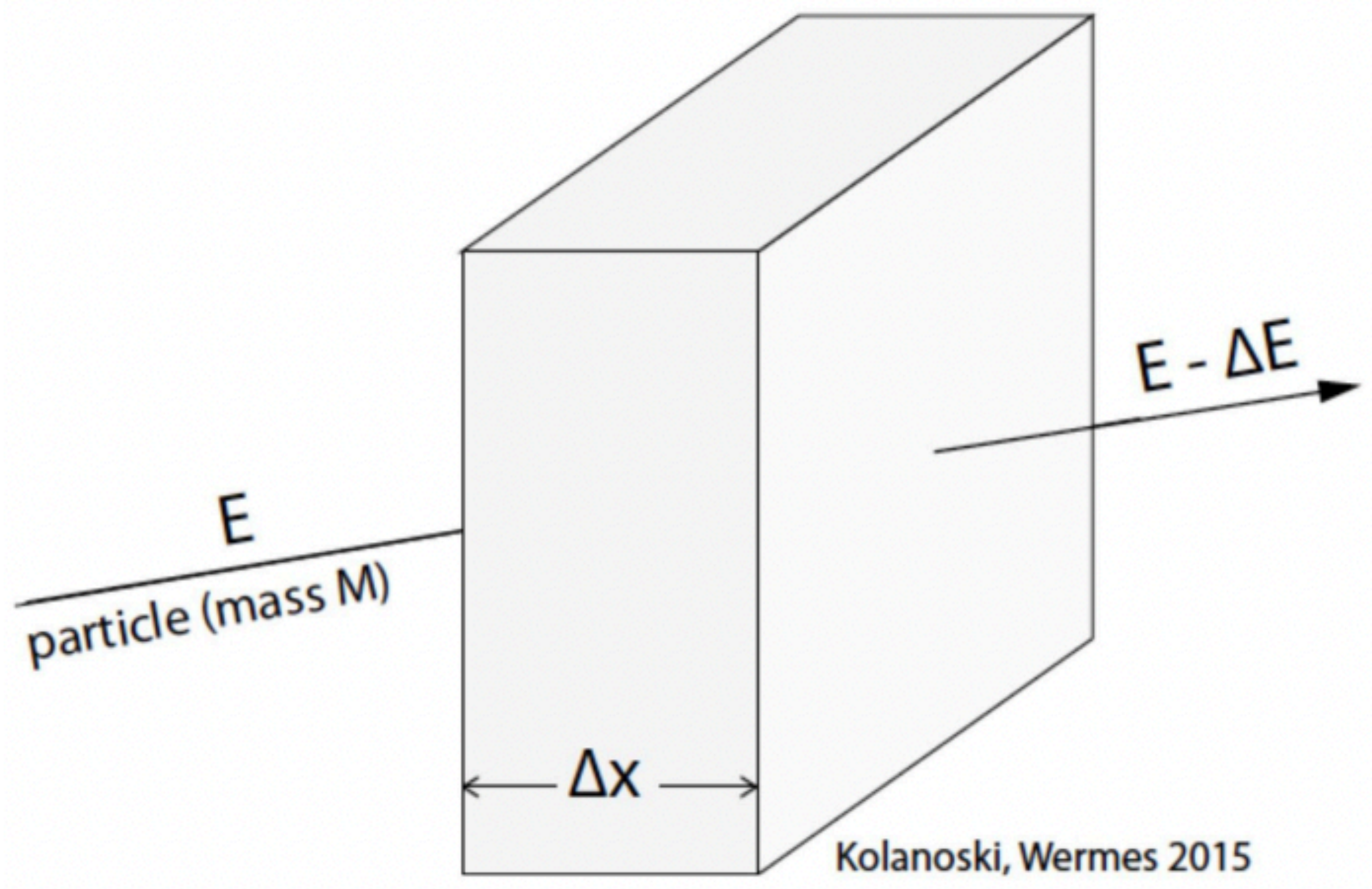
(a) n doped



(b) p doped

Detector Physics

- A charged particle traverses a material of thickness ΔX
- Upon exiting the energy of the particle has decreased by ΔE
- The basis of **all** particle detectors: collect ΔE from the material and gain information about the particle based on that



Uranium Decay Chain