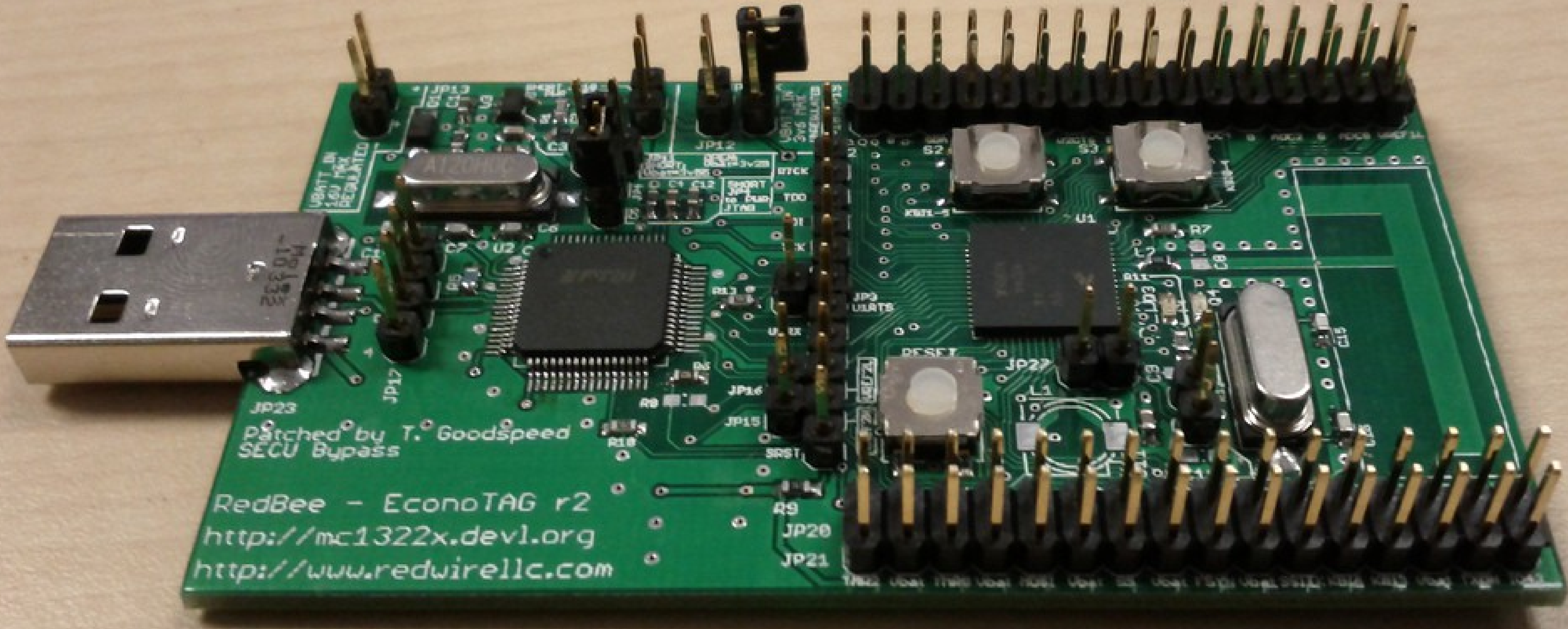
Travis Goodspeed

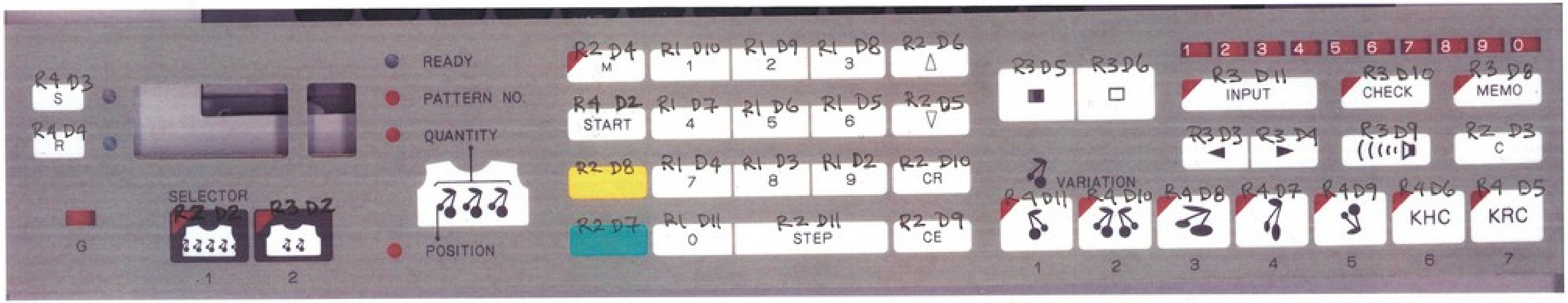


Nifty Tricks and Sage Advice for Shellcode on Embedded Systems

ARTO
abduction

MAKE YOUR AVATAR HERE!!!
DONE!
INVERT
CLEAR
CANCEL
TRAVIS'S AVATAR

Button Matrix Encoding KH-930 Knitting Machine

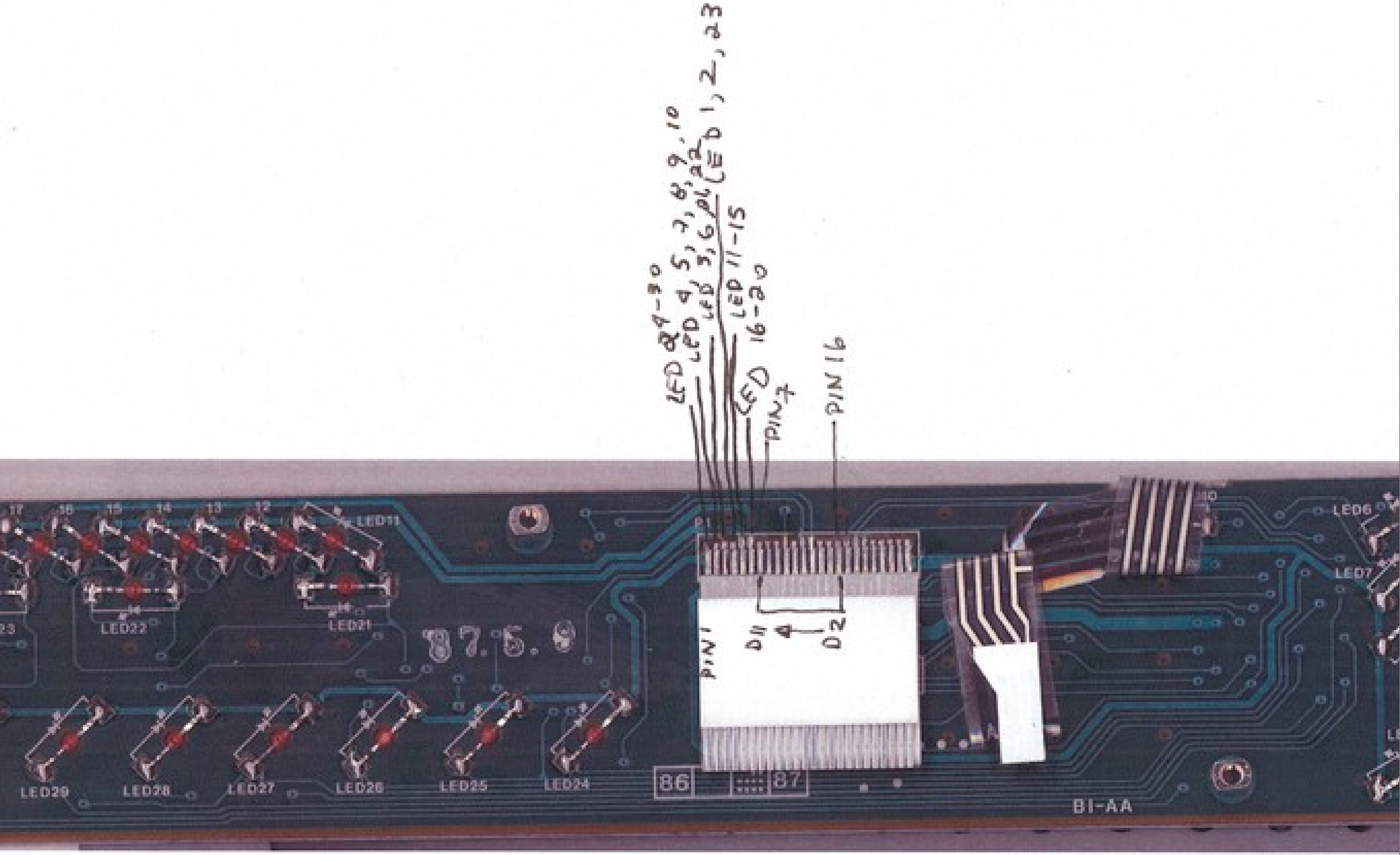


On the board rows are in 4 pin ribbon cable, on mainboard denoted on P8 as 1,2,3 4.
On the board columns are diodes D2 – D11 on mainboard, and pins 7–16 on large ribbon cable between boards.

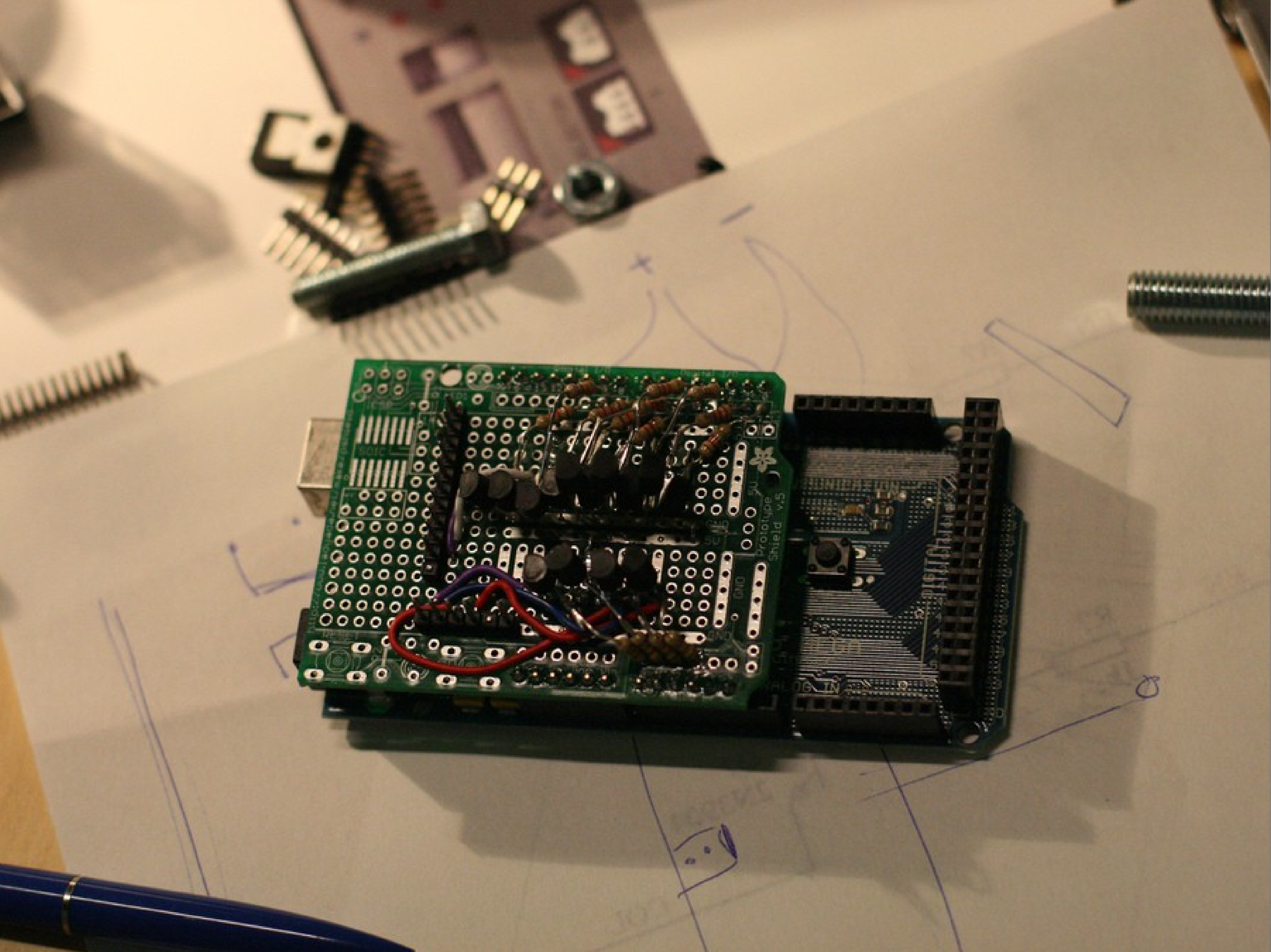
rows	
0	R1
1	R2
2	R3
3	R4

columns	
0	D2
1	D3
2	D4
3	D5
4	D6
5	D7
6	D8
7	D9
8	D10
9	D11

unused: R3D7



Column pulling resistors under ribbon cable.
pull up resistors



Travis Goodspeed

Nifty Tricks and Sage Advice for Shellcode on Embedded Systems

Thank you Kindly

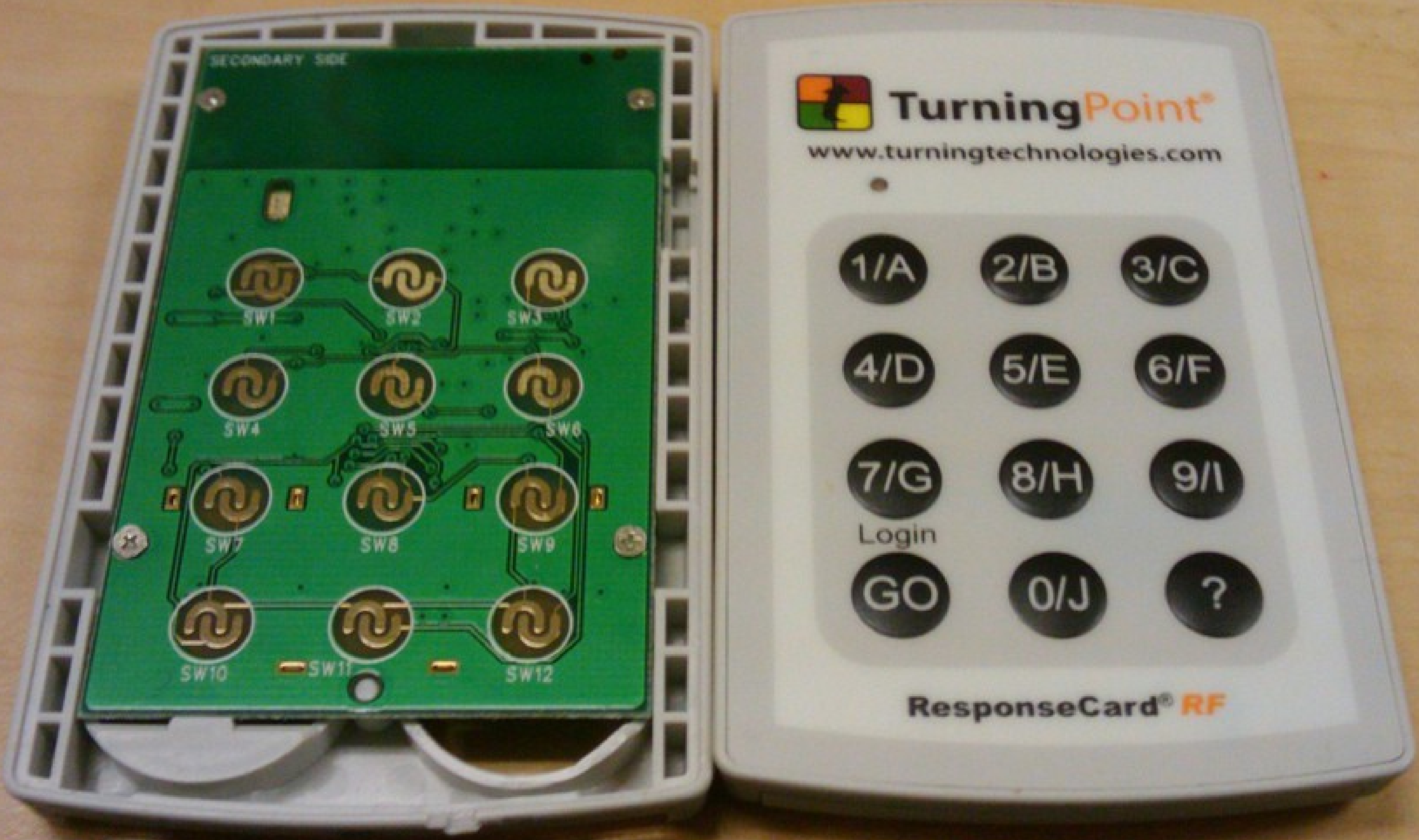
- Aurelien Francillon
  - ``Half-Blind Attacks:
    Mask ROM Bootloaders are Dangerous"
- Sergey Bratus

Let's Exploit Something Small

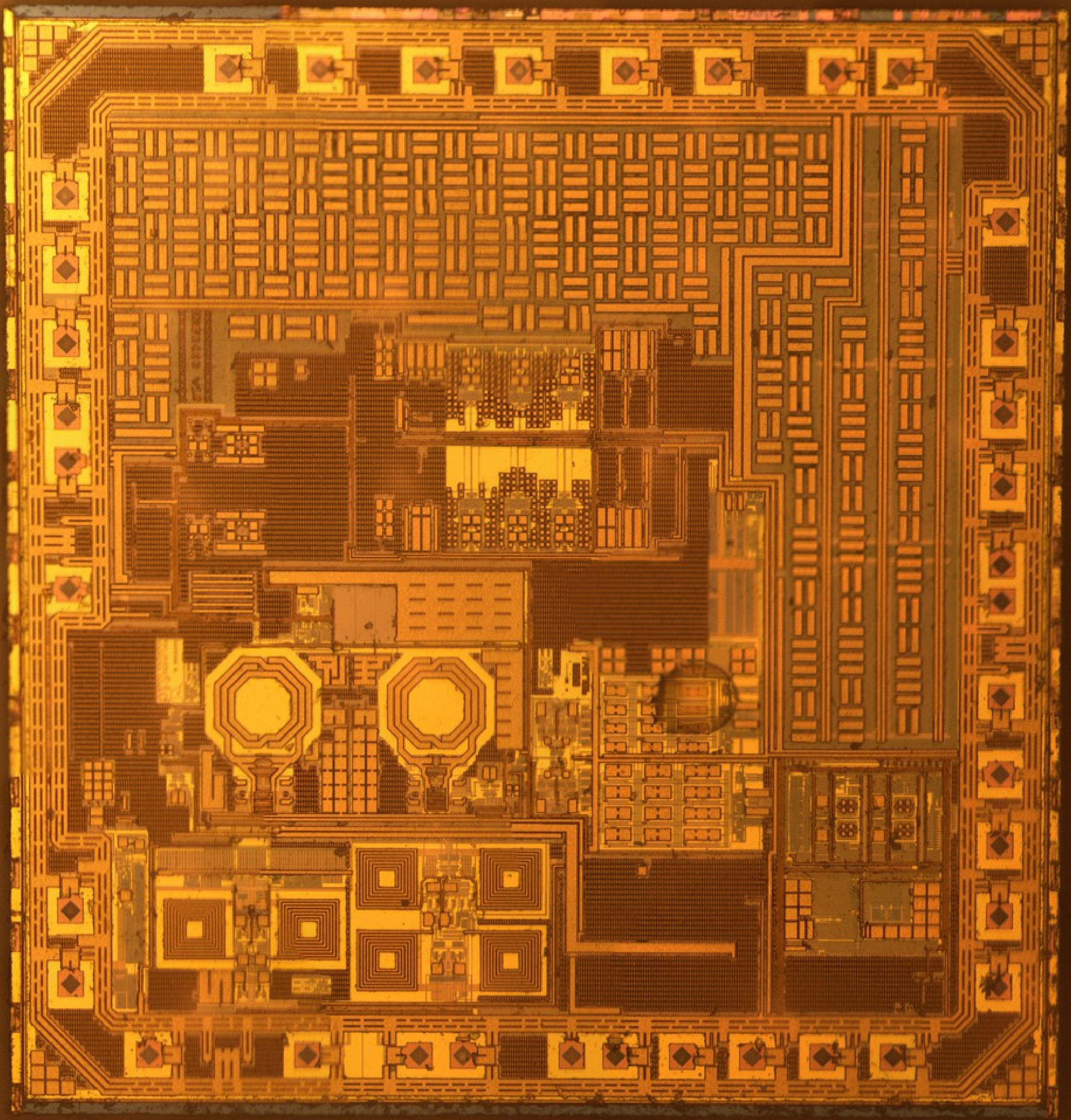
- 8, 16, and (low end) 32-bit microcontrollers
- No operating system, maybe a libc.
- Defensive features are an accident,
  - No ASLR, but still unknown code.
  - No NX-bit, but often Harvard architectures.
  - Lots of weird registers, custom code.

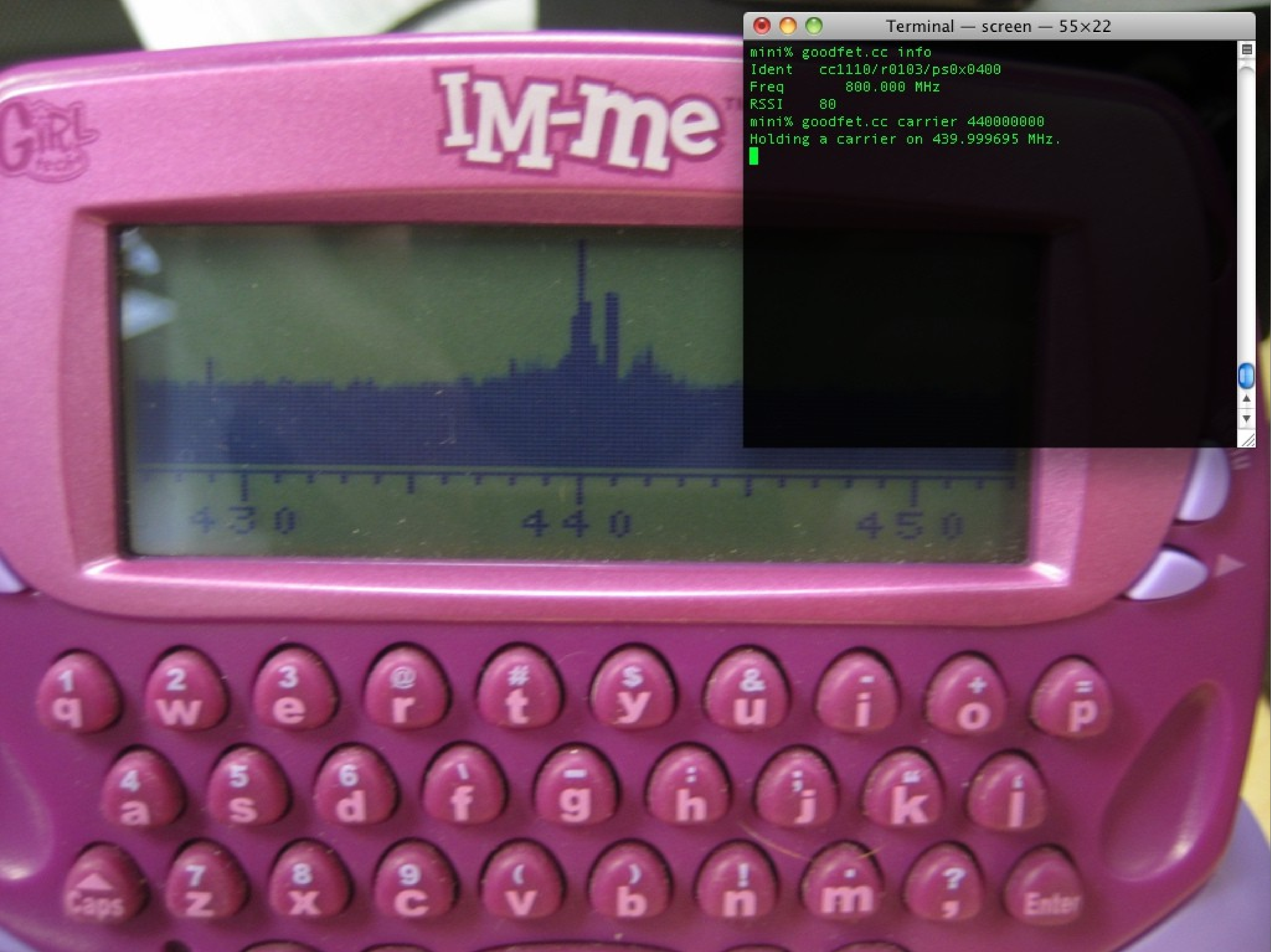
Rogue's Gallery

- 8051
  - More popular than X86, AMD64 and ARM.
  - Harvard Architecture
  - Instructions are byte-aligned.
  - Rarely able to execute RAM.
  - Thousands of different clones.


SECONDARY SIDE
SW1
SW2
SW3
SW4
SW5
SW6
SW7
SW8
SW9
SW10
SW11
SW12
TurningPoint®
www.turningtechnologies.com
1/A
2/B
3/C
4/D
5/E
6/F
7/G
8/H
9/I
Login
GO
0/J
?
ResponseCard® RF

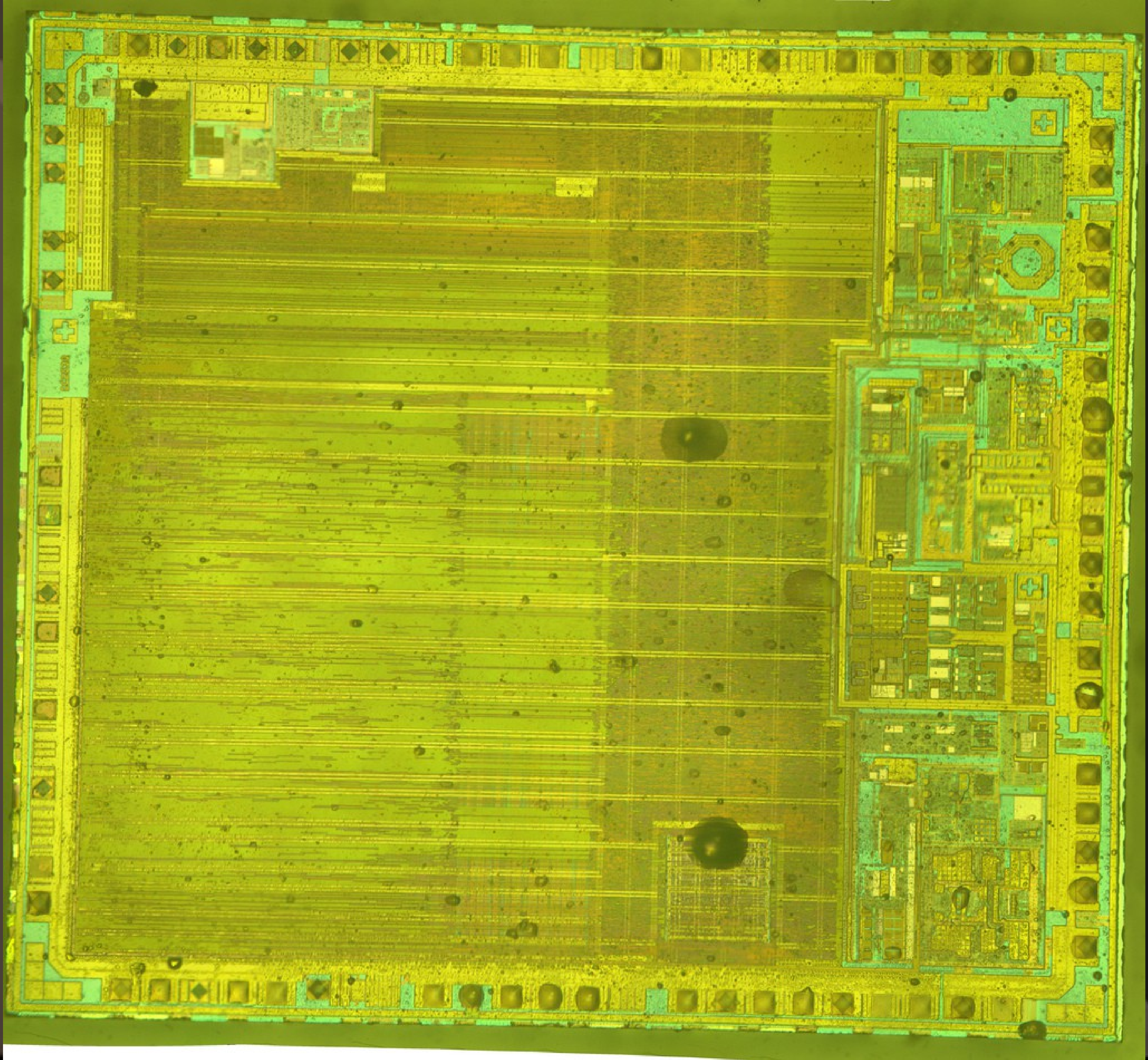
nRF24E1G





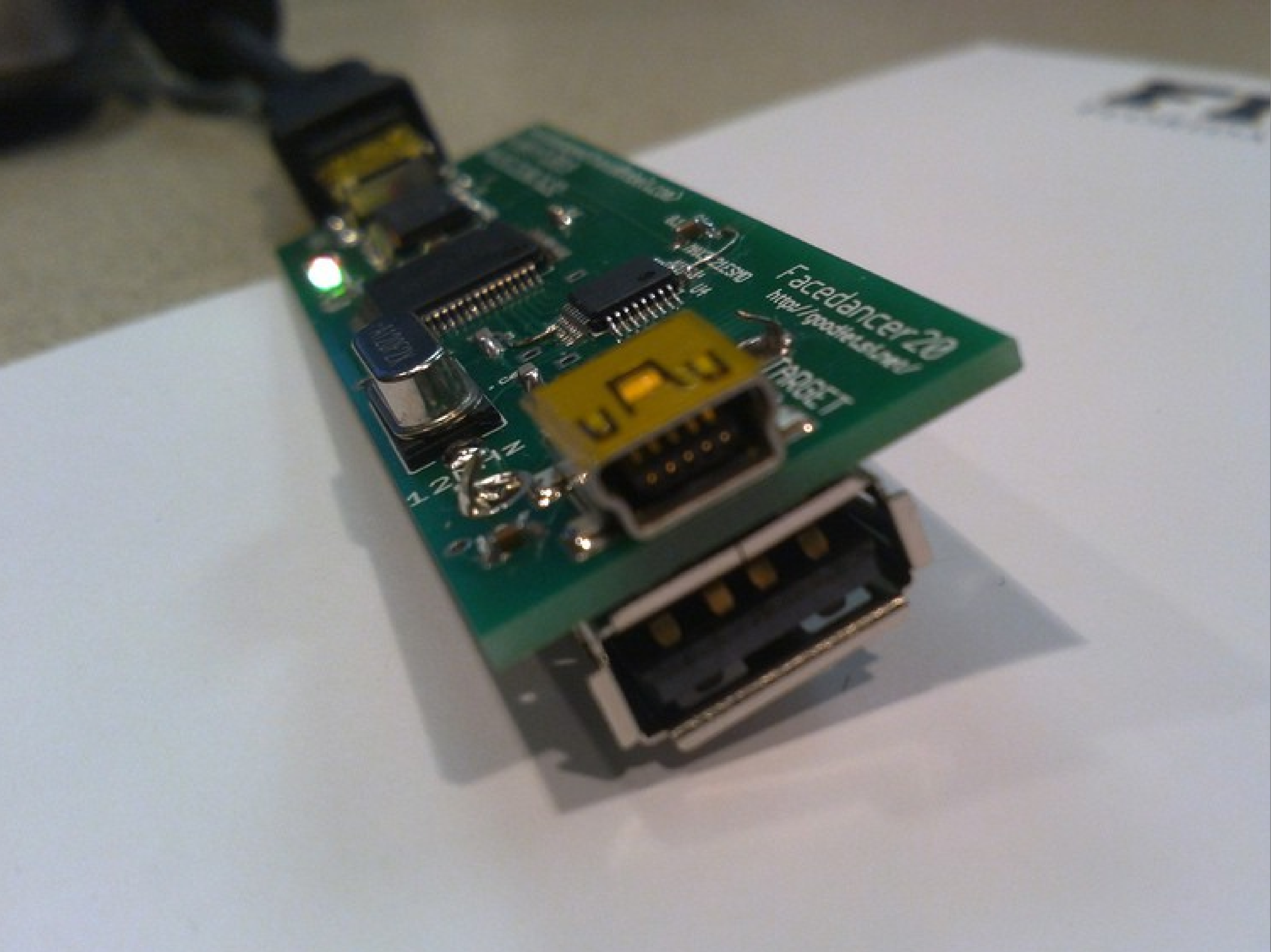
```
mini% goodfet.cc info
Ident   cc1110/r0103/ps0x0400
Freq        800.000 MHz
RSSI    80
mini% goodfet.cc carrier 440000000
Holding a carrier on 439.999695 MHz.
```

CC2530

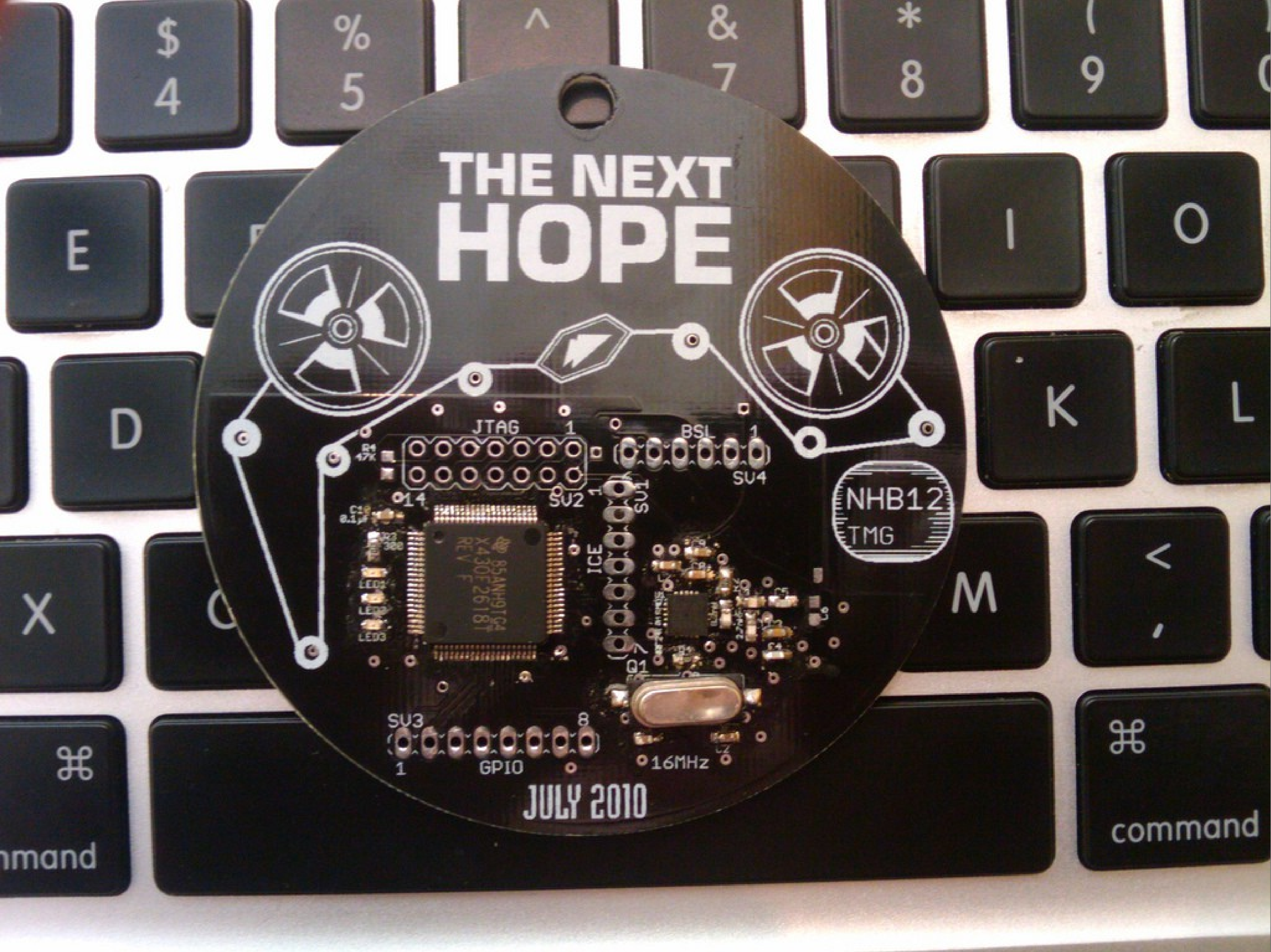


Rogue's Gallery

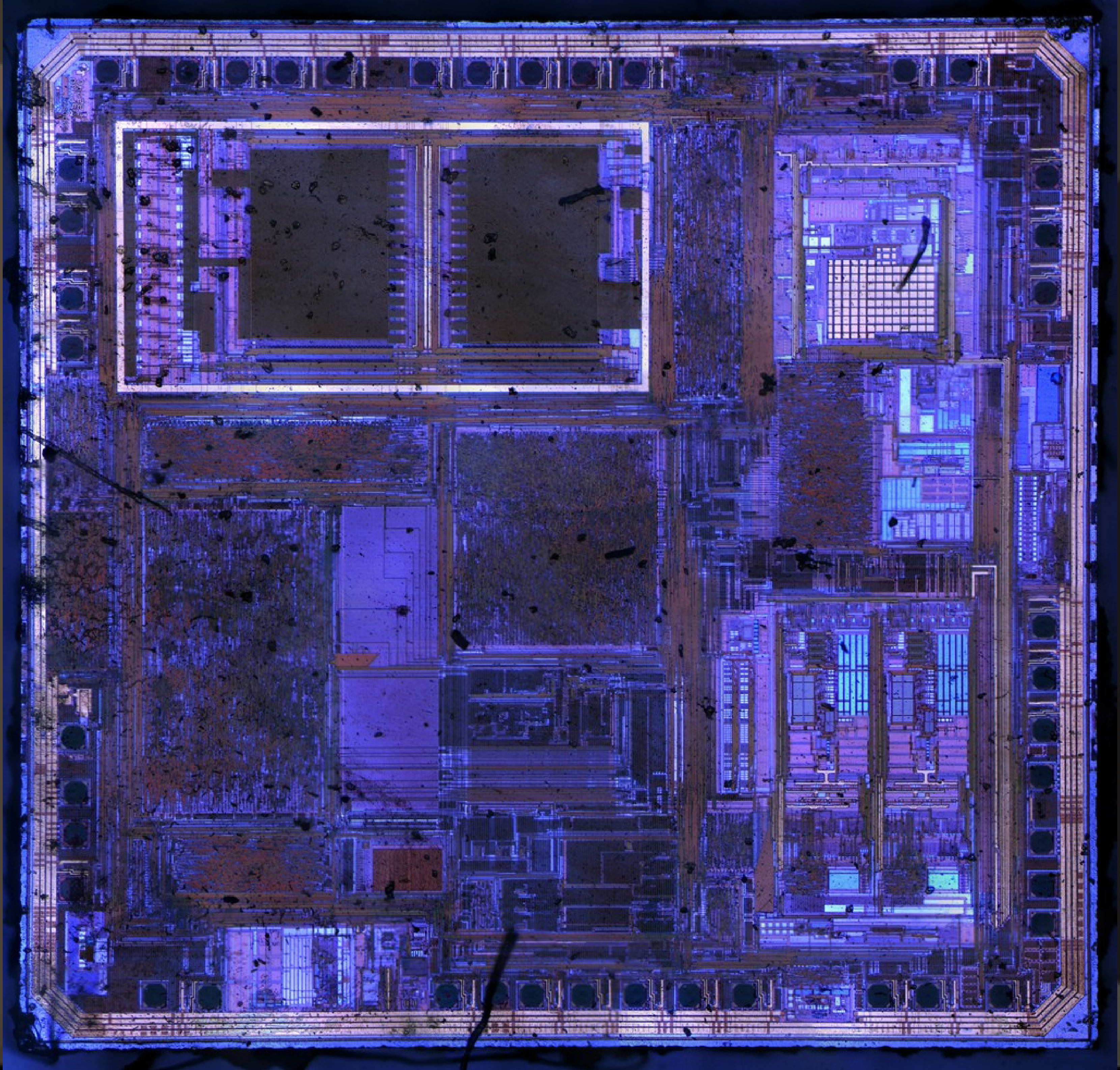
- MSP430
  - 16-bit Von Neumann
  - Most, but not all, versions can execute RAM.
  - 1kB Mask ROM Bootloader (BSL)
  - 16-bit aligned instructions, almost PDP11.
  - Used in the GoodFET, Facedancer, SPOT Connect, Metawatch, and other devices.

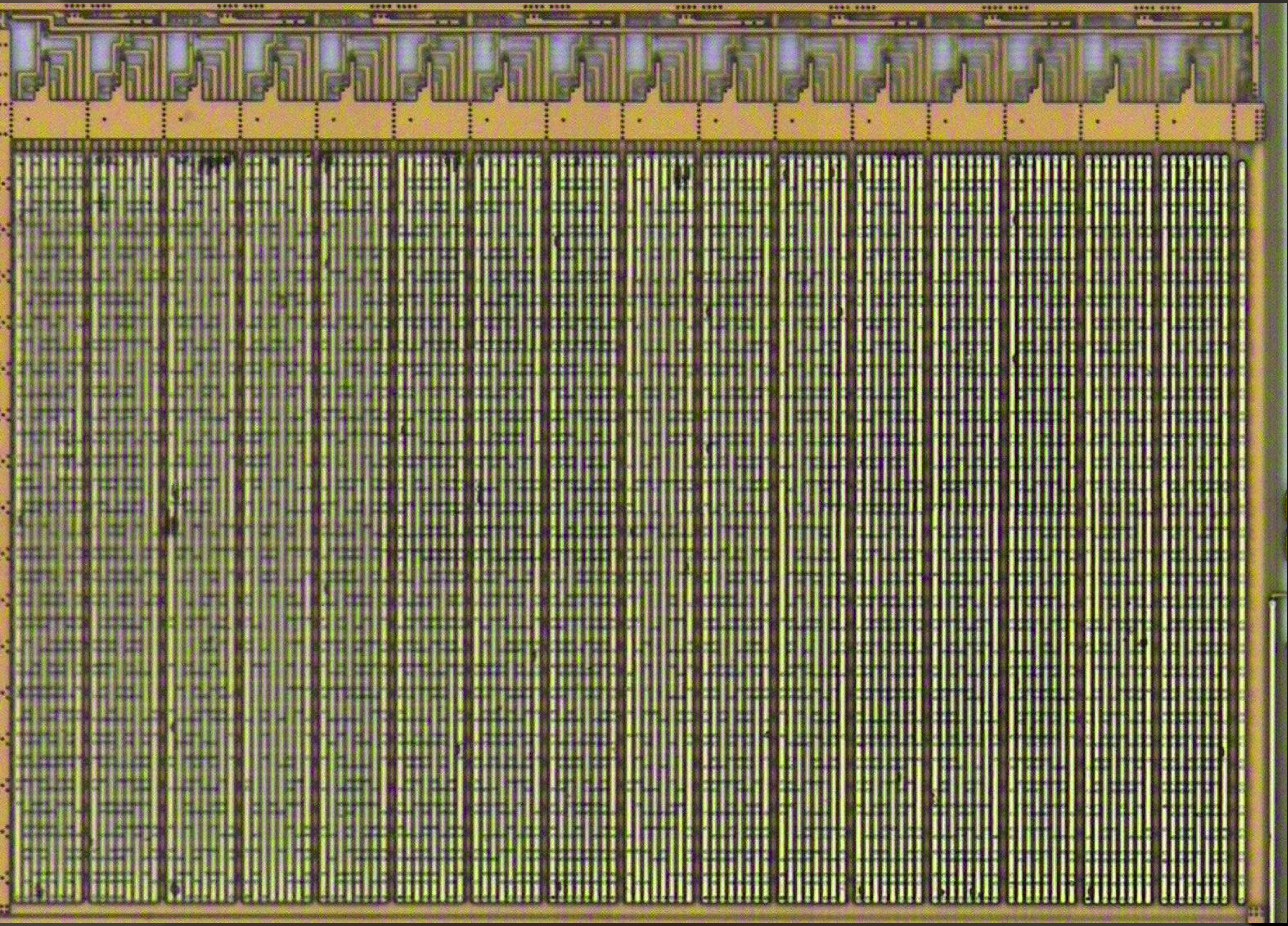

Facedancer20
http://goodfet.sf.net/
TARGET

SOS
spot
CONNECT


THE NEXT HOPE
JTAG
BSL
SV4
SV2
SV1
ICE
NHB12
TMG
LED1
LED2
LED3
Q1
SV3
GPIO
16MHz
JULY 2010

MSP430
F2274



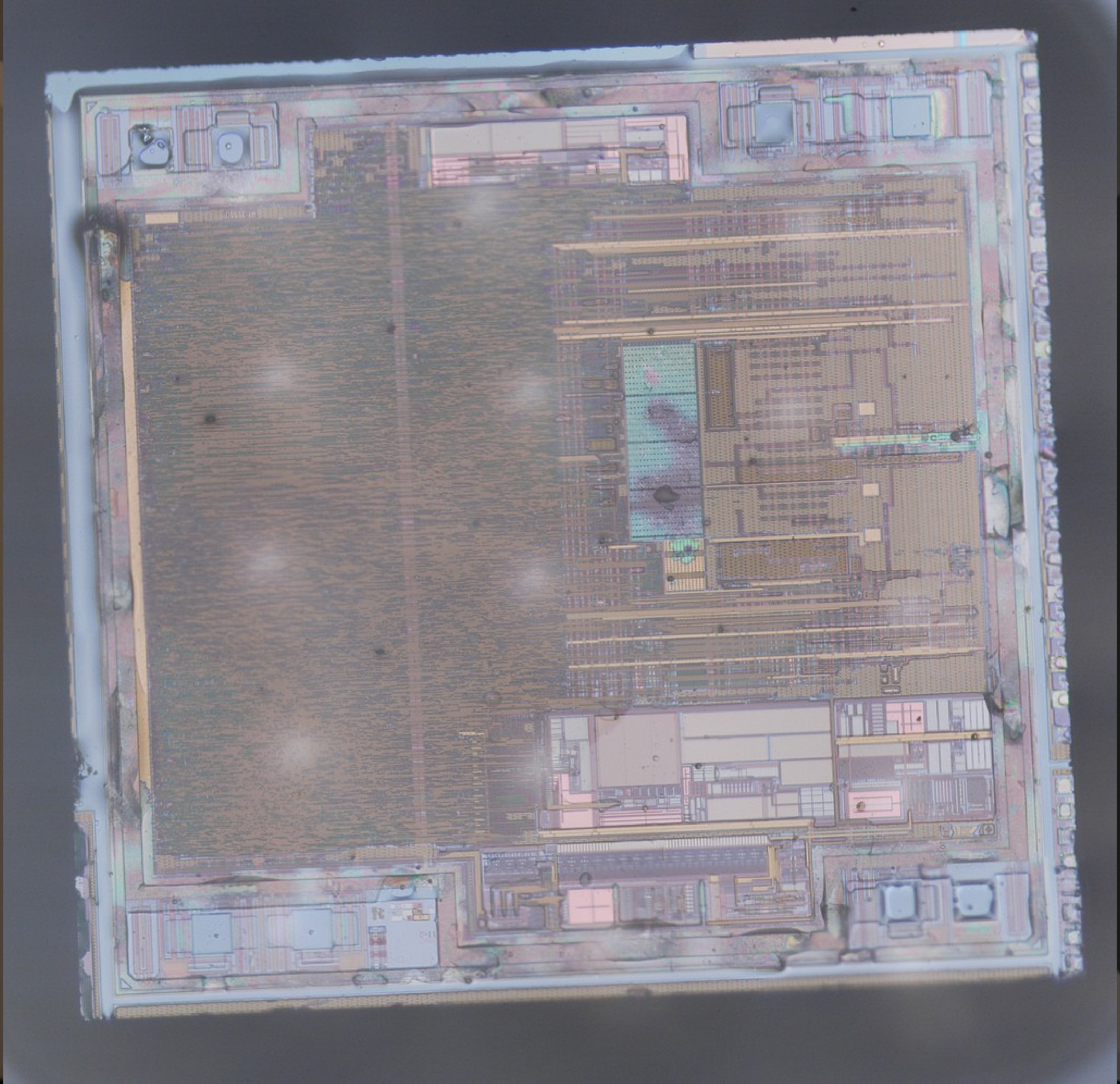


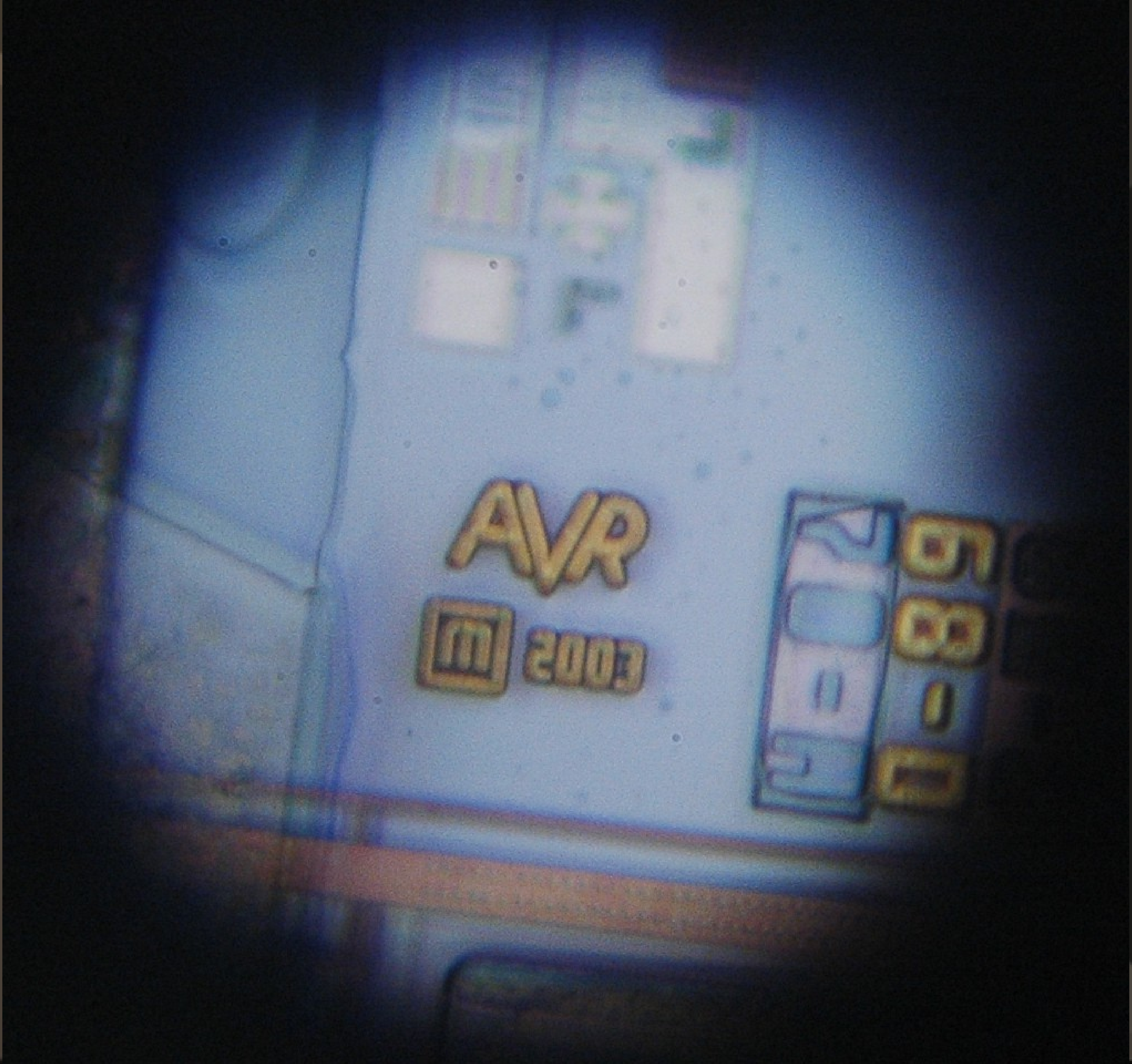
[illegible]

Rogue's Gallery

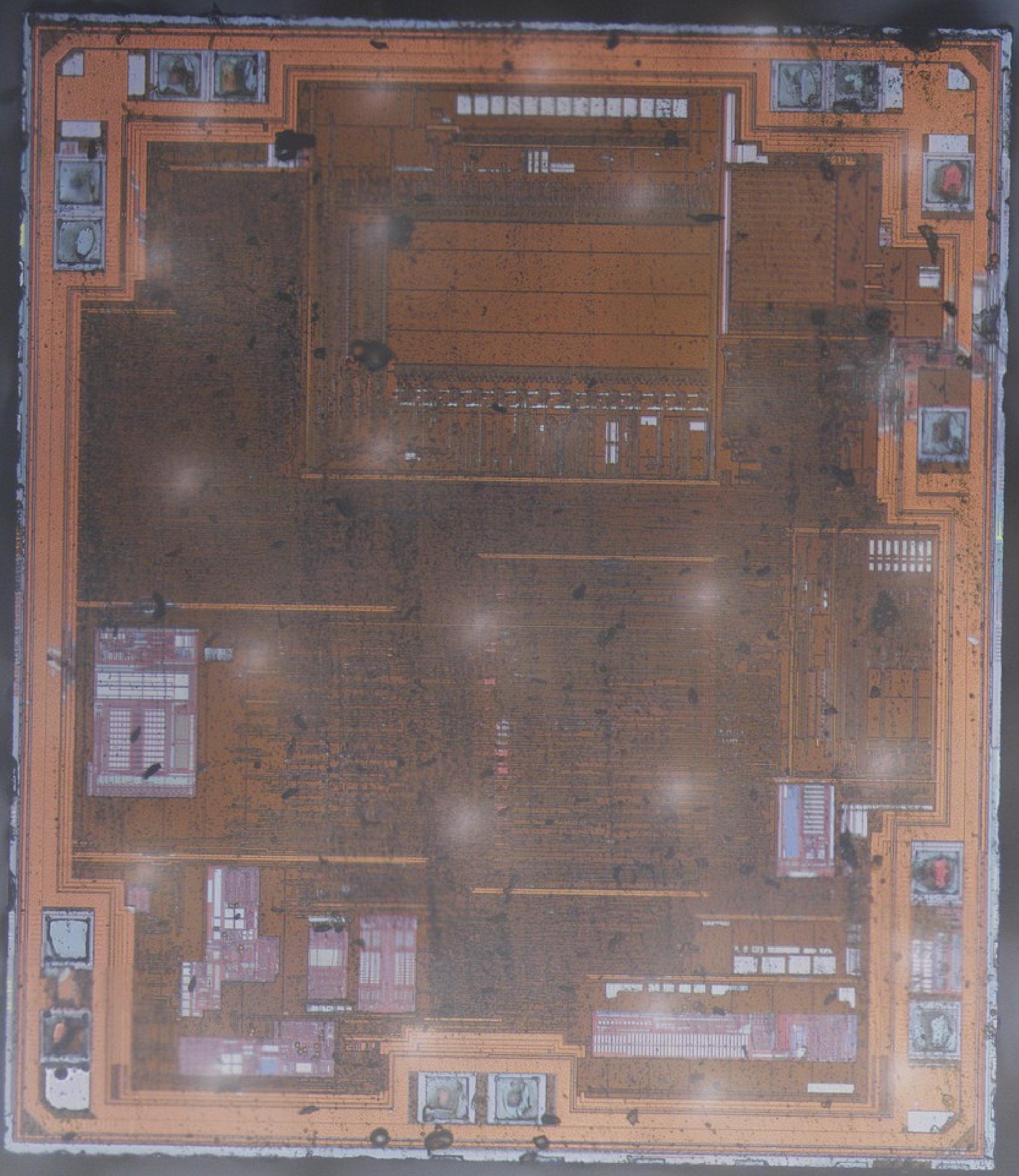
- AVR – 8-bit Harvard
- PIC – 8-bit Harvard
  - Some have hardware call stack.
- HCS08, 6502, 6805, etc.
  - Every old architecture is still around someplace.

Atmel AVR
ATTiny13V




AVR
m 2003

PIC16F684



Goals

- On a PC, we want code execution.
  - Load malware, drop a shell.
  - Hack the Gibson!
- On an MCU, we want code!
  - Exploits often used to dump firmware.
  - A PEEK primitive is as good as code execution.
- Strange exploit uses:
  - Stack smashing for temporary patches.
  - Upgrades of unpatchable firmware.

Exploiting the 8051

- 8-bit CPU, Harvard Architecture
- RAM is rarely executable.
- Dozens of clones, none of them the same.

8051 Memory Spaces

- No such thing as “just a pointer.”
- Call stack is hardware limited, sometimes two stacks.
- Different opcodes access different memories.
  - CODE – 64 kB, Mostly Flash, with a bit of ROM.
  - DATA – 256 bytes for variables and stack.
  - IO – Overlaps DATA,
    for Special Function Registers.
  - XDATA – 64kB of extended RAM.
- This architecture is everywhere.

8051 Exploitation Headaches: Executing RAM

- Class 8051 doesn't allow execution of RAM.
  - CODE and XDATA don't overlap.
- Modern chips have exceptions, but they're complicated.
  - Chips with little memory just unify the address space. &CODE==&XDATA
  - Chips with lots of memory map to different locations, small region of overlap.

8051 Exploitation Headaches: Writing to Flash

- Writing to Flash is tricky.
  - There is no standard instruction for writing Flash.
  - You could use multiple calls to a POKE primitive,
    and a good knowledge of the clocks,
    and you need to do this reliably in a loop,
    and you need to do it without native shellcode.
- There are options.
  - Varies by architecture.
  - Generally, you abuse the self-reprogramming feature.

8051 Exploitation Headaches: Writing to Flash

- 8051 was Harvard until self-reprogramming was a needed feature. Things change.
- The issue is that you can't read or execute from Flash while writing to Flash.
- Three solutions:
    - Map RAM into both XDATA and CODE memories.
    - Flash reads a JMP $-1 when busy.
    - Mask ROM contains code to copy XDATA to CODE. (RAM to Flash)

8051 Exploitation Headaches: Writing to Flash

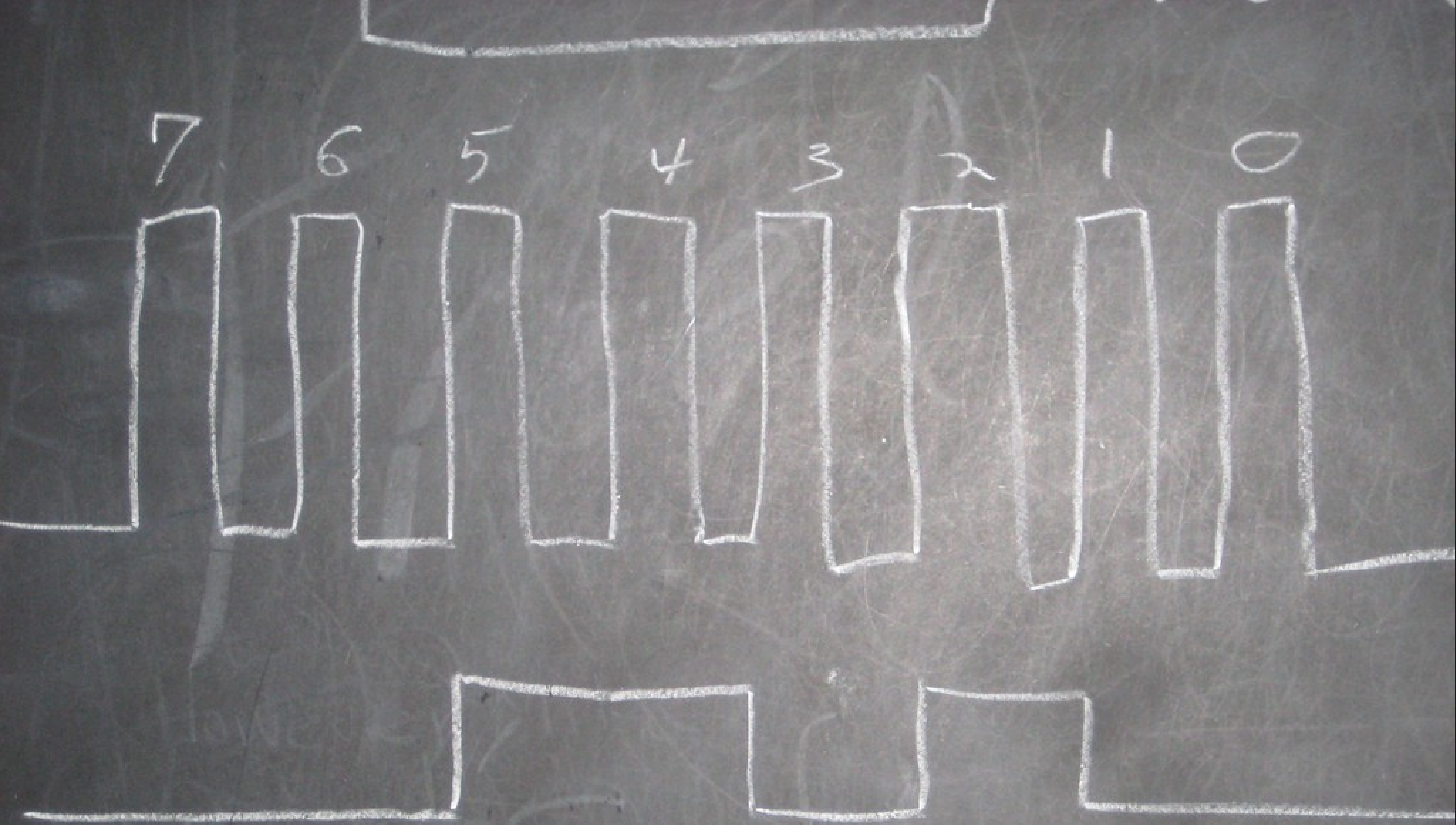
- Map RAM into both XDATA and CODE memories.
  - Just force a return into it. 1996-style exploits work!
- Flash reads a JMP $-1 when busy.
  - Much harder, especially if there's no gadget to write to flash.
  - Sometimes you can use a POKE primitive.
- Mask ROM contains code to copy XDATA to CODE.
  - Nice and easy to exploit.
  - Calling convention is often documented!

Example: GPIO Blinking

- Vuln was in a USB bootloader.
- Exploit was supposed to dump Flash and RAM.
- USB buffer is preciously small
  - Our first-stage shellcode needs to be tiny.
  - We could call the USB stack, but it's complicated.
  - We only need to exfiltrate data.
  - Let's use the LEDs!

Example: GPIO Blinking

- A tiny standalone application:
  - 1. Setup the GPIO pin directions to output.
  - 2. Blink half of them with a clock.
  - 3. Blink the other half with data bits.
  - 4. Sniff pins with a logic analyzer to get the bits.
- As shellcode,
  - 1. The GPIO pins for LEDs are already directed out.
  - 2. while(1) and let God sort it out.


7
6
5
4
3
2
1
0

Example: GPIO Blinking

- Clock LEDs look solid.
- Data LEDs blink irregulary.
- Tap one of each into a logic analyzer.

Return to Libc

- Complicated by a lack of Libc
  - It's there, but statically linked and pruned.
  - Nothing like system() or exec().
- If our goal is to get the Flash,
  we can't know what's where in Flash.
- Two tricks:
  - Return to the bootloader with privilege escalation.
  - Privilege escalation gadget can be found blind!

Example: Returning to a Bootloader

- Many chips have a bootloader in Mask ROM.
  - This is permanently a part of the chip.
  - This cannot be patched or removed affordably.
- This ROM is an excellent return-to-libc target.
  - Always at a fixed position.
  - Very few revisions to reverse engineer.
  - Rather small.
  - Includes *at least* one command shell.

Example: Returning to a Bootloader

- MSP430 Bootloader
  - 0x0C00 to 0x0FFF, just 1 kB
  - Requires the Interrupt Table as a password.
  - R11 is a global containing the password status.
- Return-to-BSL Shellcode in Six Bytes
  - MOV 0xFFFF, R11; Pretend we gave a good pass.
  - CALL 0x0C0A;   Enter a bit late to not clear R11.

Example: Blind Return-Oriented Programming

- What if we couldn't execute shellcode from RAM?
  - Some security-enhanced variants disallow RAM exec.
  - Competing processors (AVR, 8051) are Harvard.
- We could build a ROP chain
  - ROM doesn't contain enough gadgets.
  - We don't know where anything is in Flash.
  - Let's build it blind!

Example: Blind Return-Oriented Programming

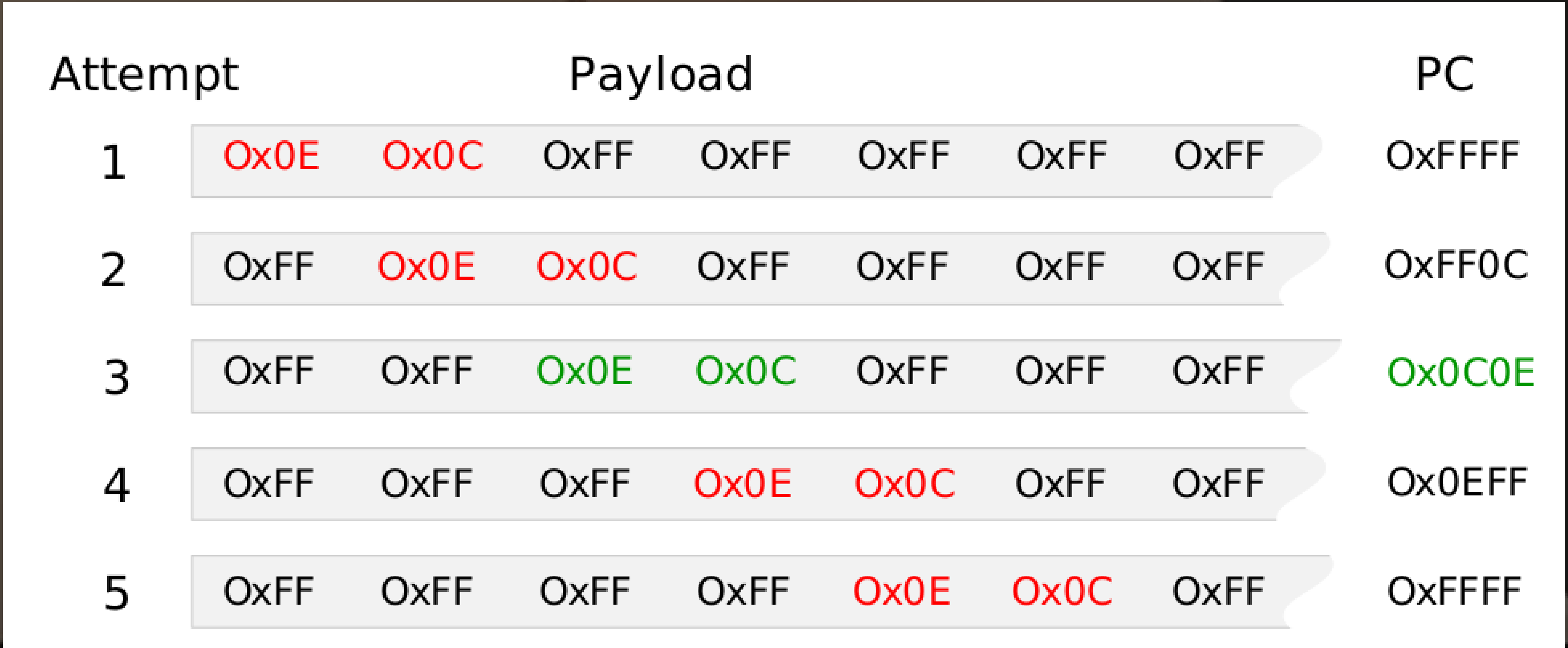
- Suppose the following
  - We have a stack-buffer overflow bug.
  - We have a copy of ROM, but not of Flash.
  - We cannot execute RAM.
- Plan of attack,
  - Use ROM entry point to find return address offset.
  - Scan for RET statements in Flash by crashes.
  - Try each gadget in turn.

How the hell does this work!?

- The gadget we need is rather common, rather small.
- We have a very small address space.
- We're not trying to be Turing Complete.
- We have a feedback mechanism,
  - Crash indicates the stack is mis-constructed.
  - No crash indicates we're getting some gadget.
  - Side effects tell us which gadget.

Example:
Blind Return-Oriented Programming

- 1. Fuzzing gives us a stack buffer overflow.
- 2. Varying our offset verifies our control of the Program Counter by a successful jump into ROM.



Attempt	Payload							PC
1	Ox0E	Ox0C	OxFF	OxFF	OxFF	OxFF	OxFF	OxFFFF
2	OxFF	Ox0E	Ox0C	OxFF	OxFF	OxFF	OxFF	OxFF0C
3	OxFF	OxFF	Ox0E	Ox0C	OxFF	OxFF	OxFF	Ox0C0E
4	OxFF	OxFF	OxFF	Ox0E	Ox0C	OxFF	OxFF	Ox0EFF
5	OxFF	OxFF	OxFF	OxFF	Ox0E	Ox0C	OxFF	OxFFFF

Example: Blind Return-Oriented Programming

- Now we control the PC, but we don't know the password. We need a ROP gadget like ``POP R11", which is common in function epilogues.
- 3. Move the BSL entry one word up in memory, with a random address in its place.
  - If this enters the bootloader, we might have found a “RET” instruction.
  - If it doesn't, we've found a gadget of some sort.

Example:
Blind Return-Oriented Programming

- Now we have some gadgets, but we don't know what they do.
  - 59 valid gadget entry points in my target.
  - 1/50 to 1/150 gadgets/addresses in other samples.
  - Varies drastically by architecture and compiler.
- 4. Try all gadget addresses with the appropriate stack layout. Bootloader pops open!

Example: Blind Return-Oriented Programming

- Final call stack, higher addresses at the top.
  - 0x0C0E – Bootloader entry, called last.
  - 0xFFFF – Value to pop into R11 by our gadget.
  - 0x???? – Address of a ``POP R11" gadget.
- Unknown address doesn't have many candidates,
  - Must be at an even address before a RET.
  - ~8,000 possibilities in address space, easy to search.
  - ~59 possibilities before RET, easier to search.
  - Two gadgets, 59**2 or ~4,000 tries.
  - Three gadgets, 59**3 or ~200,000 tries.

RAM Patching

- On higher-end chips, you patch RAM.
  - Many faster chips can't execute Flash directly.
  - RAM patches are less likely to brick the target.
  - Very useful for backdoor development.
- But RAM gets overwritten.
  - You'll need to hook functions that overwrite the IVT.
  - It works pretty much like a DOS TSR.

Flash Patching

- Suppose you can overwrite Flash, but you can't erase it.
  - Common when patching the IVT directly.
- NOR Flash isn't like RAM.
  - You can clear bits individually, but only set them as a page.
  - Overwrites are a bitwise AND.

Flash Overwrites

- 0xFFFF at erasure
- 0xDEAD written.
- ~0xDEAD cleared.
- 0xDEAD remains.

- 0xDEAD at start.
- 0xFF00 written.
- ~0xFF00 (0x00FF) cleared.
- 0xDE00 remains.

Flash Patching

- Given only a POKE primitive, you can more easily clear bits than set them.
  - Page writes are complicated.
  - Might break code that's needed to boot or to POKE.
- What tricks can help us choose the right bits to clear?

Flash Patching

- On the MSP430, RAM is beneath Flash.
  - By clearing significant bits,
    you can redirect a CALL to a target in RAM.
  - CALL 0xBEEF; Call to function in Flash.
  - CALL 0x02EF; Call to function in RAM.
- On 8051, 0x00 is a NOP.
  - By clearing bytes, you can NOP-out code.
  - Opcode table is conveniently arranged by bytes.

Parting Thoughts