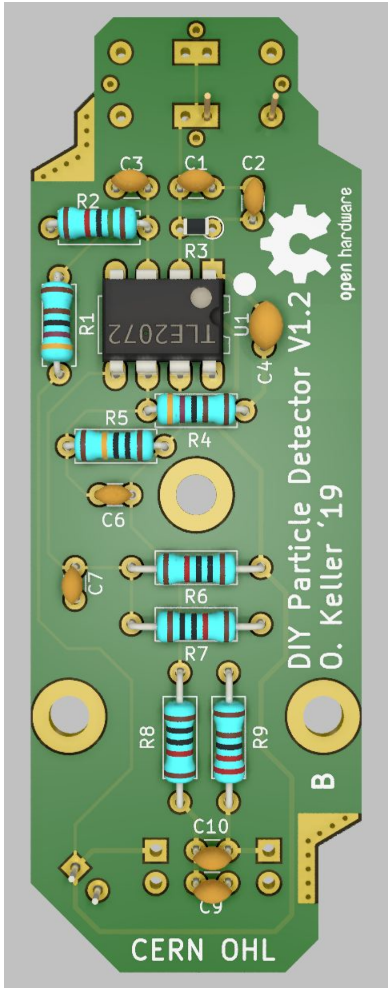


A short, practical guide to particle detection

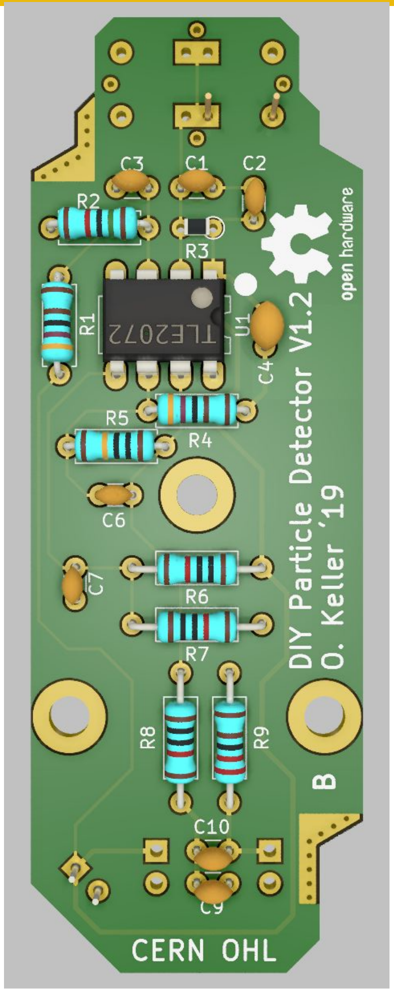
Belle 2 academy | 2022 Bonn

Peter Lewis

DIY particle detector

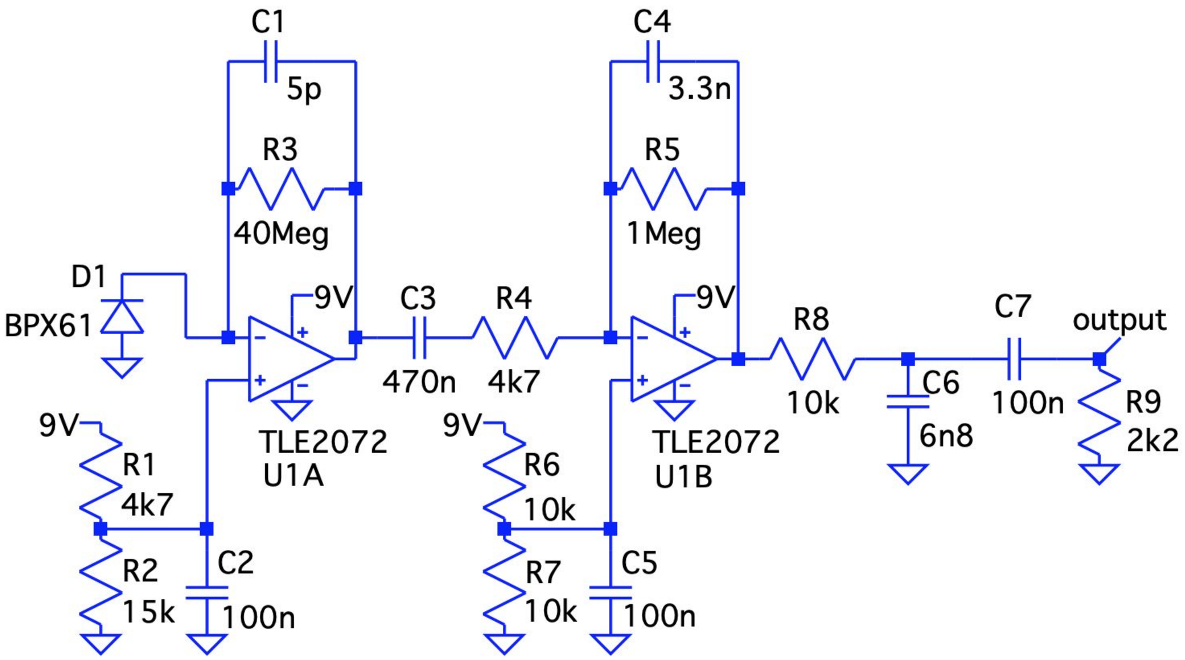
Electron detector

- Build a DIY electron detector
- We have all the parts [PIN diodes, amplification, boxes]
- You just need to assemble and test
    - (source: Uranium glass)
- You will learn some theoretical fundamentals:
    - Detector physics
    - Analog electronics
- You will gain some practical skills:
    - Soldering
    - Assembly
    - Testing
- Plus, you can take it home with you!



DIY particle detector

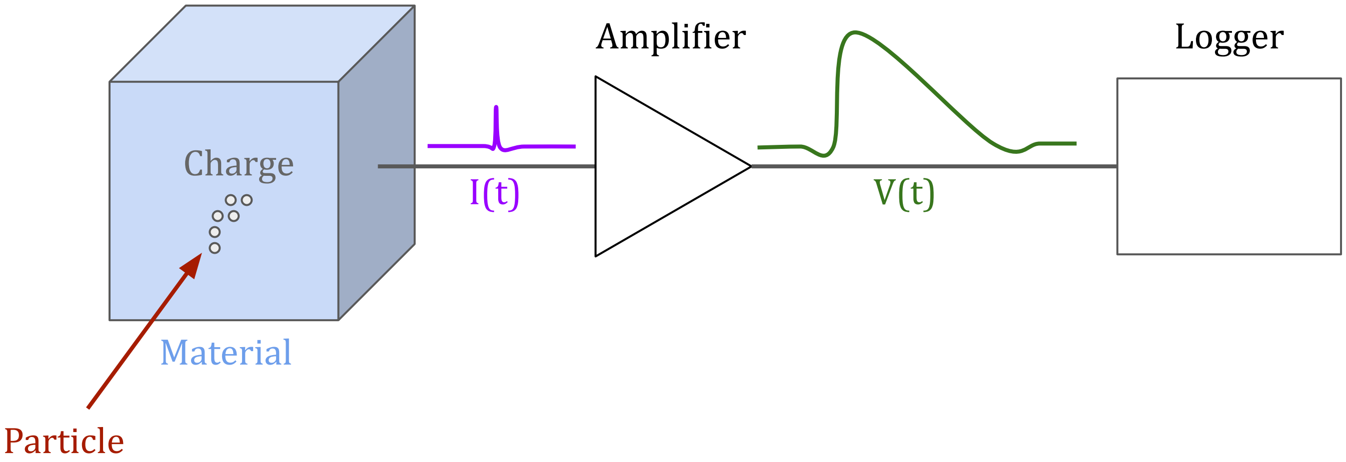
Can you "read" this like a book?



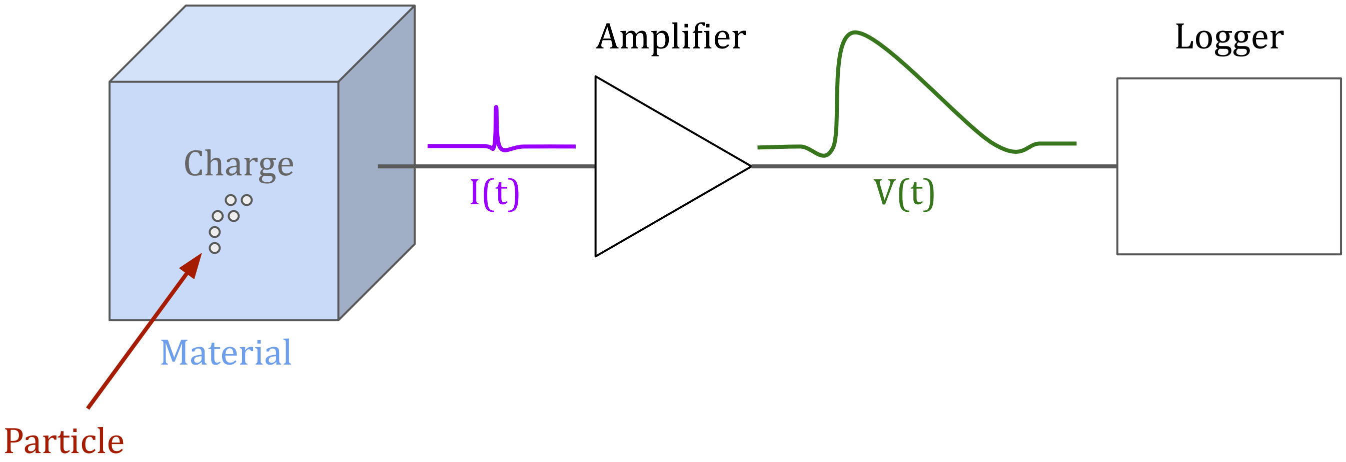
Don't worry, you will!

Principles of particle detectors

Basic detection principles

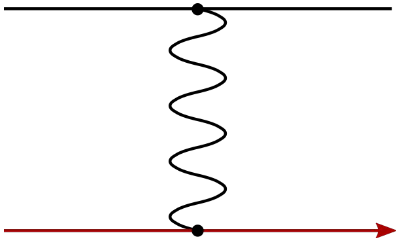


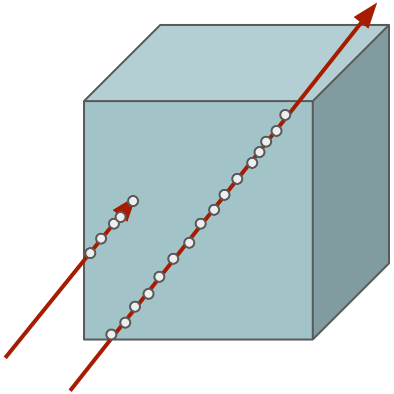
Basic detection principles



To interpret the result, we need to know **how particles interact with matter**. So that's where we start.

Let's start with **charged particles**



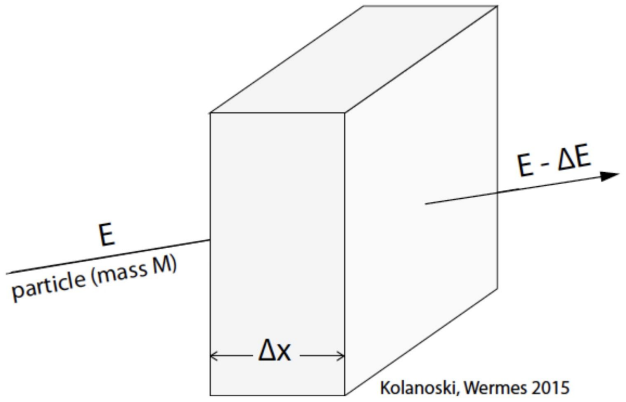


There are a **large number** of *primary* electromagnetic interactions. Each interaction causes **small energy loss** or **small deflection**. Particle can **transit** or **stop** in material.

dE/dx

Definition

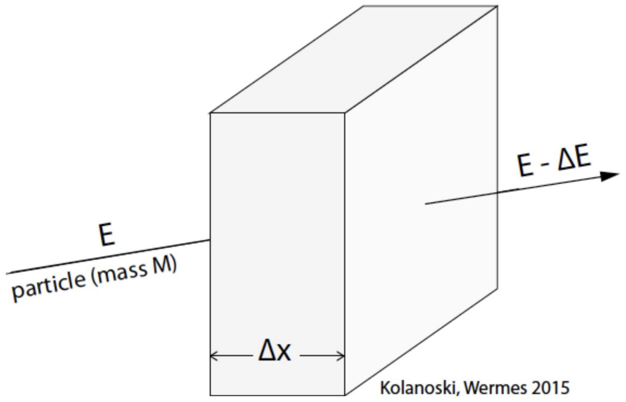
- A charged particle traverses material of thickness Δx
- Upon exiting, the energy of the particle has decreased by ΔE
- The basis of ~all particle detectors: **collect ΔE from the material**



dE/dx

Definition

- The deposited energy ΔE probably depends on:
  - Δx
  - Material density ϱ
  - Particle mass M and charge ze
  - Particle kinetic energy T and velocity β
- The key to detector design is understanding **dE/dx**



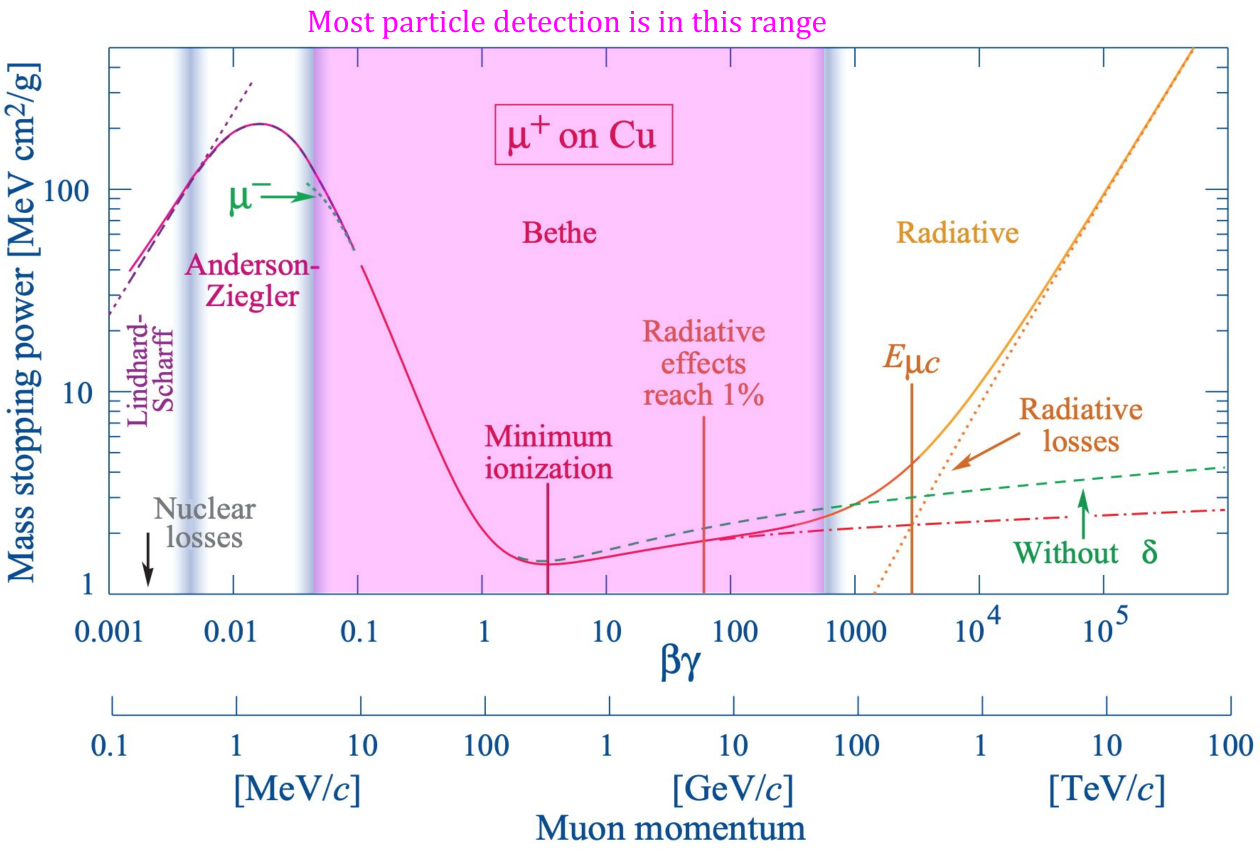
$$\left[\langle\frac{\mathrm{dE}}{\mathrm{dx}}\rangle\right] = \frac{\mathrm{MeV}}{\mathrm{cm}}$$ *Linear* stopping power

or

$$\left[\langle\frac{\mathrm{dE}}{\mathrm{d\tilde{x}}}\rangle\right] = \frac{\mathrm{MeV}}{\mathrm{gcm}^{-2}}$$ *Mass* stopping power

$$\tilde{x} = \rho x$$

Energy loss via *ionization*

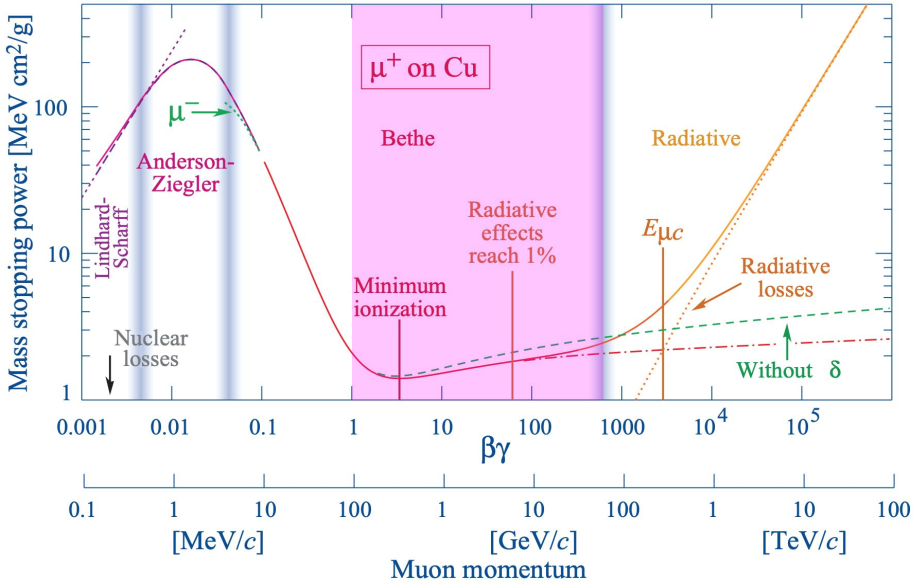


Minimum ionizing particles

“MIPs”

- For a broad range of momenta, energy deposited **does ~not depend on momentum**
- Minimum at $\beta\gamma \sim 3$
  - $\sim$250 MeV for muons
  - $\sim$1 **keV** for electrons (!)

→ In most nuclear/particle physics, electrons are **not** MIPs but everything else **is**



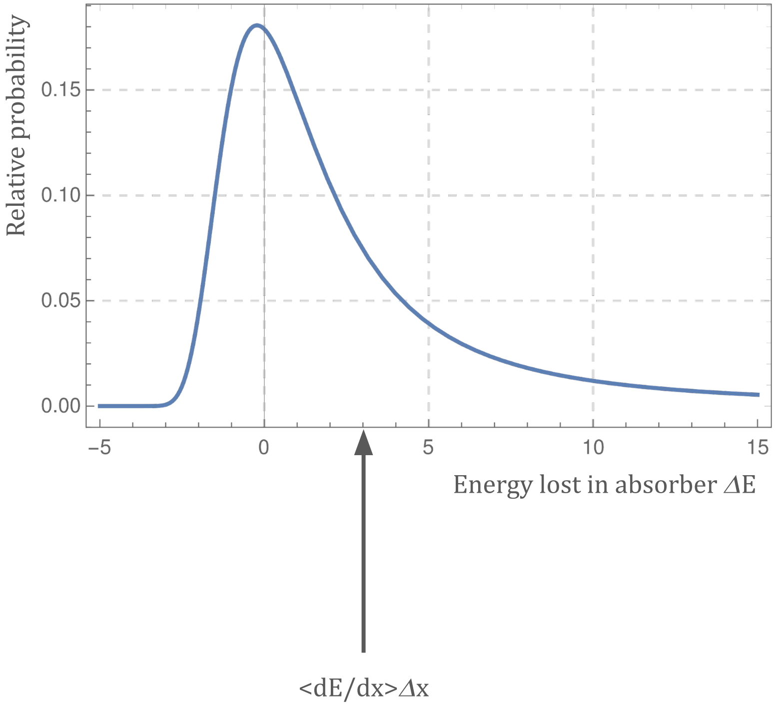
Fluctuations in $\Delta E/\Delta x$

Energy lost in a fixed-width absorber

- So far, we have been looking at the *mean* dE/dx, but (from PDG):

> Few concepts in high-energy physics are as misused as $\langle dE/dx \rangle$. The main problem is that the mean is weighted by very rare events with large single-collision energy deposits. Even with samples of hundreds of events a dependable value for the mean energy loss cannot be obtained. Far better and more easily measured is

- This is a statistical effect due to the **rare,** (relatively) **high-dE** nature of *secondary scatterings* (→ delta rays)



Fluctuations in $\Delta E/\Delta x$

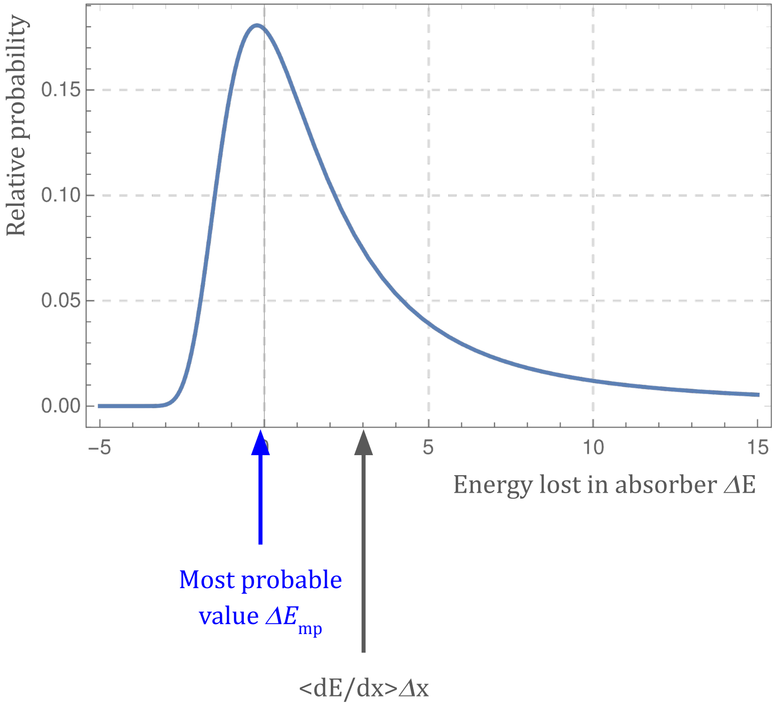
Landau statistics

- ...continuing the PDG quote: "...Far better and more easily measured is the **most probable energy loss**..." (ΔE_{mp})
- The PDF characterizing the energy lost in an absorber ΔE is the "Landau distribution":

$$P(\lambda) = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\lambda + e^{-\lambda}\right)\right]$$

$$\lambda \equiv \frac{\Delta E - \Delta E_{mp}}{\xi}$$

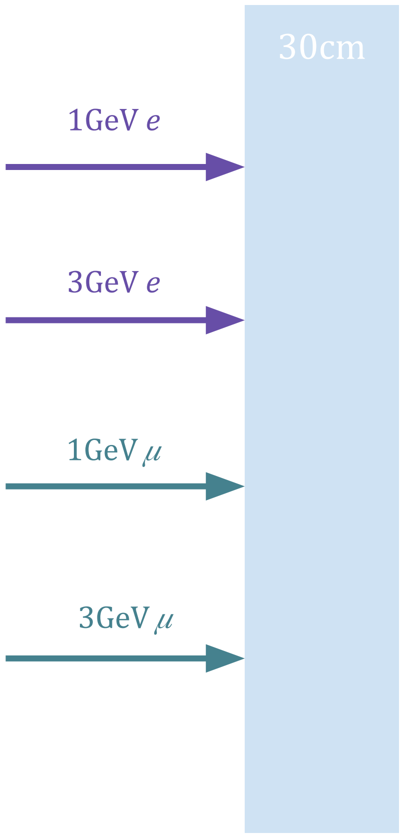
Material constant



Quick quiz

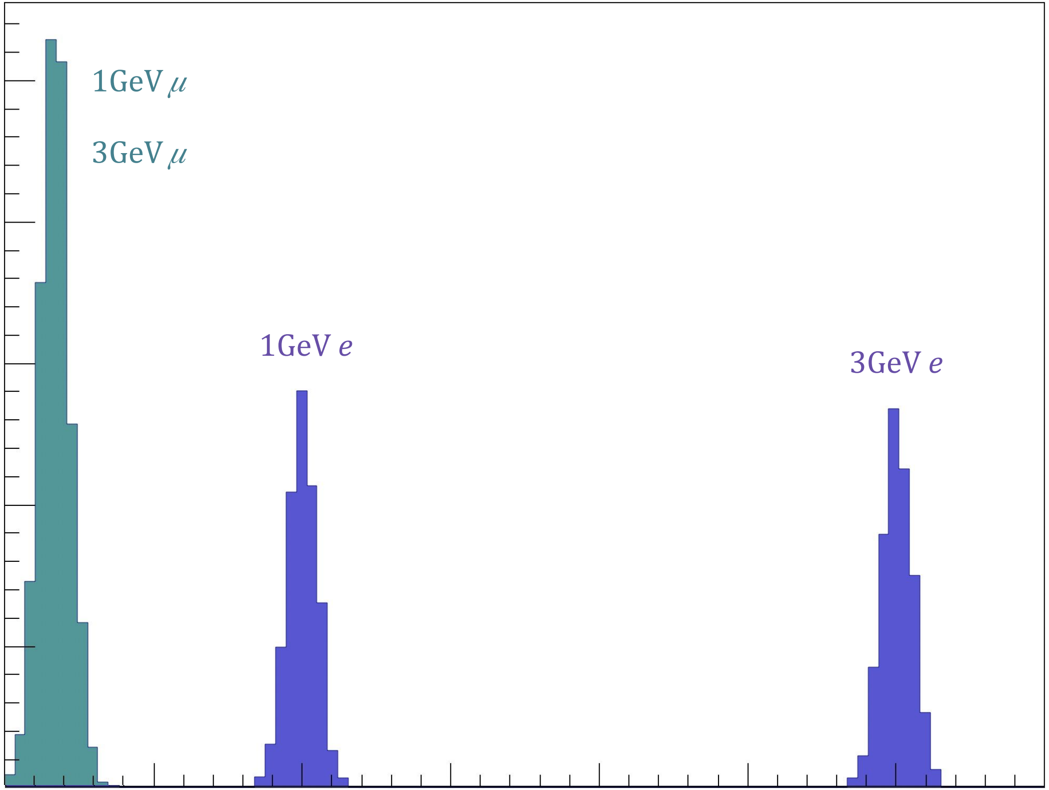
dE/dx summary

- Consider the Belle II electromagnetic calorimeter
  - Consists of **30cm**-thick CsI crystals (**effective Z=54**)
- Imagine our physics consists of a **50/50 blend of electrons and muons**, and a **50/50 blend of 1GeV and 3GeV particles**
- Considering *dE/dx* losses, draw a *qualitative* **histogram of energy deposited in the crystals**

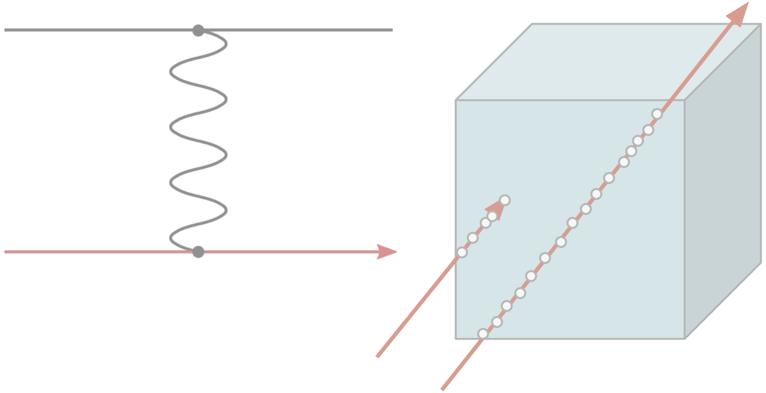


Quick quiz

dE/dx summary

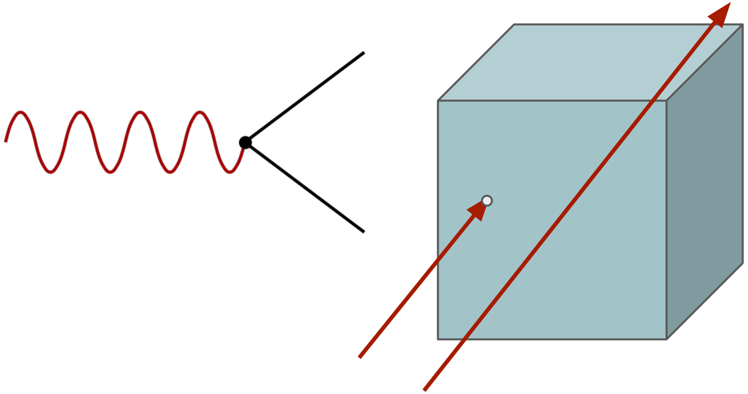


charged particles



There are a **large number** of *primary* electromagnetic interactions. Each interaction causes **small energy loss** or **small deflection**. Particle can **transit** or **stop** in material.

photons

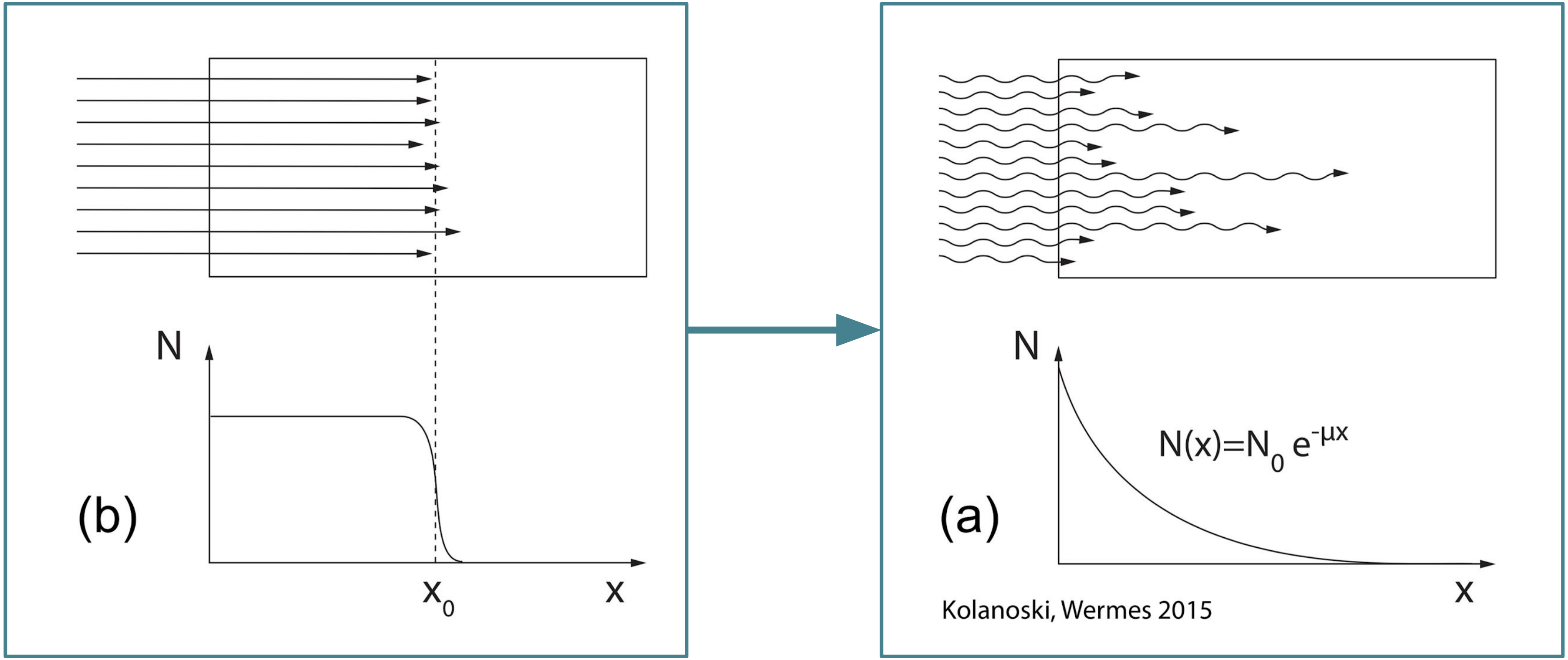


There is a **probability** of a single *primary* electromagnetic interaction. The interaction causes complete **absorption**. Photon either is absorbed or isn't.*

Interactions with matter: photons

charged particles

photons

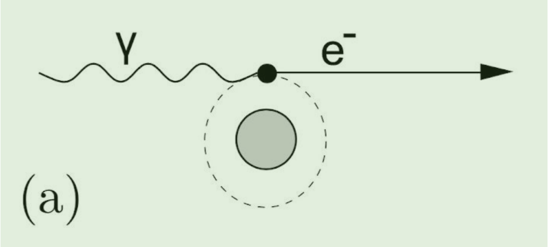


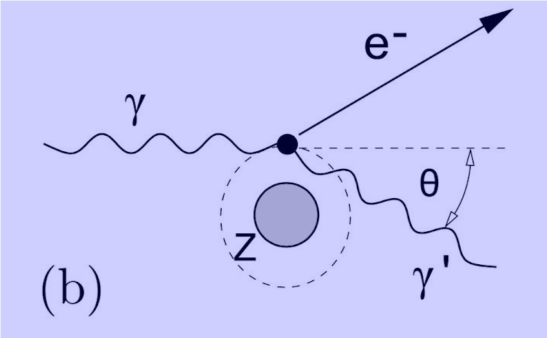
Kolanoski, Wermes 2015

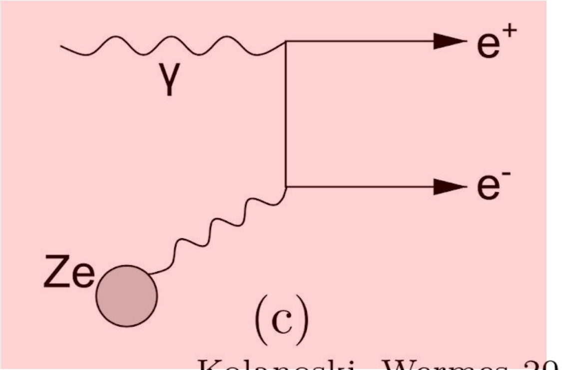
Photons

Overview

- Three primary process:
  - (a) photoelectric effect
  - (b) Compton scattering
  - (c) pair production



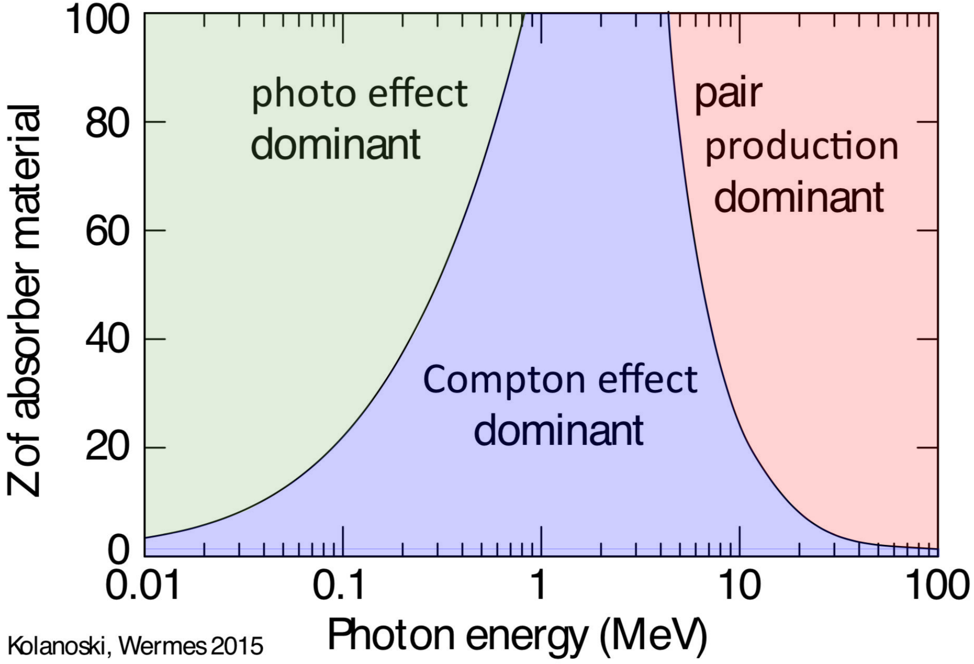




Kolanoski, Wermes 2015

Photons

Absorption



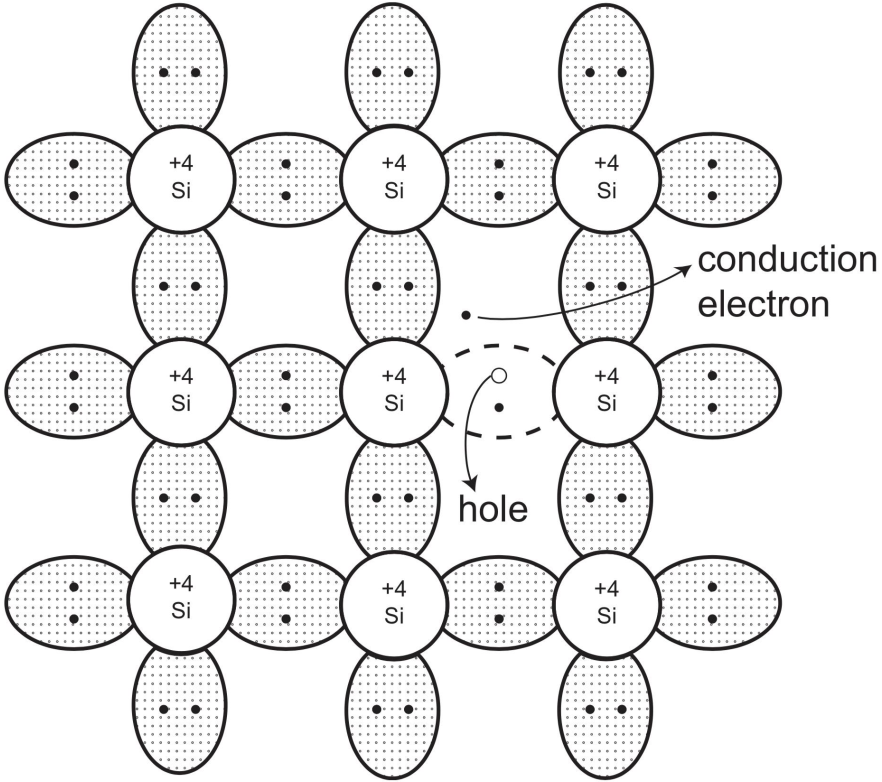
PIN diodes

This is what we're using this week. Let's see how they work…

Intrinsic semiconductors

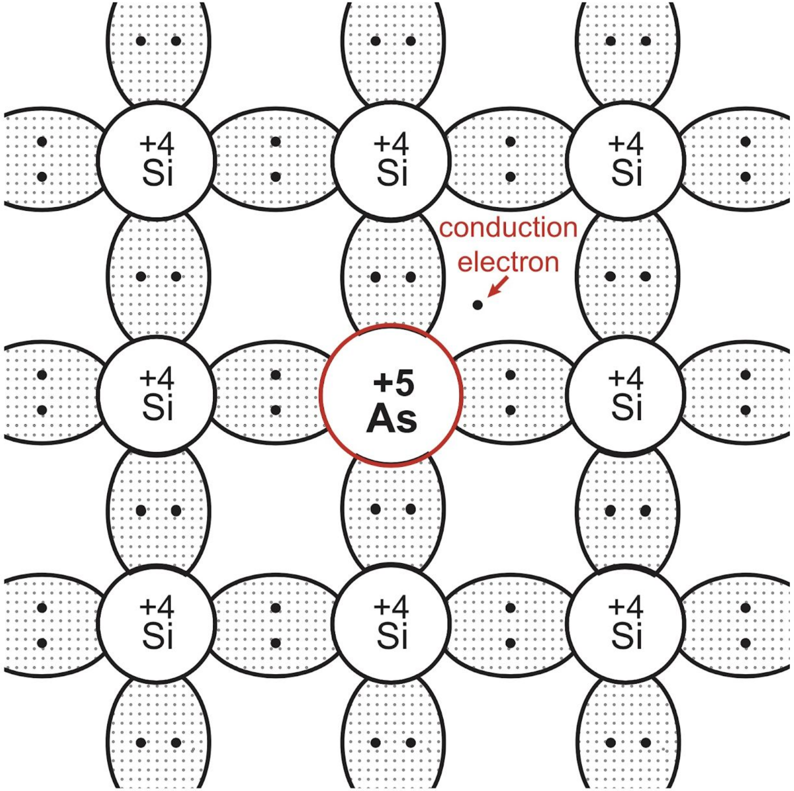
Review

- *Intrinsic* semiconductors are **undoped**
- Conduction arises from movement of **electrons** and **holes**
- Electrons can be moved from the **valence band** to the **conduction band** by acquiring at least the energy of the **band gap**
- In semiconductors, electrons can be kicked up to the conduction band from **thermal energy**

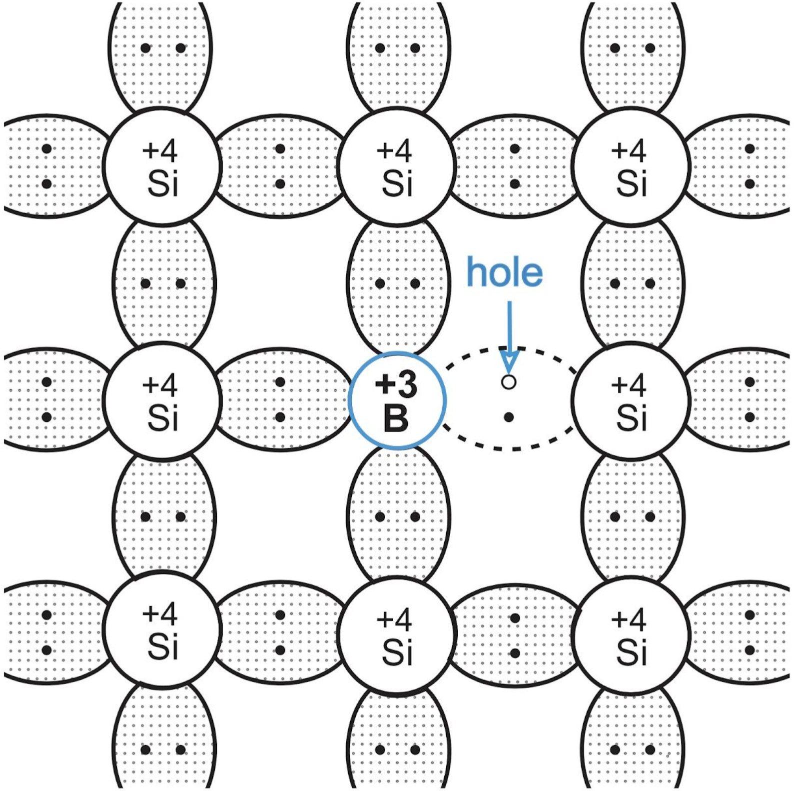


Semiconductor detectors: basics

Doping semiconductors can make them eager electron *donors* or *acceptors*



(a) n doped

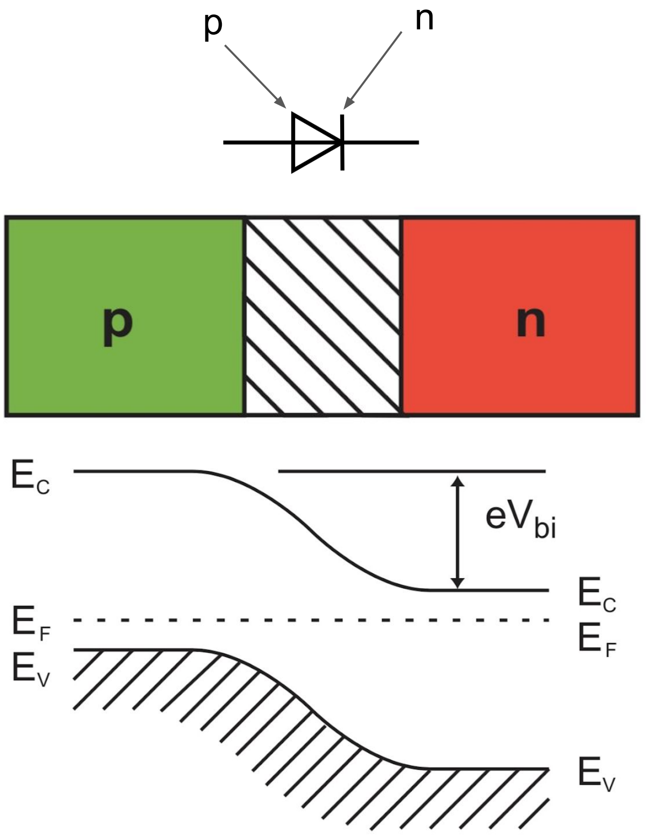


(b) p doped

Junctions

PN junctions: **unbiased**

- A basic electronic component is a **PN diode** made from a single PN junction
- As drawn, this **doesn't conduct** because the *depletion region* is an insulator
  - (recombination region of electrons/holes)
- The *intrinsic* potential over the depletion zone is called the "built-in voltage" V_{bi}
- The **band diagram** now shows bent energy levels at the junction

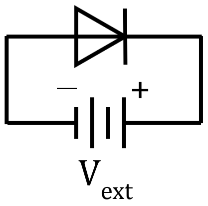


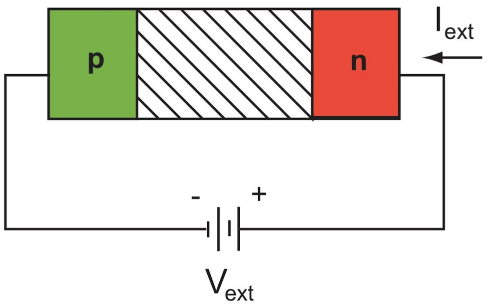
Junctions

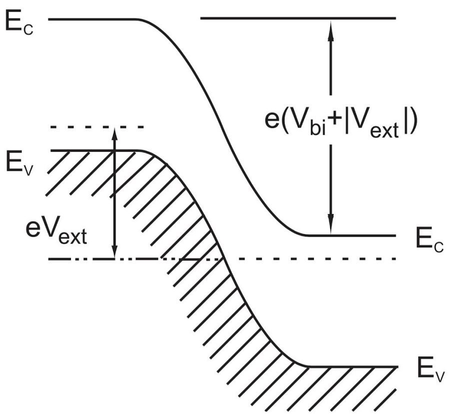
PN junctions: **reverse biased**

- Now apply an external *reverse bias* V_{ext}
- The applied field **adds** to the built-in field
- This **increases the slope** in the depletion layer, thus **expanding** it
- This is the typical case for **particle detectors**

Note: **conductance** is far higher in forward biased case compared to reverse biased case. A diode can be *roughly* thought of as a "**one-directional conductor**" where the "arrow" in the circuit diagram shows the *direction of preferred current flow*



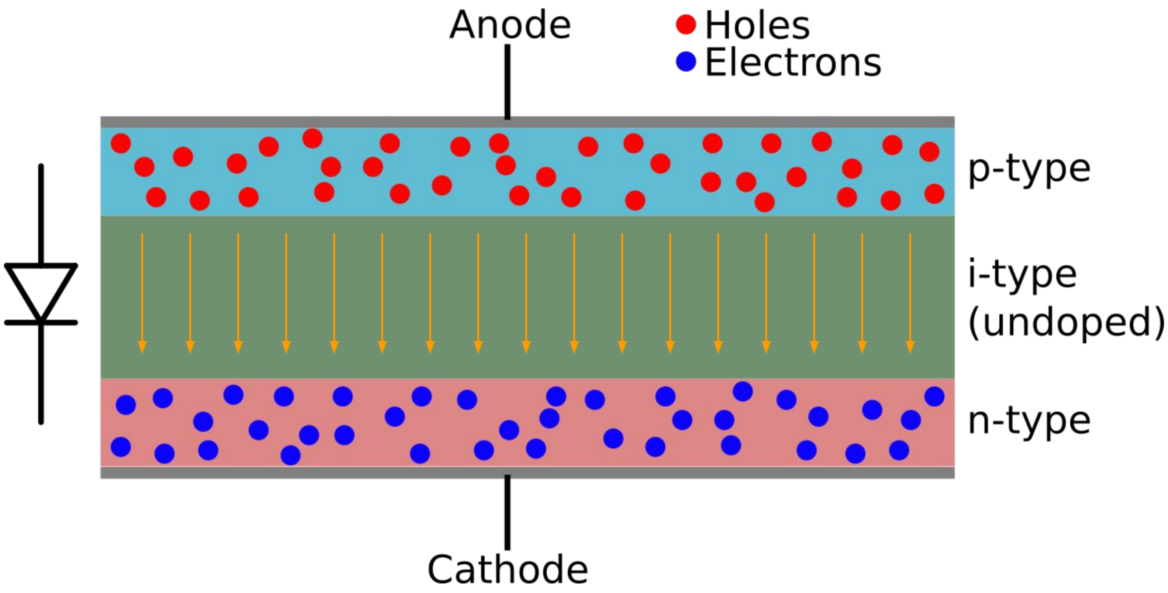




PIN diodes

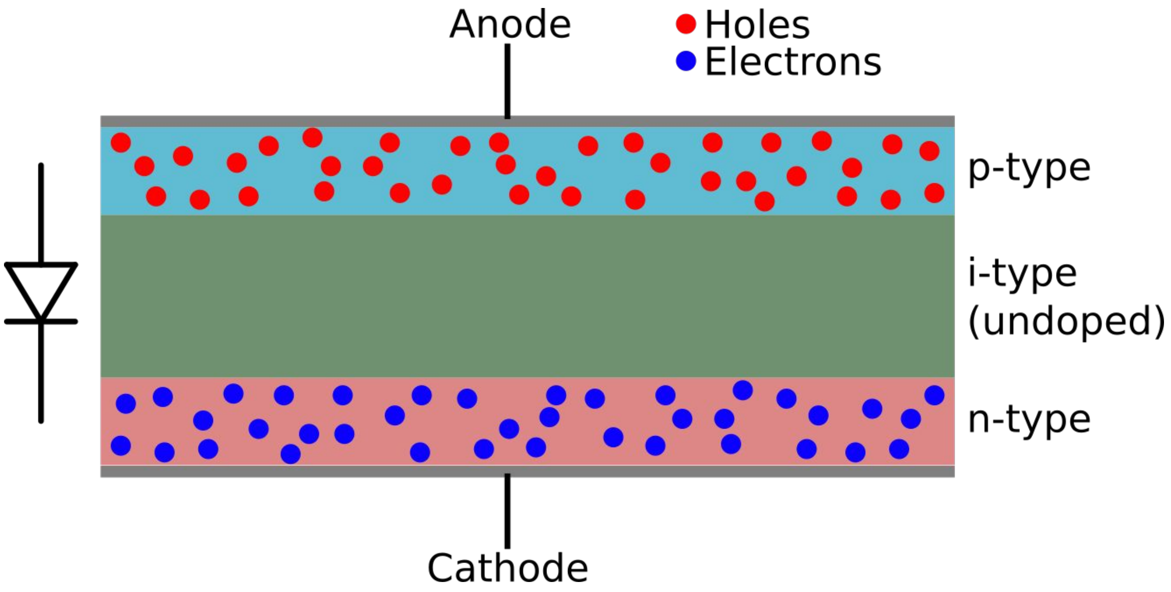
Insert a large **intrinsic** (*undoped*) layer

- Much larger depletion layer than in PN diode (roughly the whole *I* layer)
- The *built-in field* sweeps charge out of depletion region

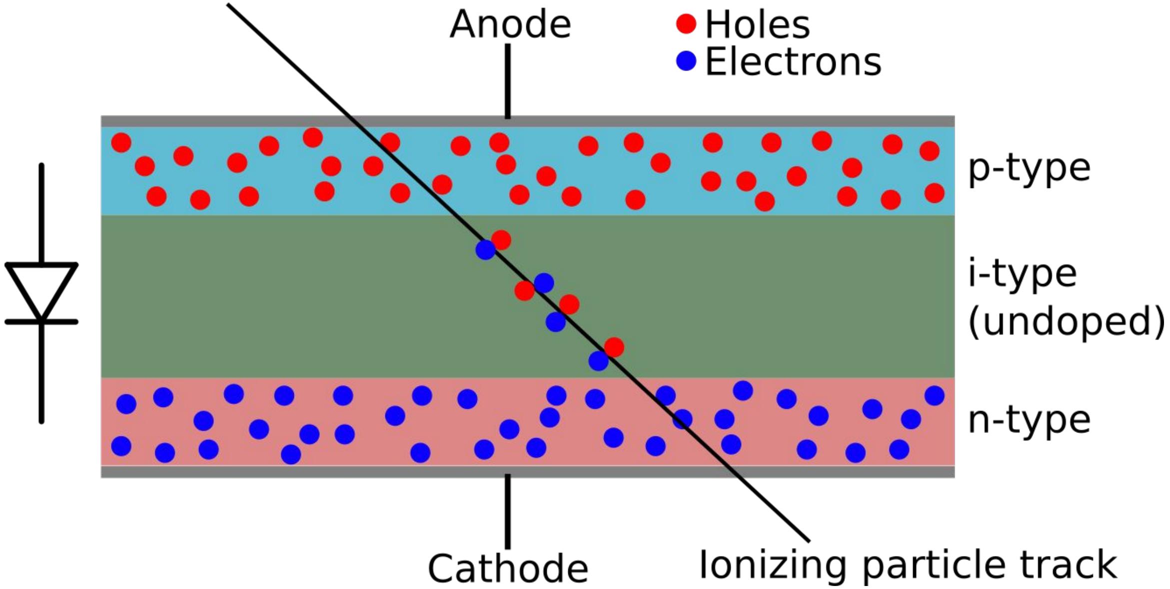


This is instantly useful as a particle detector…

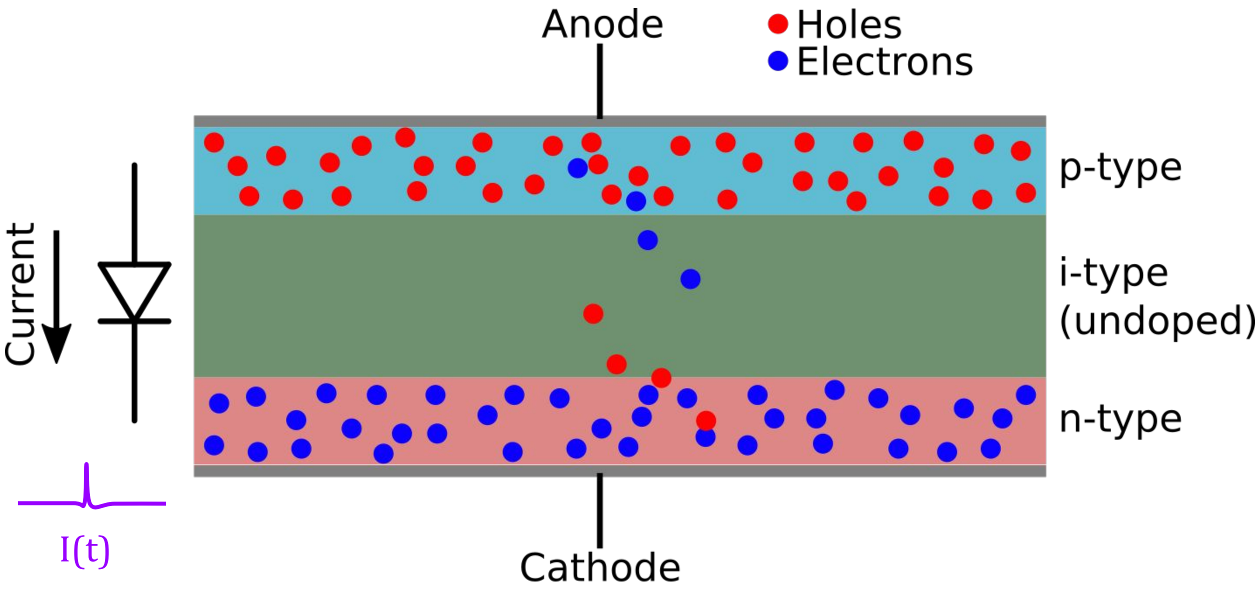
PIN diodes



PIN diodes


Anode
Holes
Electrons
p-type
i-type
(undoped)
n-type
Cathode
Ionizing particle track

PIN diodes


Anode
Holes
Electrons
p-type
i-type
(undoped)
n-type
Current
I(t)
Cathode

PIN diodes

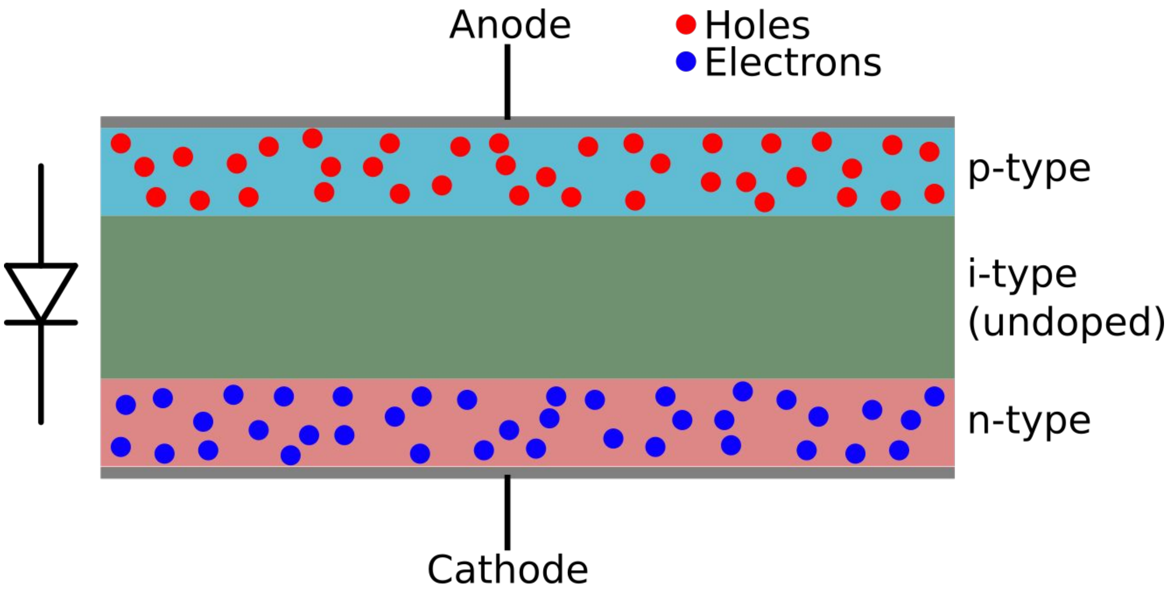
Some nice features

- Entirely passive
- Super cheap (<1 euro)

However…

- Charge collected is *very small*
- Electron/hole pairs also arise from other sources (thermal noise/dark current…), obscuring signal

We can improve this…

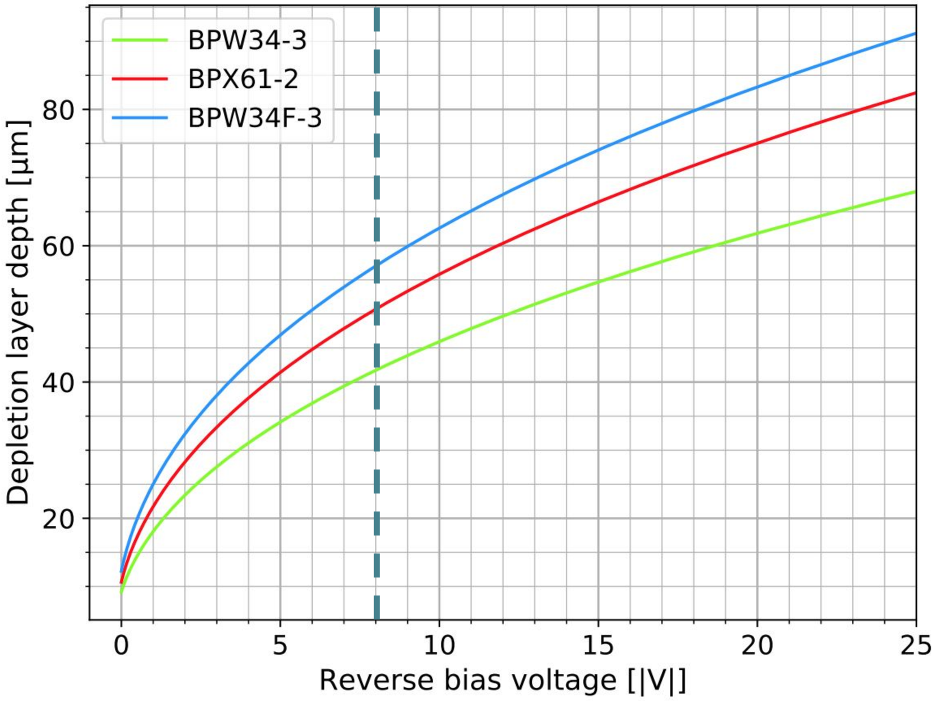


Reverse biasing

Effects in PIN diode

- Increases depletion layer depth → **more charge** collected
- Decreases capacitance → decreased noise → **improved signal:noise ratio**

Our detectors will use 8V reverse biasing for this reason



Quick questions

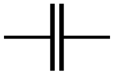
DIY detector

- Why is our simple detector specifically an **electron** detector?
- What modifications would we need for
  - MIPs?
  - Alphas?
  - Photons?

Some electronics basics

Heuristic definitions: **everything is a resistor**

A **resistor** is something that resists **current flow**



A **capacitor** is a resistor that **resists *steady* current flow**

An inductor is a resistor that resists ***transient* current flow**

A **diode** is a resistor that strongly **resists current flow in only one direction**

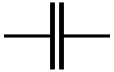
Every electrical engineer in the world just dropped dead from horror. Let's use a *tiny* bit more rigor…

Related question: when a resistor resists current flow, what happens to the energy? What about a capacitor?

Impedance

Generalization of the concept of **resistance** for dynamic currents

$$Z_R = R$$



$$Z_C = \frac{1}{IfC}$$

$$Z_L = IfL$$

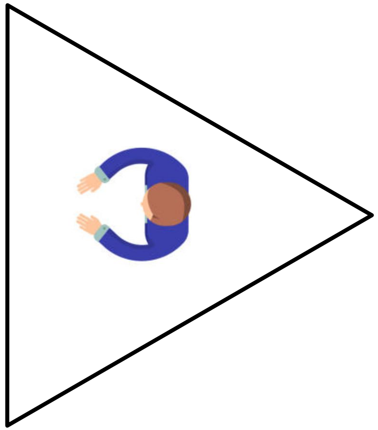
Note: if you take apart a lot of analog electronics, you'll see lots of resistors and capacitors, but few inductors. **Why**?

Impedance is **complex-valued** to keep track of phases and stuff, but you can still write Ohm's law:

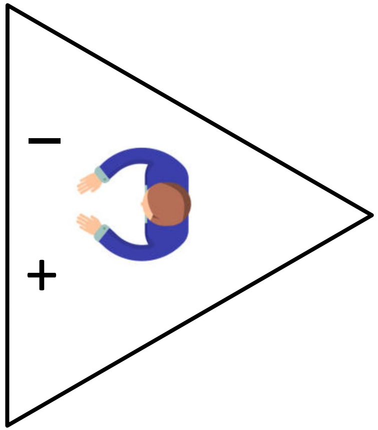
$$V = ZI$$

A bedtime story

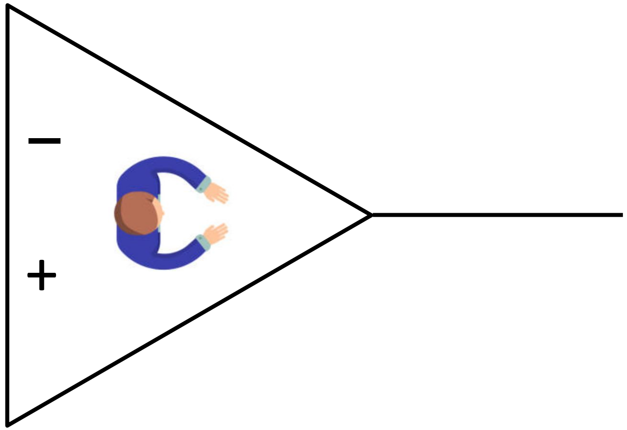
Inside a little triangle lives a tiny little man named Mr. OpAmp…



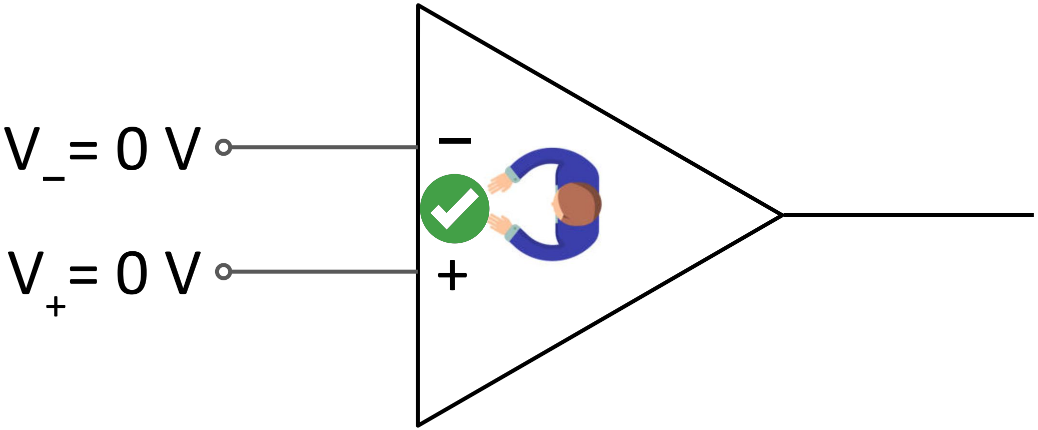
He is constantly monitoring two inputs, which we can label + ("*noninverting*") and − ("*inverting*")…



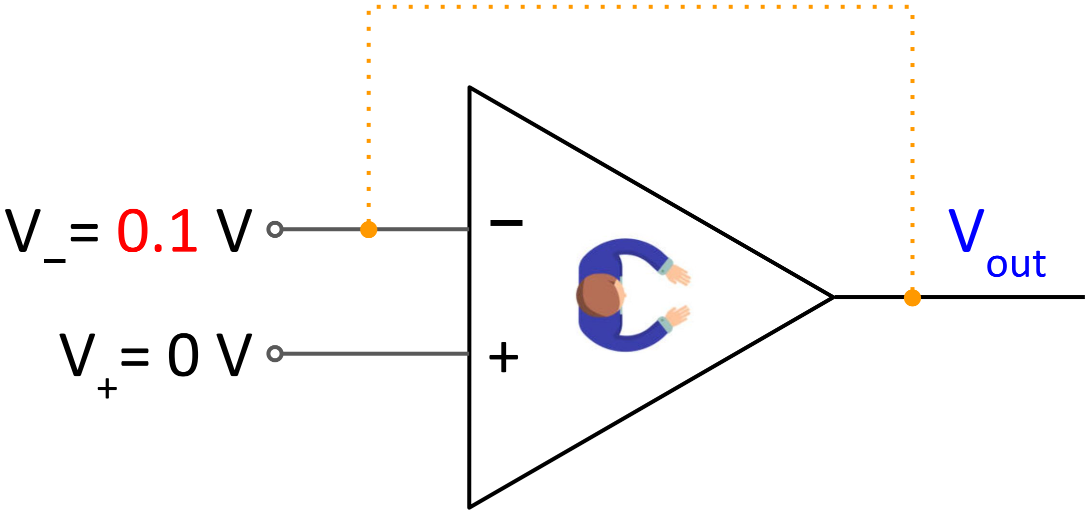
He can control a **single output** however he wants…



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

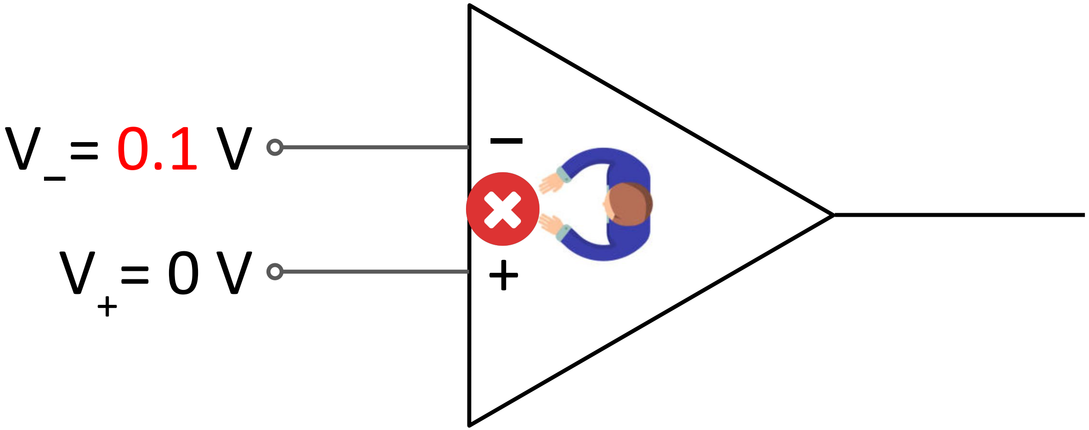


…and he *believes* that there is a connection from the output to the (−) terminal (*feedback*)…



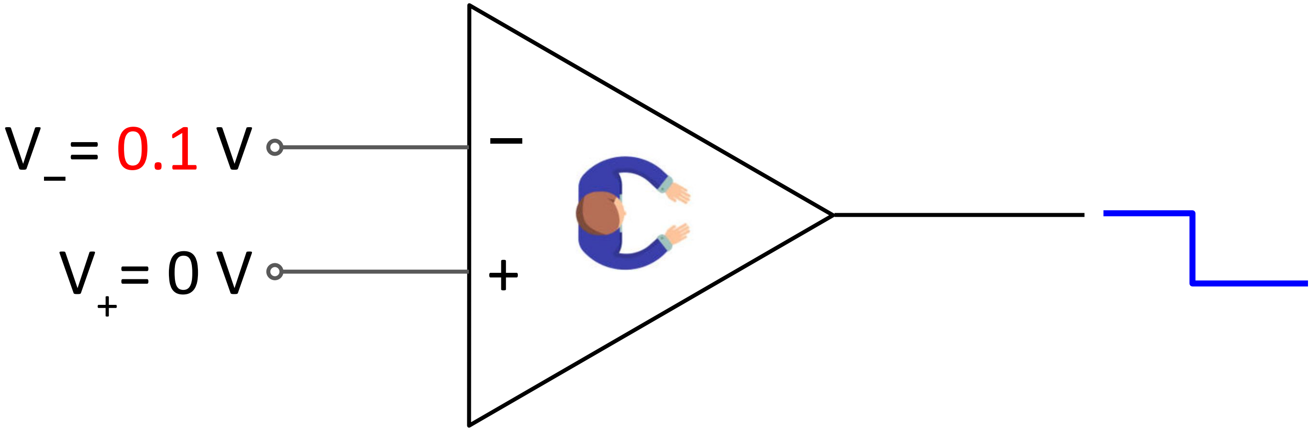
…so if he sees a voltage difference, he tries to fix it by controlling the voltage of the output, which he adjusts dynamically while monitoring the inputs continuously.

Let's mess with him a little bit: we'll send +0.1V to the (−) input.



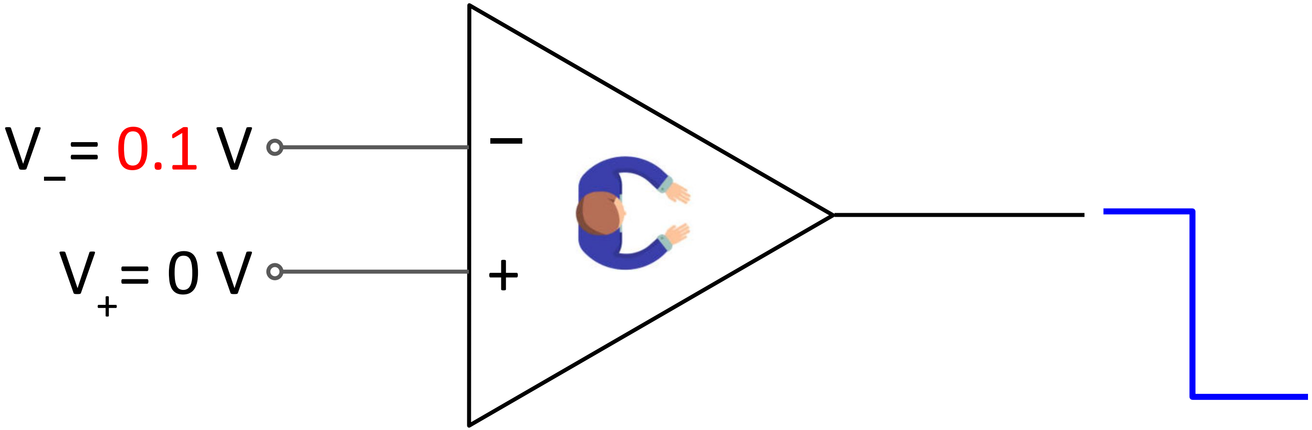
Oh no! He must fix this…

Since he *thinks* there is feedback, he will send out some negative voltage to try to equalize the inputs…



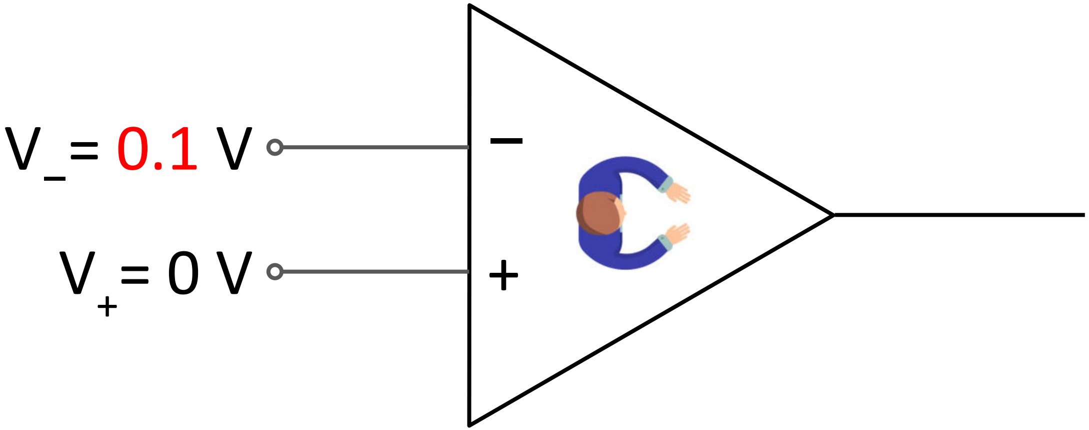
…but as he does, he notices that the (−) input is still too high, so he has to send out more…

…but since there *isn't* really a connection, he keeps on sending more and more voltage to try to correct the problem, until he sends **all the voltage he has**…

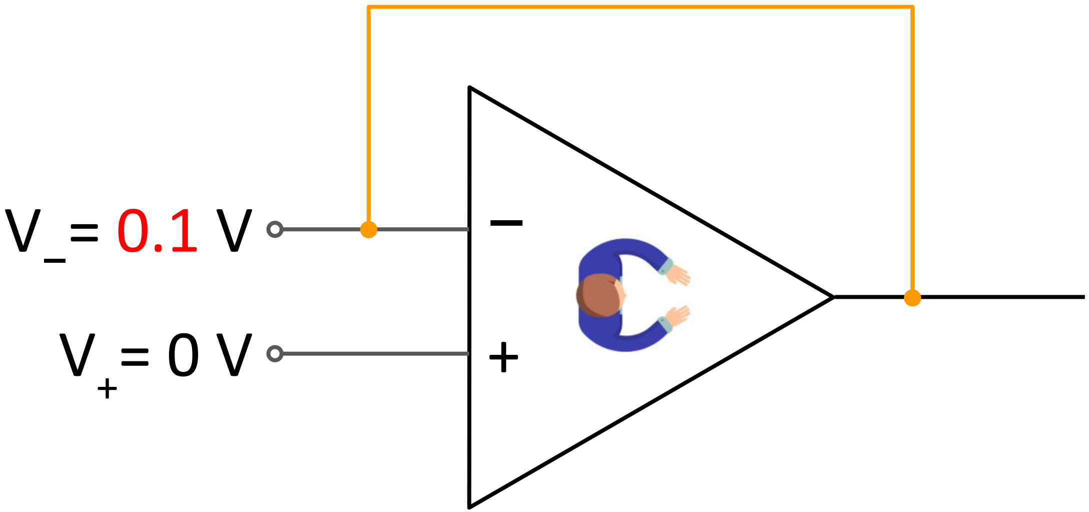


Question: what is the function of this device? What would you call it? What is not so great about it?

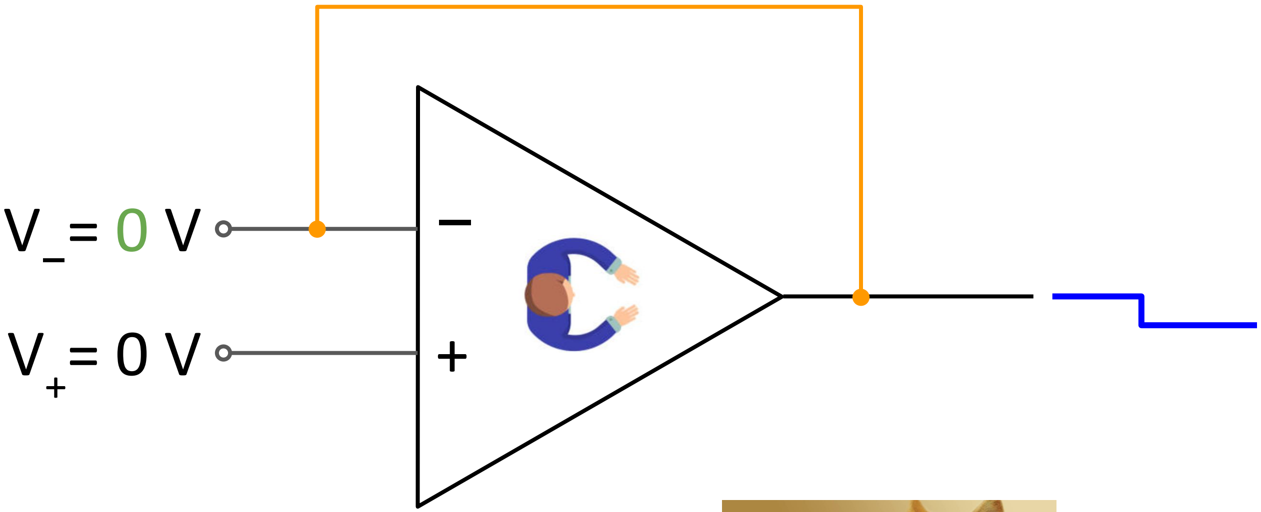
This is an *inverting amplifier*, but it amplifies **any voltage difference** into **maximum output**—it preserves no information about the *difference*. (It's a *comparator*.)



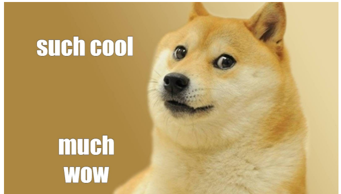
OK, but what if he's right? What if there **is** a connection to − (*negative feedback*)?



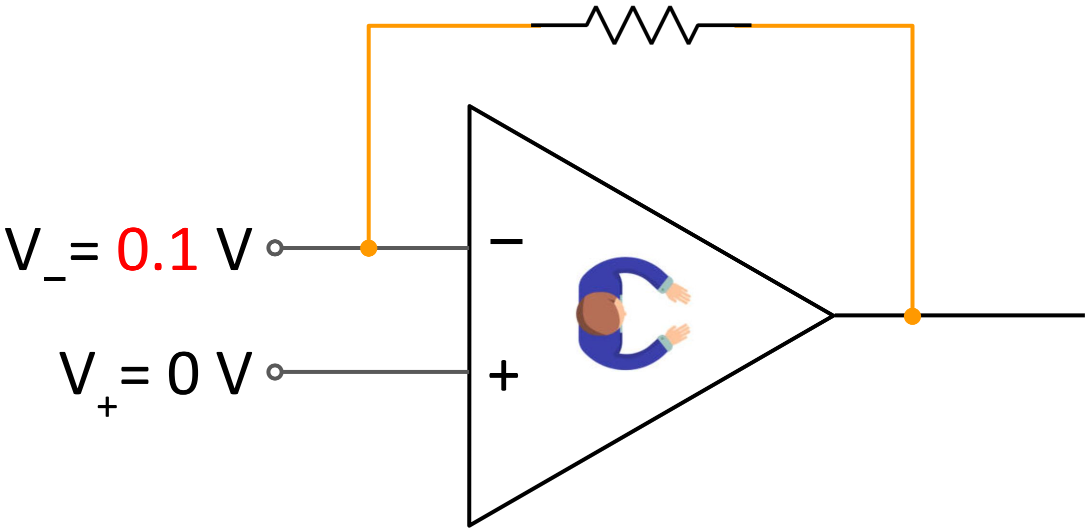
Well, now he can instantly fix the problem by sending out **−0.1V.**



So this is a device that turns **0.1V** to **−0.1V**…

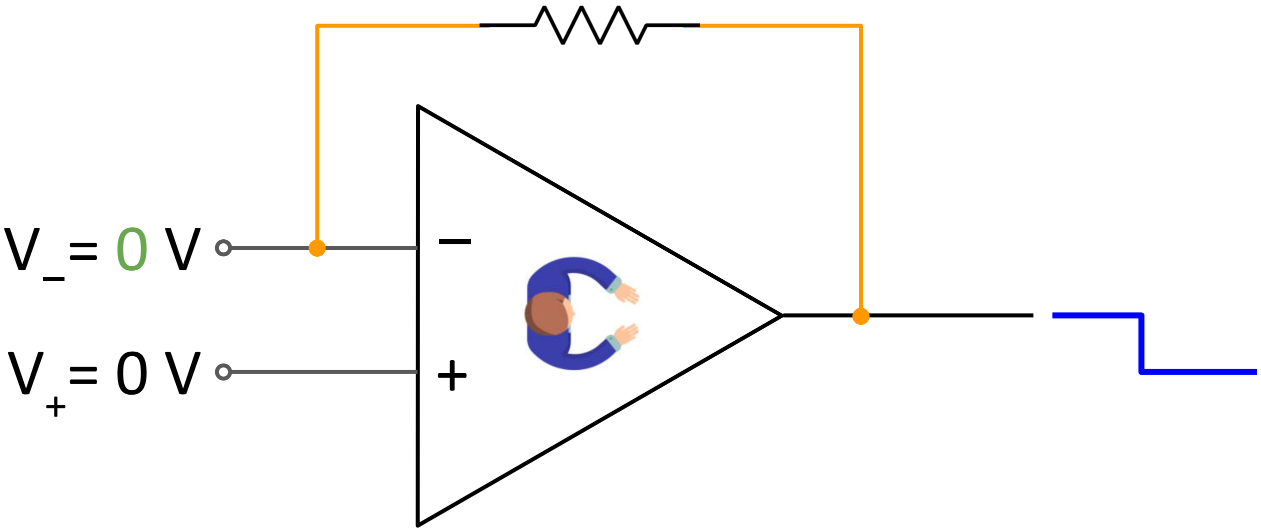


OK, but let's exploit his assumption, by adding a **resistor** to the feedback…



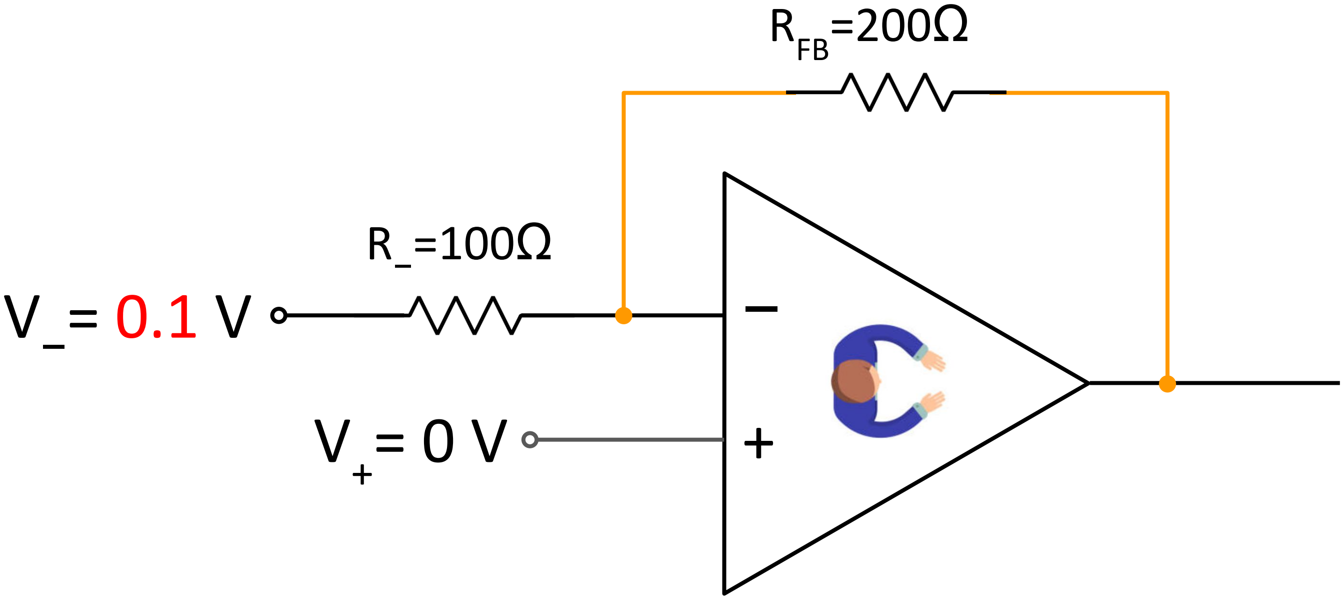
What happens now?

Well, he has to send out *more* voltage to correct the same problem…



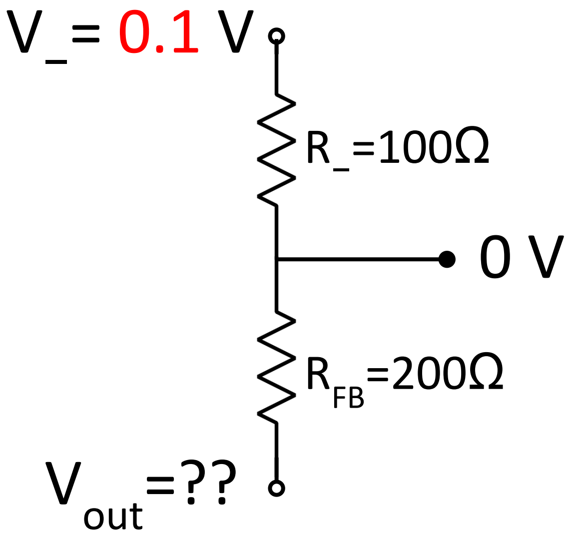
If you use the output, you can now use this as an (inverting) *amplifier* with *gain*!

But wait… the feedback has **resistance**, while the input has none, so he can **never win.** So let's add a resistor to the input…



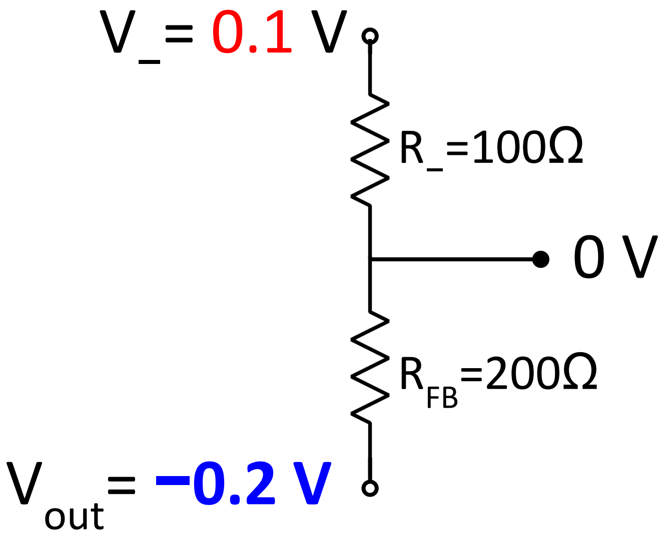
Question: what voltage will he need to send out?

This is a simple resistor ladder*… what is V_{out}?



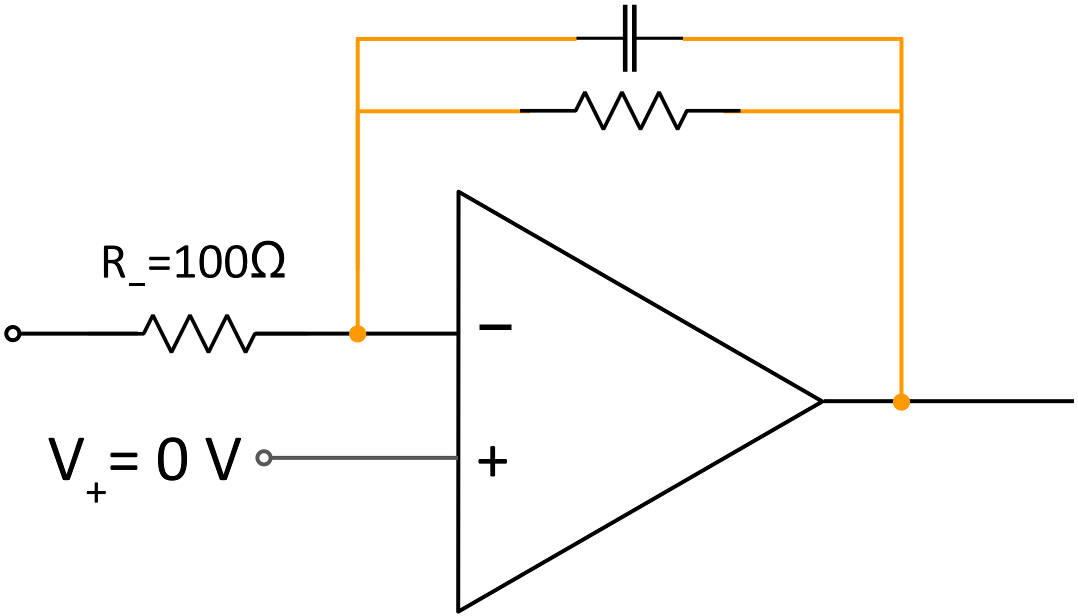
* the input has ~**infinite impedance** so it doesn't contribute to the ladder

Evidently, we can control the **gain** of the amplifier: $G = -R_{FB} / R_-$



Cool! But wait…

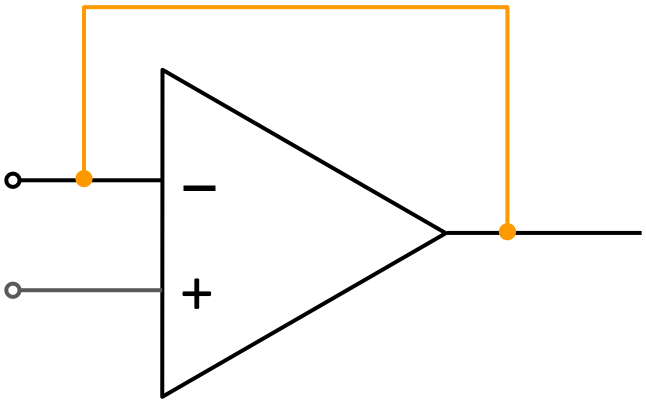
Real-world amplifiers ~always have feedback **capacitors…** can you guess why?



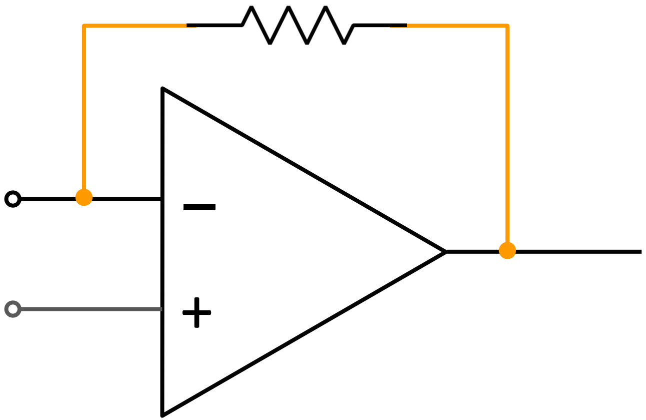
Think about the capacitor as a *frequency-dependent feedback resistor*…

With a feedback capacitor:

At *high frequencies*

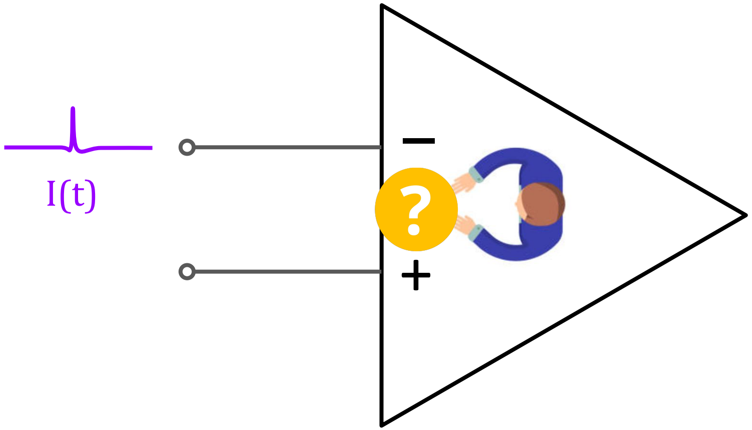


At *low frequencies*



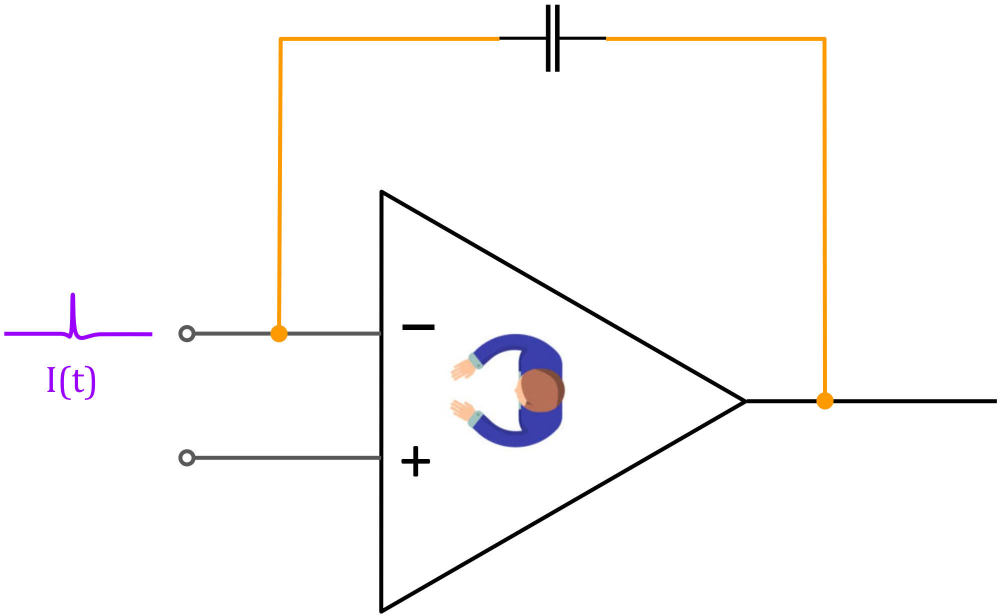
No (unity) gain for high-frequencies, max gain for low frequencies: this provides *noise filtering* (among other things!)

But *hold on*! Our PIN diode will output a *current*, not a voltage… but Mr. OpAmp is only concerned with comparing *voltages*…



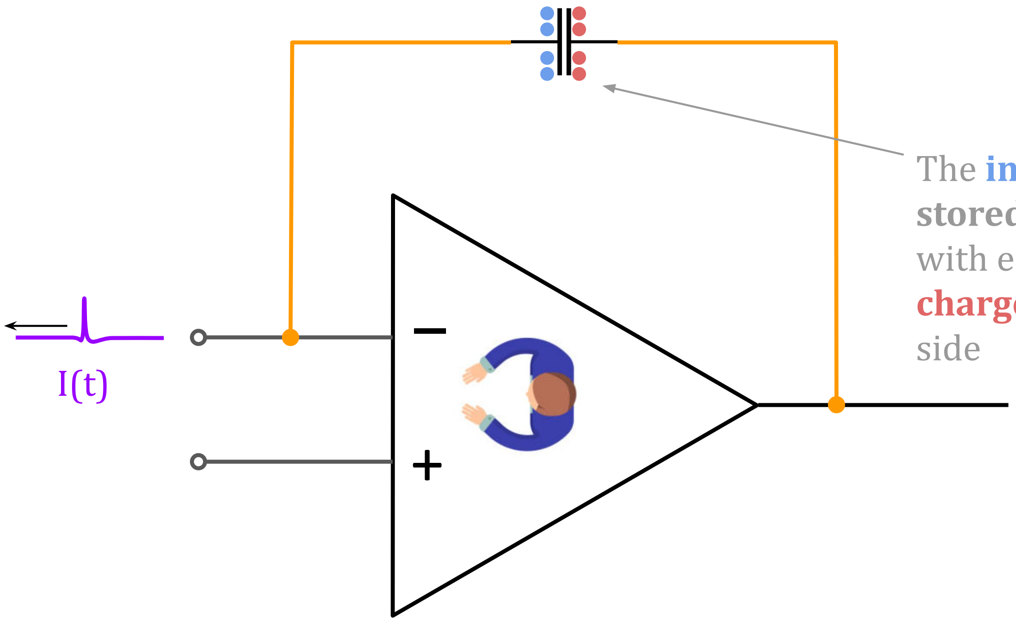
…what can we do to make him sensitive to *charge*?

Let's put a capacitor here…



What happens now?

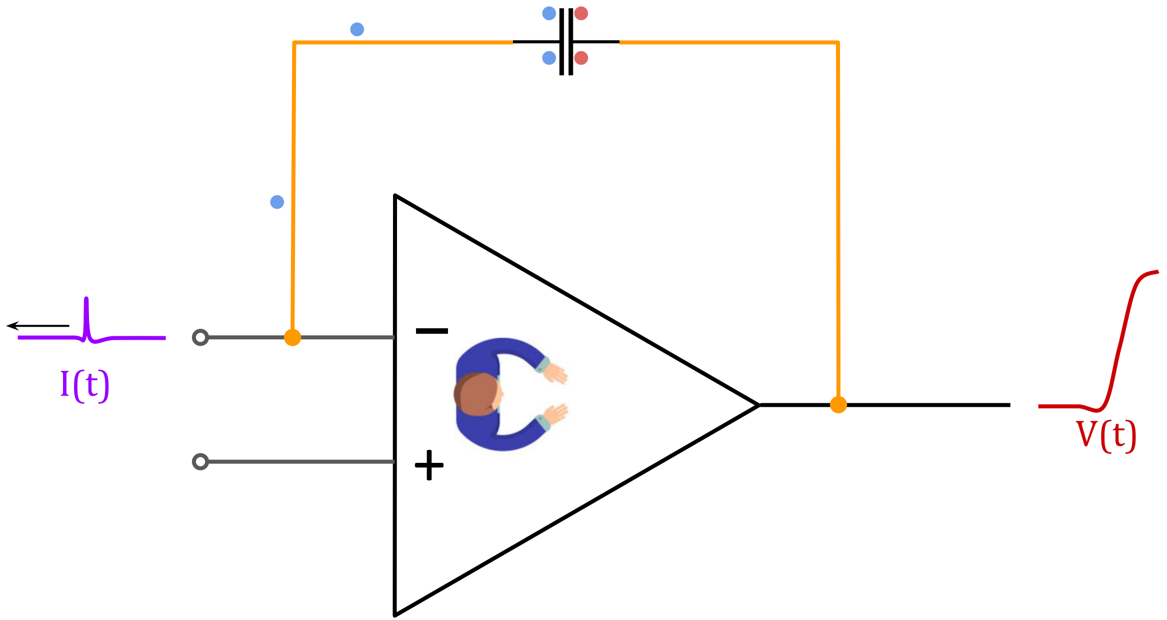
The capacitor will do capacitor things: adding charge q will lead to a **voltage difference** of q/C across the capacitor…



The **input charge** is **stored** in the capacitor, with equal-and-opposite **charge** from the output side

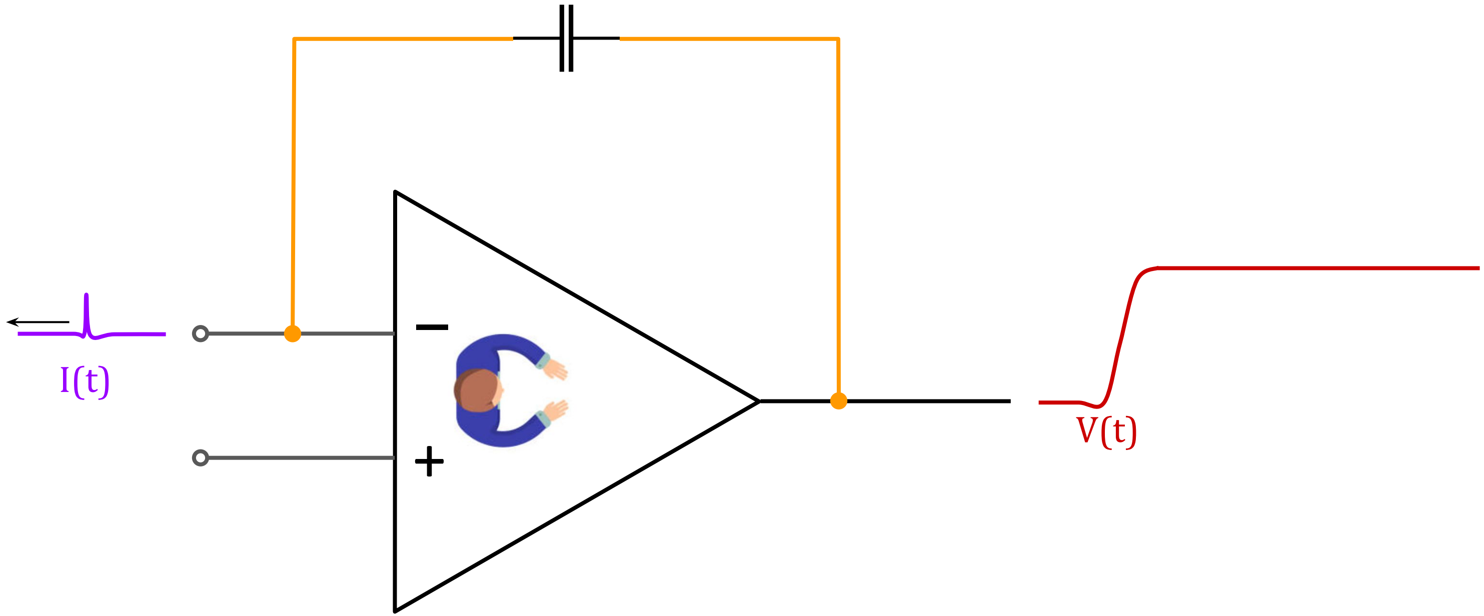
So now Mr. OpAmp will see a voltage signal **proportional to the deposited charge**…

So Mr. OpAmp starts sending out voltage, which begins to cancel the capacitor voltage, *discharging* the capacitor, reducing the input voltage until it is **equalized**.



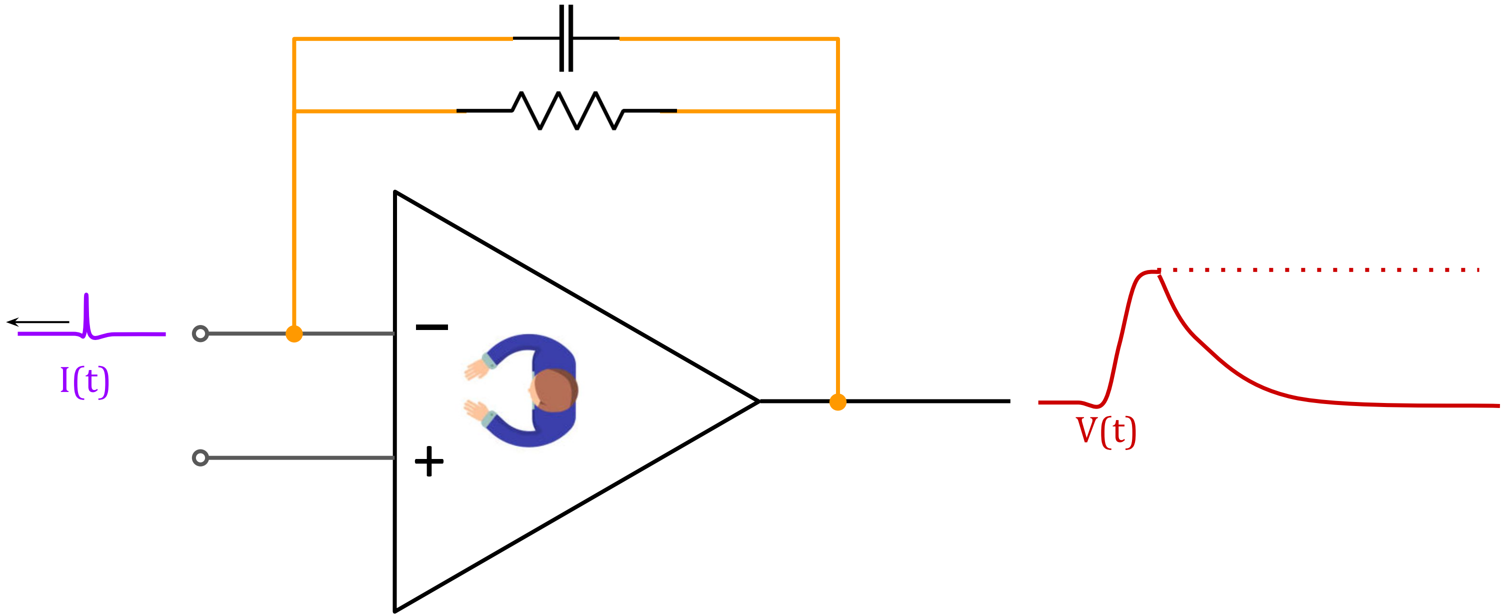
But wait! The input charges are *not gone*; no charge flows through a capacitor. So if he stops sending voltage, the charges will accumulate again…

He’s **stuck**! Without removing the injected charge, Mr. OpAmp can never return to normal. Whoops!



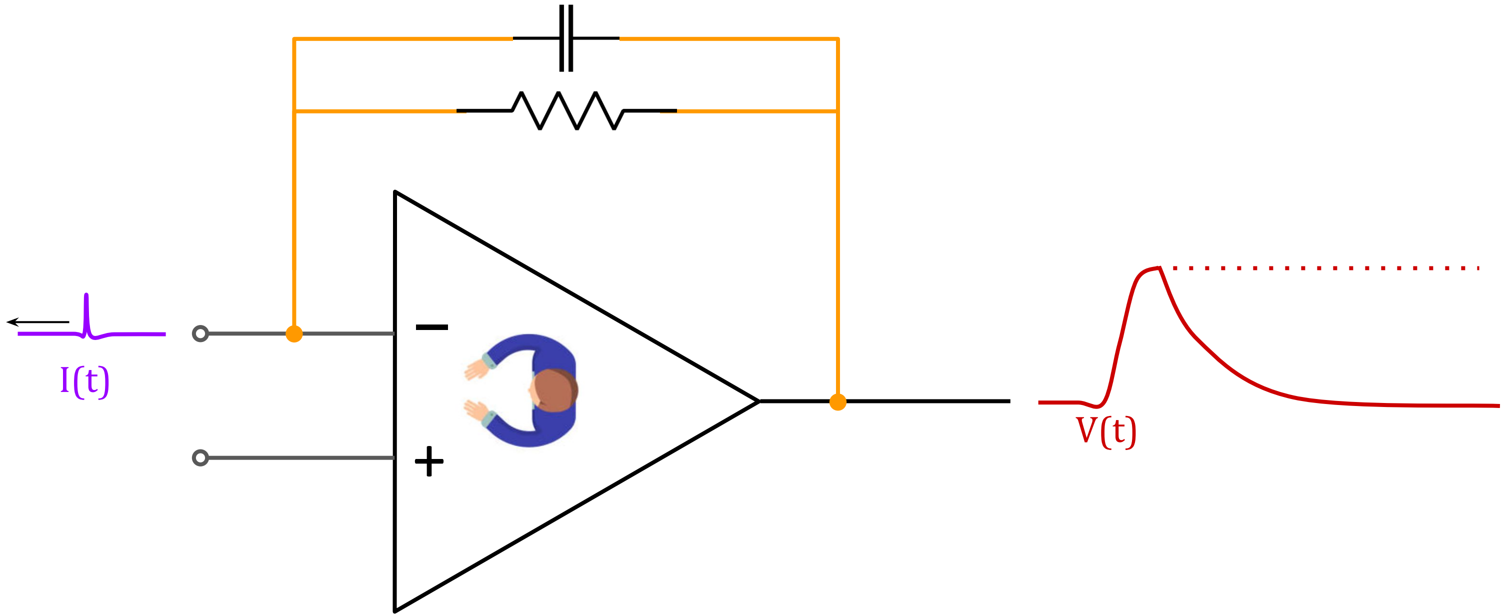
But at least the output voltage is proportional to the input charge (it has *integrated* the current pulse), so we have preserved our dE. How do we reset the amplifier now?

Let's add a **big** resistor in parallel to the capacitor. Now we allow charge to slowly drain out of the input. Mr. OpAmp can then relax and prepare for the next pulse…



Question: what determines the **shape** of the decay?

We have built a **charge-sensitive (pre)amplifier**. Its gain is $\mathbf{1/C}$ and the decay time of the pulse is $\boldsymbol{RC}$.

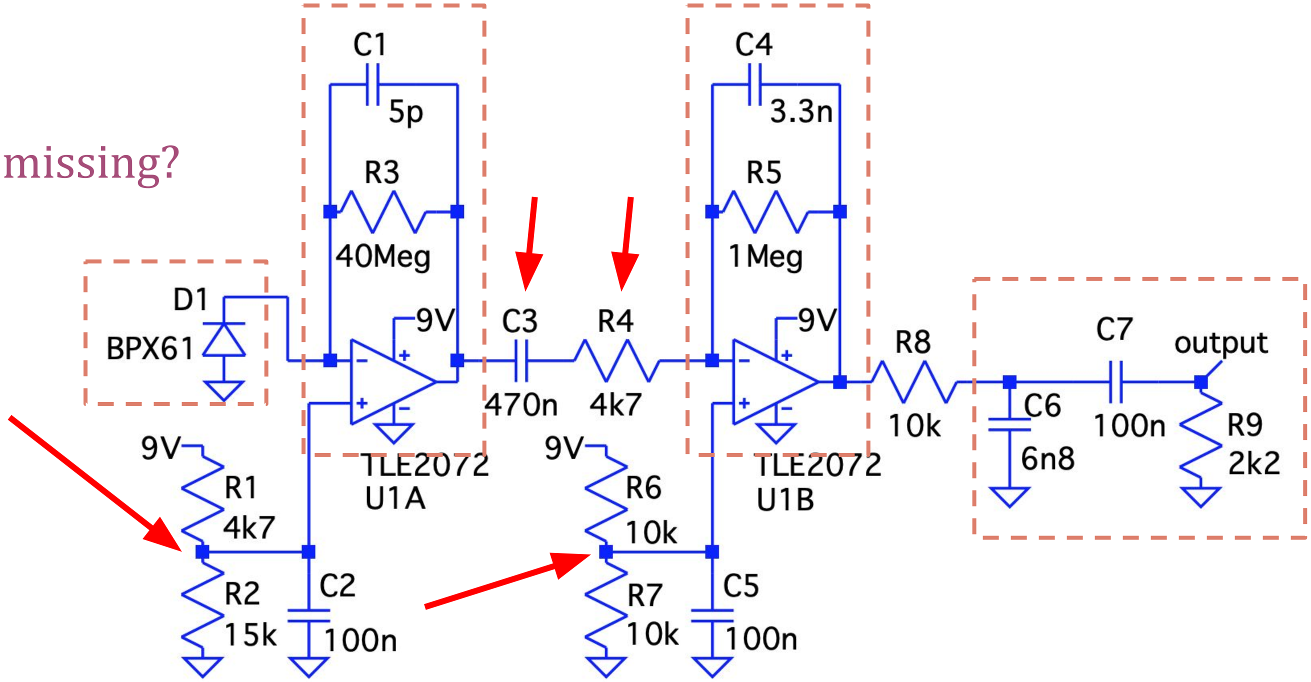


In almost all cases you will first use a **charge sensitive amplifier** followed by a **voltage amplifier**… the main difference is relative values of R and C, and no input R

Mr. OpAmp is an (*ideal*) **Op**erational **Amp**lifier. They are used for *tons* of things.

You can now qualitatively explain **everything** going on here and calculate gain:

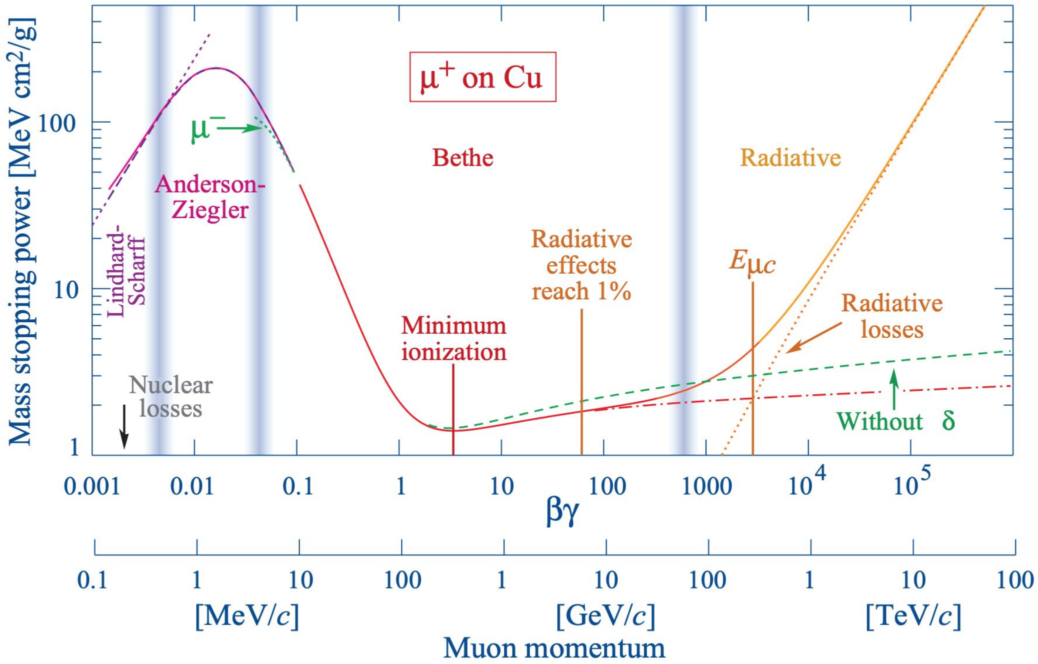
Q: what is missing?



A question:

The circuit outputs a voltage **directly proportional to the charge deposited**. So, can we do *spectroscopy* with this device with:

- MIPs?
- Electrons?
- Alphas?
- Photons?



One last thing… why do we always, *always* put stuff in metal boxes?

Electronics

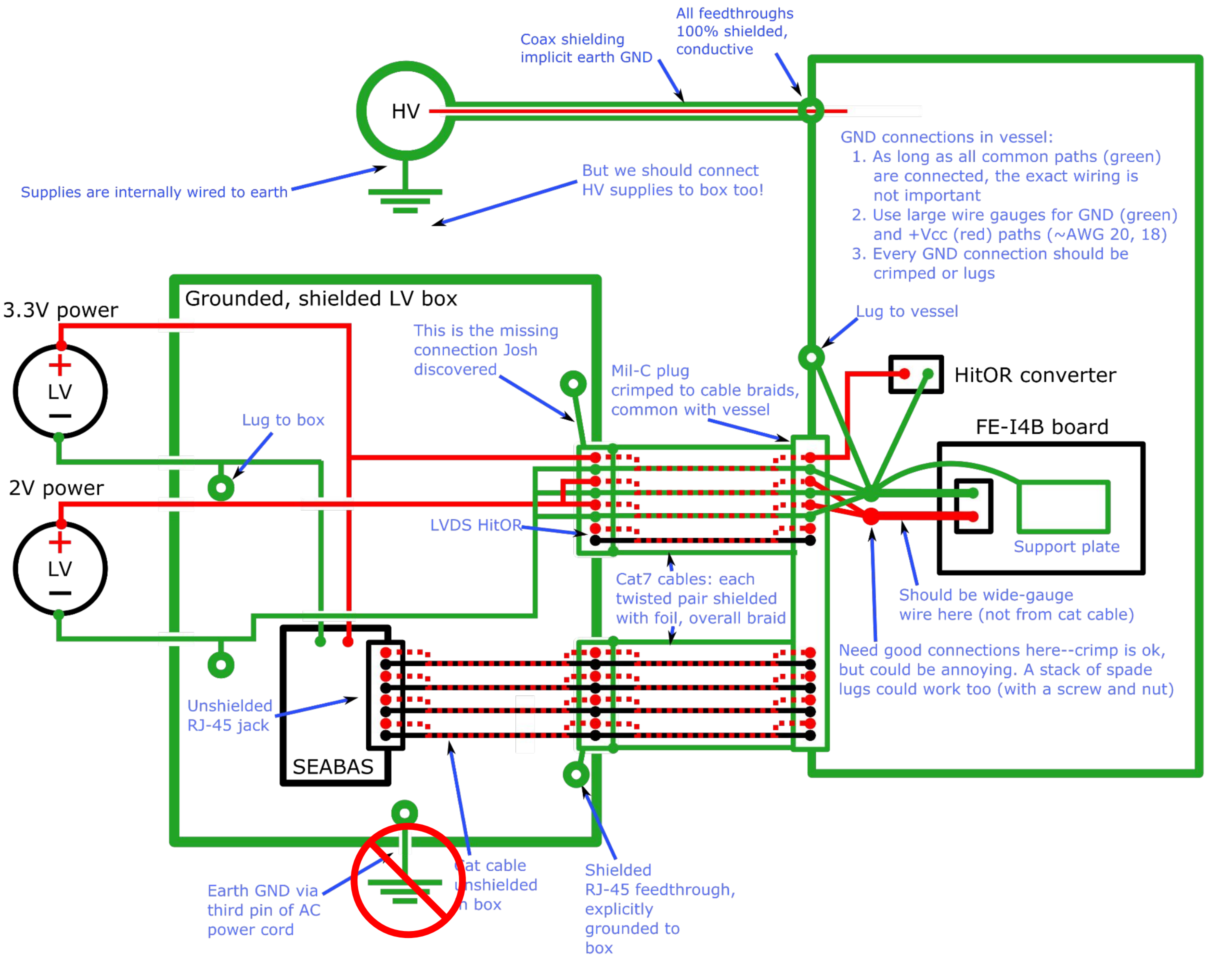
Our amplifier is *awesome* at taking **small transient currents** and turning them into **big voltages**.

Small transient currents can be caused by stuff we really don't like:

- *Induction* of current by radio-frequency EM waves (like cellphones)
- *Capacitive* coupling of detector with other nearby electronics

To make a very long story short… always *shield* every part of your device with a **grounded** conductor (Faraday cage)…

Electronics



Best practice:

Shield everything

Design the grounding; be clear what is connected to what

Require very low resistance from shields to earth ground

Only **one** path to earth ground*

Any questions?

If not: enough talking, let’s build!