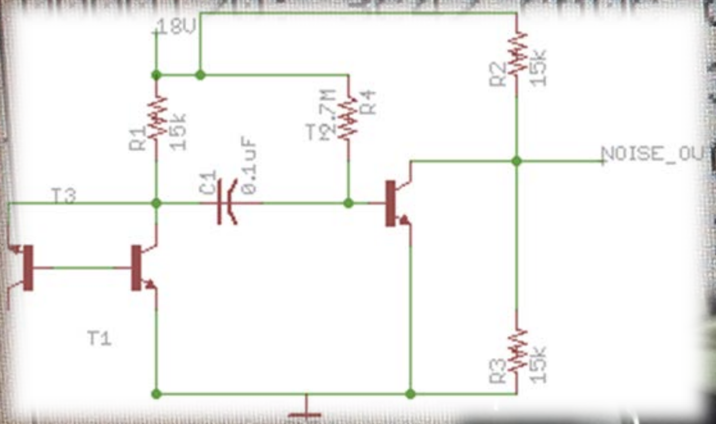
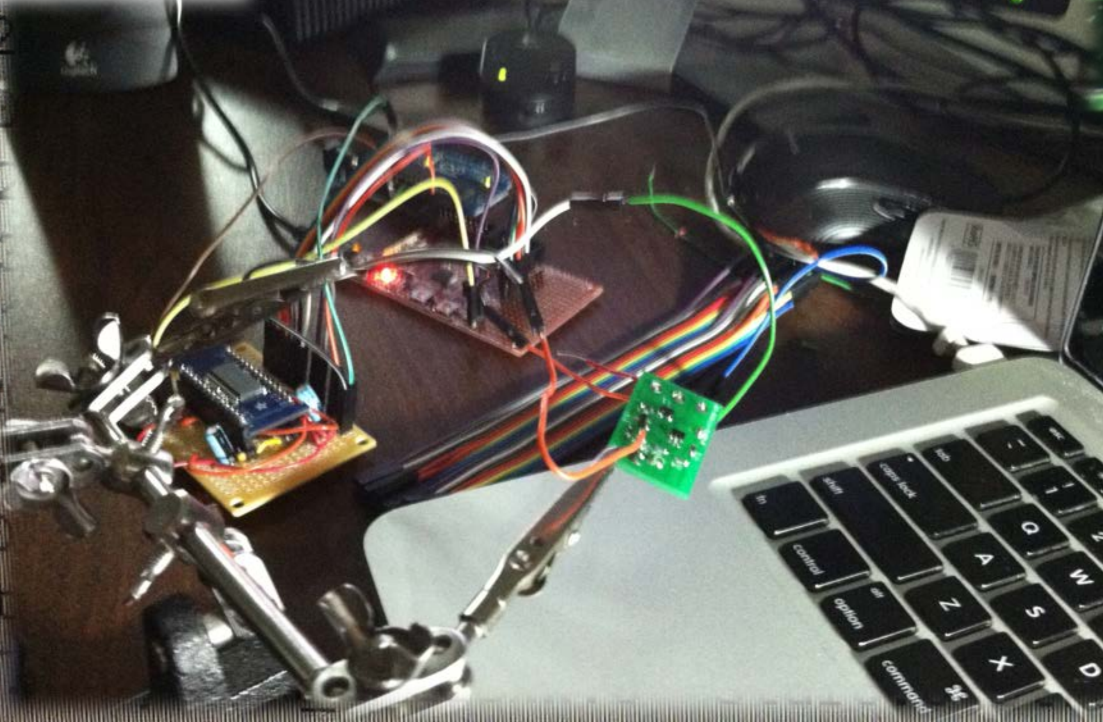
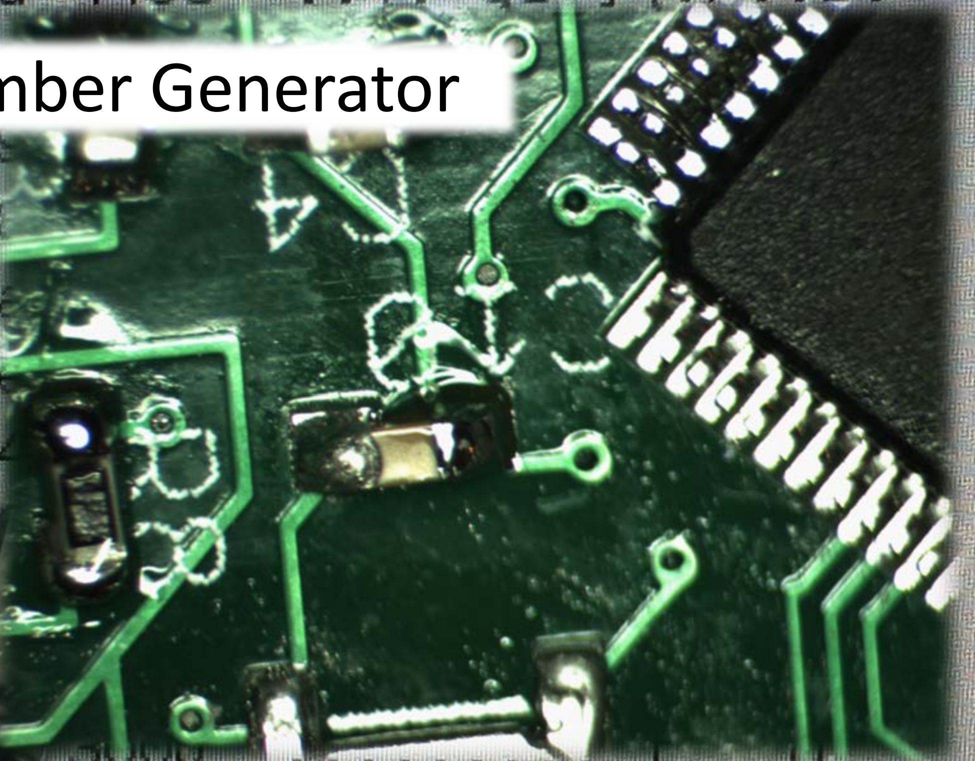
# Yet Another (Kind Of Bad) Hardware Random Number Generator







```
0000110: 3f12 161b 9136 061a 1d0e 1e8e 1b1
0000120: 3c42 cb0c df31 2902 1435 3203 0f0
         3c72 5b0b 1b71 1525 18a
         040b 3f0f 2c01 1f30 0d3
         273d 0369 4732 dd13 3c4
0000180: 172
0000190: 180
00001a0: 05
00001b0: b2
00001c0: 3e
00001d0: 12
00001e0: 1a
00001f0: a0
s -m ian@sievert
desc.o core_cm3                     ng.o adc.o cpu.o cmd.o   sy
handlers.o LPC1xxx_startup.o -lm
```

```
343a  .!Z....T....`W4:
5700  .4..>@,..w....W.
2123  >;..{.bT.{=YmI!#
ed91  ...."`4......>..
1503  ..-W....(..
5116  ..X...<..4.
```

Ian Kilgore
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2014-03-18

# I built a thing and I’m gonna talk about it

- Half theory
- Half case study
- ~~Half manbearpig~~

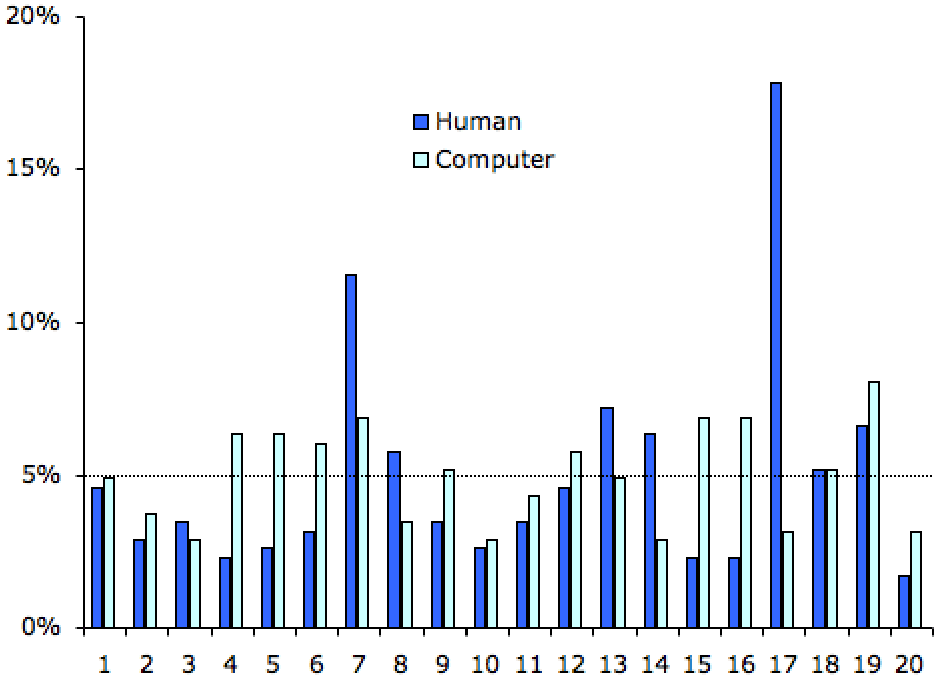
- Maybe I’ll just yell for an hour about the so-called “moon”

**WHO KNOWS??**

Photo © hectoriz CC BY-NC-SA 2.0

# People are bad at random – 1/2

- We are pattern-matching cognitive-bias meat machines
- General handwaving from your presenter re: bias, influence, determinism
- Read a book



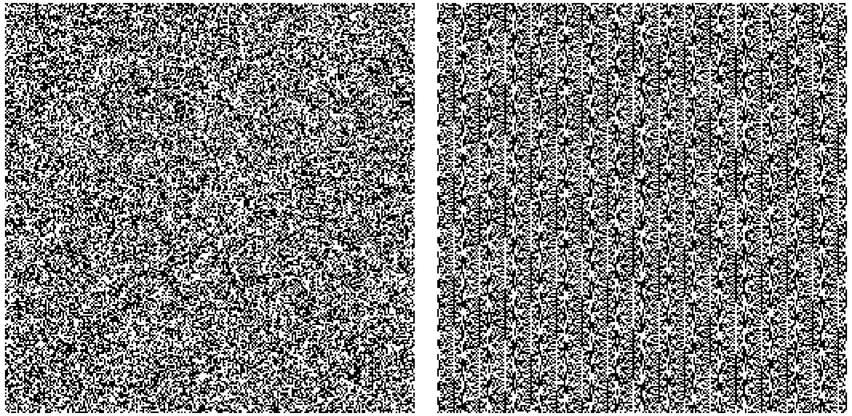
[1] Cognitive Daily, “Is 17 the ‘most random’ number?” by Dave Munger
http://scienceblogs.com/cognitivedaily/2007/02/05/is-17-the-most-random-number/

# People are bad at random – 2/2

- People are bad at FAKING random

- A: 0110100110011011010100111
- B: 1000101101100111111110001

# Computers are bad at random



RANDOM.ORG

PHP rand() on Microsoft Windows

(After [21])

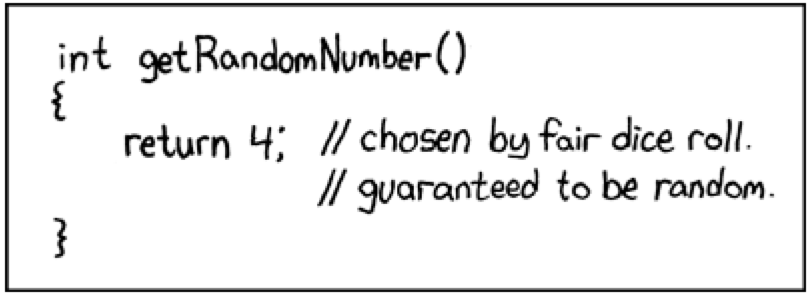
- Psuedo-Random Number Generators
  - Deterministic
    - Starting from an initial state (seed), algorithm will always produce the same sequence
    - Canonical seed is system time. (predictable). There are better ways
    - Number of embarrassing errors due to poorly-seeded PRNG
      - Netscape [16] (predictable seed: hashed time, PID, PPID)
      - Debian OpenSSL [17] (predictable seed: PID only, after entropy commented)
  - Periodic
    - Sequence does not grow beyond *n* bits
    - Finite internal state
- Entropy sources [15]
  - User input
  - Thermal
  - etc
- PRNG seeded with entropy source
- /dev/random, /dev/urandom

Photo © Joshua Davis, CC-BY-SA 2.0

# Are there TRULY random sources?

- What does that even mean?
- No, seriously, what does that even mean?
- No, seriously
- What does that even mean

- Impossible to prove [20]
- Leave it to the philosophers



```
int getRandomNumber()
{
    return 4;  // chosen by fair dice roll.
               // guaranteed to be random.
}
```

© Randall Munroe CC-BY-NC

- “Good enough”: cannot be predicted
  - **In the information theoretical sense**
  - Note *your inability* to predict does not mean unpredictable (stock market)
- Statistical tests: diehard [9], dieharder [10]
  - “Try it and see”. Judge likelihood
  - Possible to flip a fair coin 1,000,000 heads in a row. Unlikely.

# Quantum sources

- Photon + beam splitter
- Radioactive decay
- Shot noise

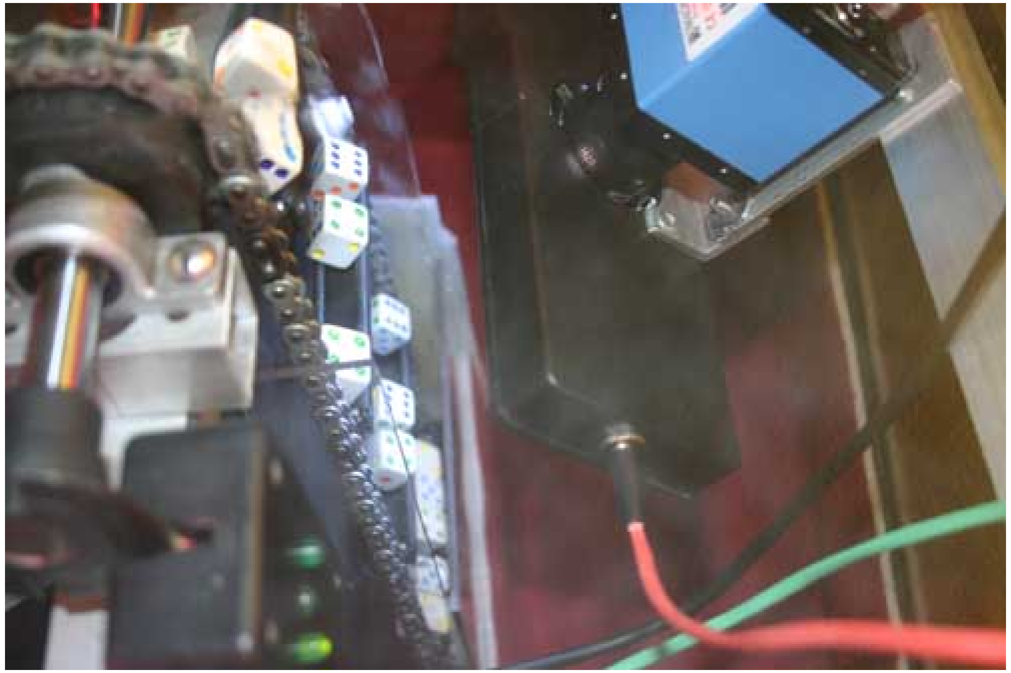
# Chaotic sources - Theory

- Chaos Theory ≠ Heisenberg Uncertainty Principle
- mad about this:

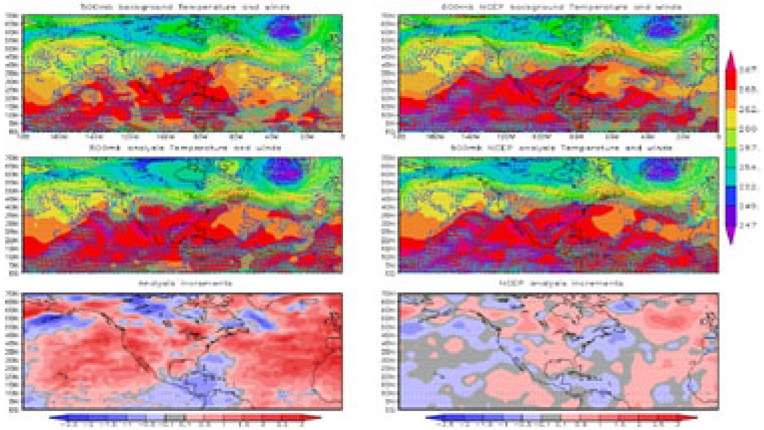
- A chaotic system is:
    - theoretically deterministic
    - practically impossible to predict
        - extreme sensitivity to initial conditions
        - nonlinearity
        - topological mixing
- “Butterfly Effect”
- Weather is chaotic
    - Even ignoring quantum effects, weather models are extremely sensitive to initial conditions
    - Forecasters run 100s of models and consider most likely outcomes (e.g. “% chance of rain”)
- Nate Silver’s book [11]

# Chaotic sources - examples

- Dice-o-matic [19]
- Weather: Random.org lightning radios
- Lava lamp
- Thermal noise, Brownian noise



http://gamesbyemail.com/News/DiceOMatic


500mb background Temperature and winds
600mb NCEP background Temperature and winds
500mb analysis Temperature and winds
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analysis increments
NCEP analysis increments
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http://www.nasa.gov/centers/goddard/news/topstory/2005/esmf.html

***Credit: Carlos Cruz, Shujia Zhou, Northrop Grumman IT/GSFC; Arlindo da Silva, GSFC; Erik Kluzek, NCAR; Weiyu Yang, NCEP.***

# Do we need good random numbers?

Photo © Peter Pearson CC-BY-SA 2.0

- Three use cases
  - High-volume
  - High-security
  - Make-believe
- Ex:
  - Scientific computation (sometimes)
  - Poker [8]
  - Lotteries [22, 23]
  - Debian package signing
  - Cryptography, esp. one-time pads
  - Sometimes the problem is just perceptual – Games by E-mail “Dice-o-Matic”

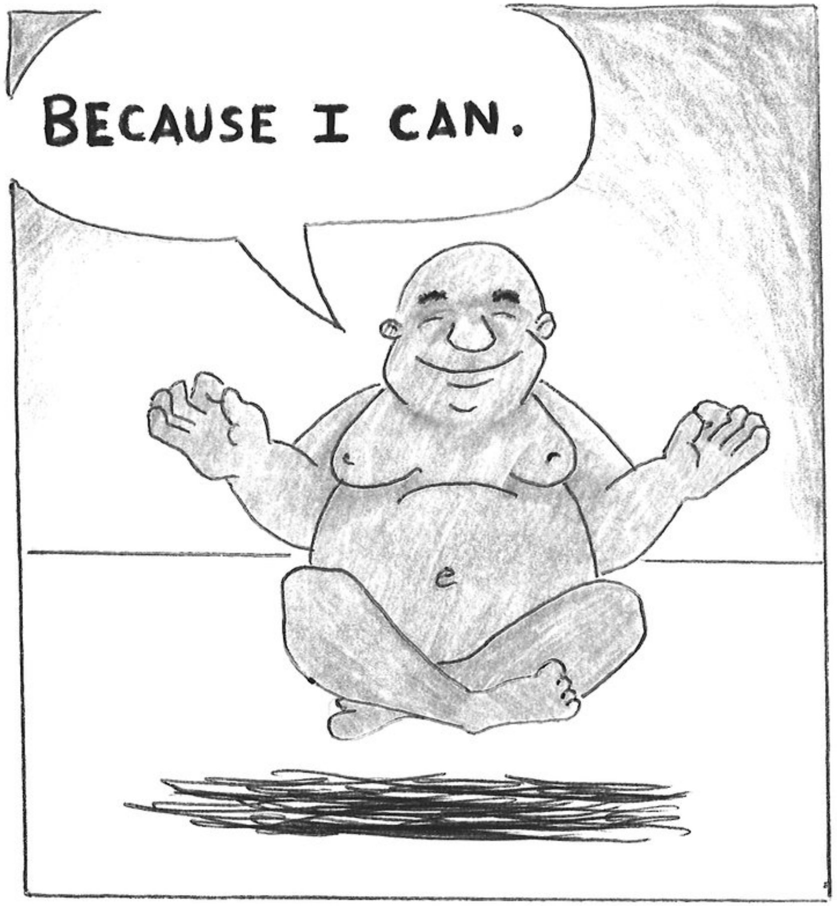
# An Aside About Threat models, or:

## Information security is fun to think about, but don’t be insufferable about it

- A funny paper [5] that I’m otherwise mad at with describes two canonical threat models:
  - “Basically, you’re either dealing with Mossad or not-Mossad.”
  - “If your adversary is not-Mossad, then you’ll probably be fine if you pick a good password […].”
  - “If your adversary *is* the Mossad, **YOU’RE GONNA DIE AND THERE’S NOTHING THAT YOU CAN DO ABOUT IT**”

Photo © Israel Defense Force, CC-BY-SA 2.0

# Previous slides aside, why *really* build this?



© Jacob Barrett http://www.realcostofprisons.org/comix/barrett/

# Avalanche noise - physics

Photo © Tim Sackton CC BY-SA 2.0

- PN junction (diode)
- One-way current flow under normal conditions
  - Pause while ik draws furiously on the whiteboard about PN junctions (if time)
- Strong reverse-biased E field causes avalanche breakdown
- Impact ionization
  - energetic e- knocks another e- out of the valence band
  - creates another electron-hole pair
  - In presence of strong E field, this process can continue through width of depletion region- multiplication
  - In a diode, this is effectively multiplication of shot noise (& other phenomena)
- McIntyre, R. J. "Multiplication noise in uniform avalanche diodes." *Electron Devices, IEEE Transactions on* 13.1 (1966): 164-168.

# Avalanche noise – predictability (1/2)

- Wiki says avalanche noise isn’t quantum

- Electron ‘gas’ is hardly classical

# Avalanche noise – predictability (2/2)

- Still, suppose that electrons in Si are classical gas
- Chaotic phenomenon which requires nearly-perfect knowledge of N initial states
    - (Heisenberg is getting antsy, but we're pretending it's classical; Uncertainty is a wave thing)
- Good discussion on wiki talk page [2]
- Let's do some Fermi/Napkin math:
    - Mean Free Path $\lambda$ on the order of:
        - 10 angstrom [3]
        - Largest measured ~135 angstrom [13]
    - Mean Free Time $\mathrm{T} = \lambda / V_d$
    - Drift velocity $V_d \sim 10^4\ m/s$
    - $\sim 10^{13}$ collisions per electron per second
    - Conservative order of magnitude estimate of N ~ $10^{10}$ electrons in our PN junction
        - (difference in between 1 $\mu m^3$ and molar volume of intrinsic Si)

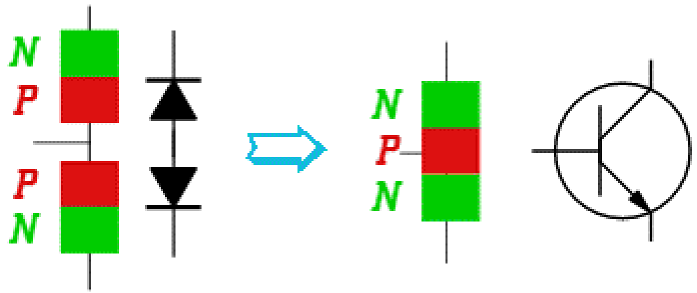
So even if we consider the phenomenon to be classical (which it isn't):

**There's a !@#$' lot of Really Wild !#$@ going on**

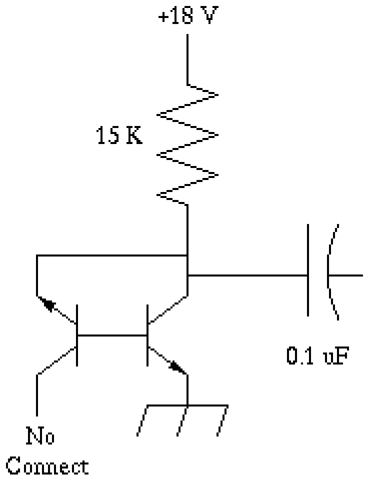
# Avalanche noise – TRNG design

Will Ware, 1995 [4]

Also basically everyone alive has built one of these

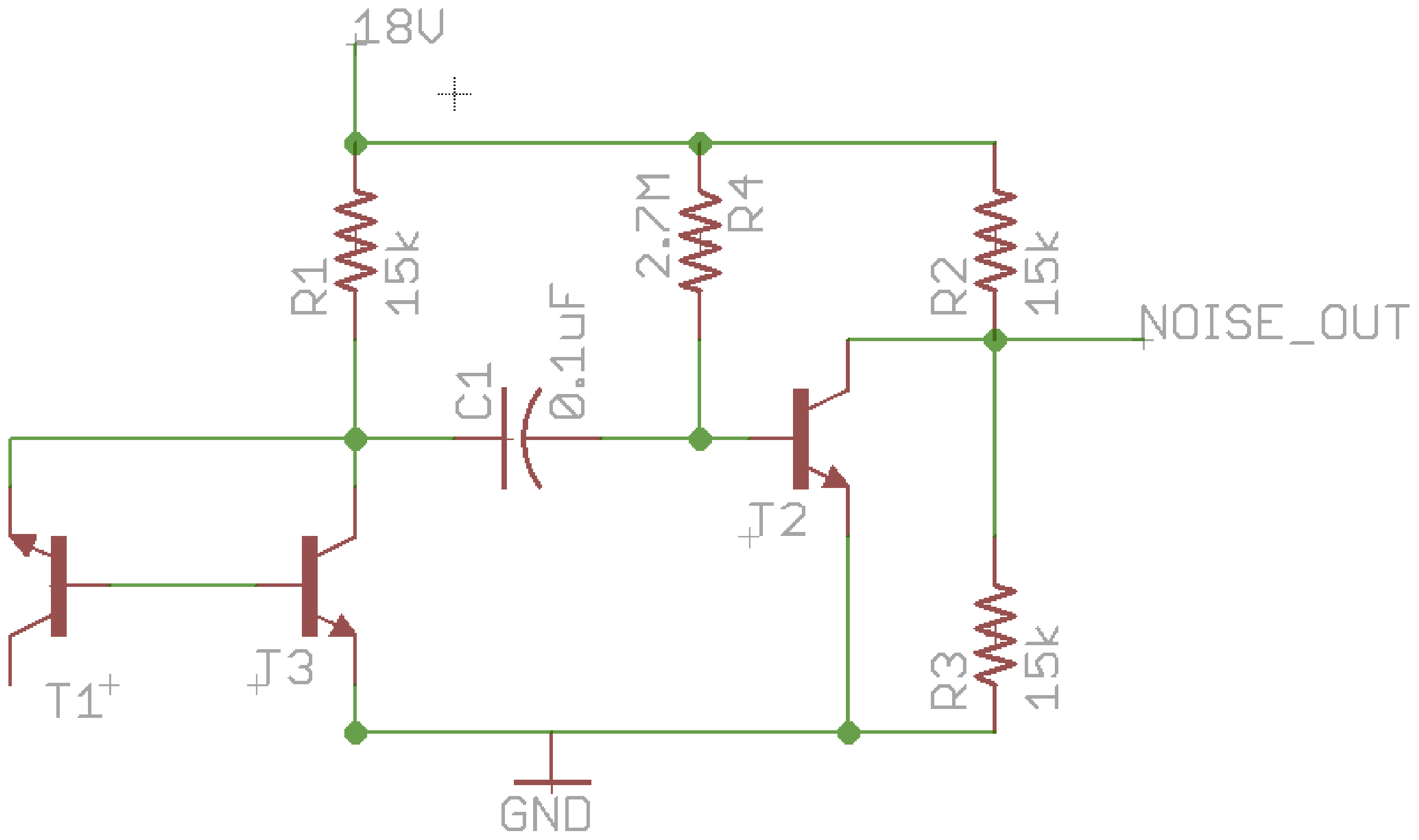


(After [14])

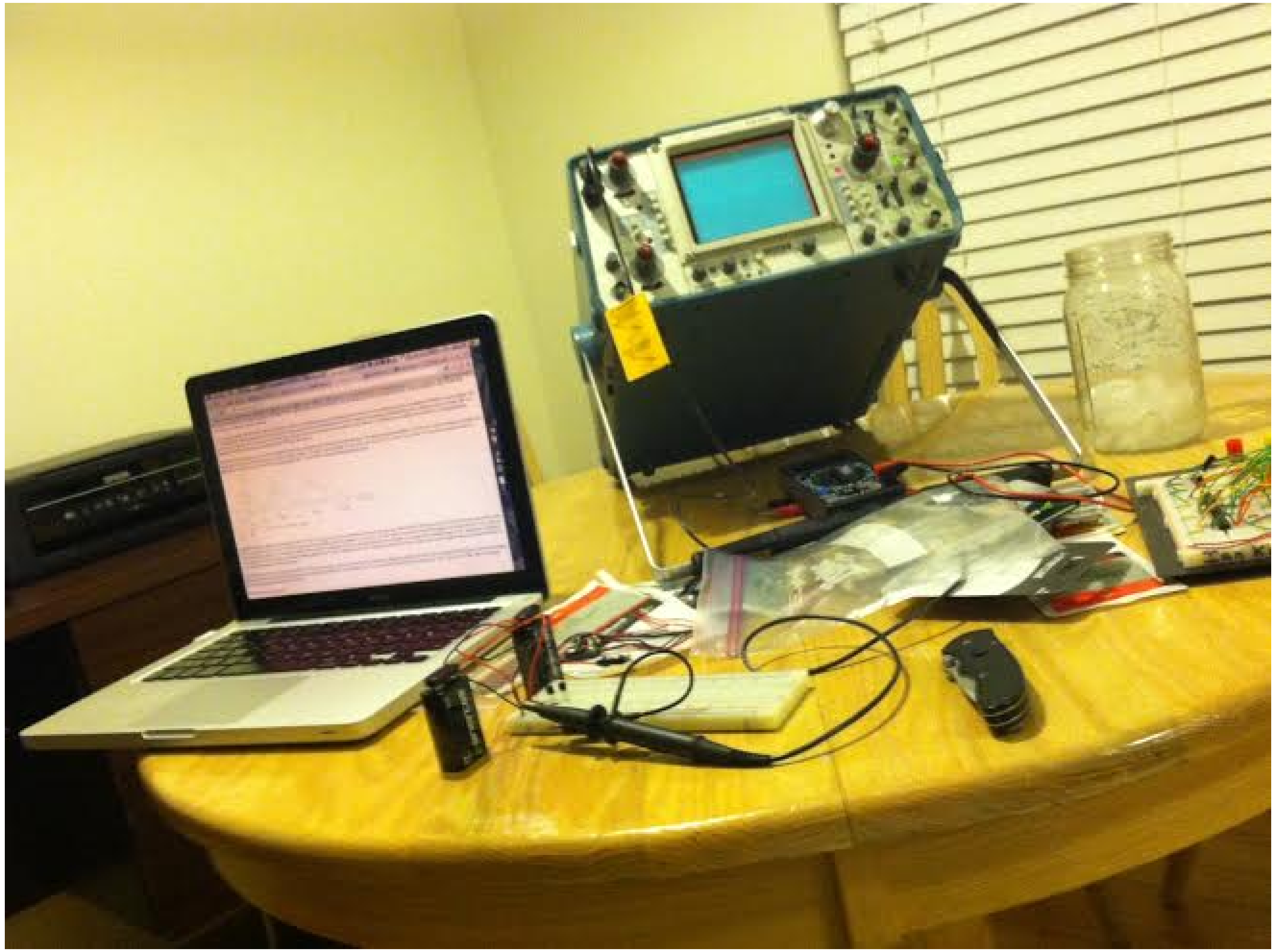


- First transistor
  - Collector N/C
  - One PN junction between base & emitter
  - Like a reverse-biased diode
- Why not diode?
  - Rectifying diodes designed for high breakdown voltage.
  - Zener diodes & others with low breakdown voltage designed to minimize avalanche noise
- Second transistor is C-E amplifier
- Capacitive coupling (high-pass filter) at output

# Prototype



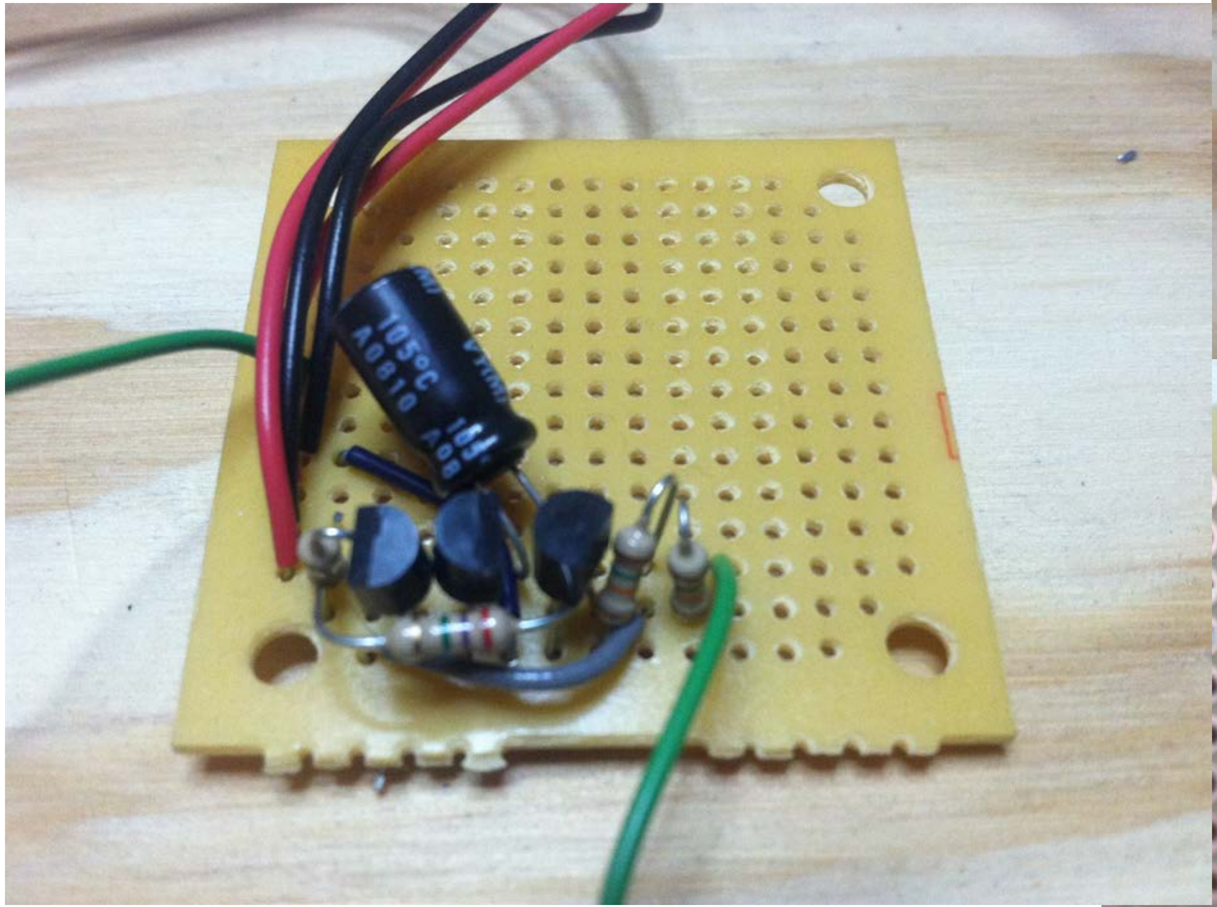
# Breadboard Prototype (failure)

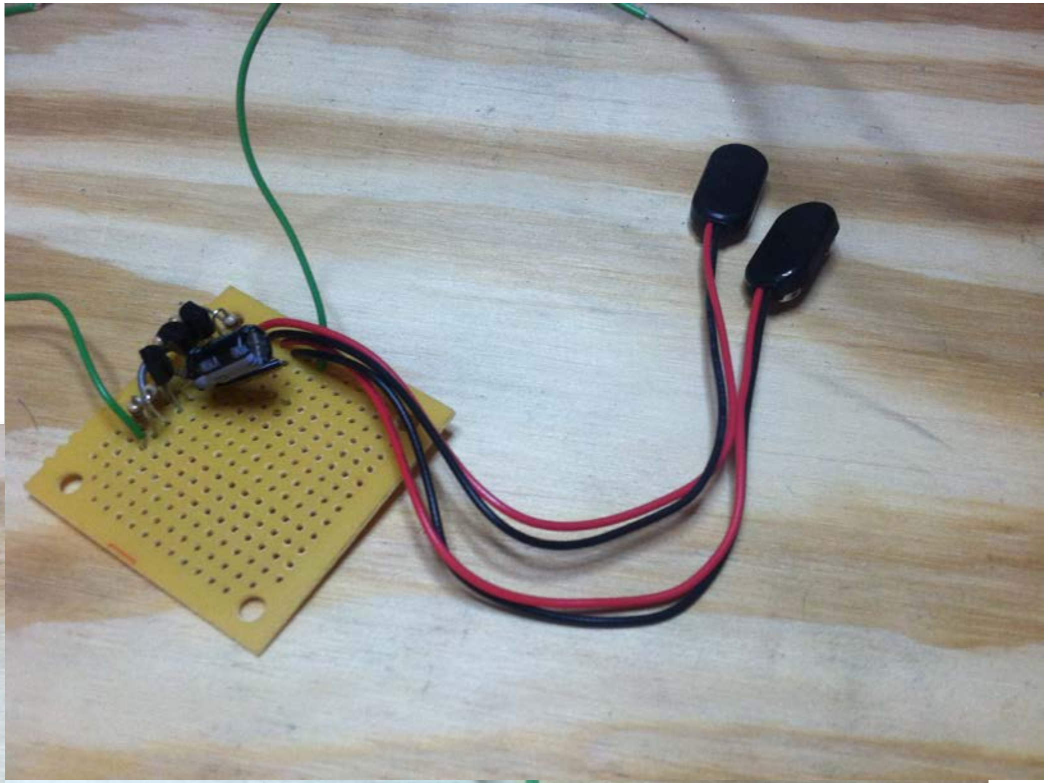


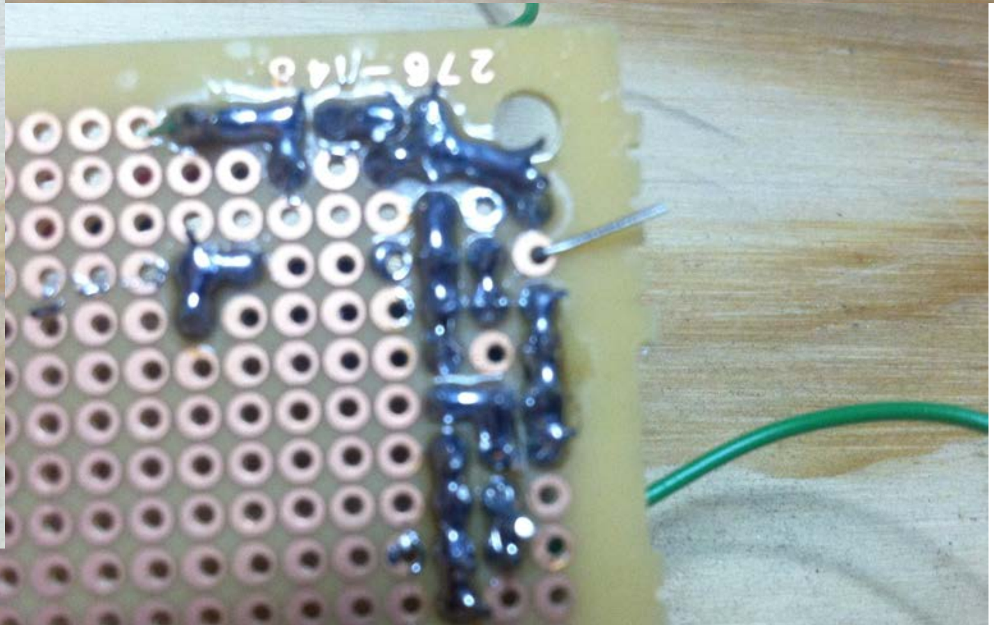
- Breadboard is a big box of parasitic reactance
- Also/or probably I hooked something up wrong

# Perfboard Prototype

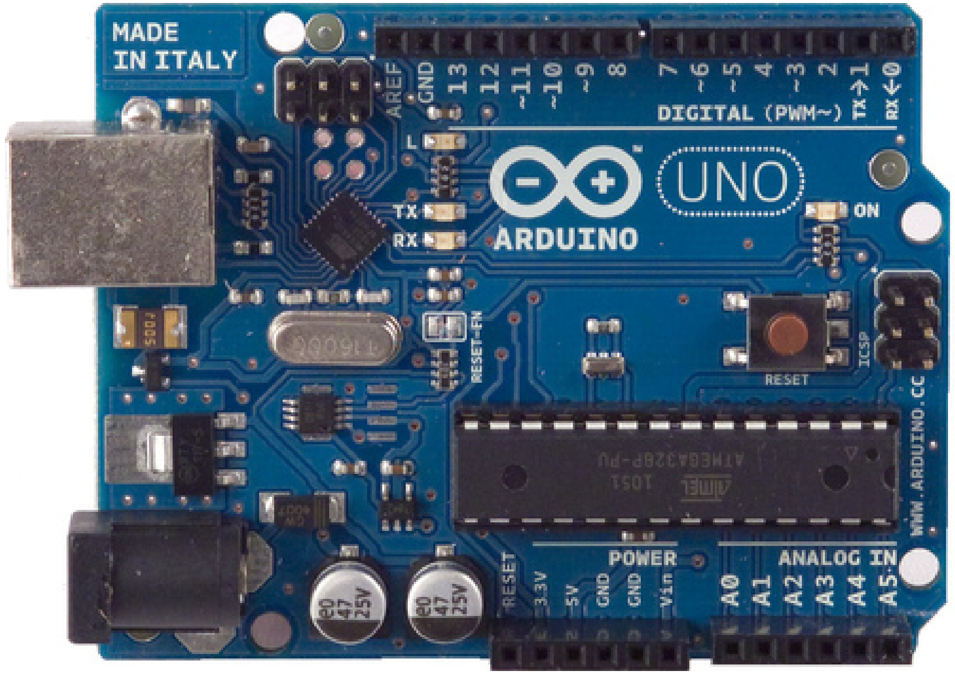
- Perfboard makes me mad
- More on this later







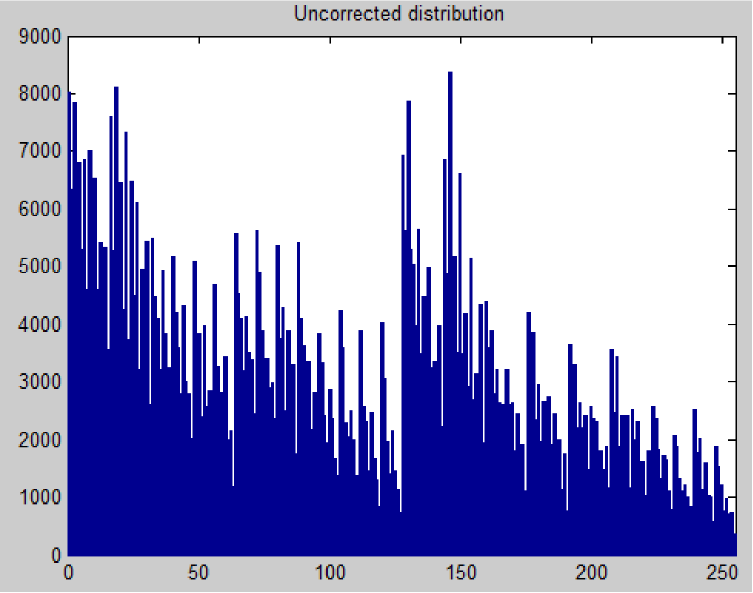
# Interface

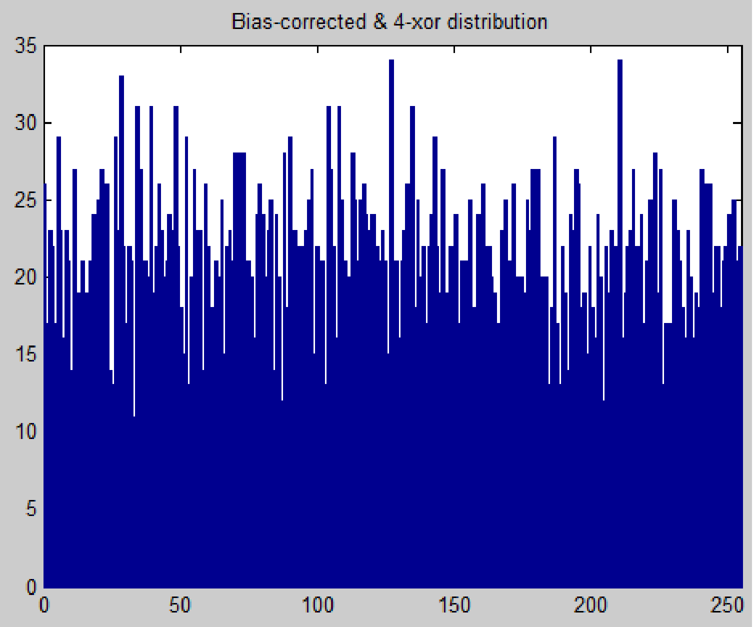


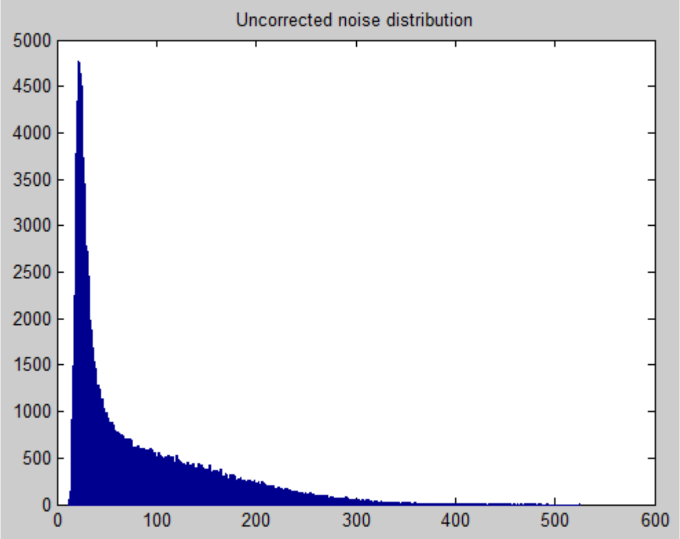
10-bit ADC, ~70k samples/sec
(~15 μs)

# Distribution/bias/correction

- Distribution not uniform
  - Still random (we hope- more later), just biased
  - Consider sum of a pair of dice
  - Can expect to get 7 more often than 12
- Software whitening
  - von Neumann's algorithm: take bits two at a time
  - 00 -> discard
  - 01 -> take 0 (or 1)
  - 10 -> take 1 (or 0)
  - 11 -> discard
  - (Think about it)

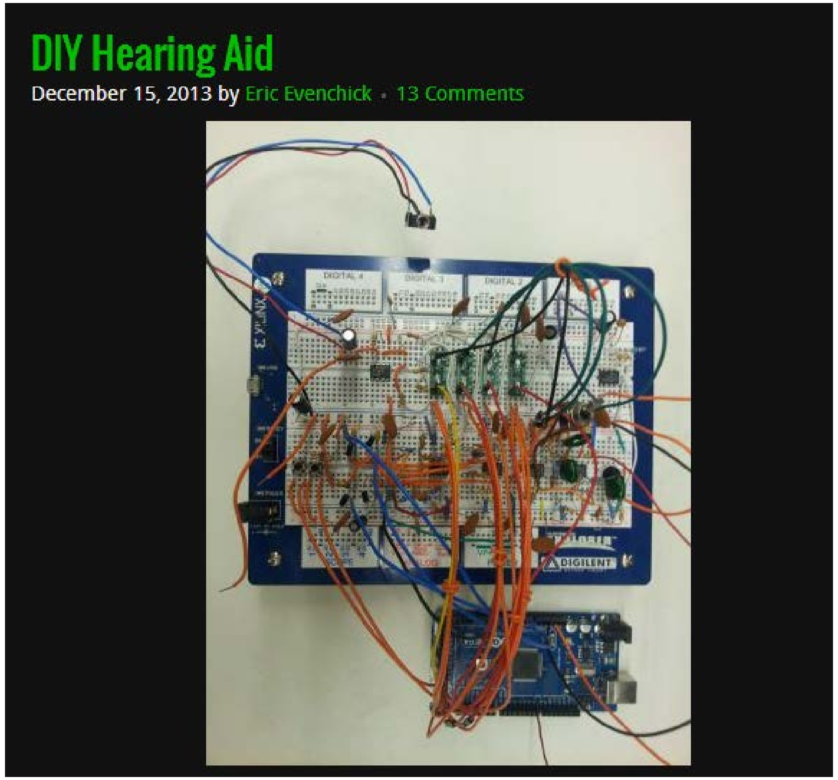






# Iteration

- Most hacks end at the PoC/prototype
- Good reasons for this
  - Do A Thing vs "plumbing"
  - Prototype took several hours and several dollars
  - Final revision: 100s of man-hours, 6 months wall-clock time, ??? dollars
- Goals
  - Single board, USB
  - Avoid "kits" / breakout boards in final revision
  - Speed
  - Also it should work



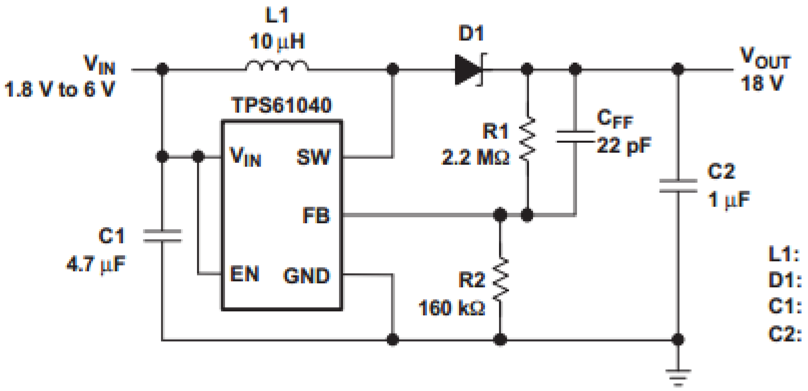
DIY Hearing Aid

December 15, 2013 by Eric Evenchick • 13 Comments

http://hackaday.com/

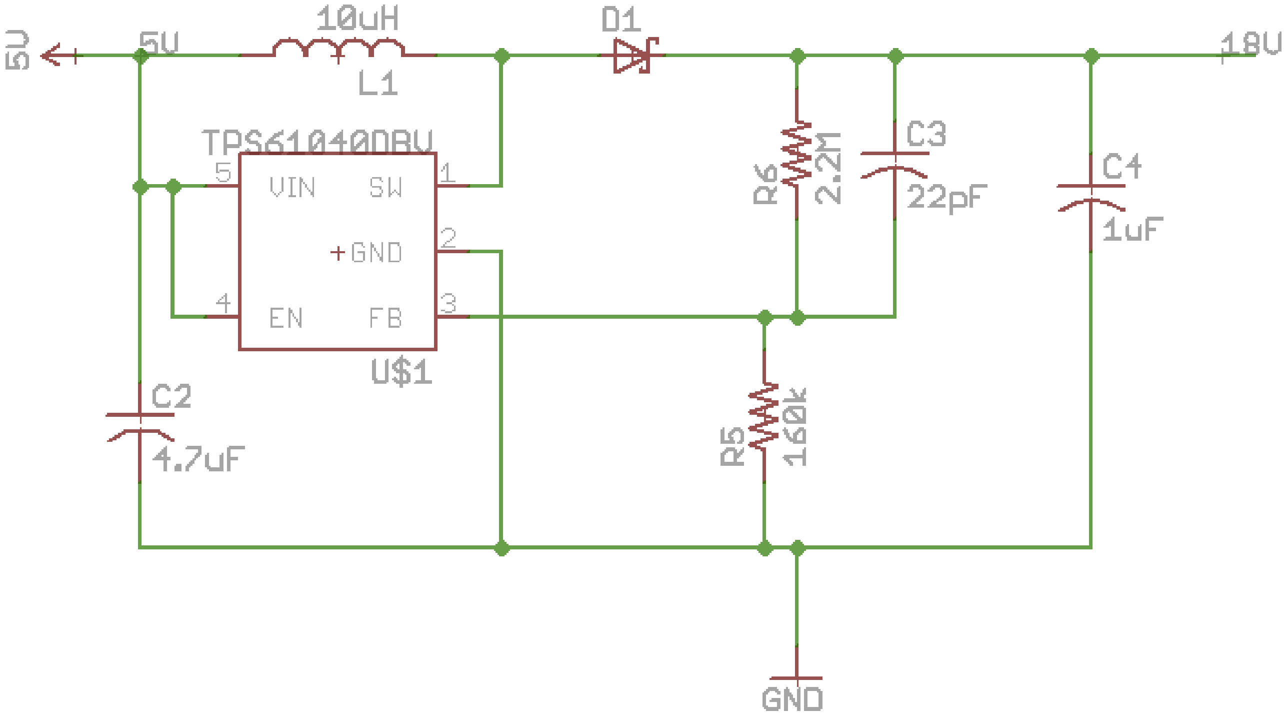
# Iteration – Power

- Eventually, run on USB (5V).
- Need 18V
- TPS61040 DC/DC boost converter
- Applications in datasheet

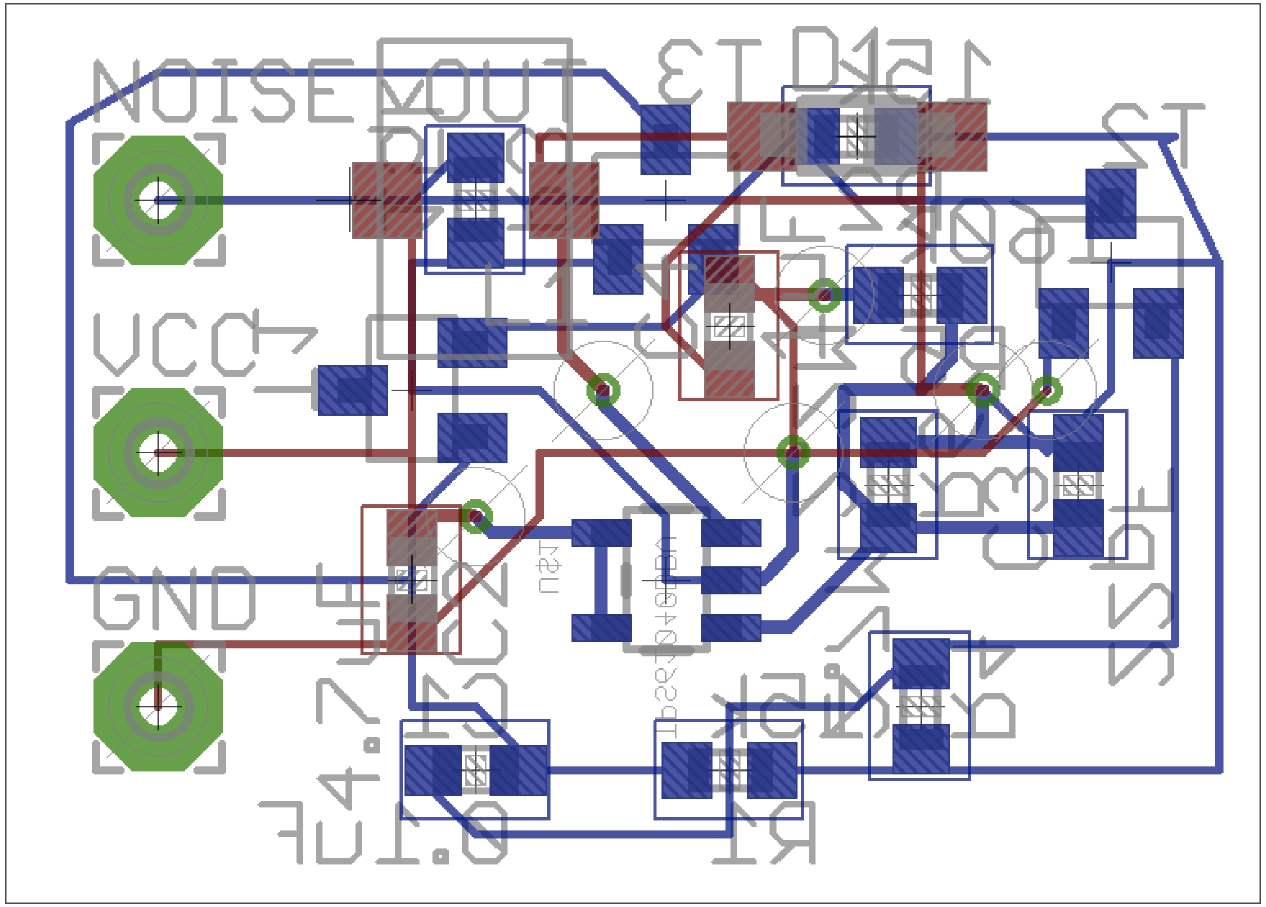


| | |
|---|---|
| L1: | Sumida CR32-100 |
| D1: | Motorola MBR0530 |
| C1: | Tayo Yuden JMK212BY475MG |
| C2: | Tayo Yuden TMK316BJ105KL |

**Figure 16. LCD Bias Supply**

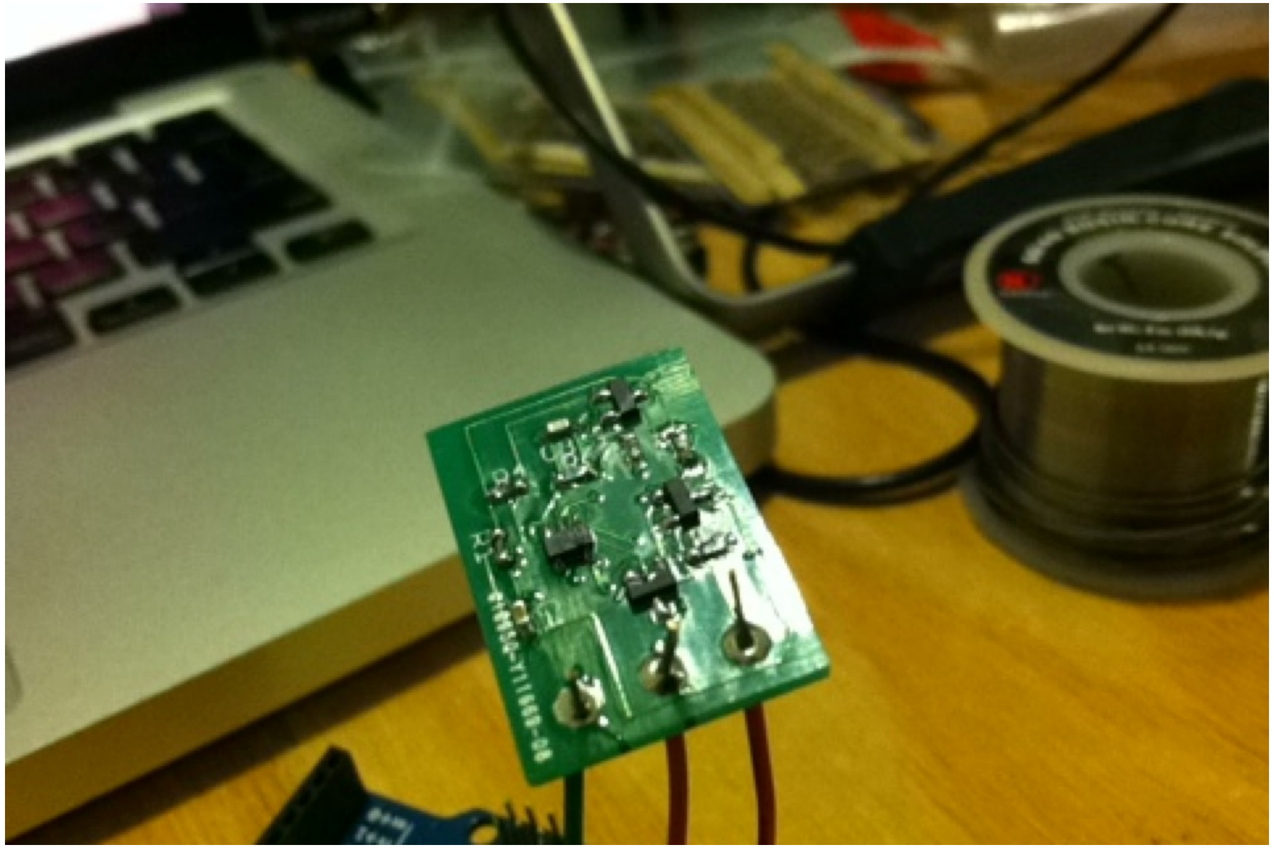


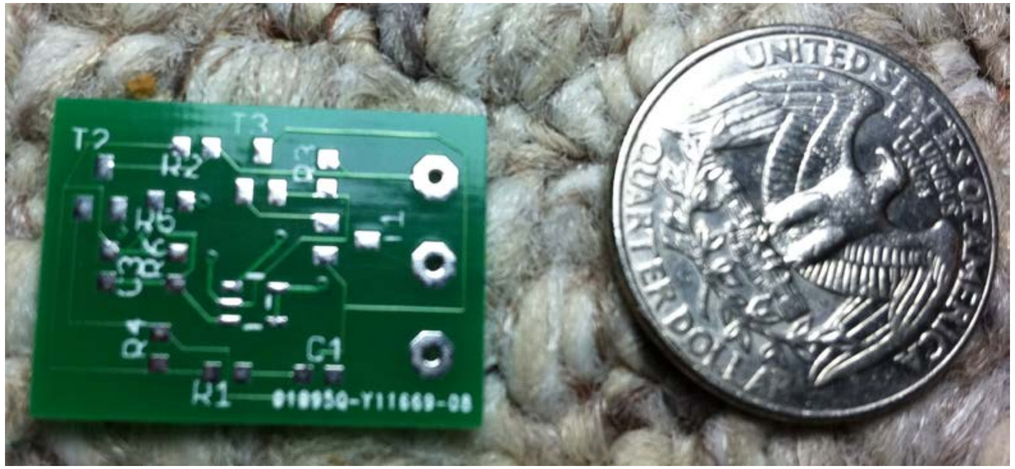
# Iteration - PCB

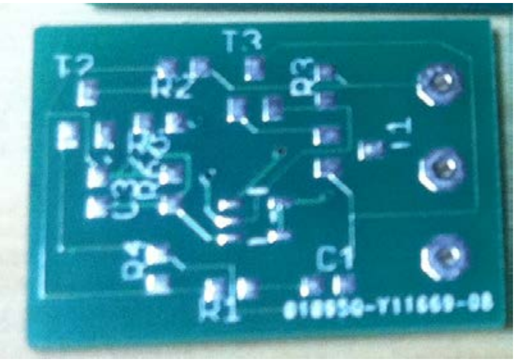


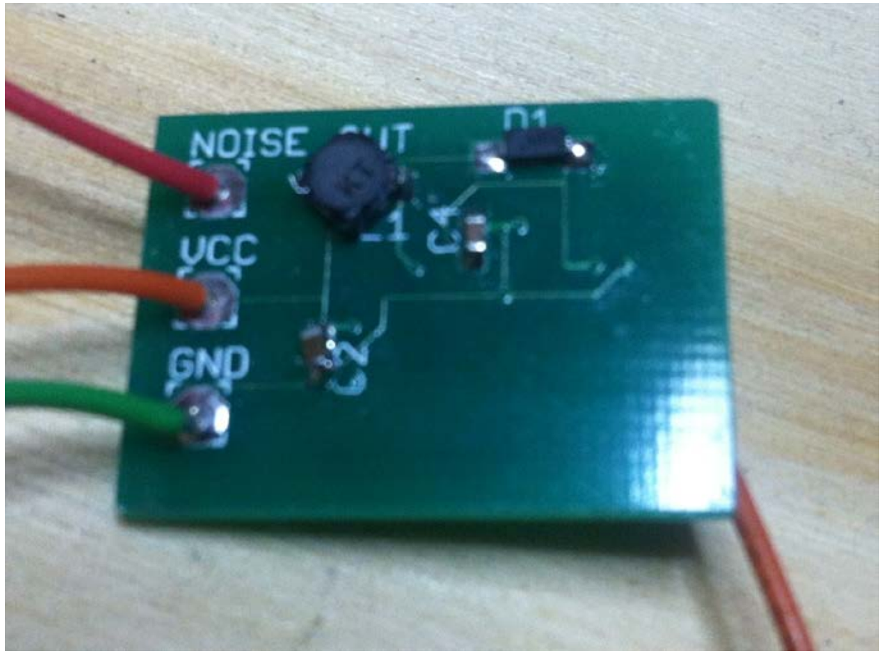
- Integrate physics mechanism & power supply
- PCBs manufactured by seeedstudio Fusion PCB service
- Real cost is time (~1 month)
- Errors are “expensive”

# Iteration - PCB



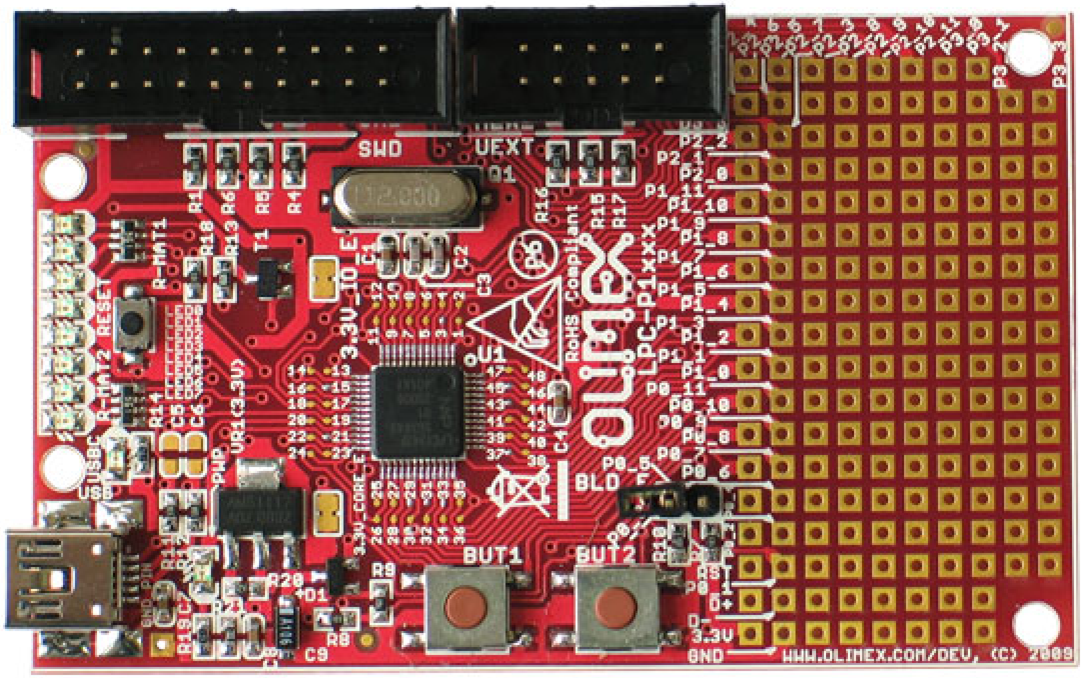






# Iteration – LPC1343

- Olimex dev board [7]
- ARM microprocessor, up to 72MHz
- Faster ADC
- Native USB 2.0
  - !!
  - vs. FTDI, V-USB, …
  - bootloader
- Wrote firmware: RNG enumerates as a USB mass-storage device. Writes fail, reads return random data.
- 40x faster (vs Arduino) (notes 2013-09-20 (1))



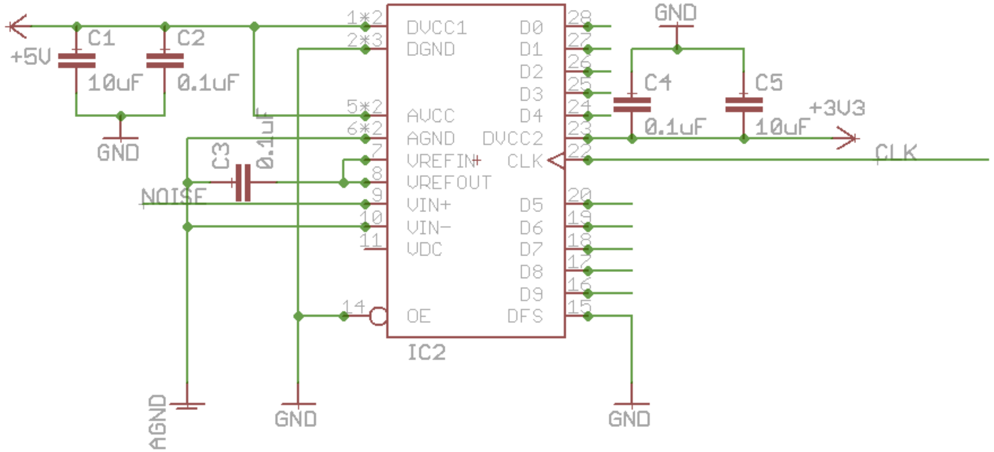
# Iteration – ADC – 1/3

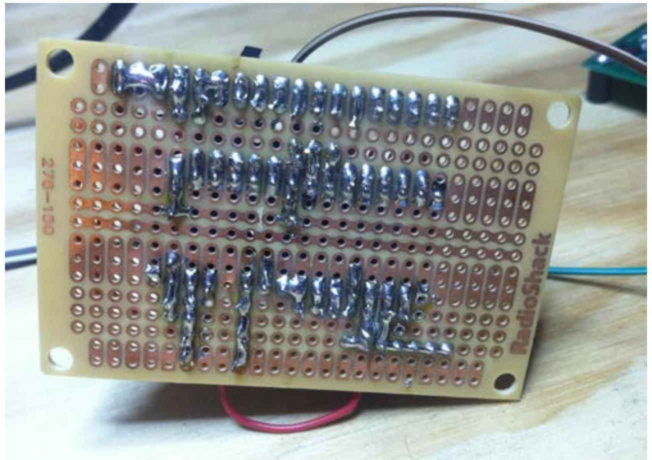
- Intersil HI5767/2CBZ [18]
- Running at 12 MSPS (notes 2013-09-21 (1))
- Pin-compatible drop-in replacements up through 60MSPS available.
- Limited now by MCU's –digital– I/O sample rate, and the USB bus
- End-to-end: "whitened" random bits at 50 kilobytes / sec
- 400x speedup vs prototype
- (notes 2013-10-11 (1))

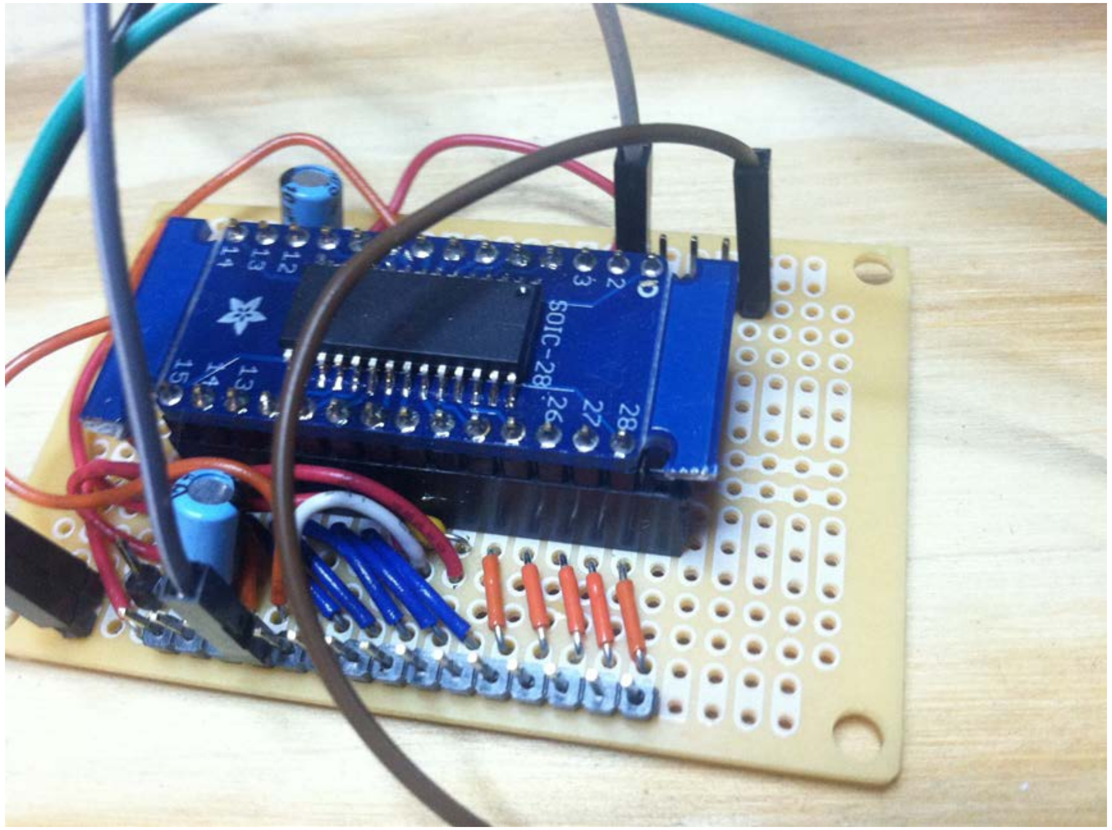
Photo © Alfonso Sintjago CC BY-NC-SA 2.0

# Iteration – ADC – 2/3

- First PCB + Separate ADC on perfboard + LPC1343

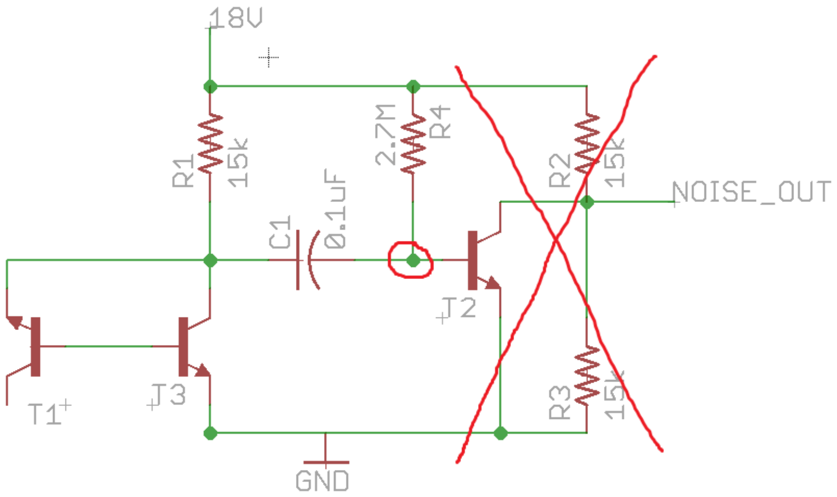


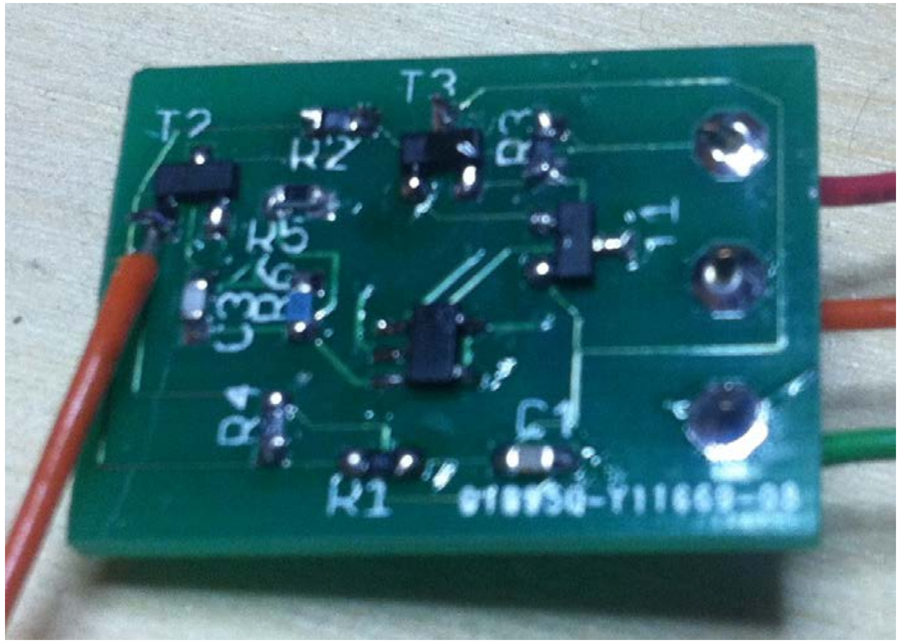




# Iteration – ADC – 3/3

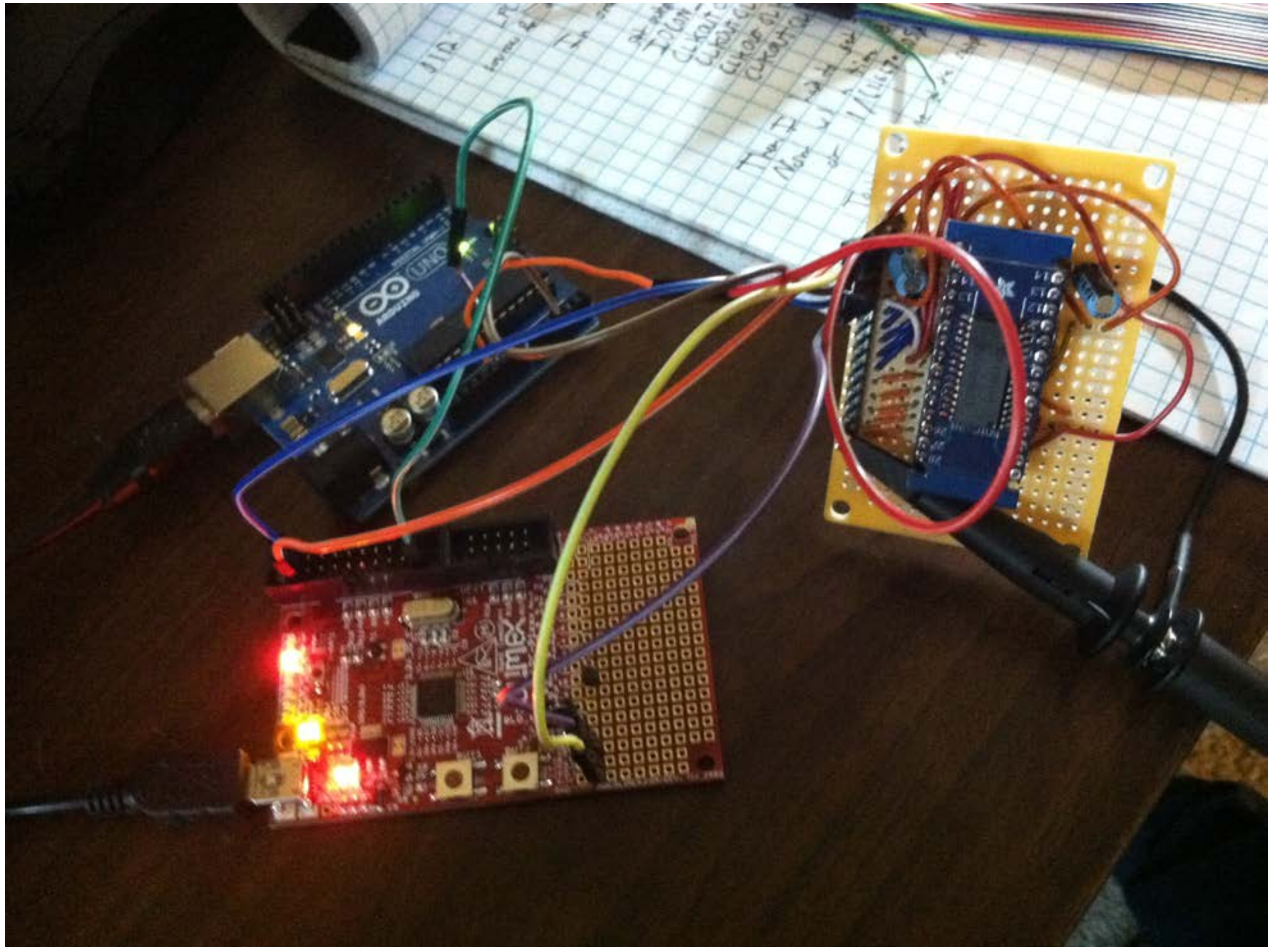
- PROBLEM! Get rid of one amplifier b/c ADC expects 1V p-p
- Jerry-rigged initial PCB



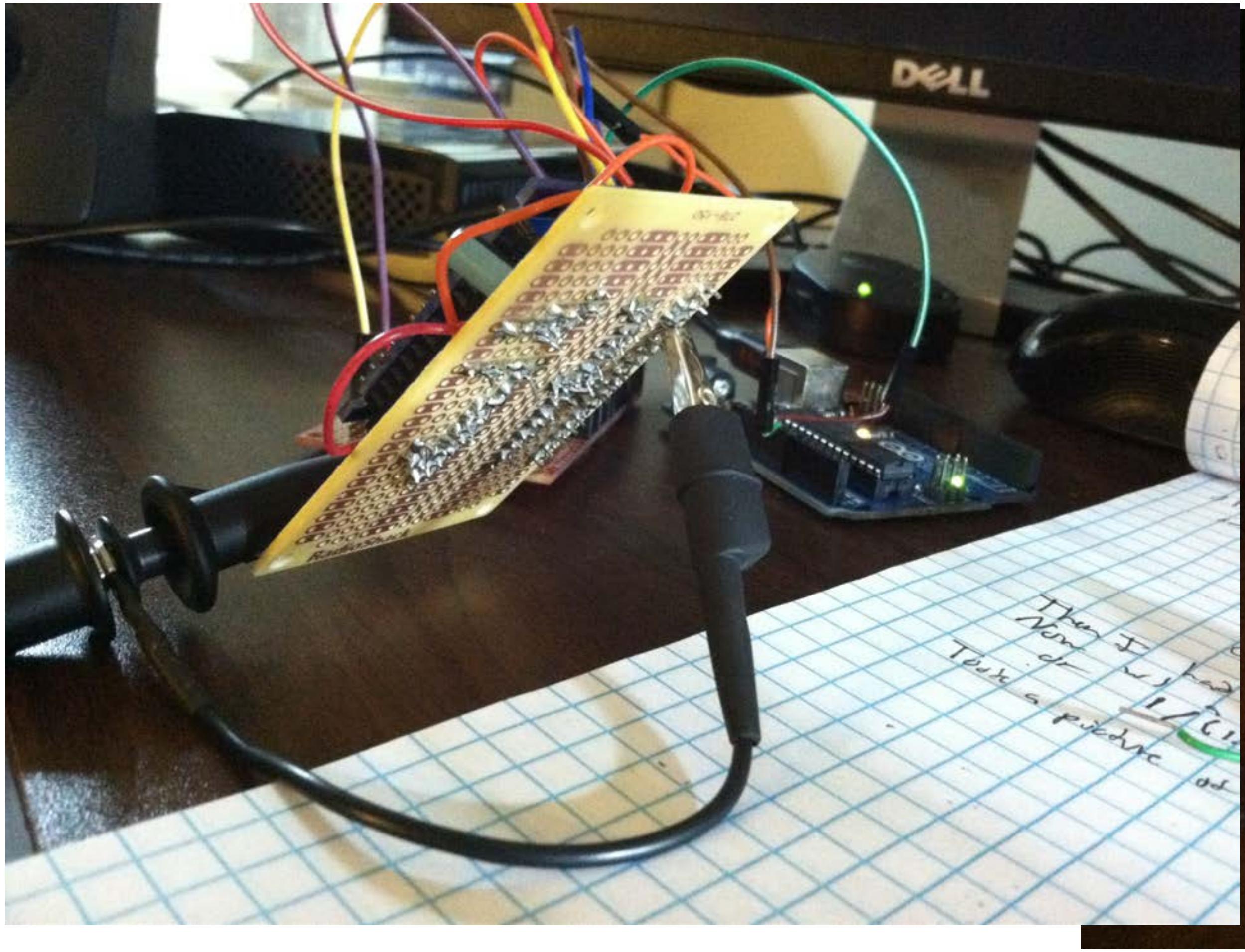


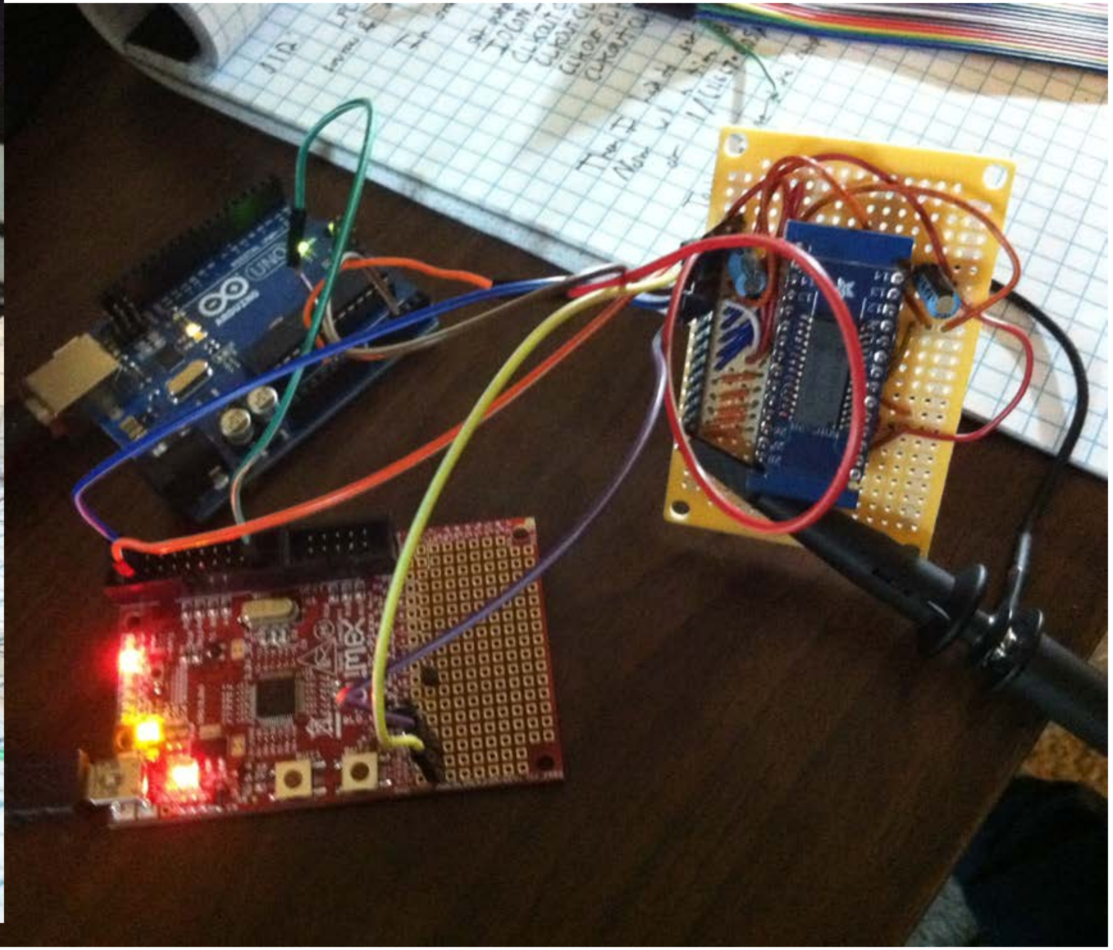
# Integration

- Hacked-up PCB (5V)
  - Physics mechanism
  - 5V -> 18V power supply
- ADC “breakout board” (5V)
- Olimex LPC1343 dev board (3.3V)
- Arduino uno (providing 5V)
- A whole mess of wires/problems
  - Running out of physical pins
  - Common ground
  - etc

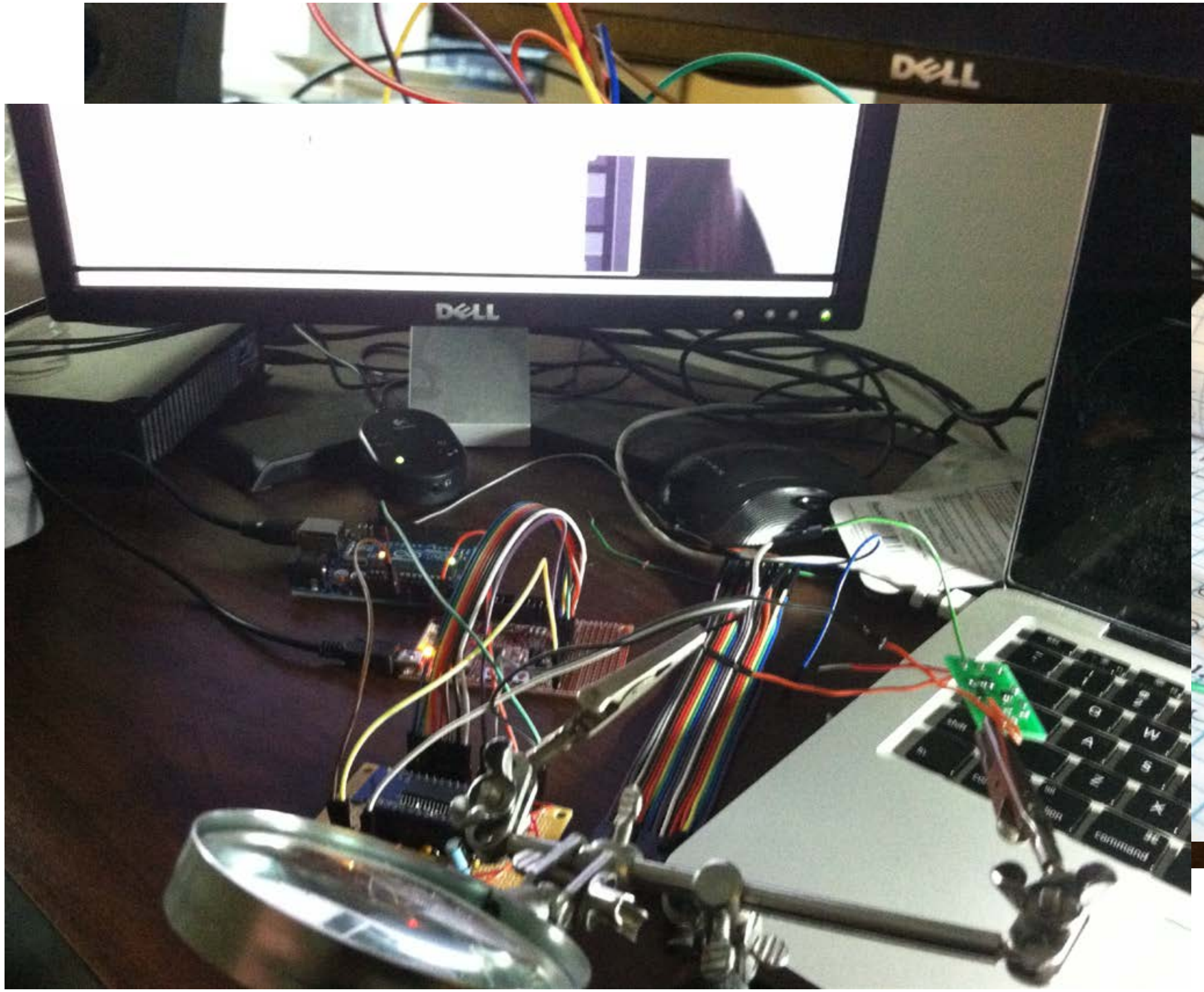


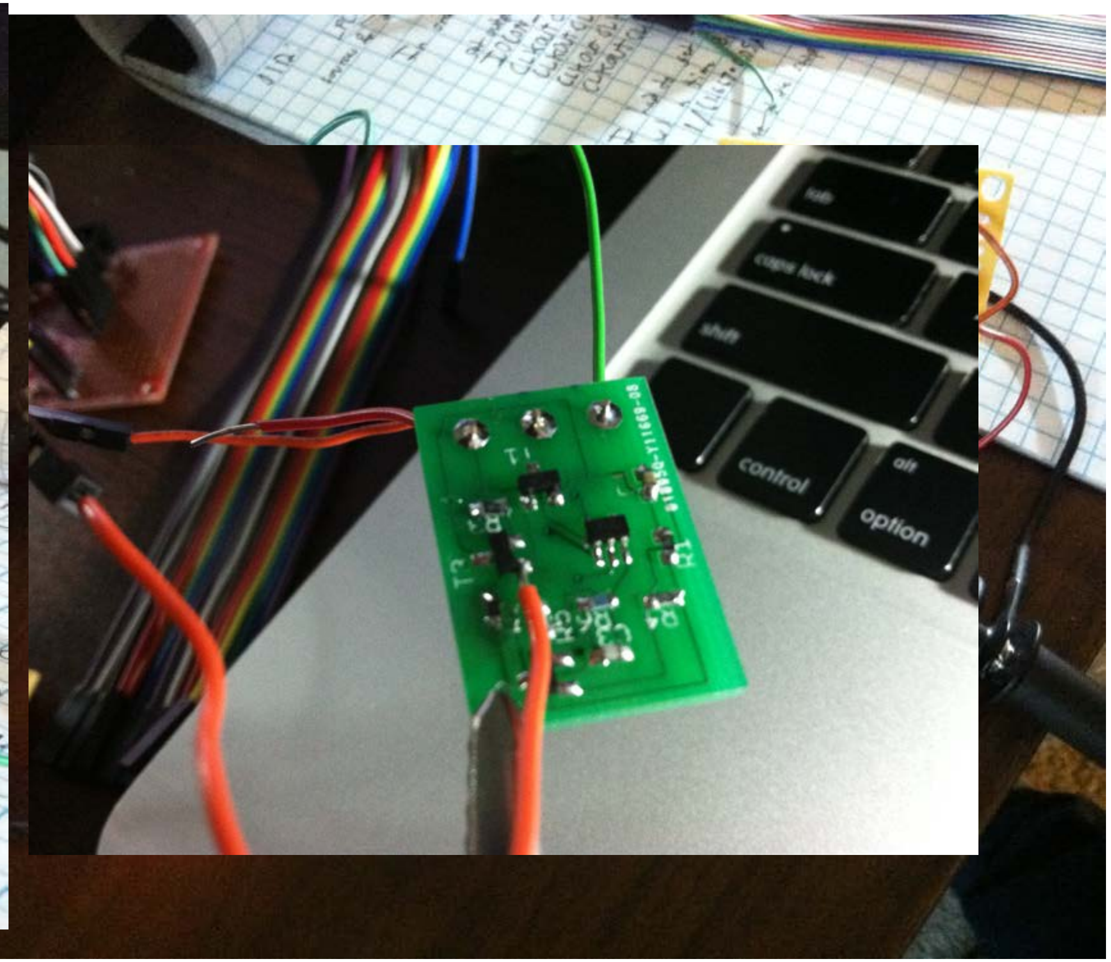
# Integration



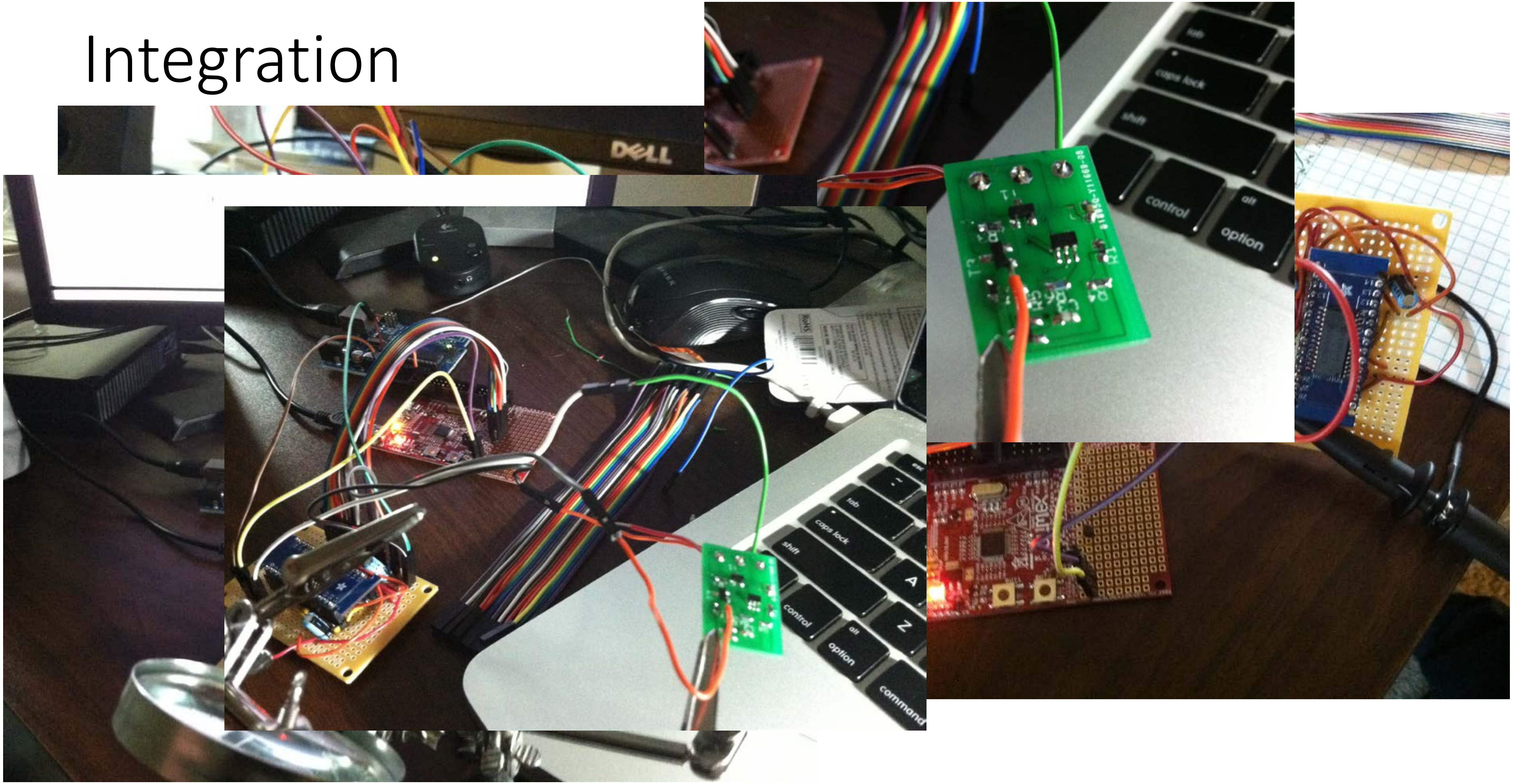


# Integration



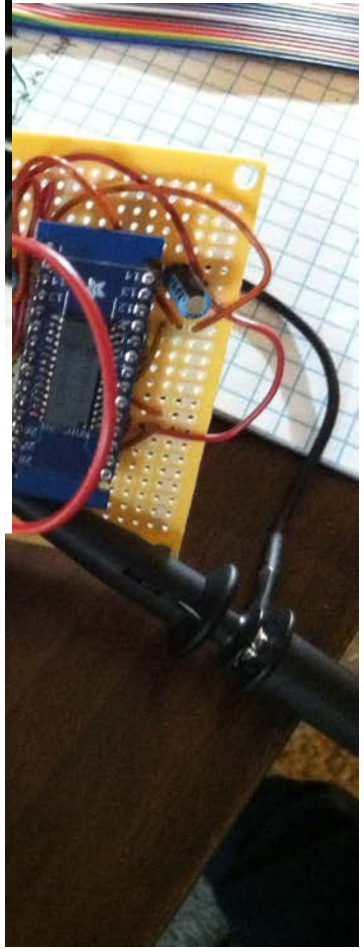


# Integration



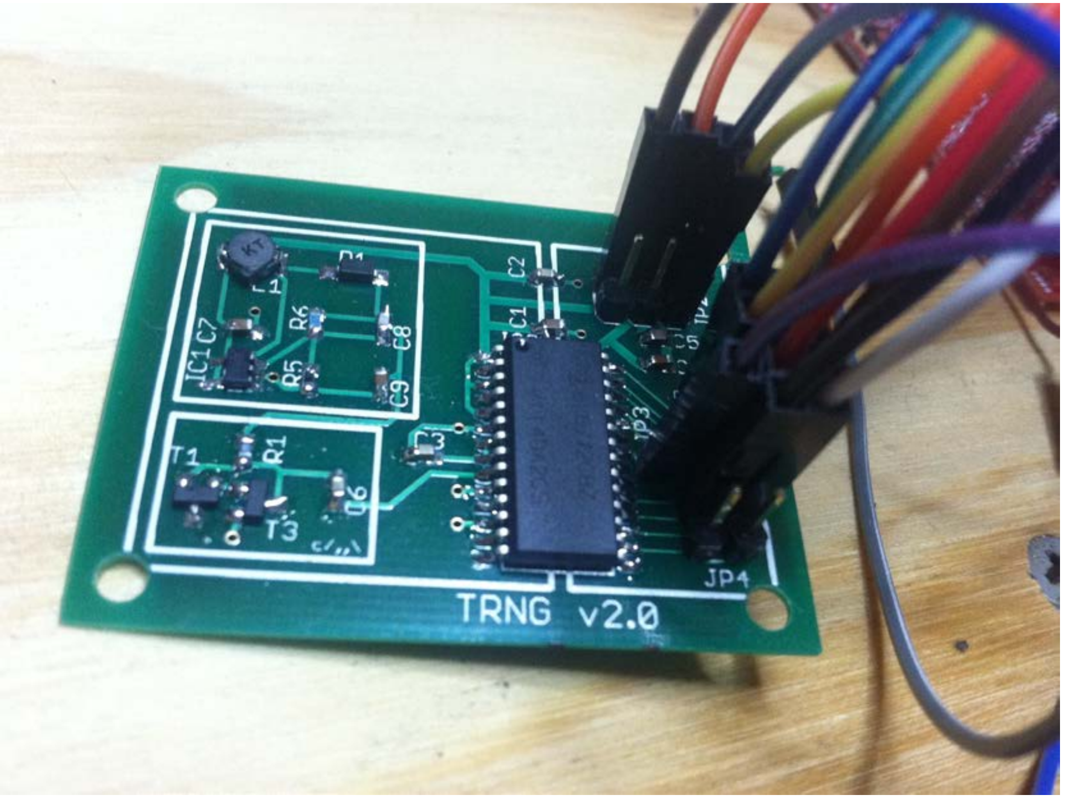
# Inte

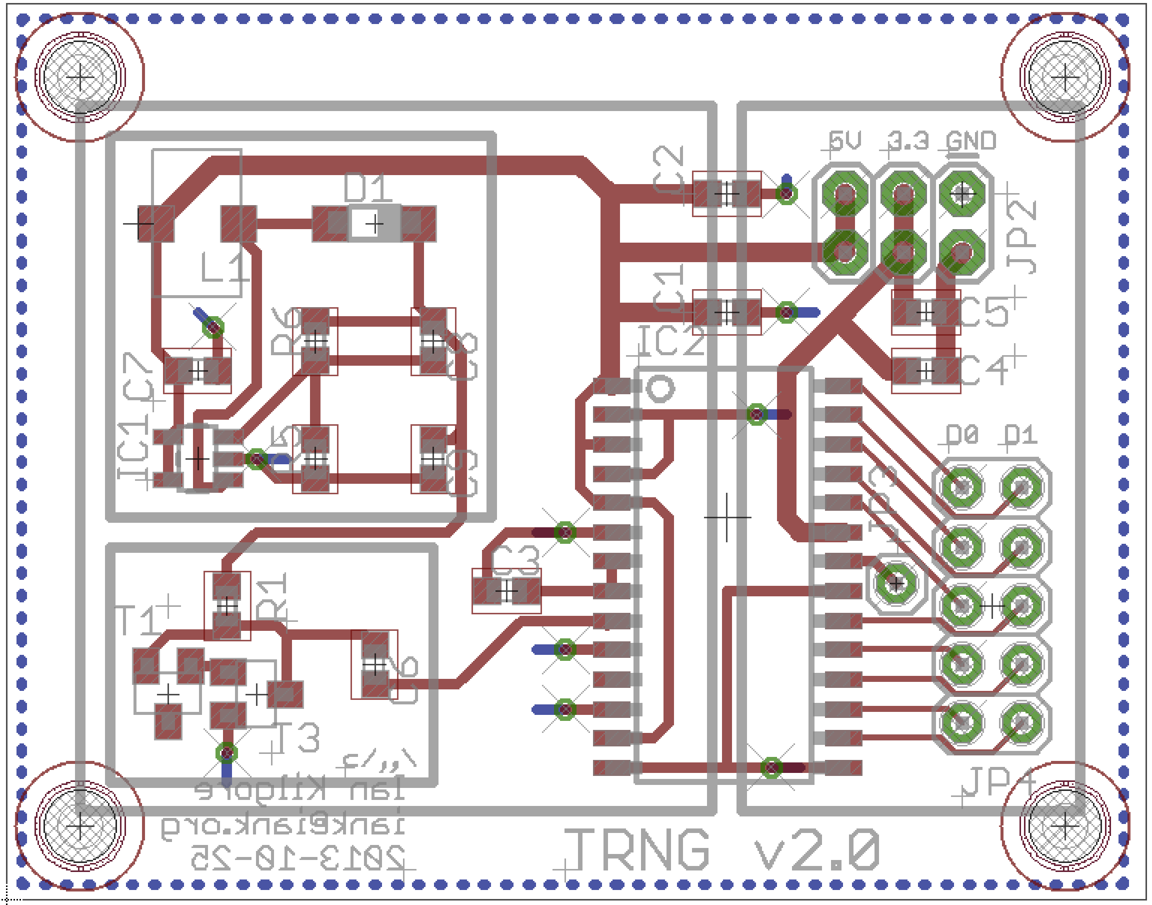
I AM BEAR OF VERY LITTLE BRAIN,
AND MANY WIRES BOTHER ME



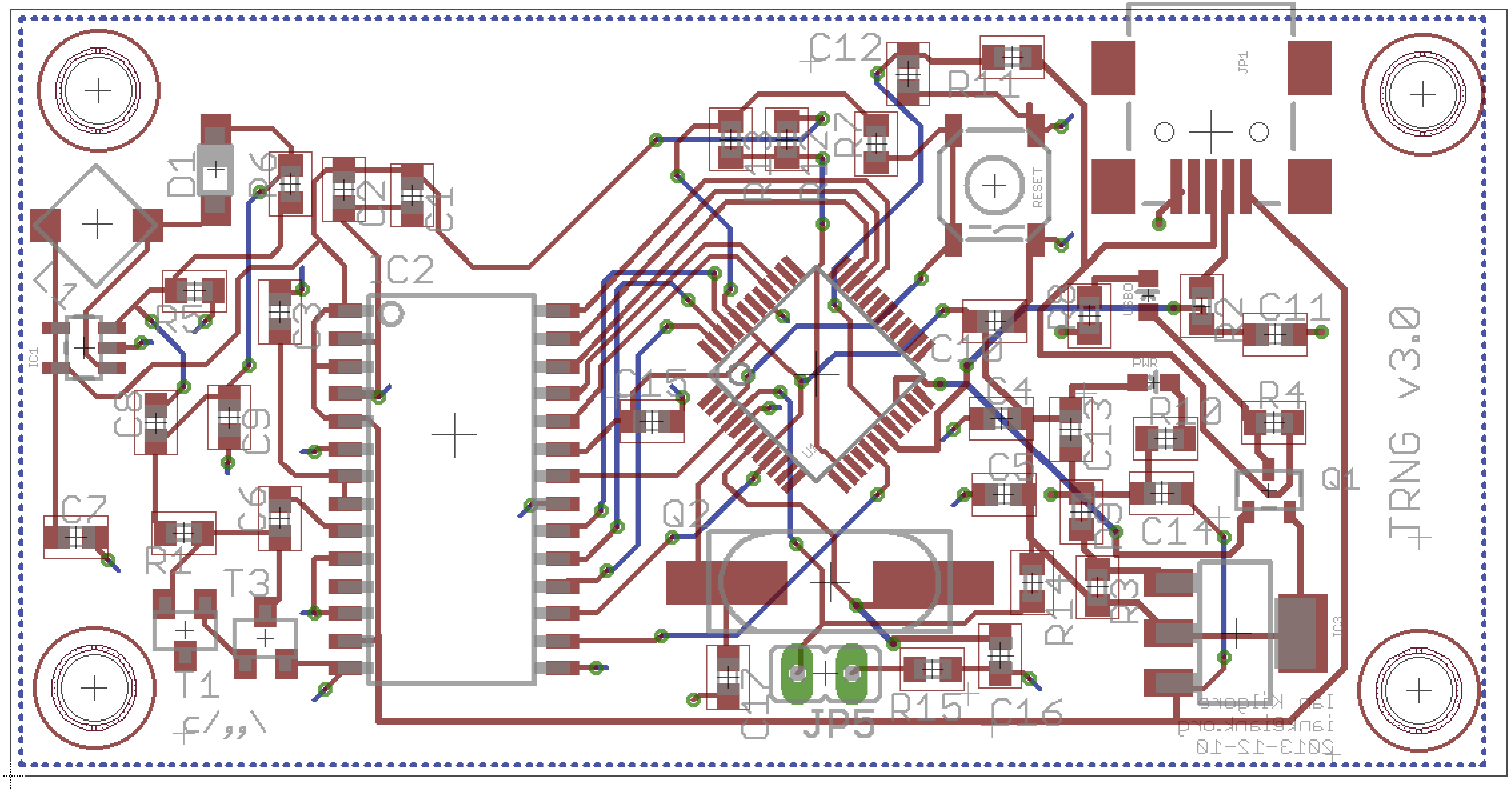
# Integration

- Second PCB: physics, PSU, ADC
- Still external LPC1343 dev board

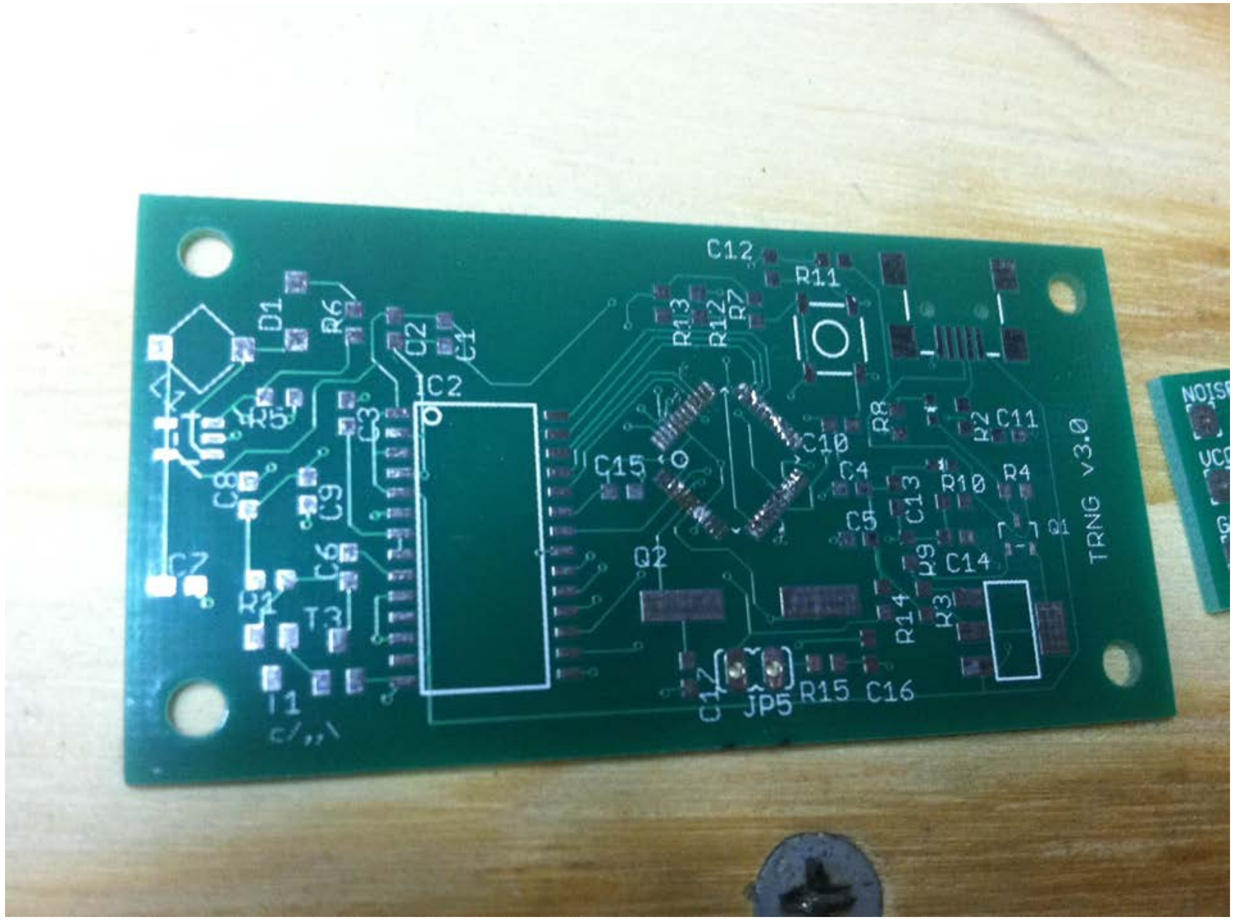


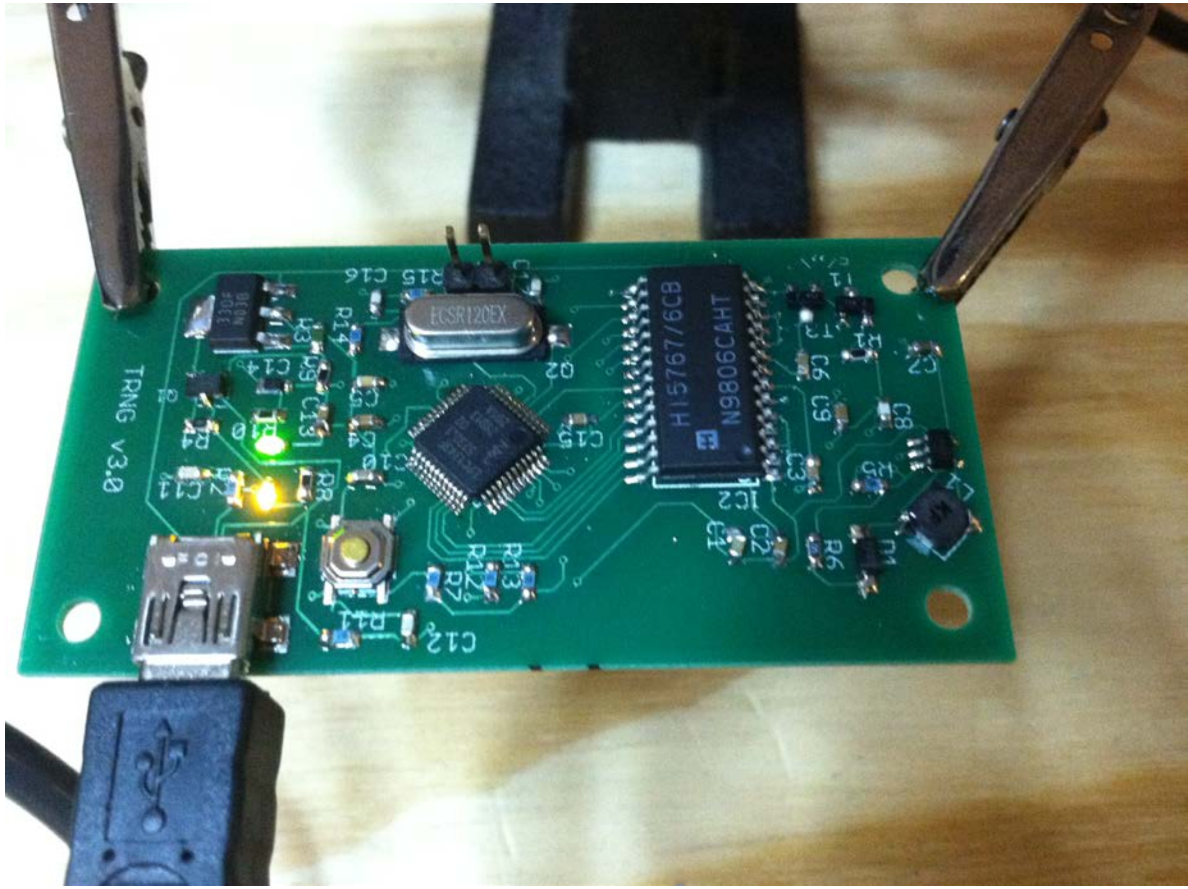


# Integration

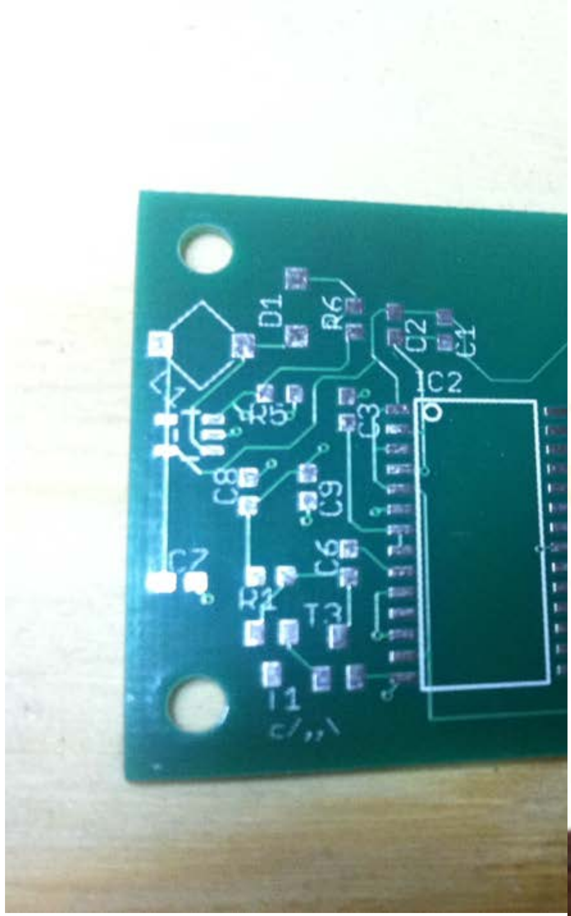


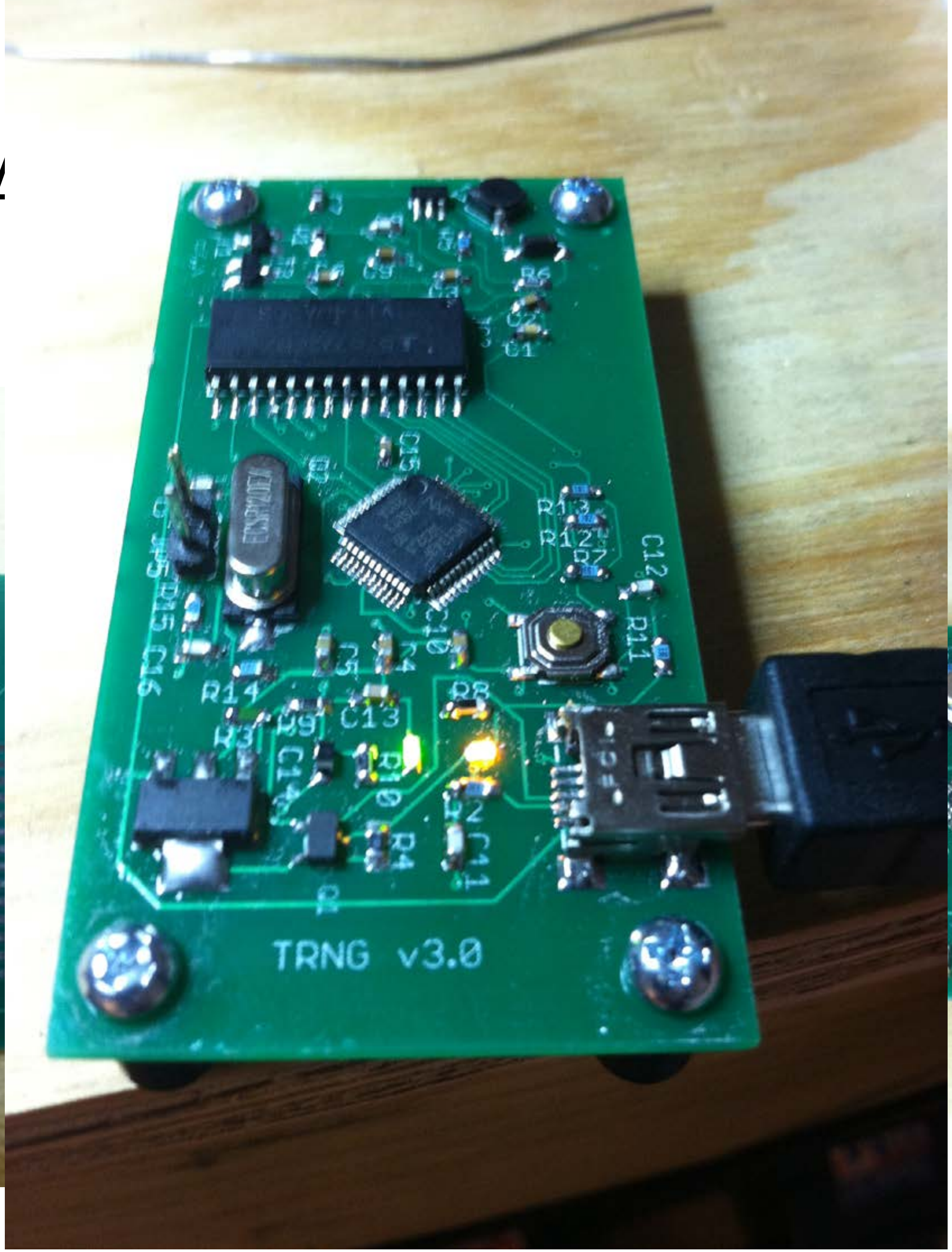
# Final PCB, Assembly





# Final PCB, A

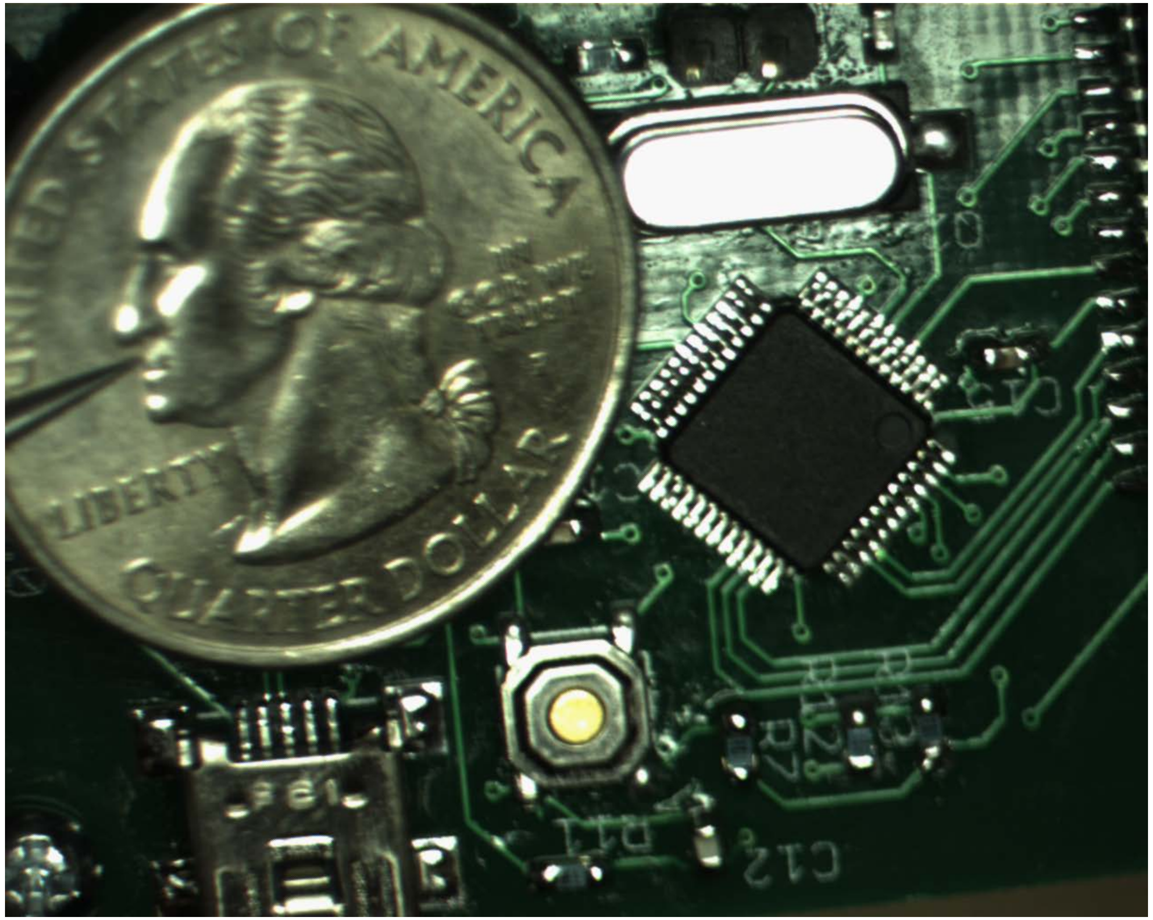

D1
R6
C2
C1
IC2
R5
C3
C8
C9
C7
C6
R1
T3
T1

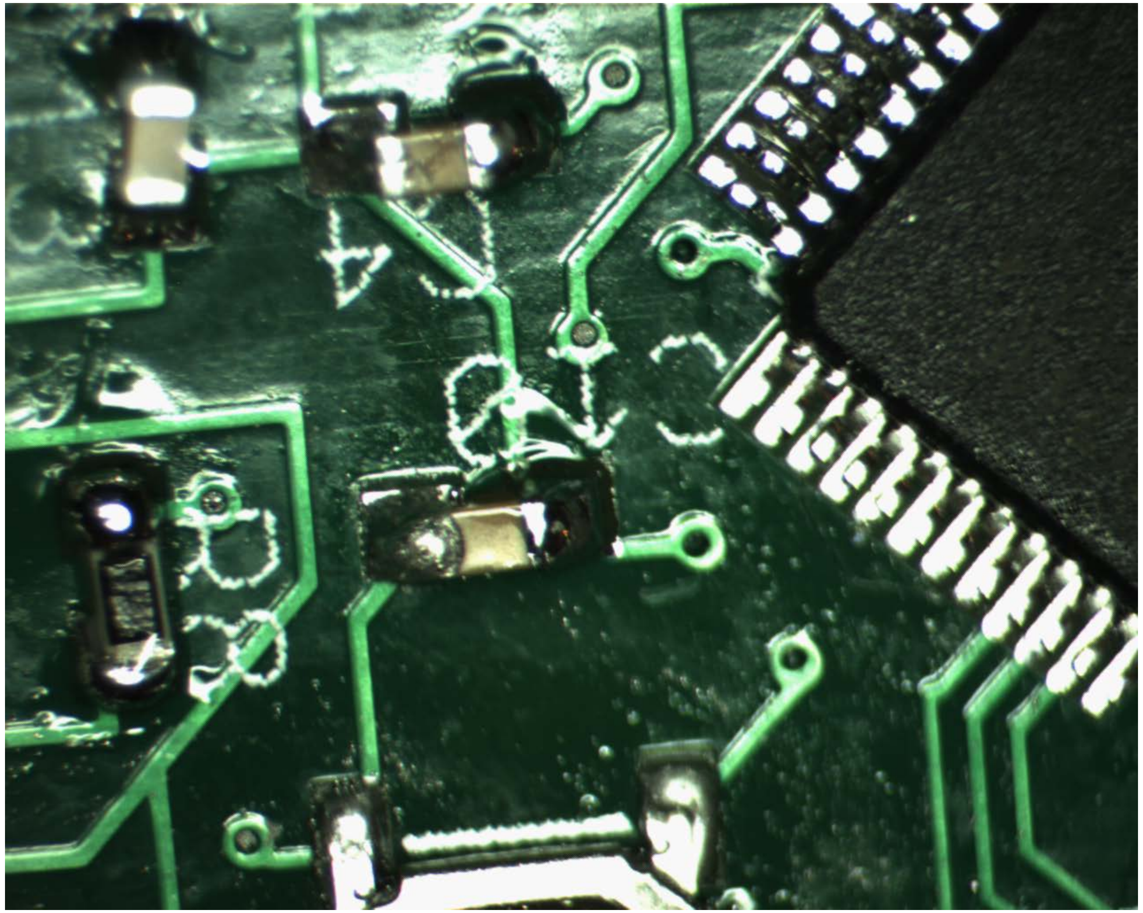

TRNG v3.0
R13
R12
R7
C12
R11
R14
R9
C13
R3
R8
R10
R4
C11
C5
C4
C10
C16
C14
R6
C2
C1
C9

ECSR120EX
HI5767/6CB
N9806CAHT
IC2
Q2
C15
C6
C9
C8
C3
C2
R6
D1
R13
R12
R7
C12

# Aside: Good tools are important

- Fine-pitch SMD components
- We've been well beyond $10 soldering "gun" territory for a while now
- Spend the $$ or get access to a lab/hackerspace/friend


UNITED STATES OF AMERICA
LIBERTY
IN GOD WE TRUST
QUARTER DOLLAR
C12



# Results

- Software whitening done in firmware
- Data rate reduced to 9 kilobytes / sec

http://iank.org/trng/2014-01-16_dieharder_test.txt

# Future Work

- Code for: I’m done with this now, but here’s some things I could have done incrementally better
- Reduce board area 30-50%
  - Reduce 0603 to 0402 or smaller
  - Reduce wasted space between components
- Increase ADC sample rate
- Implement whitening in CPLD

Photo © Kyle Daylor CC BY 2.0

# Never use this

- Not a differential circuit. Poor PSRR
- Easily-influenced externally
- In general don’t roll your own crypto, this applies to hardware too (especially?)
- There’s like a million of these, seriously. don’t use mine.

Photo © Tomás Fano CC BY-SA 2.0

- Random is HARD and I got a lot of things wrong too
- Good news is it’s crypto-hard, which means nobody really cares

# Questions?

Photo © Henk Wallays CC BY-NC 3.0

# Resources

- Detailed writeup (eventually) and these slides: http://iank.org/trng.html

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- [19] http://gamesbyemail.com/News/DiceOMatic
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- [23] http://harpers.org/archive/2011/08/0083561