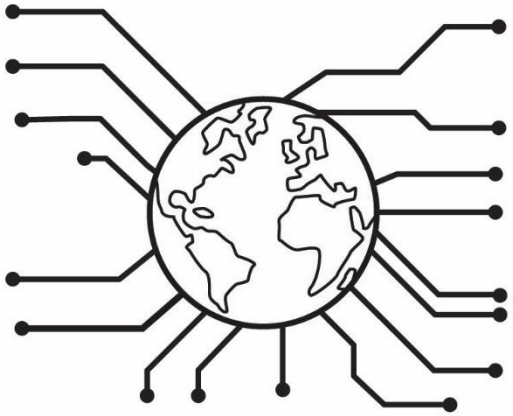


6.900

Lecture 1

February 4, 2025

TODAY

- What is this class about?
- Tiny intro to this semester's projects
- HW/SW product design and teardown
- PCB schematic design best practices

All lecture slides will be on efi.mit.edu
No need to take notes here

6.900 staff

Instructors

Joel Voldman

Joe Steinmeyer

TAs

Kailas Kahler

Srinidhi Venkatesh

Hasan Zeki Yildiz

And several special guests

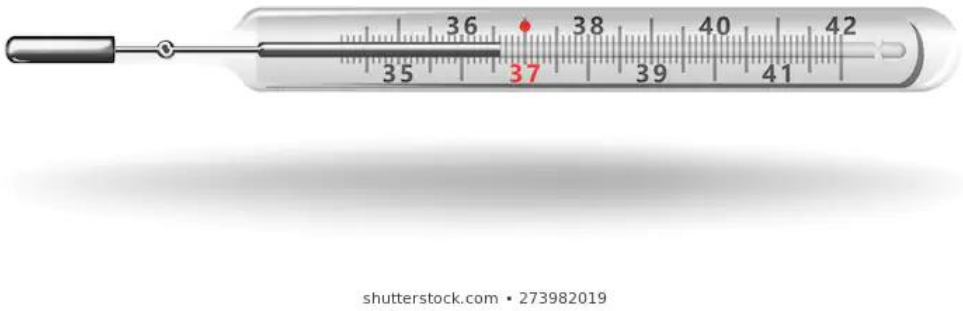
Brian Goldberg (MIT Office of Sustainability)
Jeff Parenti (City of Cambridge)
Tony Hu
BOSE engineers
…

Consider the medical thermometer

Why do we use medical thermometers?

What features do we want?

mercury thermometer



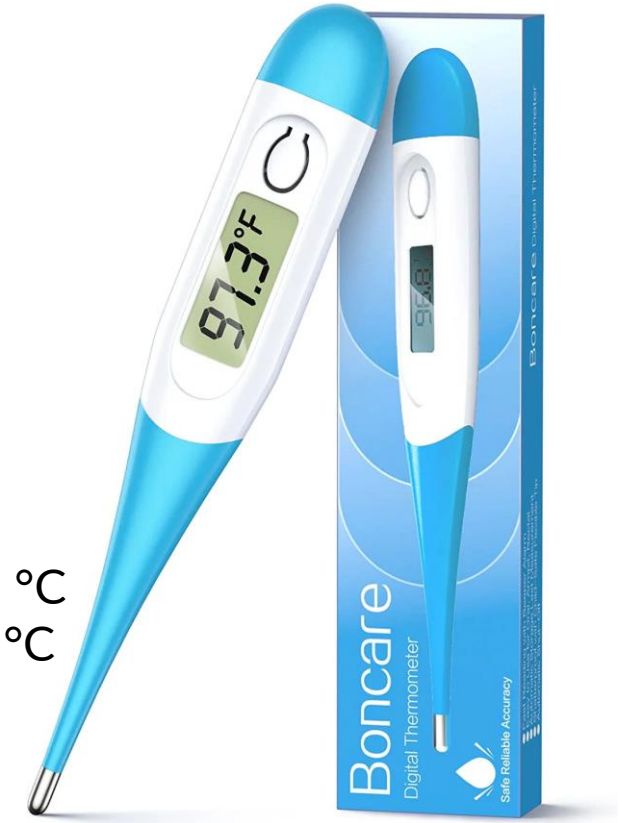
alcohol thermometer

Consider the medical thermometer

ear thermometer

Range: 34-42.2 °C
Accuracy: ±0.2 °C
Time: ~3 sec
Price: $55

oral thermometer



Range: 32-42.9 °C
Accuracy: ±0.1 °C
Time: ~10 sec
Price: $7

Today's thermometers

Consider the medical thermometer

ear thermometer

Range: 34-42.2 °C
Accuracy: ±0.2 °C
Time: ~3 sec
Price: $55

oral thermometer

Sensing, electronics, computation, actuation (display)
[some even have Bluetooth communications]

Consider the drill/driver

Why do we use drill/drivers?

What features do we want?

handheld screwdriver

handheld drill

Consider the drill/driver

time →

manual

corded drill/driver
~1900s

cordless drill/driver
1978

cordless drill/driver with brushless motor, tool tracking, etc.
today

circuits, actuation

sensing, electronics, computation, comms, actuation

Isolated cases?

These are all hardware/software systems

Our definition: a system that has most of:

- Sensing
- Electronics
- Computation
- Software
- Communications
- Control
- Actuation

Though not a formal law, products ➔ HW/SW over time

To develop these systems

We need expertise in

- Sensing
- Electronics
- Computation
- Software
- Communications
- Control
- Actuation

} **our focus**

And yes,

- Industrial design, mechanical, thermal, manufacturing, medical, economics, marketing, etc.

To develop these systems

In industry, you'll probably be on a team that does ~1 of these functions

But you'll be a better engineer if you can understand the rest to some extent

In this class, we'll undertake this *full stack* design

So we'll need to synthesize material *across* classes

Our *responsibility* as engineers

ars TECHNICA

BIZ & IT TECH SCIENCE POLICY CARS GAMING & CULTURE

HIGH AND DRY —

SmartDry's useful laundry sensor to be cloud-bricked next month

Sensor for already dry clothes relied on smartphone app, servers to wor

KEVIN PURDY - 8/30/2022, 1:14 PM

WIRED

BACKCHANNEL BUSINESS CULTURE GEAR IDEAS POLITICS SCIENCE SECURITY MERCH

SIGN IN | SUBSCRIBE

KLINT FINLEY BUSINESS APR 5, 2016 6:06 PM

Nest's Hub Shutdown Proves You're Crazy to Buy Into the Internet of Things

Nest's decision sends a pretty clear signal that you just can't rely on "Internet of Things" things.

REVOLV

Our *responsibility* as engineers

neural implant for cluster headaches

Our *responsibility* as engineers

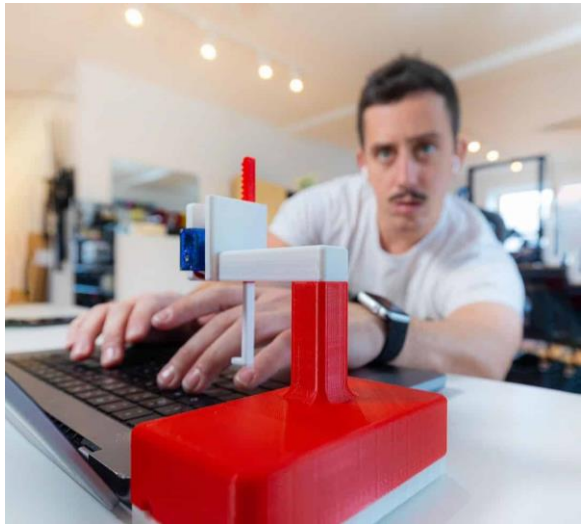
Our *responsibility* as engineers

as engineers who can develop extremely powerful technologies,

we must be mindful of the *implications* of the choices we make in those designs

Let's talk about *impact*

- There are many reasons to create new HW/SW systems
- Arguably, every HW/SW system has impact…



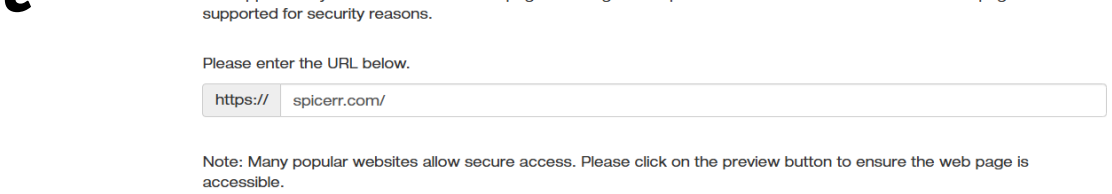
tHe tEeN TyPEr™, Matt Benedetto [Unnecessary Inventions]

Our reason: to improve the world around us…to use our skills to help those who can't do what we can do

Let's talk about *impact*

- There are many reasons to create new HW/SW systems
- Arguably, every HW/SW system has impact…

BigBelly's Solar trash compactor and recycling cans



Our reason: to improve the world around us…to use our skills to help those who can't do what we can do

Our projects this term

- We'll spend Thursday's lecture on this in detail
- We're partnering with two organizations via MIT's PKG Center
- Two different projects

PKG

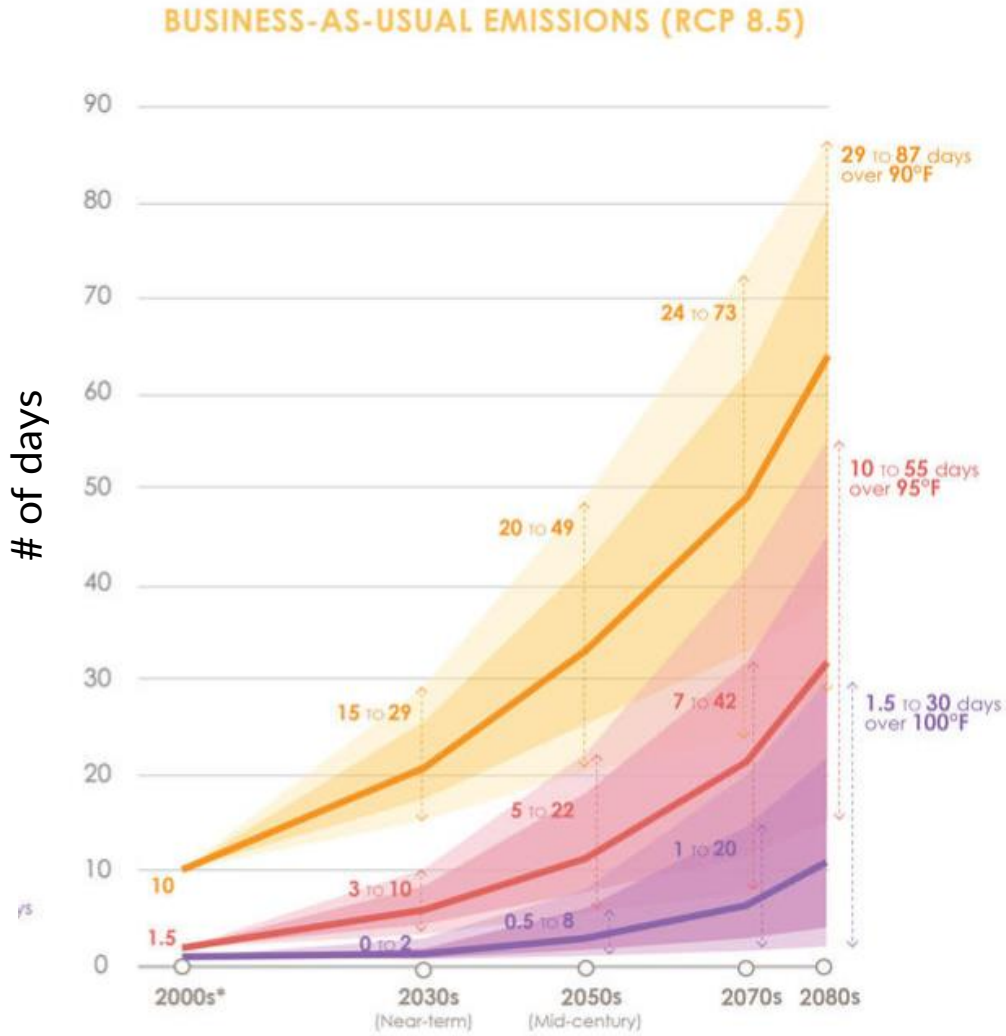
PRISCILLA KING GRAY
PUBLIC SERVICE CENTER

MIT Office of Sustainability

CITY OF CAMBRIDGE

MIT Office of Sustainability (MITOS) heat monitor

- MITOS is working with SA+P and now us to understand heat islands at MIT
- Boston is getting hotter



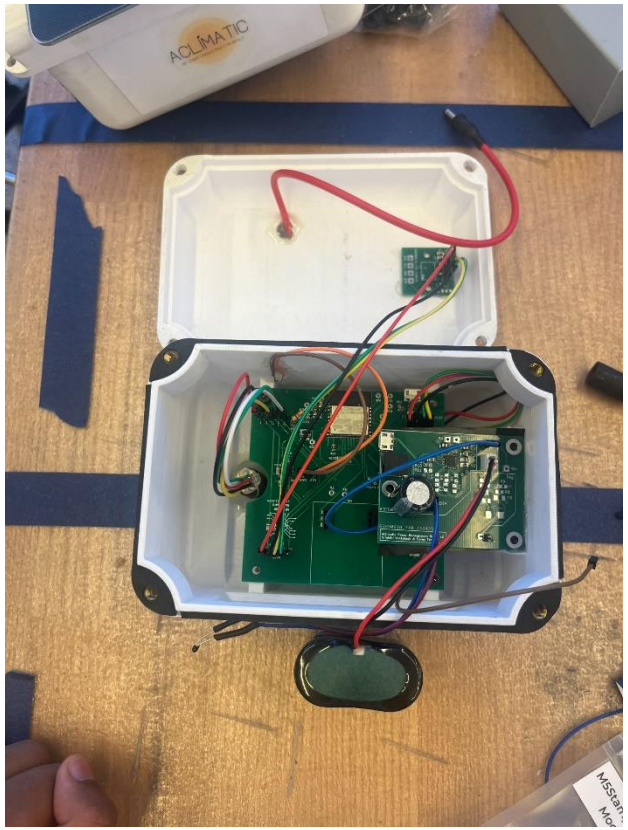
https://www.boston.gov/environment-and-energy/heat-resilience-solutions-boston

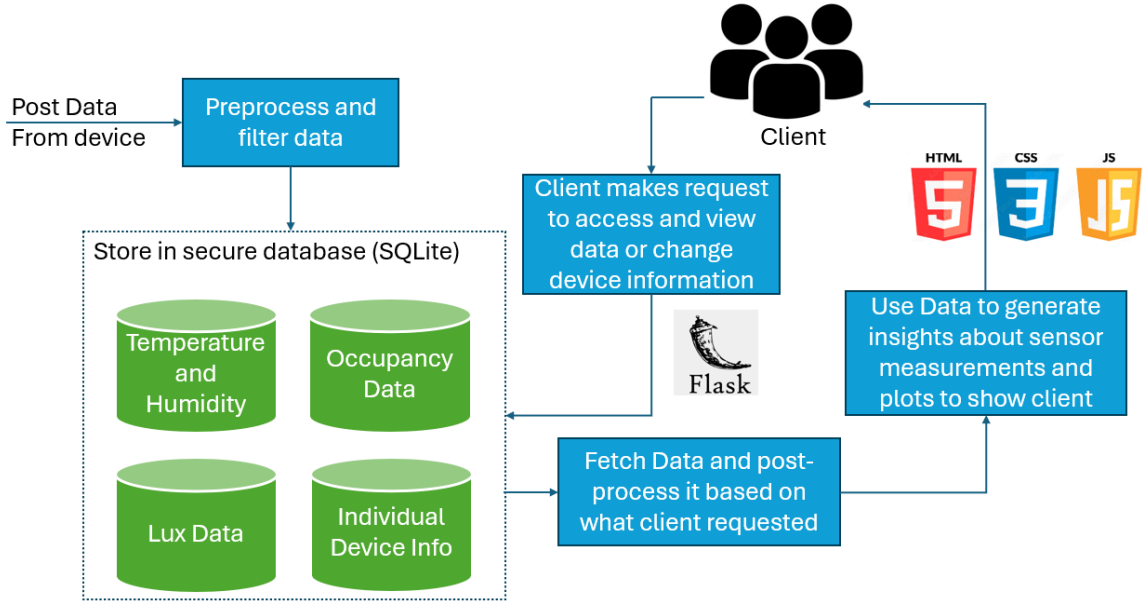
MIT Office of Sustainability (MITOS) heat monitor

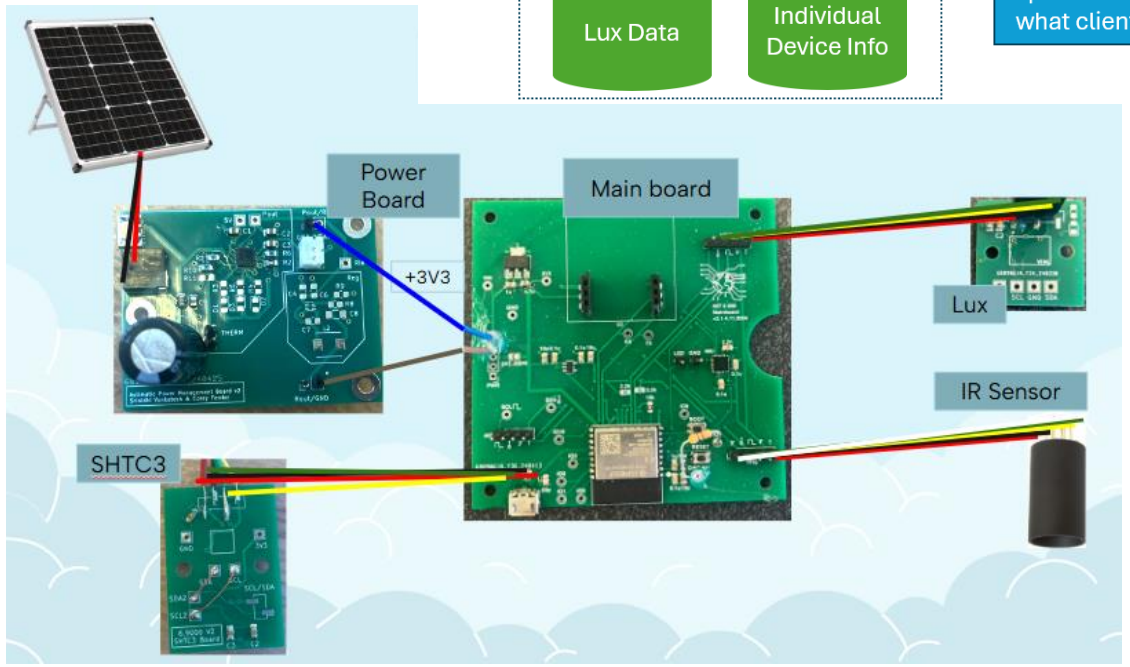
- MITOS is working with SA+P and now us to understand heat islands at MIT
- Boston is getting hotter
- What about MIT?
- Can we measure hyperlocal heat?

MIT Office of Sustainability (MITOS) heat monitor

- Spring 2024 class
  - Developed this system
  - Deployed during summer 2024

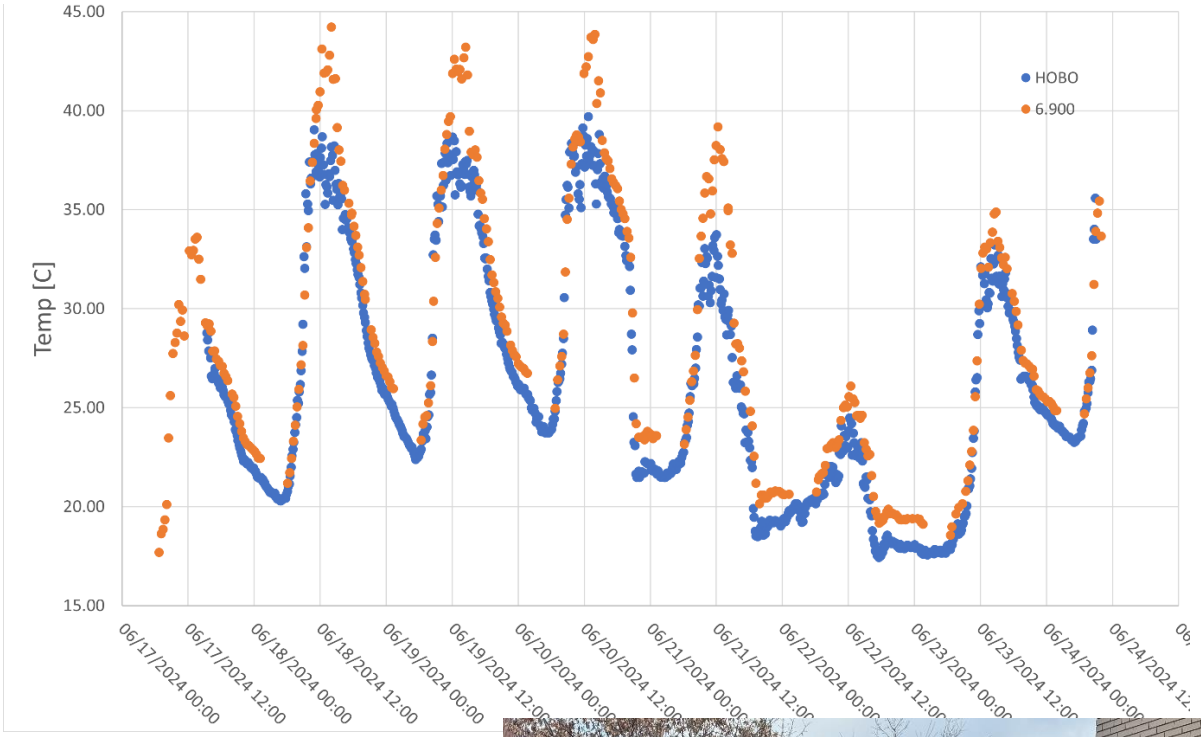




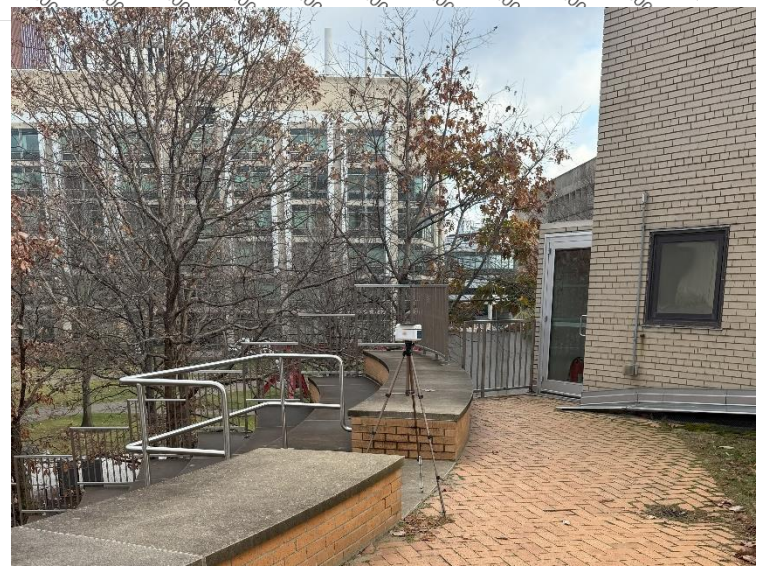


MIT Office of Sustainability (MITOS) heat monitor

- Worked outside for several months!
- Some challenges
  - **Air temperature accuracy**
  - **System failures/debugging**
  - **Assembly**
  - **Cost (~$300 BOM @ 100 units)**



Research-grade radiation shield



City of Cambridge Bike Lane Monitor

- Cambridge has been installing separated bike lanes everywhere for the past few years
- Somewhat controversial
- But…are they getting used?
- Surprisingly hard to measure

City of Cambridge Bike Lane Monitor

- Want to measure the usage of separated bike lanes
- Sort of “easy”
  - Measure a big opaque object as it goes by
- But kinda hard!
  - Where to mount this monitor?
  - Bike lanes are pretty wide: how to measure that far away?
  - How will you power it? Communicate?
  - Cost?

Our projects this term

If we're successful, we can help MIT & Cambridge make informed decisions about

where to plant new trees, add fans or awnings, etc.

where to add new bike lanes, or remove existing ones, or incentivize usage

so that the community can be better served

and there is lots of interest in these types of systems

from other communities

What will I learn?

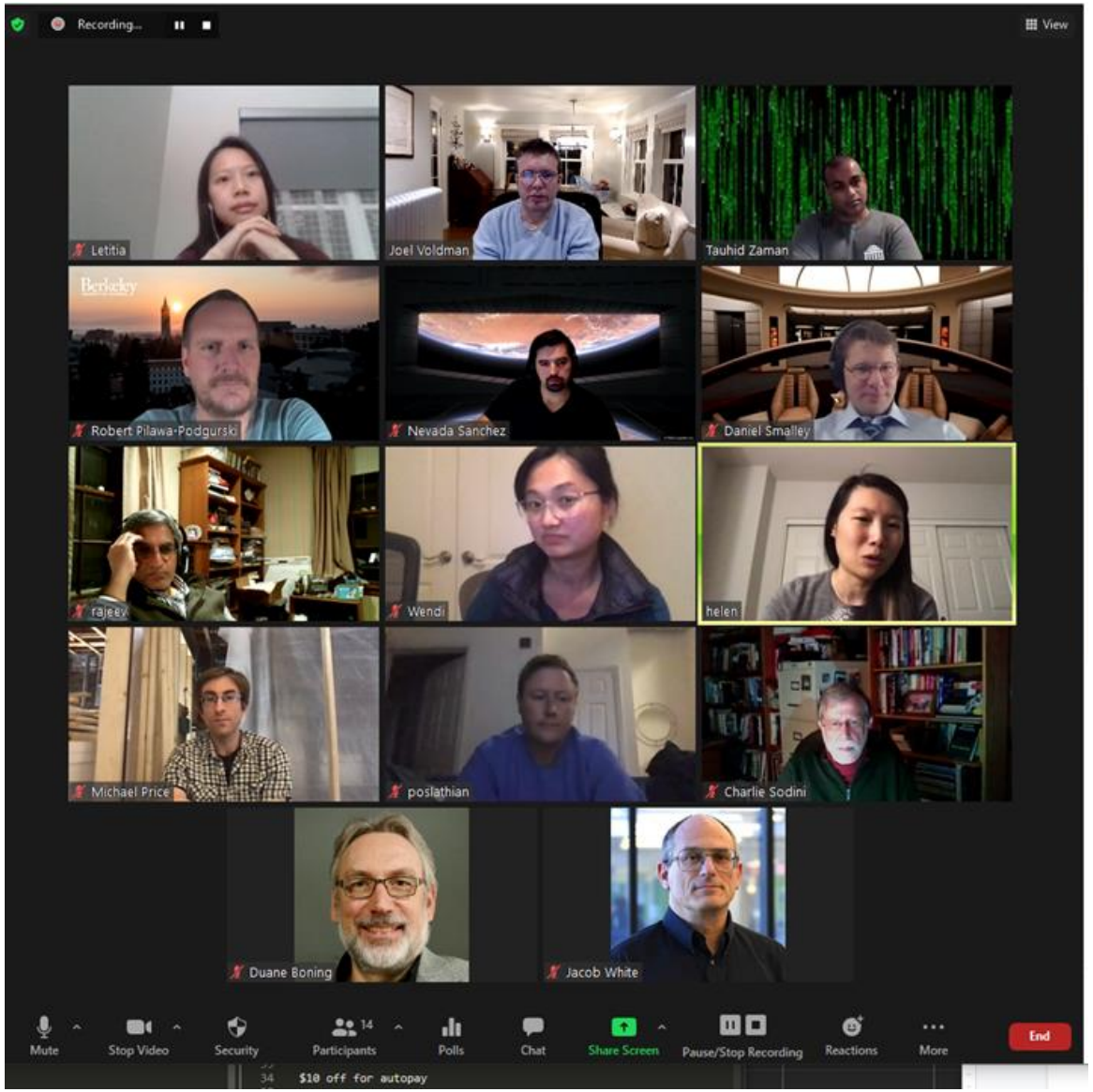
- Principled ways to design HW/SW systems
- How to go from requirements ➔ specifications ➔ system design ➔ detailed design ➔ prototyping ➔ testing & verification
- How different system design choices and partitions affect tradeoffs in meeting our specifications
- Evaluate the size, weight, power, performance, cost, lifetime, etc. tradeoffs of various designs

Mostly, how to **synthesize and apply** your knowledge from other EECS classes and **be a real engineer**

And yes, you'll build stuff

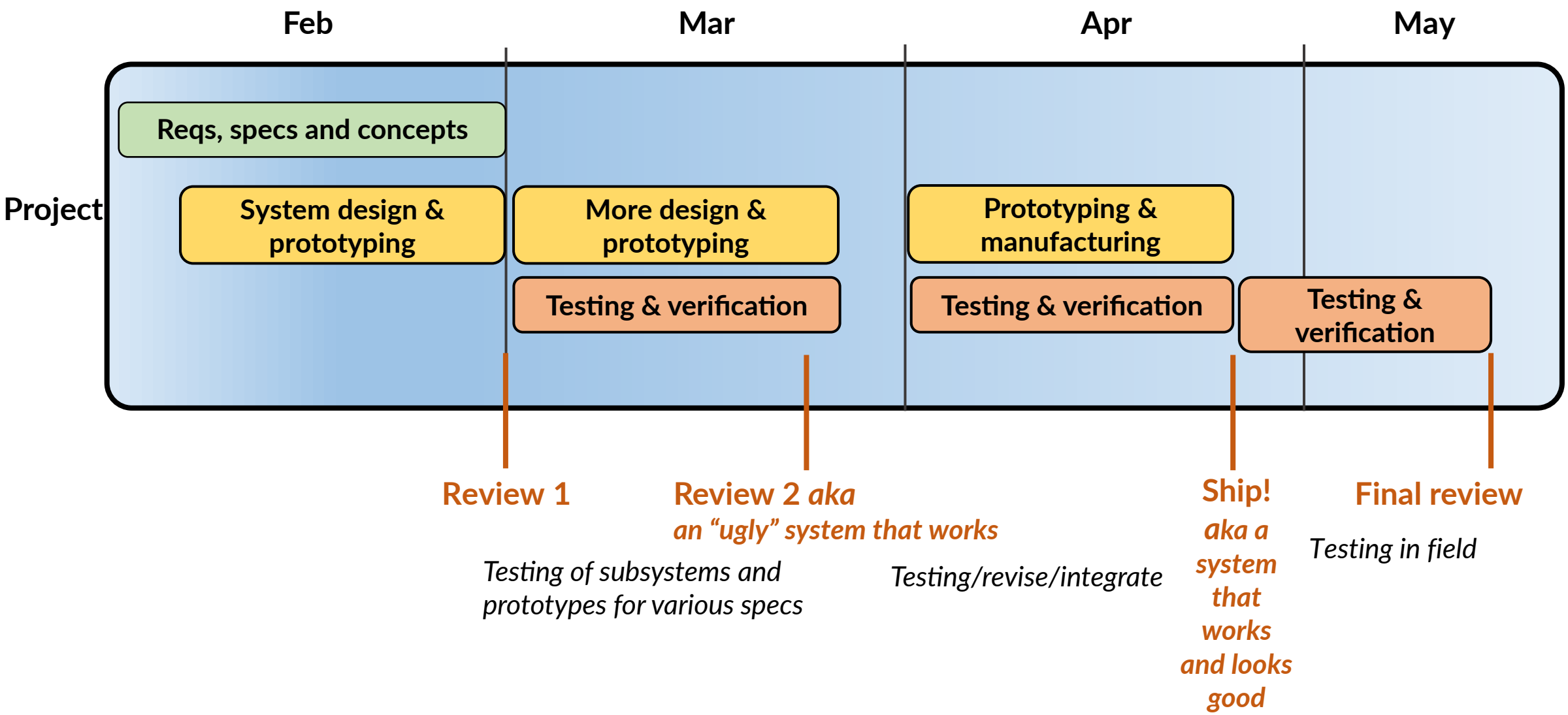
How will we do it?

- We'll work in teams…**BIG*** teams
- Why?
  - IRL, this is the way
  - Feedback from alumni
  - You can do more…together



*for EECS

Overall semester timeline



How will we do it?

- During the first half of the term, we'll design and prototype relevant subsystems
- A barebones IoT system with sensors, MCU, back-end server
- Mostly individual, some parts as a team
- Every student gets to learn electronics design, PCB schematic design & layout & assembly, firmware, 3DP enclosures, back-end server w/ database & web server
- This will give you some of the tools needed to undertake the project

Some logistics

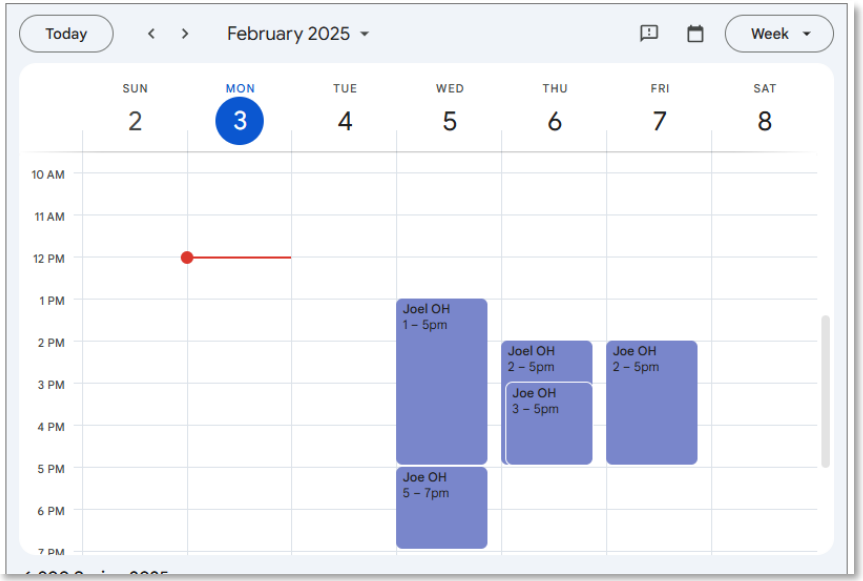
- This afternoon: team formation survey in EX00 – **due end of Saturday!!**
- Teams will go out on Sun or Mon, teams based on background **& interests**

- **Lecture attendance required**
  - Tracked via feedback form at each lecture starting Thu
- **Please no laptops or phones** during lecture

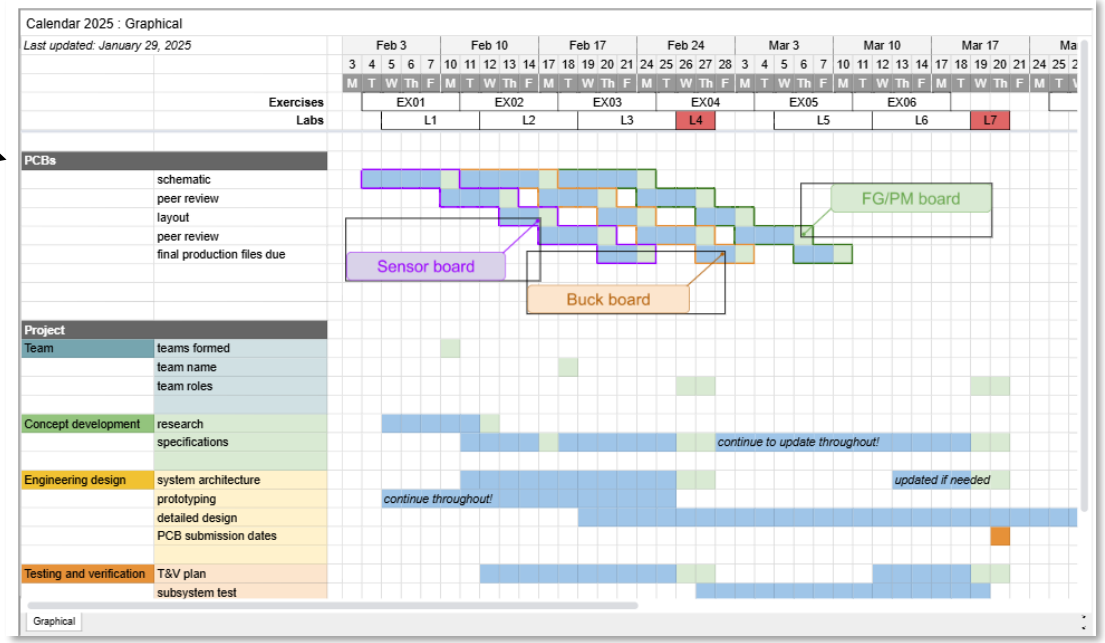
efi.mit.edu

Some logistics

- **Labs** go out on Wednesdays – starting tomorrow!
  - Go to catsoop website to install necessary software *before* you come to lab
  - Get checkoffs during staffed lab OH ⟶
  - By the end of Lab01, you will have a battery-powered cloud-connected portable weather monitor
  - By the end of EX01, you will have made a complete end-to-end IoT system…pretty cool
- **Psets** every week or so – EX01 comes out today
- **No exams**
- **Piazza** ← sign up!
- There will be presentations, but this is not a CI-M class…
- Late policy, etc. on catsoop site



efi.mit.edu/spring25/



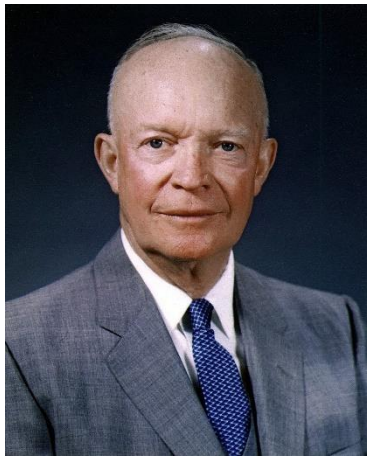
efi.mit.edu/spring25/schedule

efi.mit.edu

HW/SW product development

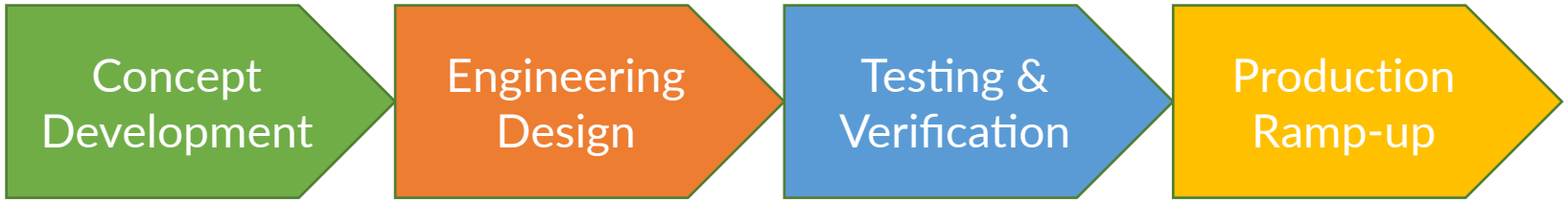
with a focus on engineering design

“In preparing for battle I have always found that plans are useless, but planning is indispensable”
--Dwight D. Eisenhower



Product development process

- Many different specific processes, terminology, number of steps, and so on, but generally

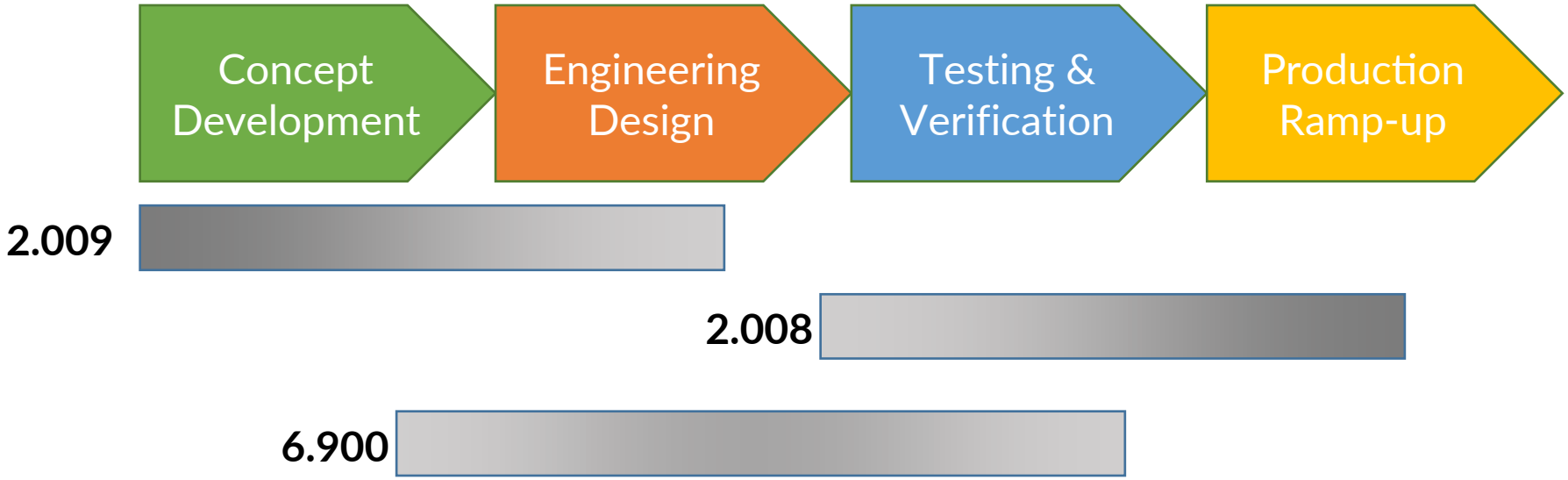


- **Concept development:** identify requirements, establish target specifications, generate concepts, refine and select most promising concept
- **Engineering design:** develop product's system-level architecture, partition into subsystems, design subsystems, prototype subsystems, integrate back into system
- **Testing & verification:** Evaluate the subsystems and complete system, verifying that it meets spec
- **Production ramp-up:** Transfer to manufacturing, verify quality, ramp up production, commercialization

We'll dive more into this next week

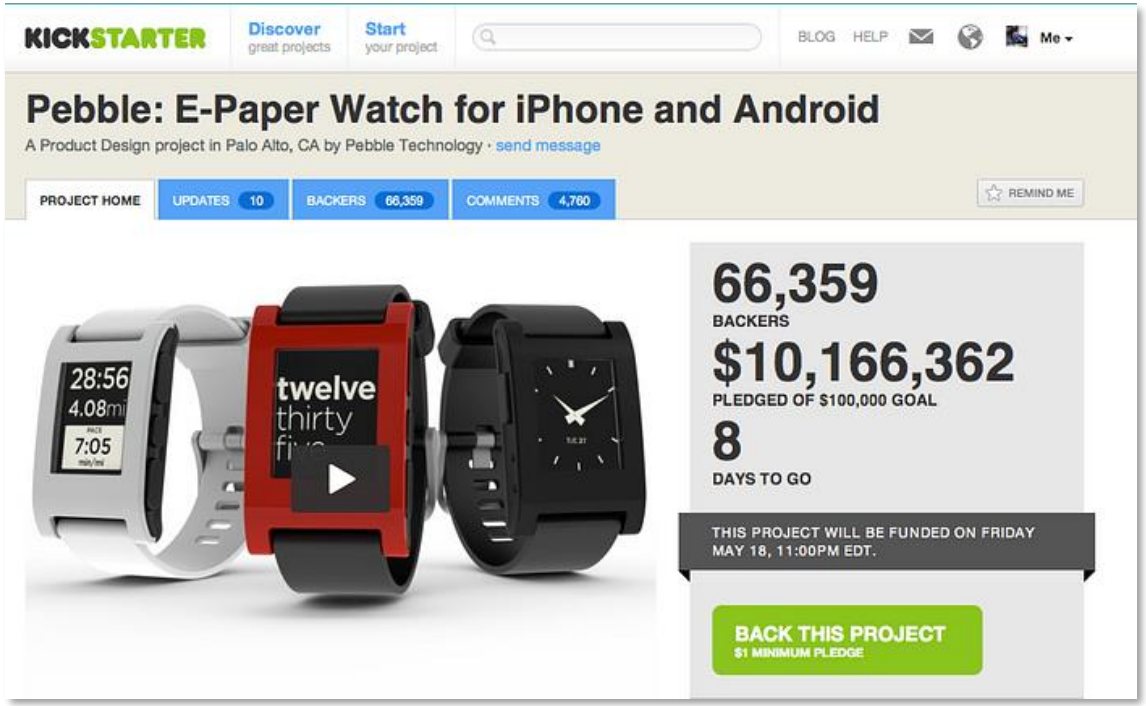
Product development process

- There are classes at MIT that focus on different aspects of this process
- It's too much for a single class!



Pebble

- The OG smartwatch: 2013
- 11th-most successful Kickstarter campaign **ever**
  - Other Pebble products are #2 and #5 on list
- Sold 2M+ units
- Shut down and sold assets to Fitbit in 2016
- Still-active hacker community



https://medium.com/@ericmigi/why-pebble-failed-d7be937c6232

Pebble

- Google released (most) code **last week!**
- Founder is restarting the company!

Google Open Source Blog

The latest news from Google on open source releases, major projects, events, and student outreach programs.

See the code that powered the Pebble smartwatches

Monday, January 27, 2025

Eric Migicovsky

← Back to Home

Why We're Bringing Pebble Back

[2025-01-27]

> "TL;DR
> We're making a new Pebble-style smartwatch.
> Want one? Sign up here - rePebble.com "

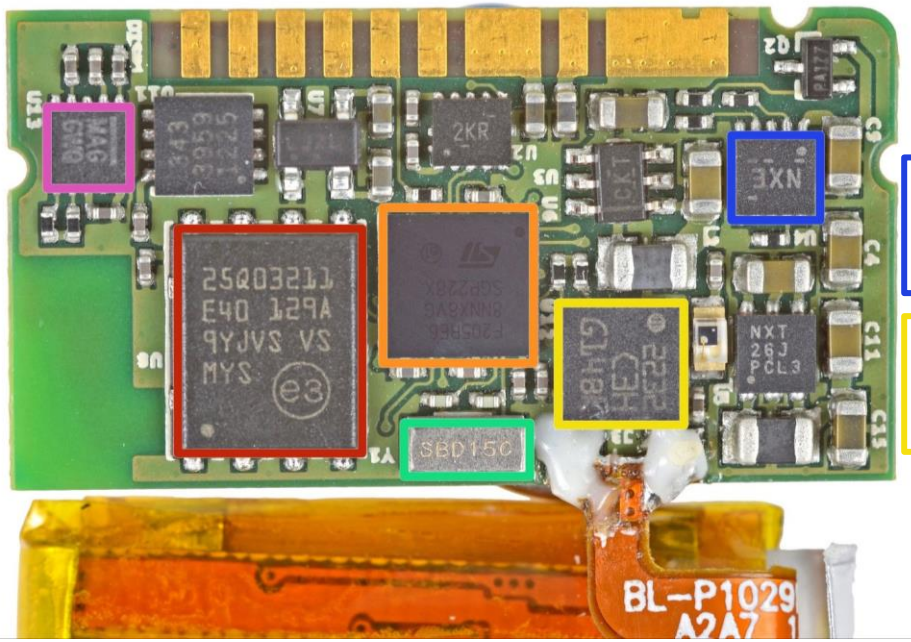
Pebble

- Teardown

Xtrinsic MAG3110 3D Digital Magnetometer

STMicroelectronics STM32F205RE
ARM Cortex-M3 MCU

Micron N25Q032A11ESE40F 32 Mb serial flash



TI BQ24040 1A
Battery Charger

STMicroelectronics LIS3DH
3-axis accelerometer

TI CC2564 Bluetooth

www.digikey.com/en/maker/projects/teardown-pebble-smartwatch/05481ebe19bd430f8e28347b56bdf654
www.ifixit.com/Teardown/Pebble+Teardown/13319

Common specifications for HW/SW products

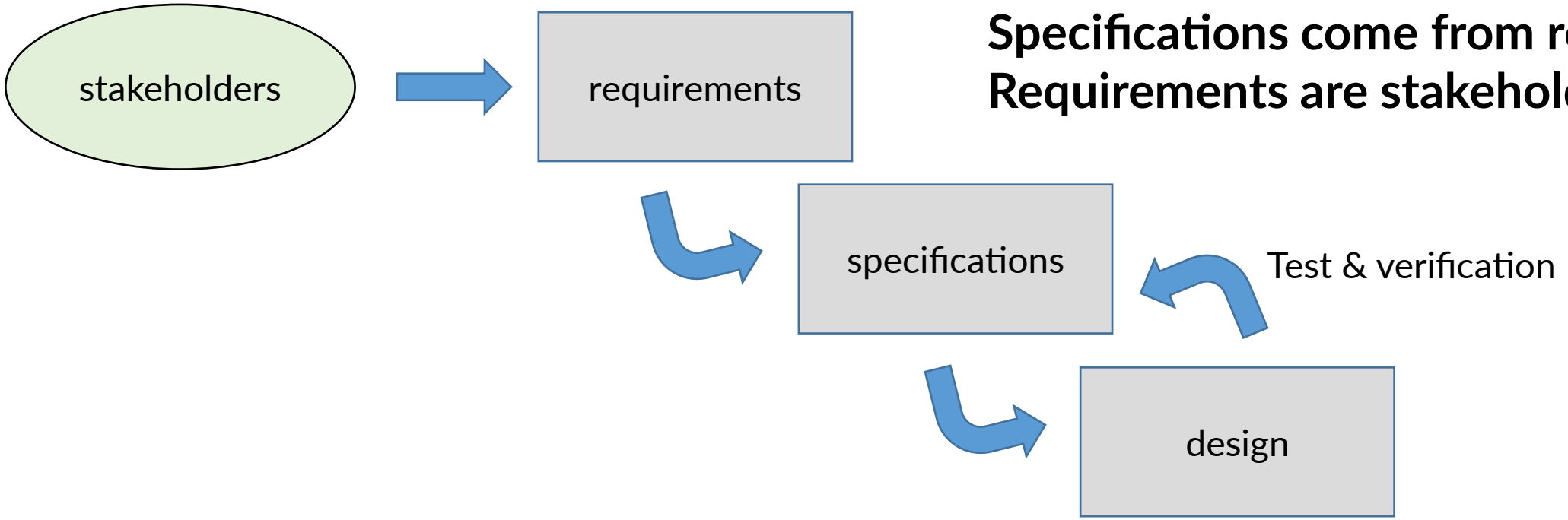
Typically,

- **Financial**
  - BOM, COGS, etc.
  - Time to market
- **Regulatory** – safety, emissions
  - Anything with a radio, plugged into wall, etc.
  - For medical (and other regulated sectors) this can be quite extensive
- **Industrial design**
  - What does it look like, what materials are used, how does it interact with the user, etc.
- **Environmental resistance**
  - Is it used indoors? In salt water? In an auto engine? On Mars?
  - IP [Ingress Protection] rating
- **Engineering**
  - Sensing, actuation, compute, comms, firmware, software, etc.
- **Security & Privacy**
  - Typically, user data is being communicated…what data? how is it being secured? who has access?
  - There may be regulatory requirements here as well: HIPAA
- **Packaging**
  - How is sent to the customer, could be simple/elaborate
- **Installation and servicing**
  - How does one go from “in the box” to “in use”?
  - Will it be serviced in the field? Will the SW be updated? Can the HW be fixed? Warranty?

These are not disjoint:
Needing to be updated after install: is that installation or engineering? Etc.

How do we develop these specifications?

Requirements, specs, and so on



Design comes from specifications
Specifications come from requirements
Requirements are stakeholder facing

We'll go into this in detail next week

PCB schematic capture best practices

Some tips to make life easier and your design more likely to work!

Schematic design

- Your first board design starts in ex01: a sensor board
- An early step in developing a board is to create a schematic
- There are two audiences for your schematic
  - **KiCad**
    - A correct schematic will allow KiCad to perform checks when you do layout
      - E.g., is the ground pin on the IC physically wired to the circuit ground
    - Can also be connected to simulation tools
  - **People**
    - For reviews, to help debug, to instruct, to share
- We thus have two overall goals
  - The schematic should be correct
  - The schematic should be easy to read

    This is just like for code

Example

- Board for an SGP41 VOC sensor

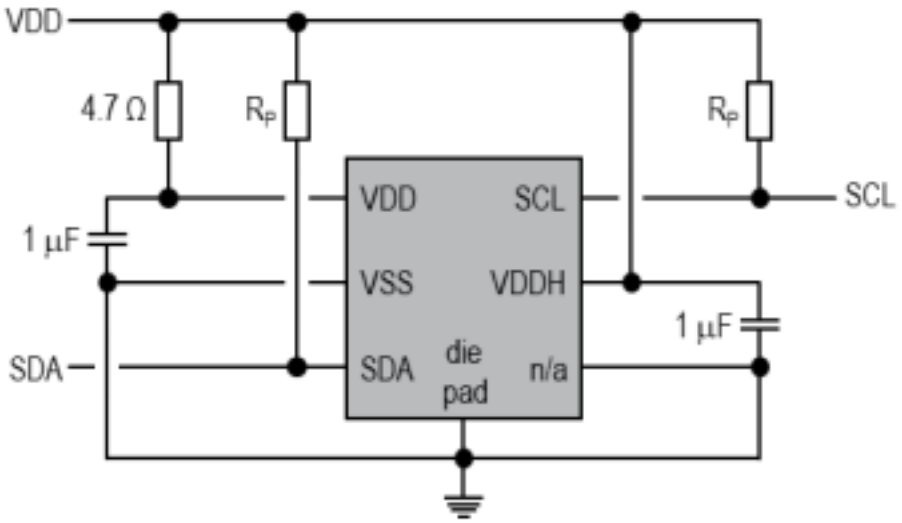


Figure 6 Typical application circuit.

SENSIRION
THE SENSOR COMPANY

Datasheet SGP41

Air Quality Sensor for VOC and NO_x Measurements

- MOx based gas sensor for air quality applications
- Outstanding long-term stability and lifetime
- I^2C interface with digital output signals
- Very small 6-pin DFN package: 2.44 x 2.44 x 0.85 mm^3
- Low power consumption: 3.0 mA at 3.3 V
- Tape and reel packaged, reflow solderable

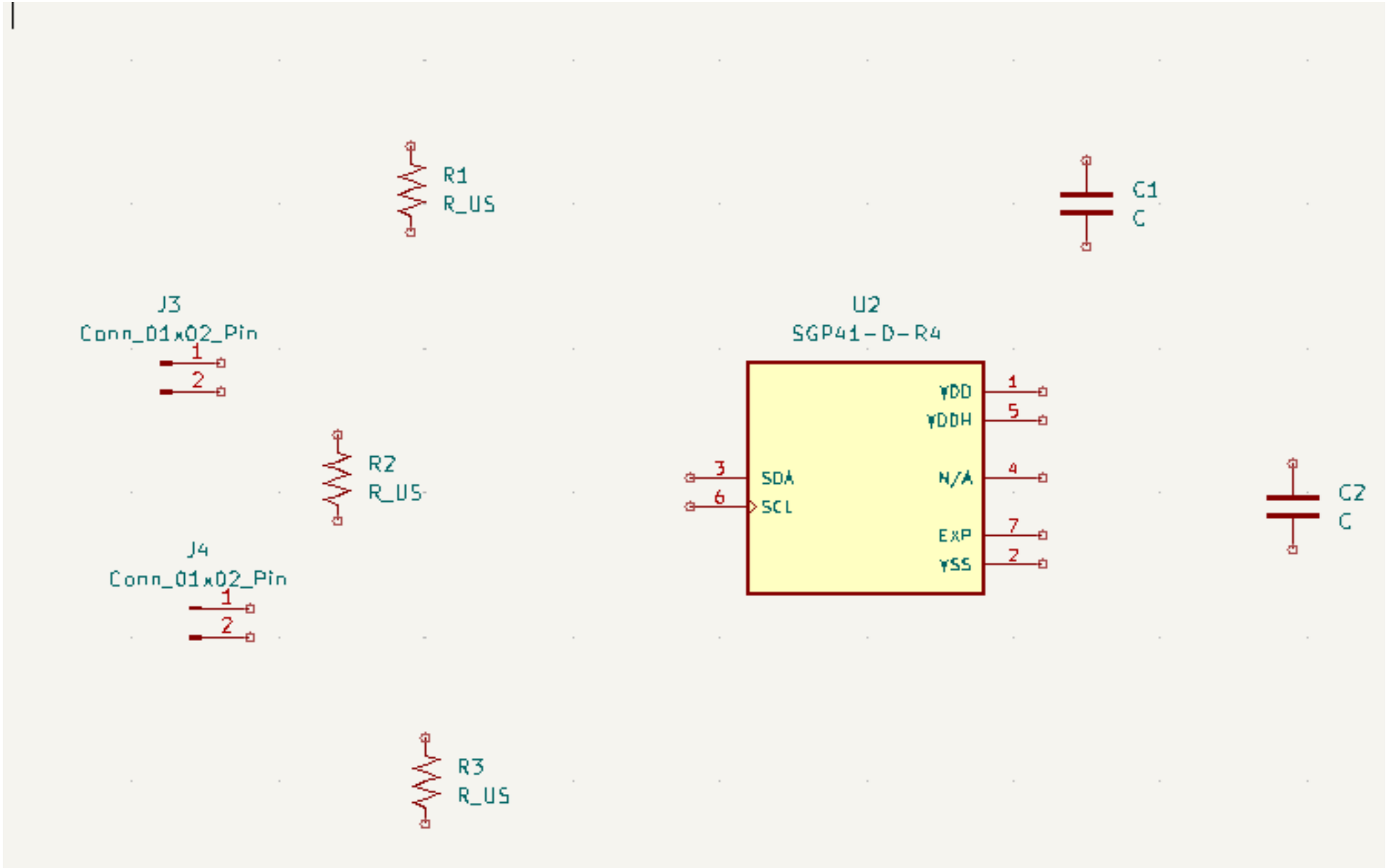
Product Summary

The SGP41 is a digital gas sensor designed for easy integration into air purifiers or demand-controlled ventilation systems. Sensirion's CMOSens® technology offers a complete, easy-to-use sensor system on a single chip featuring a digital I^2C interface and temperature-controlled micro hotplates, providing one VOC and one NO_x based indoor air quality signal. Both sensing element and Gas Index Algorithm feature an unmatched robustness against contaminating gases present in real-world applications enabling a unique long-term stability as well as low drift. The very small 2.44 x 2.44 x 0.85 mm^3 DFN package enables applications in limited spaces. Sensirion's state-of-the-art production process guarantees high reproducibility and reliability. Tape and reel packaging together with suitability for standard SMD assembly processes make the SGP41 predestined for high-volume applications.

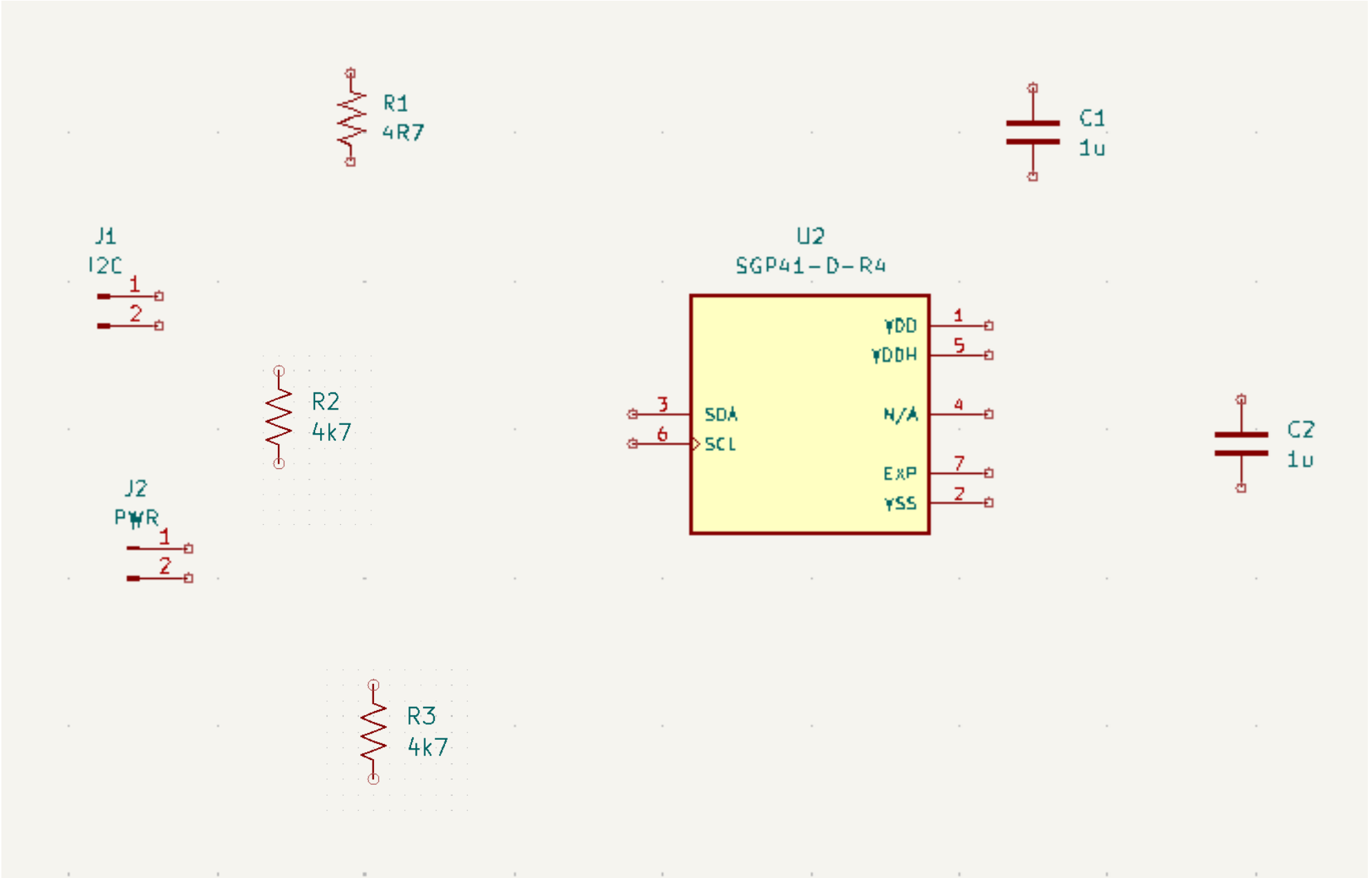
We have to translate this into a KiCad schematic

What else do we need in our circuit?

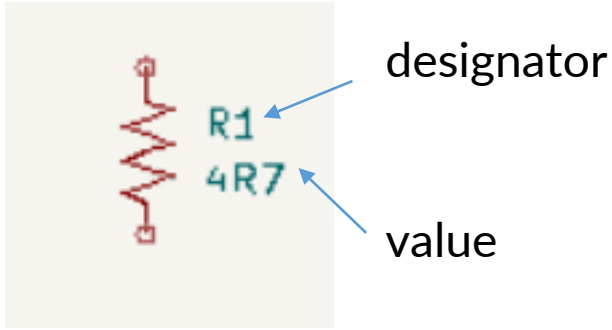
Add components to KiCad schematic

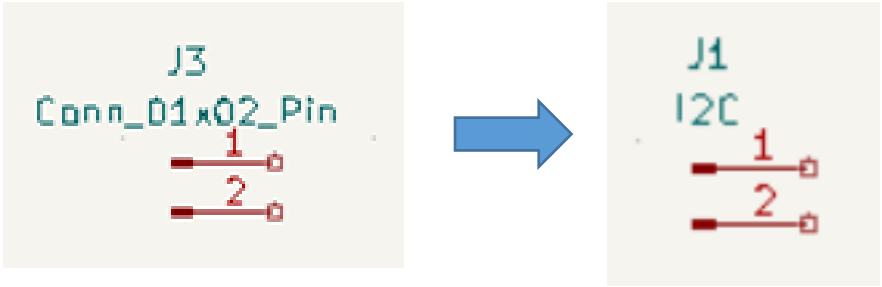


Adjust labels and values



- Use component designators
  - Renumber starting at 1 if needed
- Add component values
- Label your connectors with something that makes sense
  - I2C vs Conn_01x_02Pin



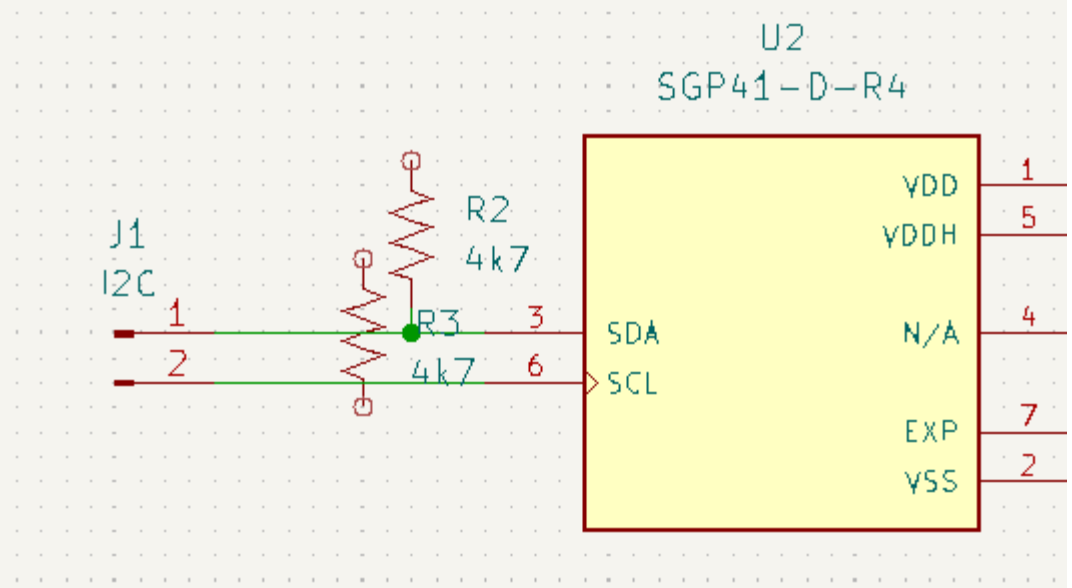


Typical nomenclature:
47 Ω = 47R
4.7 Ω = 4R7
4.7kΩ = 4k7
4.7MΩ = 4M7

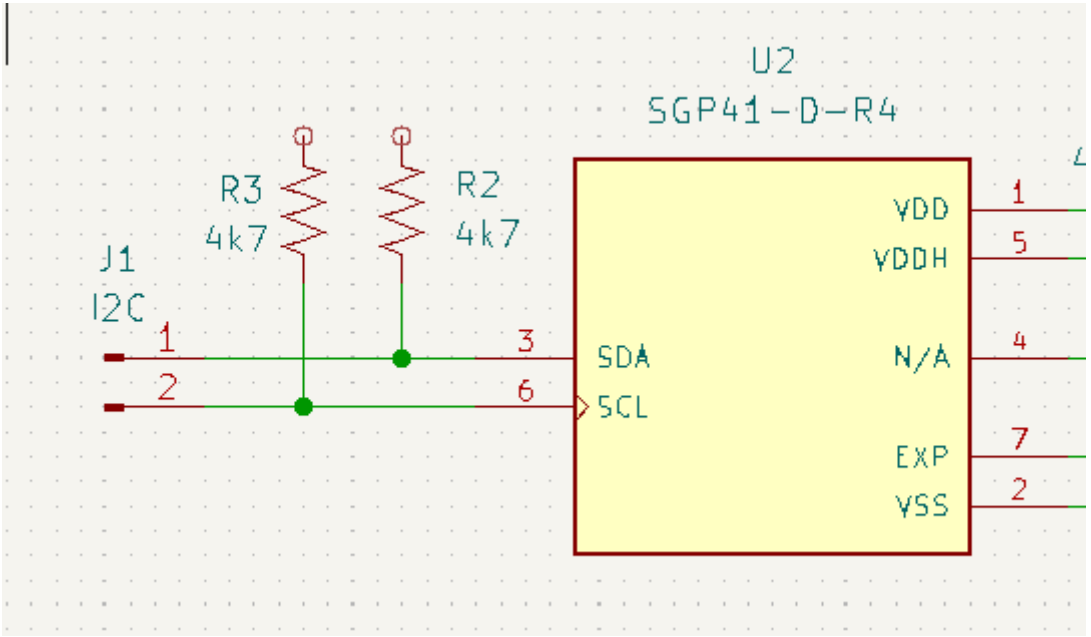
Correctness and style are connected

Starting to wire up

Not good

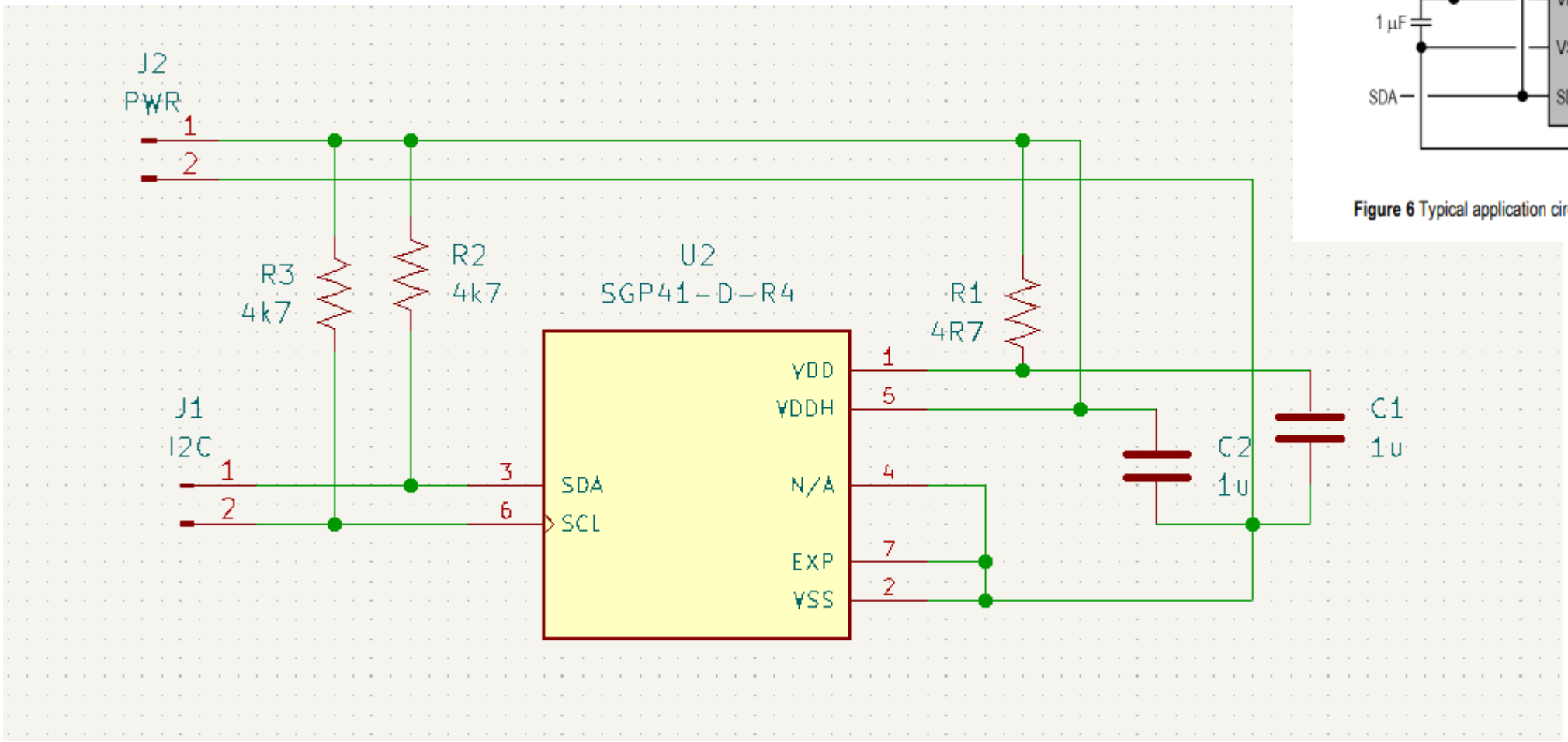


Better



- R2 and R3 text is overlapping → hard to read
- R3 is not actually connected to anything

All wired up



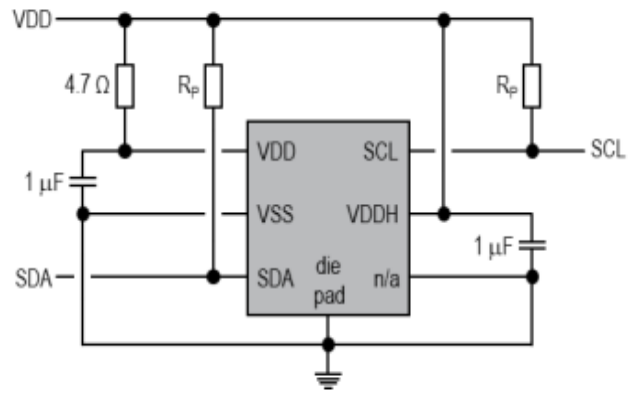
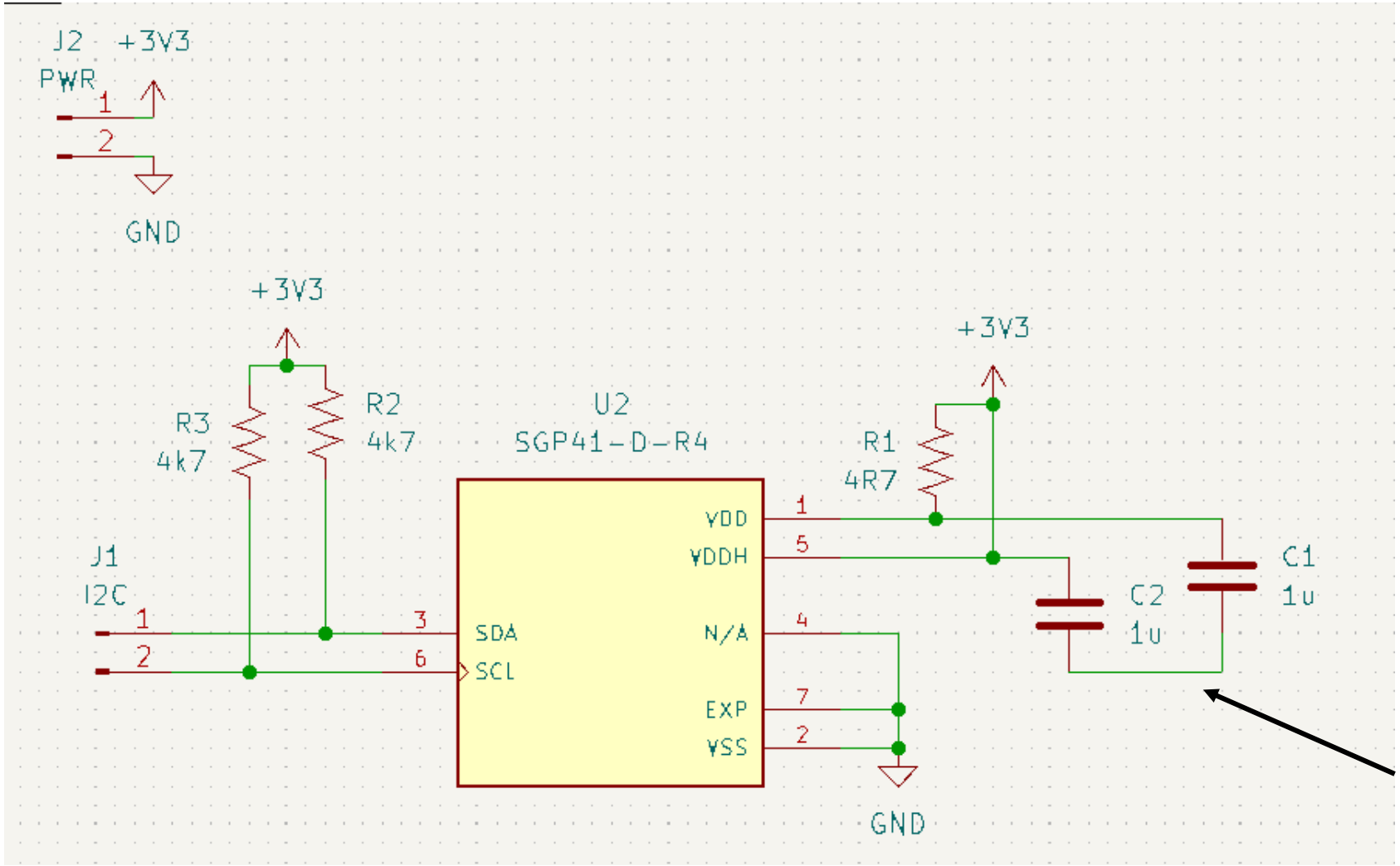


Figure 6 Typical application circuit.

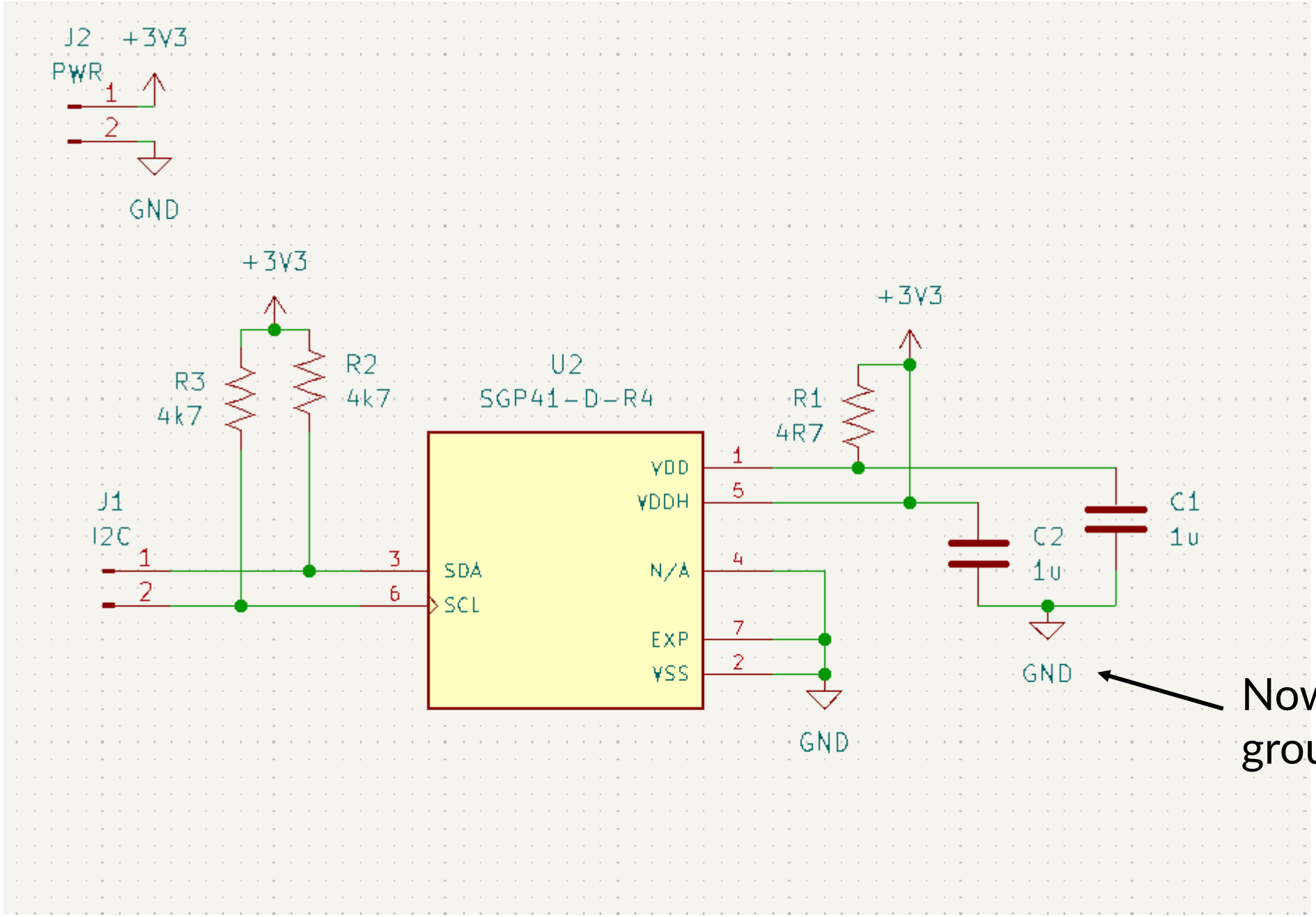
This is correct, but hard to read
Lots of overlapping wires
Hard to tell what's VDD, what's ground (VSS) by just looking

Now with power ports



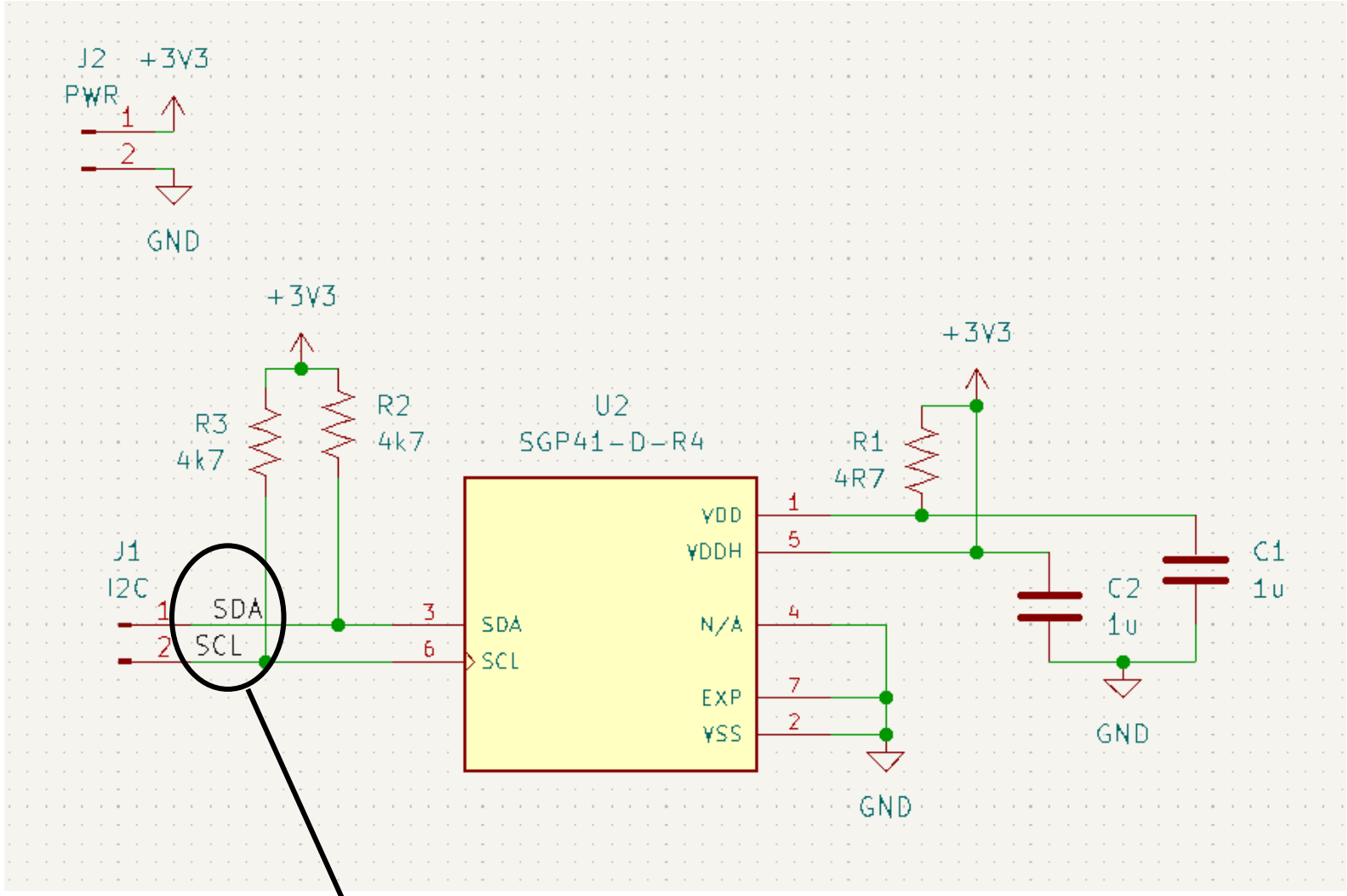
Not connected to ground

Better: Use GND and 3V3 power ports (P)
Fewer crossing wires, easier to read
Now I can see an error I made



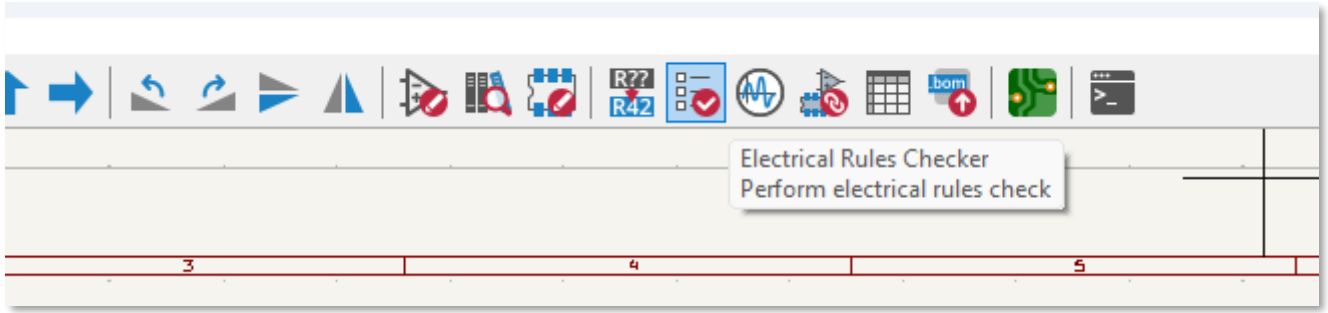
Now there's a ground

Now with power ports & net labels



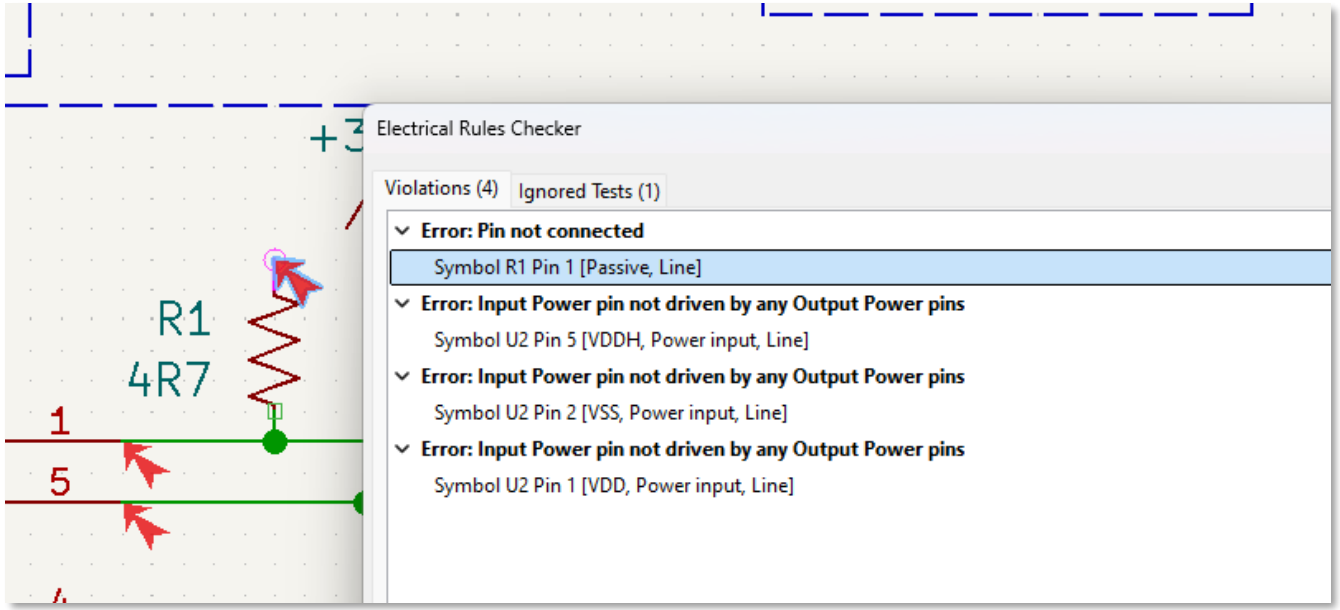
Assign SDA and SCL wires (nodes) to SDA and SCL nets
This will be really useful when we lay out the PCB
Assign all important signals to nets

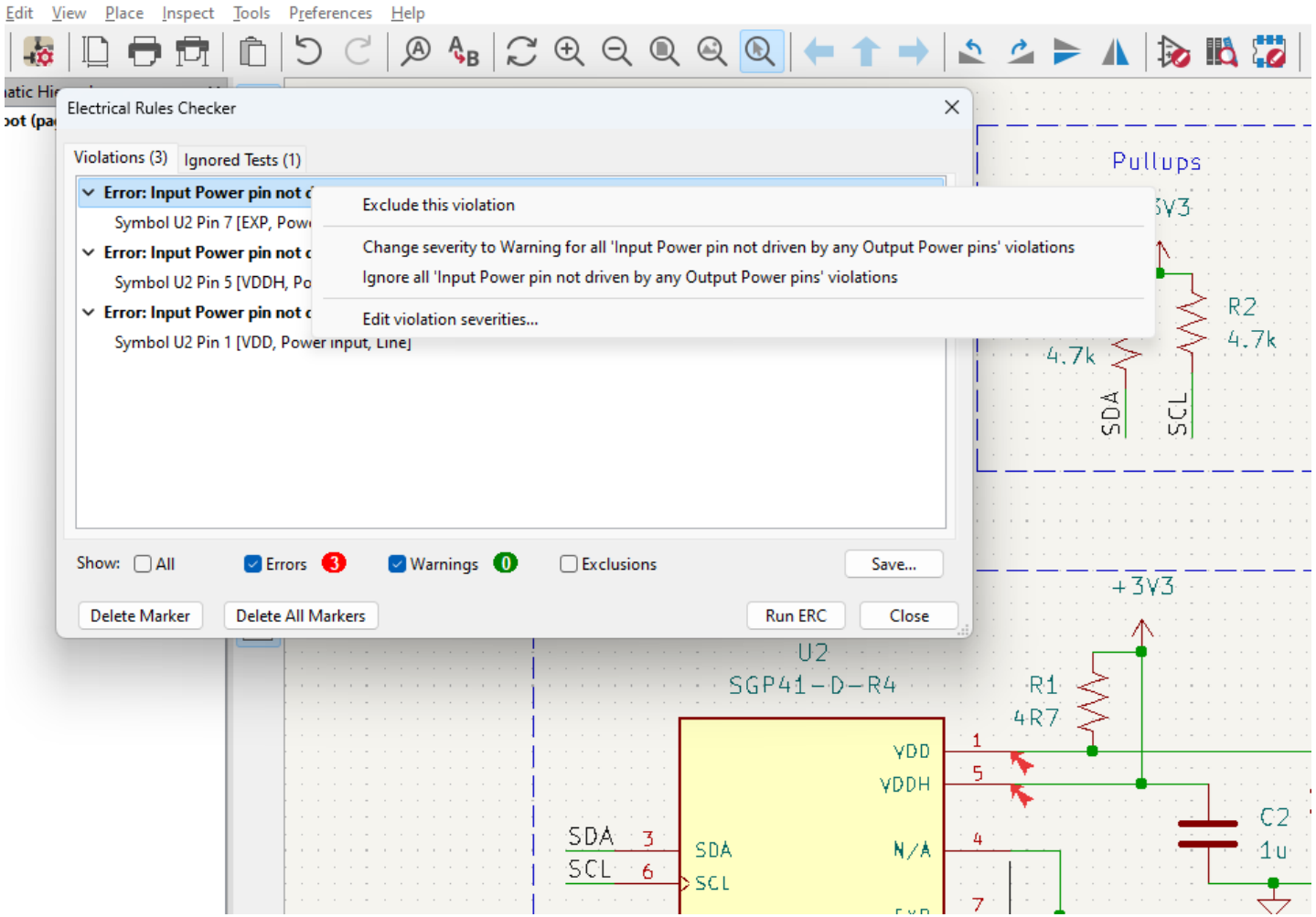
Always run your ERC



Here I disconnected R1 and the ERC found the error

If you click on the error it shows you where it is in the schematic

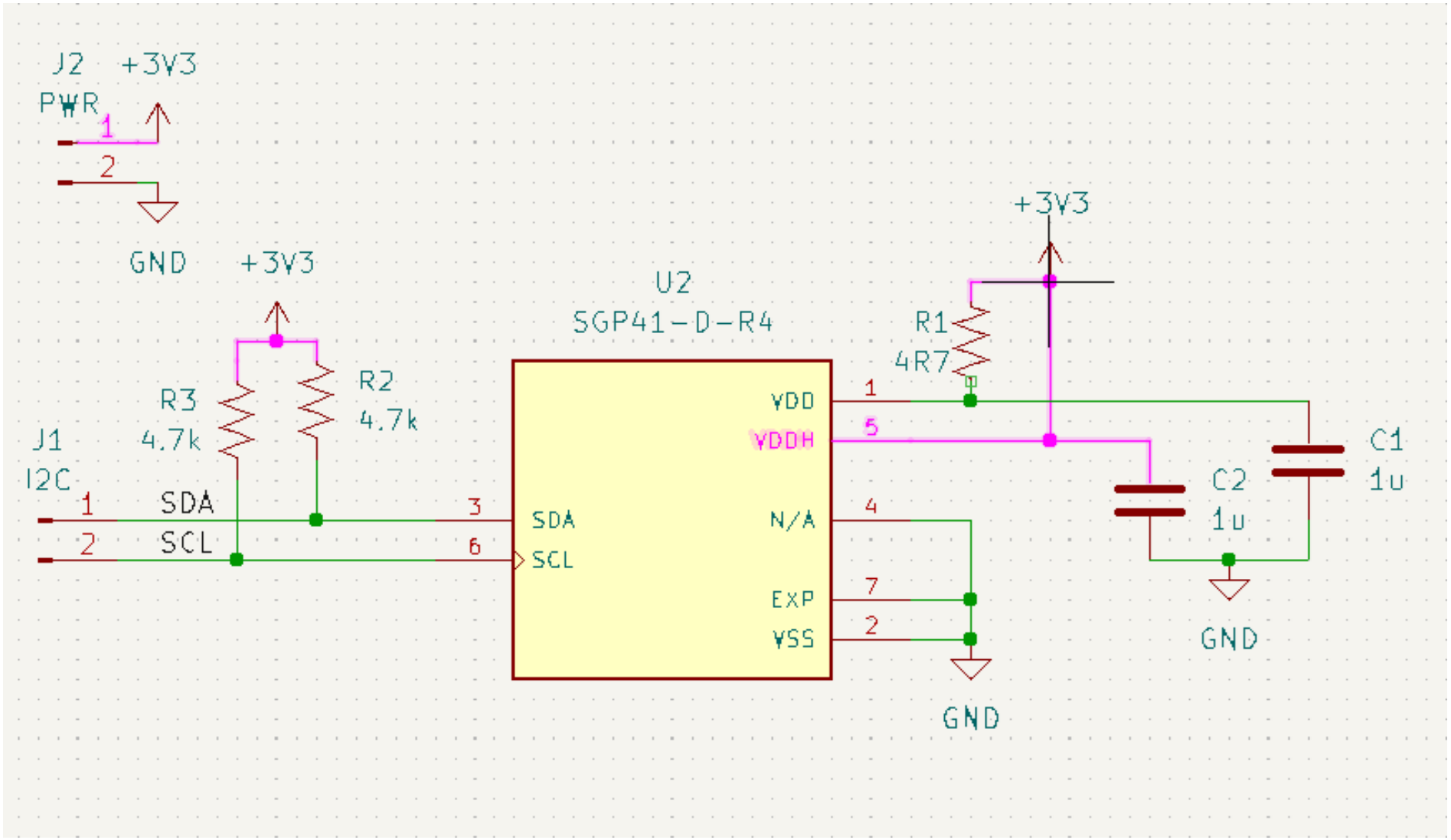




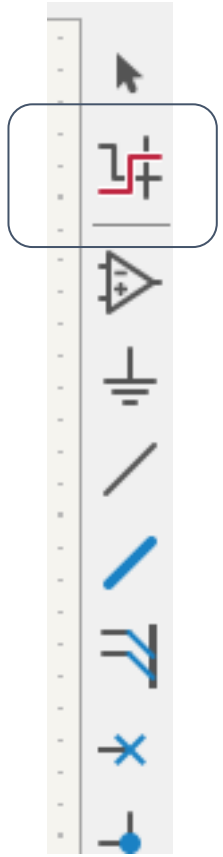
Here KiCAD is upset because my IC has power and ground pins and they don't seem to be connected to a voltage source

But we know they are, so this is one error we can "Ignore all…"

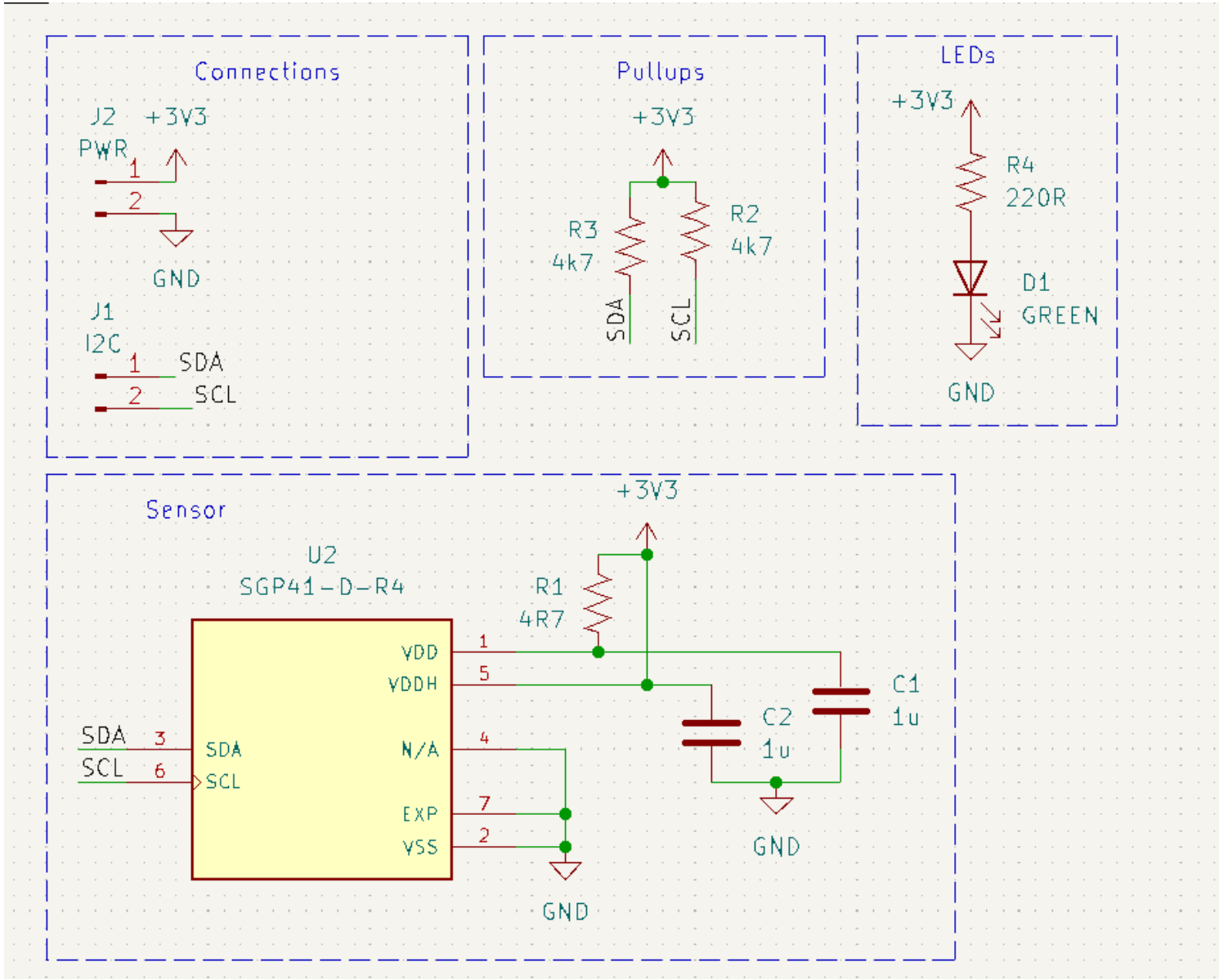
Don't ignore errors or warnings unless you understand what they mean



Now we can use



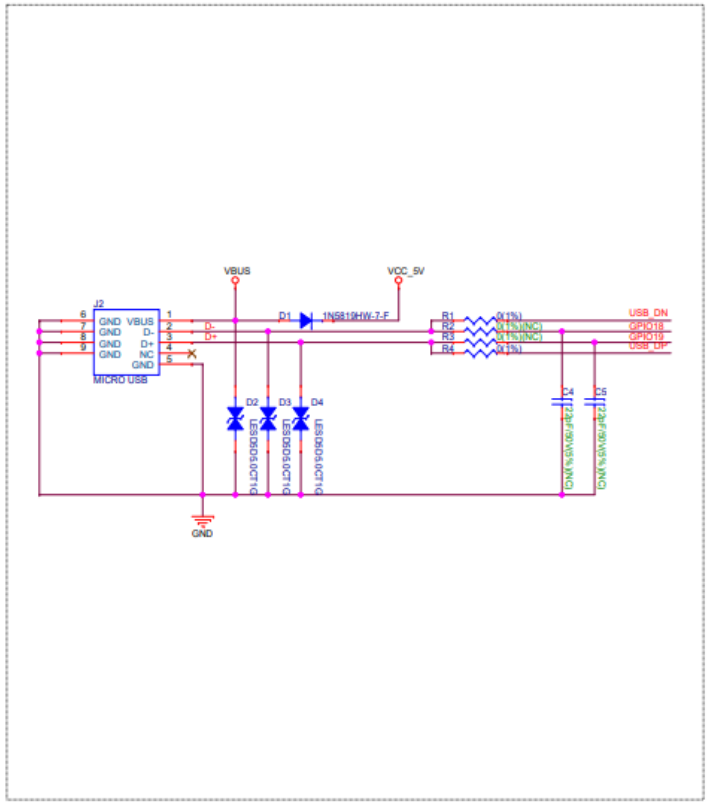
To highlight all wires of same net

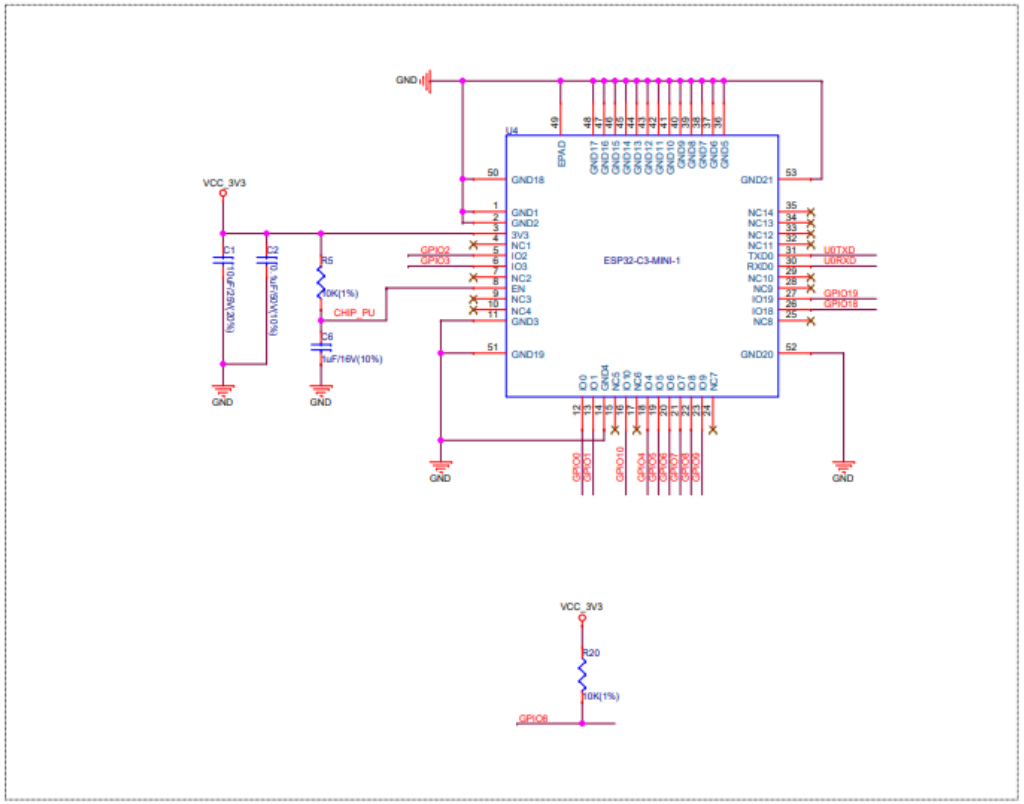


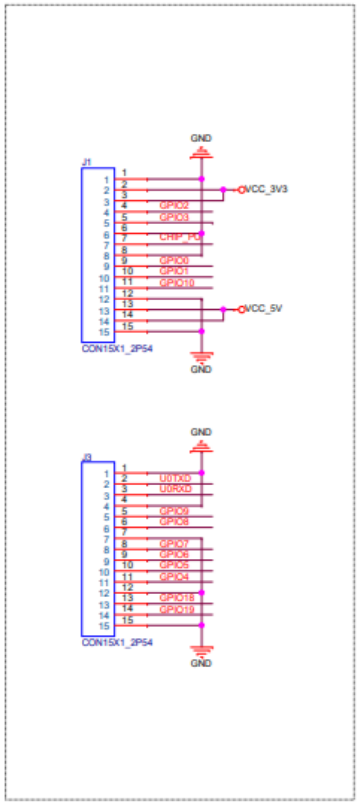
Too much?
I find this harder to read than the previous version

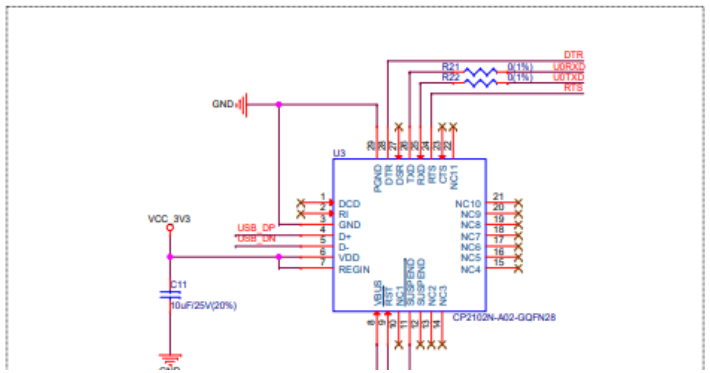
Balance use of direct connections with use of net labels

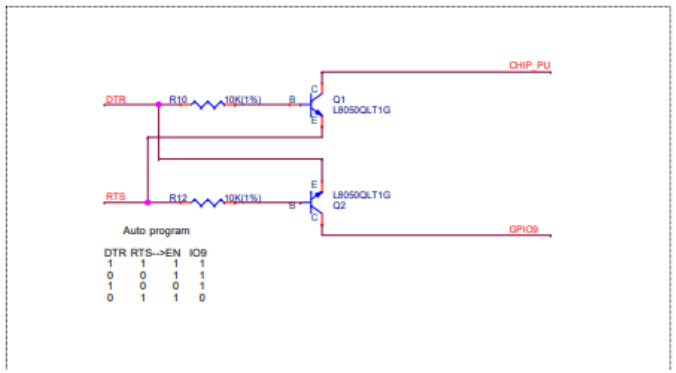
This is part of the schematic for our ESP32C3 dev board
See how they put different parts in different sections?

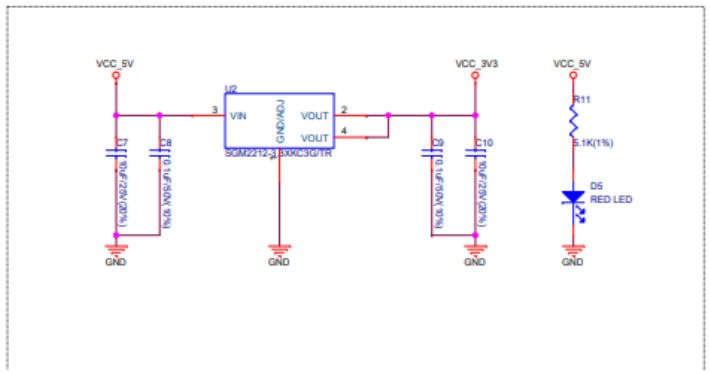




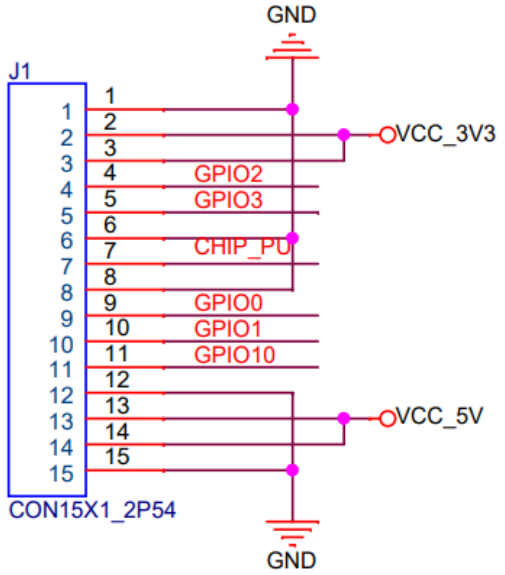


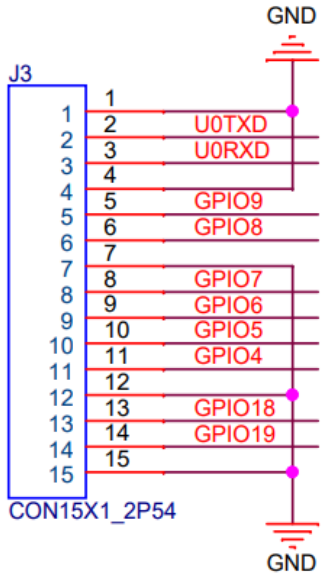




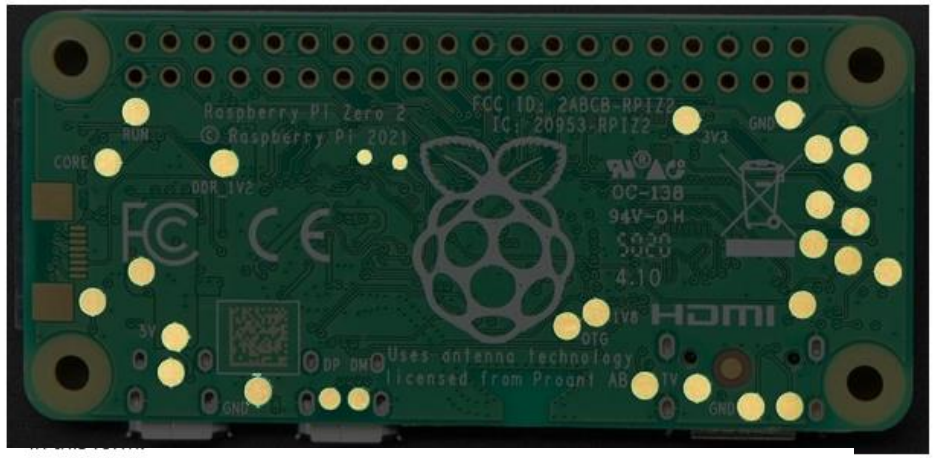


This is part of the schematic for our ESP32C3 dev board
See how they put different parts in different sections?
Net labels are useful for labeling the signals at all the connectors

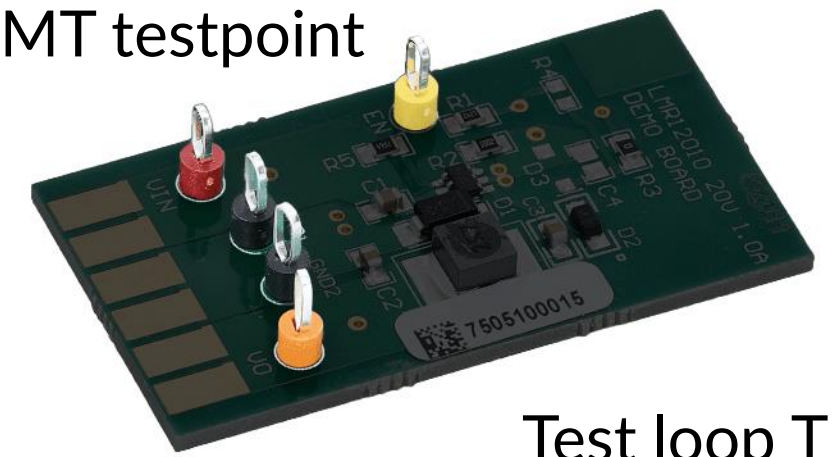




Don’t forget about debugging!
Here I’ve added 4 testpoints
Make sure every important signal has a TP

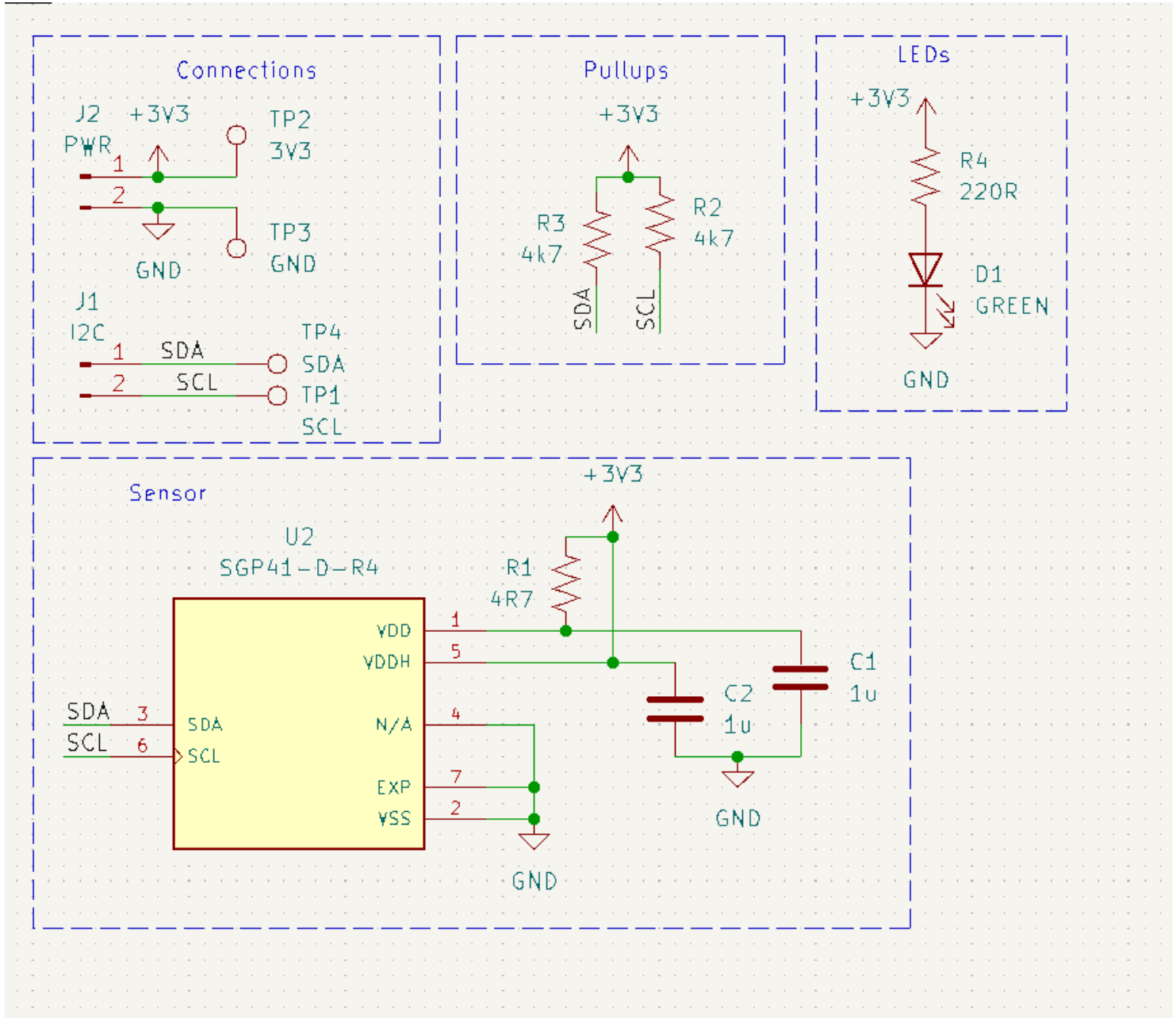


SMT testpoint



Test loop TP

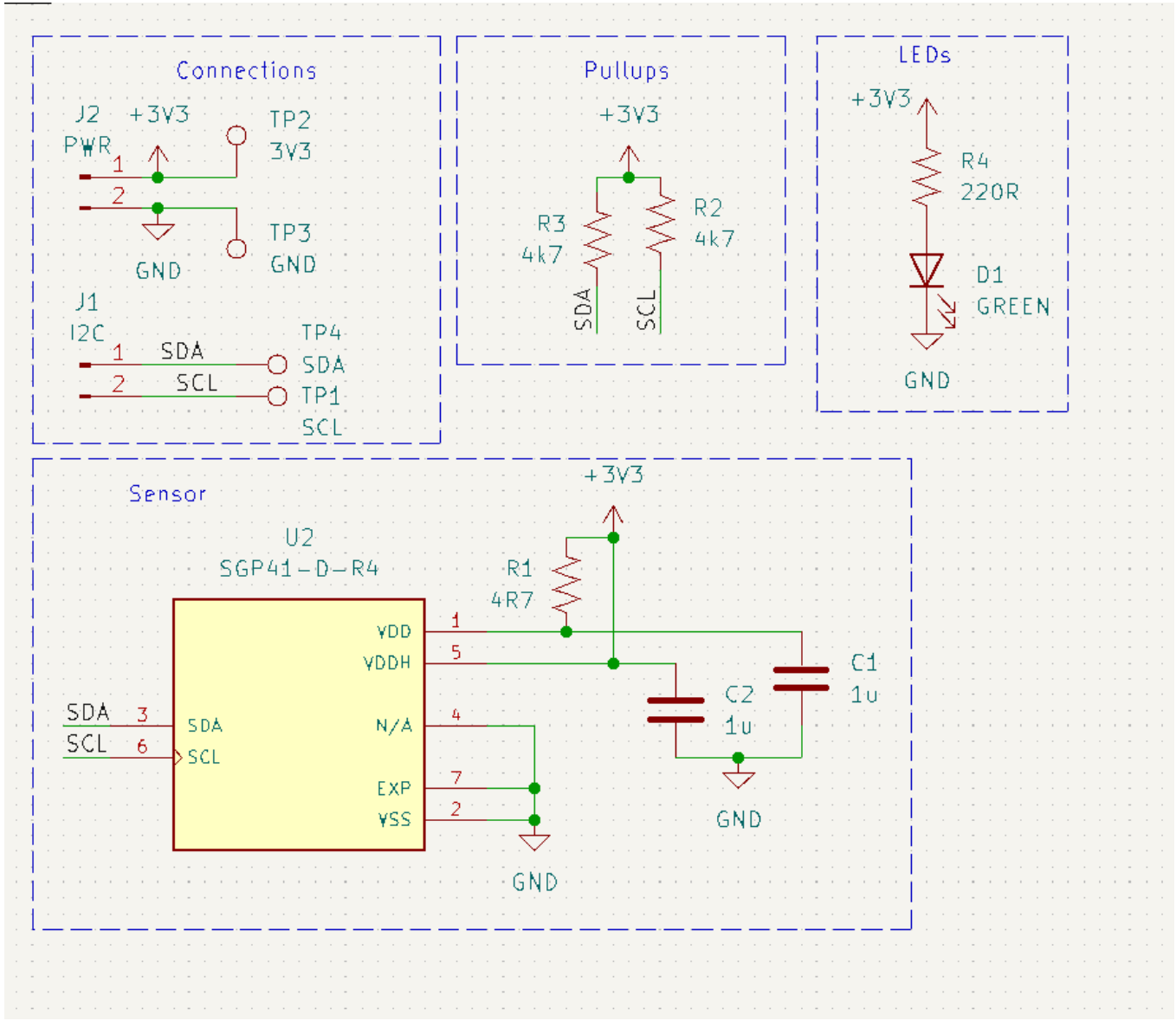
Image credit: TI, Editing credit: Winnie Szeto



Images from pcb.mit.edu

I also added an LED so we know if the board is even powered

You can add LEDs for other signals
Just be aware they will consume power, which can be annoying for battery-powered systems



You are not obligated to use every placed component, or limited to the value you denote

Example: many people put pull-up resistors on every board with I2C lines

But your MCU may have internal pull-ups, or another board may have pull-ups on those lines already. You only need one set

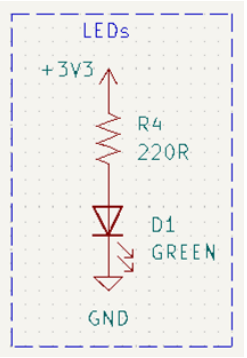
There is no problem to place components in the schematic and PCB but not install them in the actual board

You are not obligated to use every placed component, or limited to the value you denote

Example: You spec a 220R resistor for your LED. But then you decide to use a 470R resistor to reduce power consumption. That's fine.

What **really** matters is the footprint of the resistor on the PCB. If you place a 220R resistor with a 0805 footprint, you must use a 470R 0805 resistor.

That said, it's good idea to have the correct resistor values in your schematic because you will refer to that when assembling your board.



I won't go to PCB jail if I put a 470R resistor on the actual board

Closing thoughts

- Thursday we'll talk in detail about the project
- Next week we'll continue down the HW/SW design pathway
- EX01 is out today
- Lab01 is out tomorrow