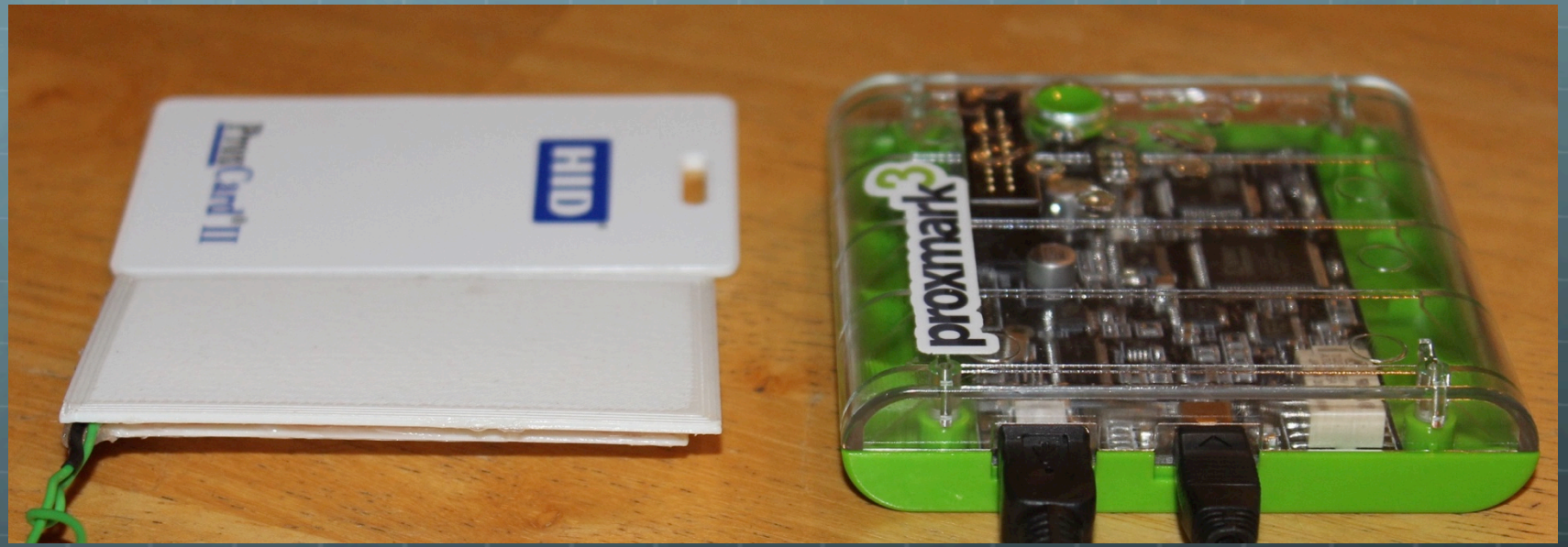


How to Train Your RFID Tools

Craig Young
Security Researcher @ Tripwire VERT

DEF CON 23 LAS VEGAS

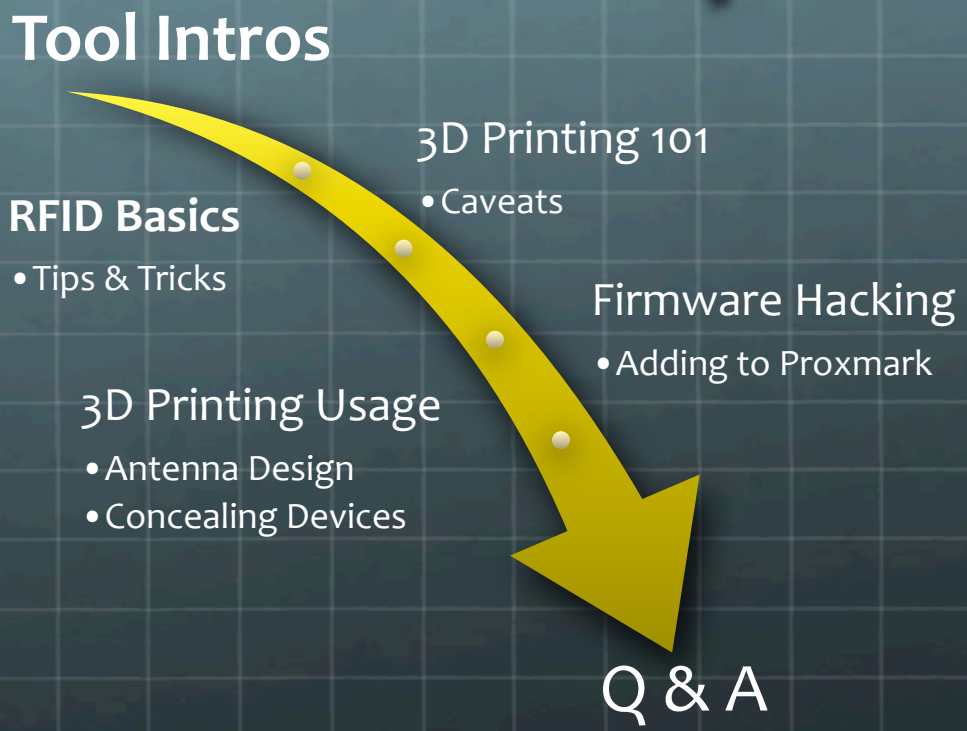
About Craig

- Security Researcher in Tripwire VERT
  - Author of IP360 content and original research
  - Identified 100+ CVEs over 2013 & 2014
  - Won 1st SOHOpelessly Broken @ DC22 using 10 0-days

Research Objectives

- Shed light on the tools for reading, cloning, & emulating
- Provide tutorial-like examples for firmware hacking
- Explore practical attacks enhanced by 3D printing
- Design antenna around 3D printed form
- Identify uses of paired embedded kits

Roadmap


Tool Intros
RFID Basics
• Tips & Tricks
3D Printing 101
• Caveats
Firmware Hacking
• Adding to Proxmark
3D Printing Usage
• Antenna Design
• Concealing Devices
Q & A

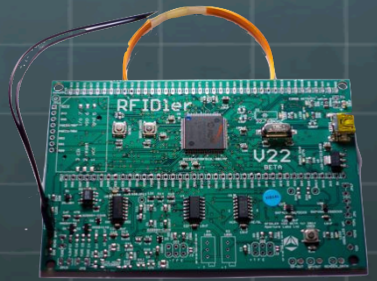
Tool Intros



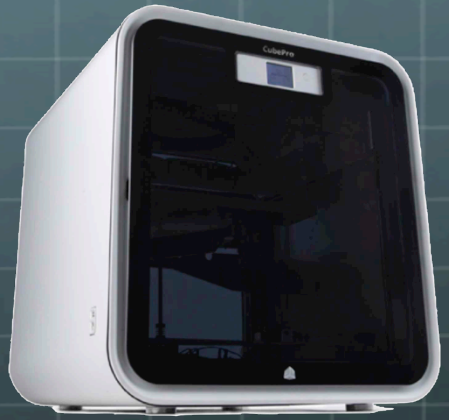
Proxmark3



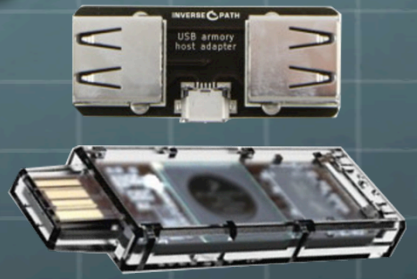
NFC USB (PN533)



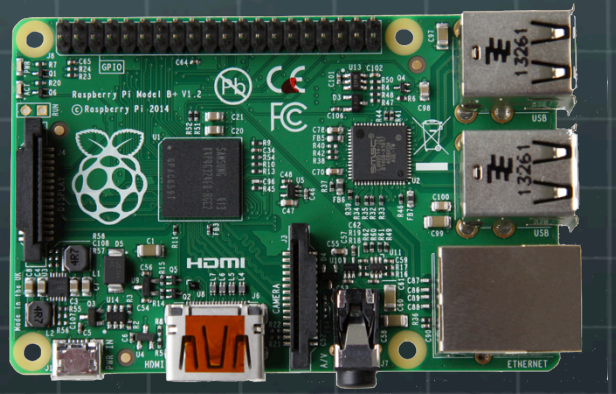
RFIDler v22



CubePro 3D Printer



USB Armory



Raspberry Pi

Tools

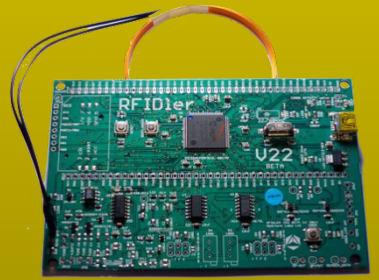
RFID



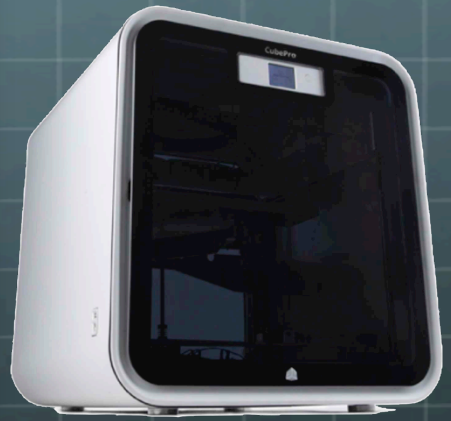
Proxmark3



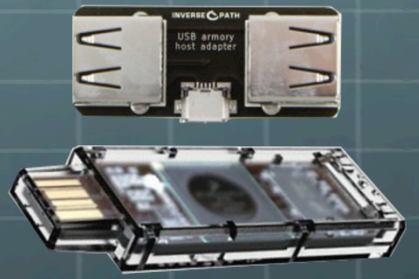
NFC USB (PN533)



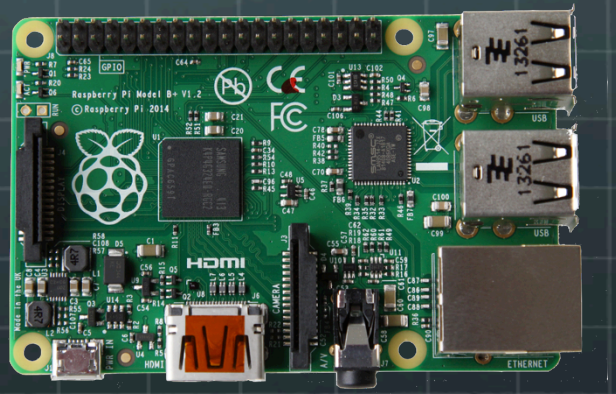
RFIDler v22



CubePro 3D Printer



USB Armory



Raspberry Pi

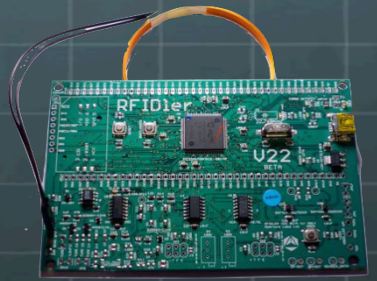
Tools



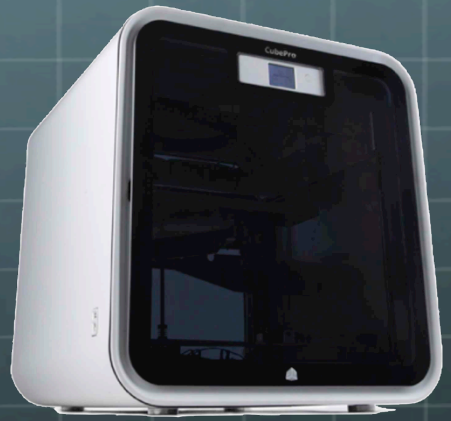
Proxmark3



NFC USB (PN533)



RFIDler v22



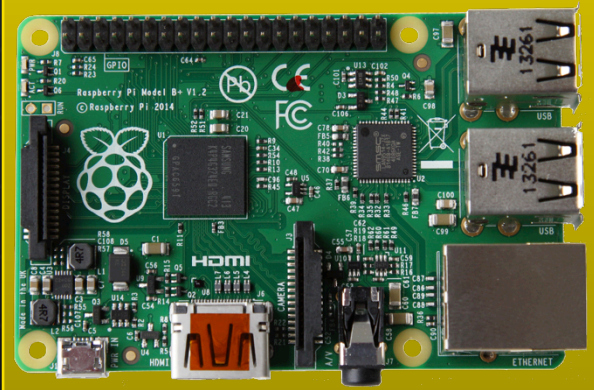
CubePro 3D Printer

Computing





USB Armory



Raspberry Pi

Tools

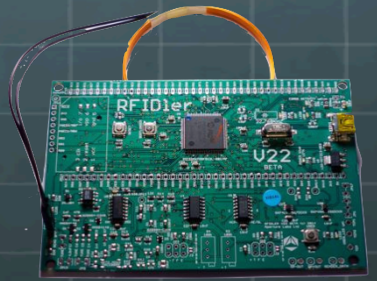
Fabrication



Proxmark3



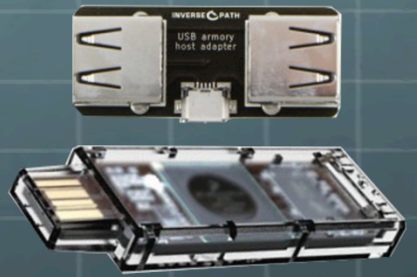
NFC USB (PN533)



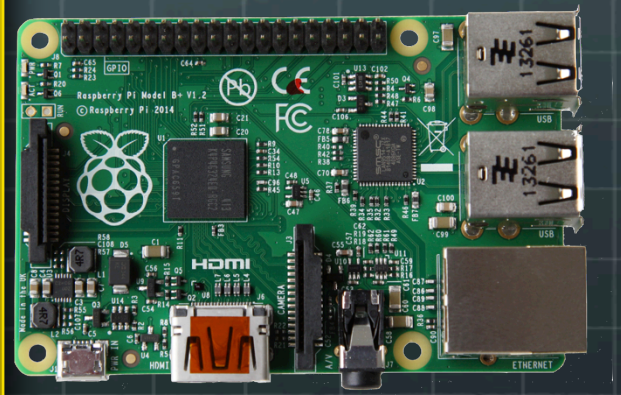
RFIDler v22



CubePro 3D Printer



USB Armory



Raspberry Pi

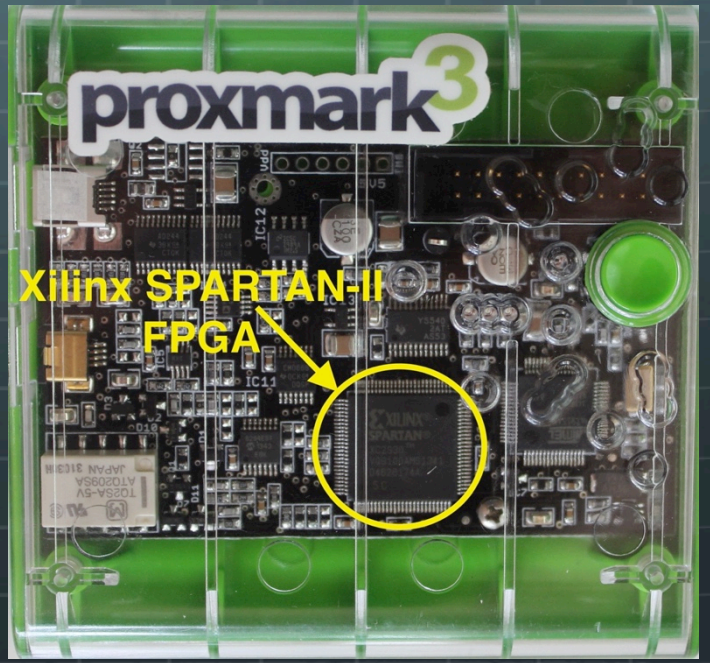
Proxmark3 Intro

- Adopted from Gerhard de Koning Gans' thesis
  - Koning Gans was analyzing Mifare transit cards
  - This system combines cheap FPGA and ARM CPU
  - Completely open source HW and SW
  - Low & High Frequency support



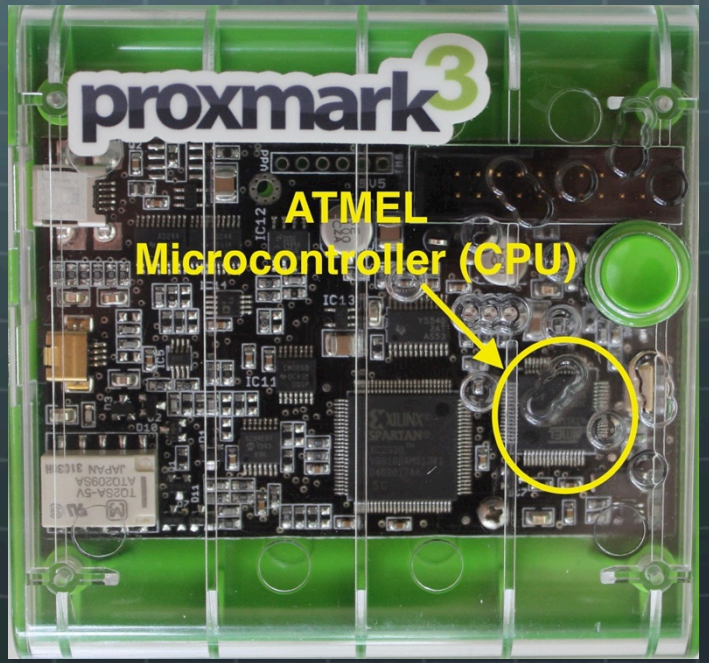
The Proxmark3 FPGA

- Xilinx Spartan-II Field-Programmable Gate Array
  - Written in Verilog for ISE WebPACK
  - Serial Peripheral Interface (SPI)
    - Coil driver
    - Analogue/Digital Converters
  - Synchronous Serial Port to CPU
  - Module based design
  - Modes specify module connections



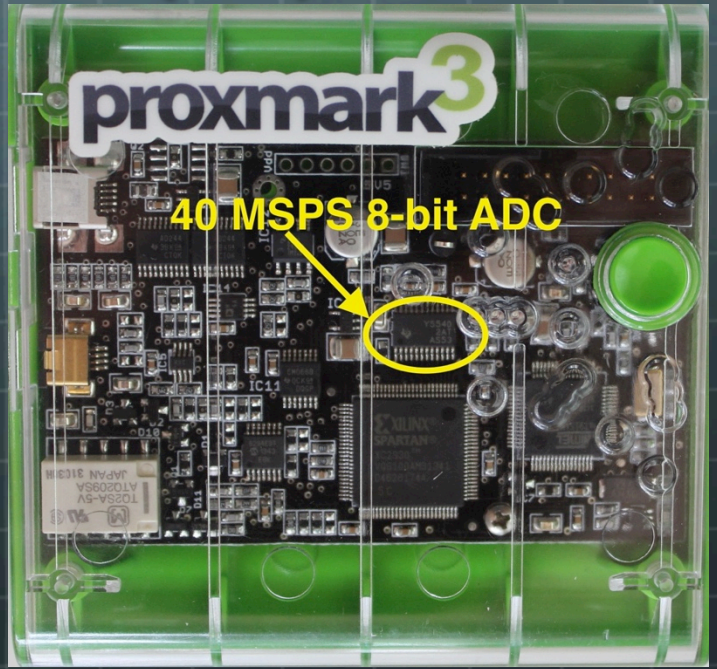
Proxmark3 CPU

- ATMEL 32-bit RISC Processor (AT91SAM7Sxx Series)
  - Coded in C
  - Receives data from FPGA
  - Encoding/decoding of bitstream
  - Handle USB data link
  - All high level functions run here



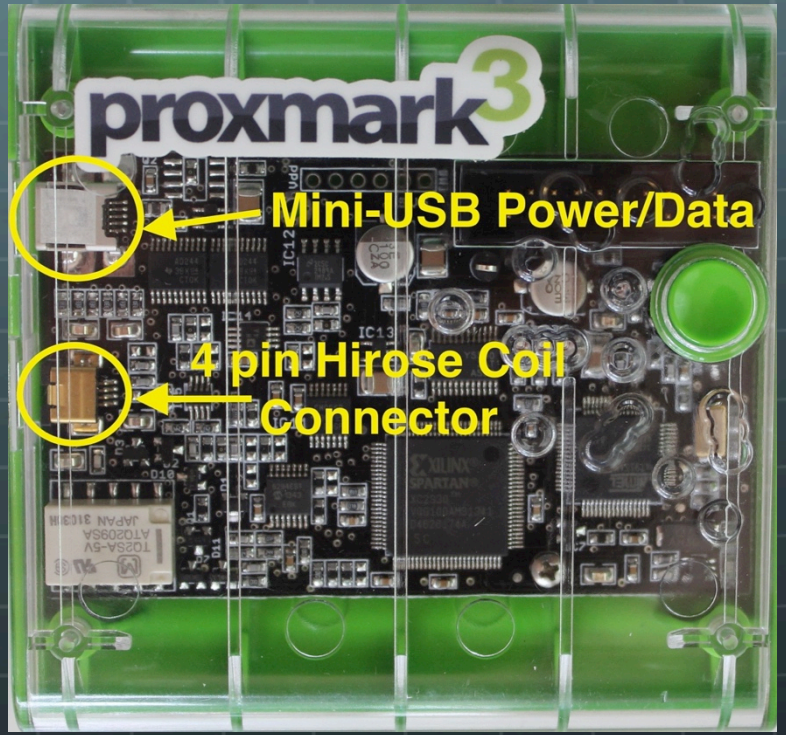
Proxmark3 ADC

- TI TLC 5540 analog-to-digital converter (ADC)
  - 8-bit resolution
  - 40 Megasamples/sec (MSPS)
  - Analog input from coil
  - 8-pin output to FPGA
  - Control via SPI



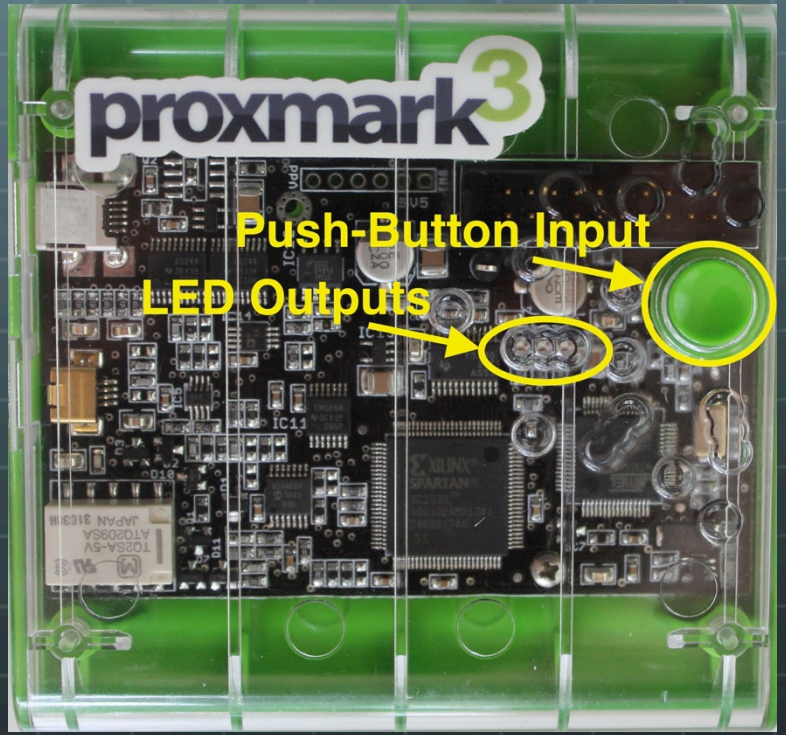
Proxmark3 Connectors

- Mini-USB
  - Provides Power
  - Data connection via USB-Serial
- Hirose Connector
  - Connection to antenna coil(s)
  - 2 wires for LF and 2 for HF



Proxmark3 Human I/O

- Single push button
  - Control PM3 without serial
  - Terminate active operations
  - Initiate firmware update
- Colored LEDs (4 total)
  - Indicate boot mode
  - Stand-alone status lights



Proxmark Commands

- lf search & hf search – Attempt to auto ID a tag
- hf 14a reader – Interrogate ISO14443a Tag
- lf read; data samples – Grab LF tag waveform
- hf mf mifare; hf mf nested – Mifare Classic Attack

PN533 NFC USB Intro

- NXP Chipset for Near Field Communications
- Hardware implementation of ISO 14443 standards
  - MIFARE Family (ISO/IEC 14443A)
  - NFC Forum Type 4 Tag 2.0 (ISO/IEC 14443B)
  - Sony Felicity Tags (FeliCa reader/writer)
  - Peer-to-Peer Data Transfer (ISO/IEC 18092)
- libNFC Compatible

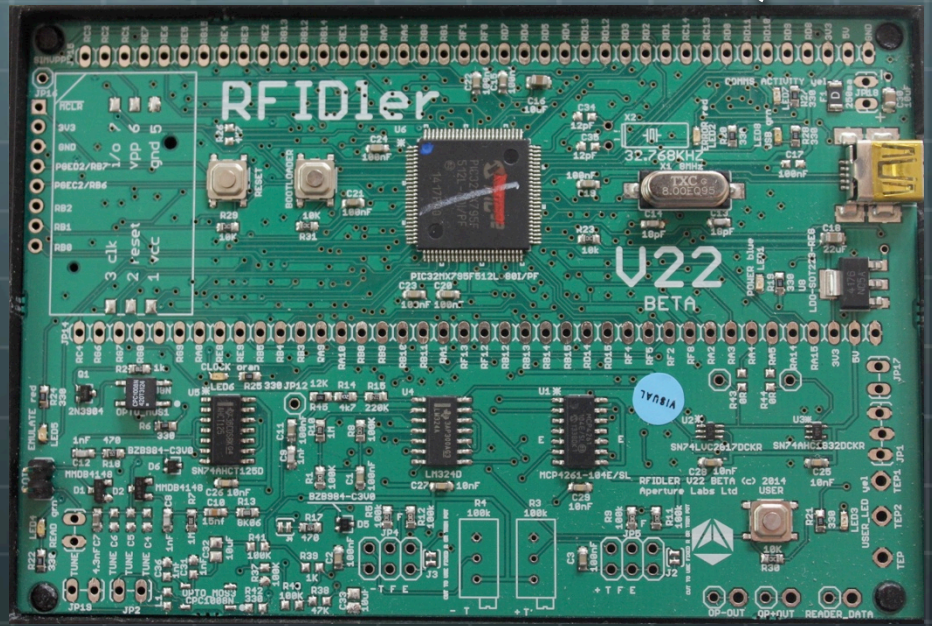


PN533 Commands

- PN533 supports libNFC including these CLI tools:
  - nfc-list – Basic Tag Enumeration
  - nfc-emulate-* – Emulate various tag
  - nfc-mf* – Work with Mifare family tags
  - nfc-relay – Use 2 devices to perform a relay attack
- Additional functionality via scripting

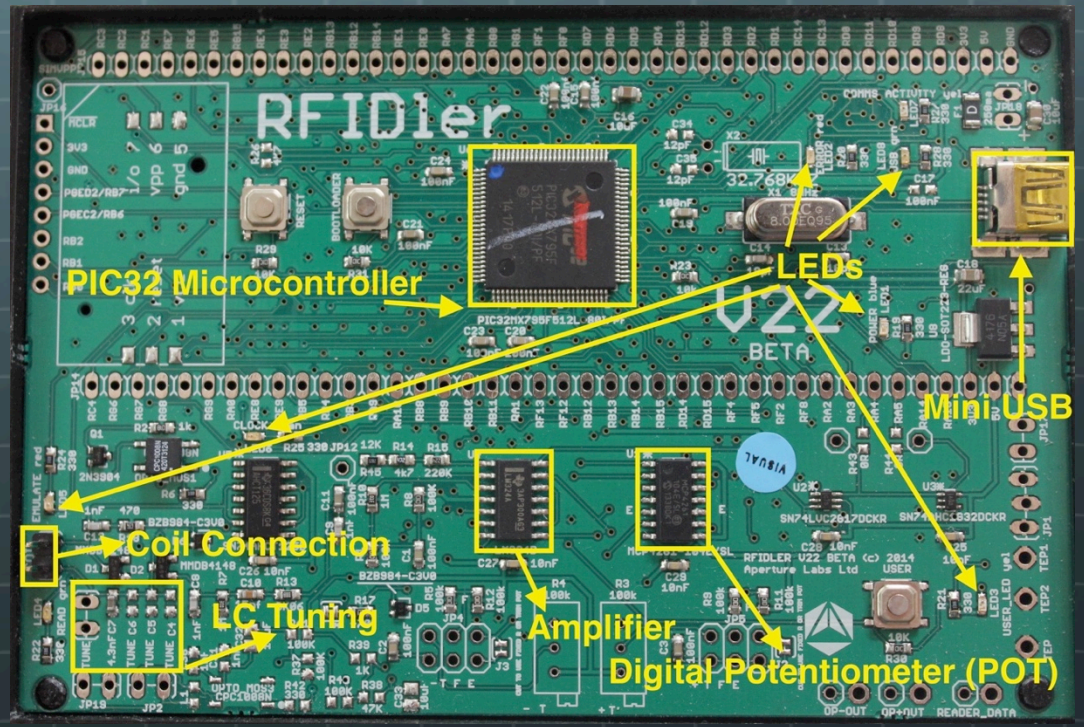
RFIDler Intro

- 125kHz-134kHz ASK and FSK reading and emulation
- V22 Beta Obtained at DEF CON 22 (coil not pictured)



Annotated RFIDler

- Digital POTs for threshold tuning
- USB Serial Interface
- LED indicators
- PIC32 for main guts
- USB Powered



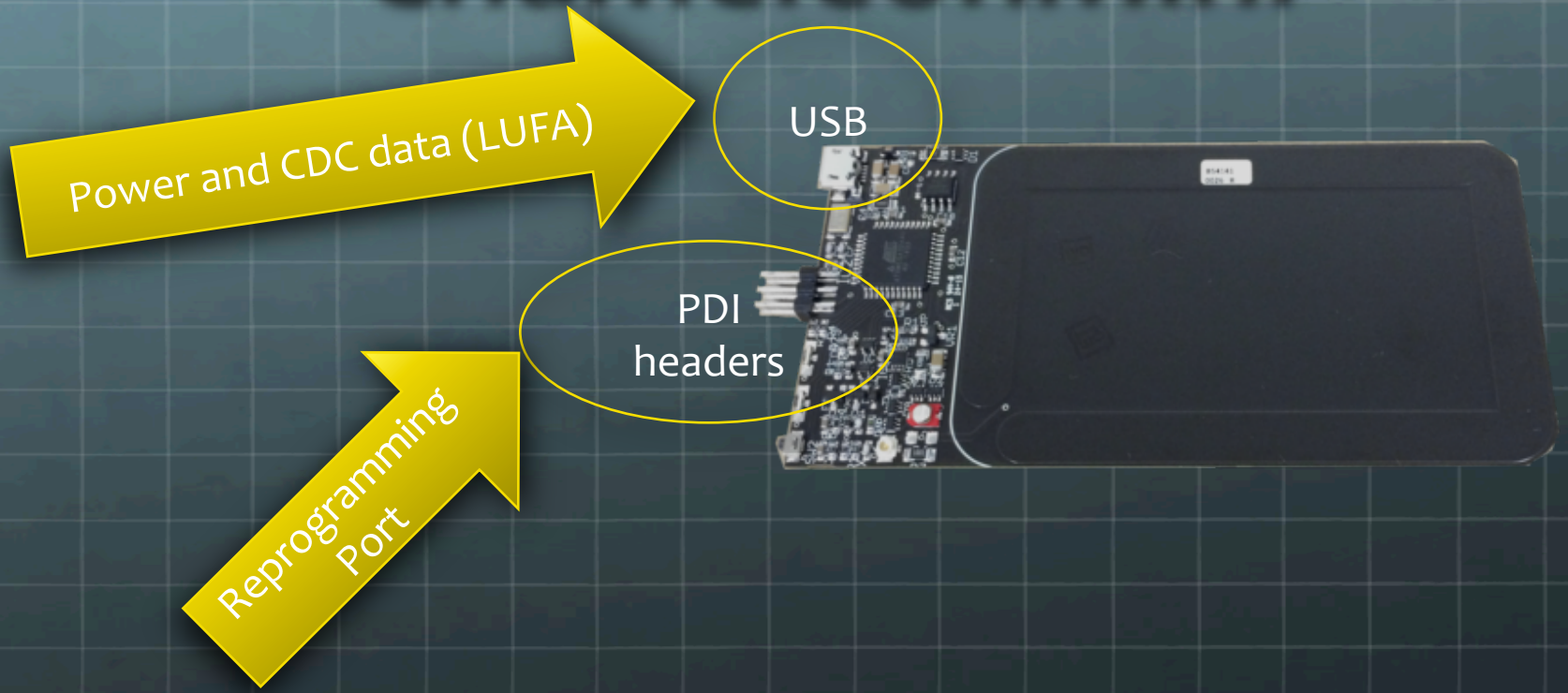
RFIDler Commands

- AUTOTAG – Demodulate tag as each known type
- SET TAG – Switch between tag formats
- POTSET - Adjust potentiometer thresholds
- READER – Realtime demodulation/decoding

LATE COMER:

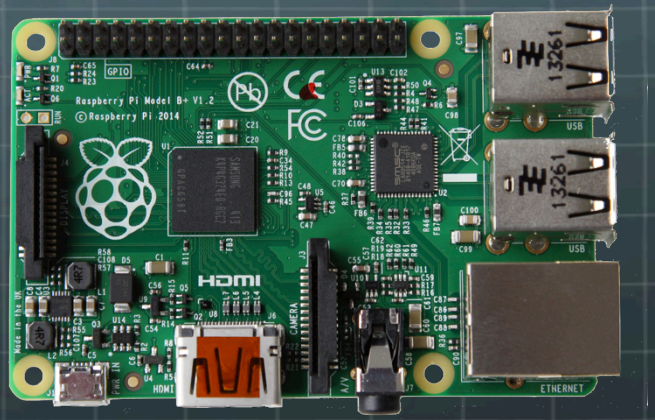
- The ChameleonMini
  - Developed by Chair for Embedded Security of the Ruhr-University in Bochum, Germany
  - ISO14443 and ISO15693 compliant emulator
  - Simulates contactless smartcards with hardware
    - Create perfect virtualized clones of a tag
- Started shipping from RyscCorp in July (hot off the press)

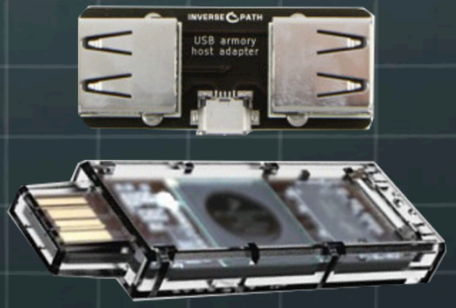
ChameleonMini



Raspberry Pi & USB Armory

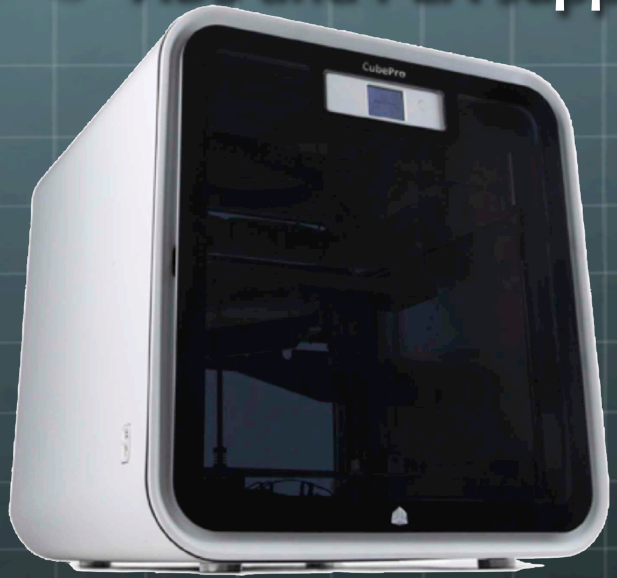
- Embedded ARM dev kit
- SD Card Storage
- USB Power & Data
- Thumb-drive ARM computer
- USB Host or Guest via OTG
- MicroSD Storage





3D Printer Intro

- CubePro with 70, 200, or 300 micron layer options
- ABS and PLA support with Nylon ‘coming soon’



- 11.2” x 10.6” x 9.06” build volume
- Up to 3 print jets for complex builds

CubePro 3D Printer Steps

3D CAD model is sliced by CubePro software into layers

Build plate receives a coating of water-soluble glue

Gears feed filament into extruder moving on X & Y

Extruder moves on X and Y; plate moves on Z for layers

Glue dissolves in water and model can be pried away

Printing Caveats

- Calibration can be time consuming and tricky
- Extruders prone to jams/clogs clogged
- Industrial design is tricky
  - Physical limitations
  - Materials science



RFID Basics

- Low-Frequency: 125kHz – 134 kHz
  - Access Control Proximity Cards: HID, Indala, AWID, etc
  - Pet chips / implantable: AVID, Fecava, ISO 11784/11785
- High-Frequency: 13.56MHz
  - Access control: HID iCLASS, NXP Mifare family
  - NFC: Contactless payment, bluetooth pairing, etc.
  - IDs: ePA (German ID card), passports, etc

What's in an RFID Tag

Tuned coil + LC = Passive RFID Tag



- Coil tuned to carrier frequency (e.g. 125kHz)
- Reader energizes coil to power chip
- Chip modulates signal by adjusting damping
  - Damping controls how the circuit resonates

Common Modulations

FSK

- Frequency Shift Keying

PSK

- Phase Shift Keying

ASK

- Amplitude Shift Keying

OOK

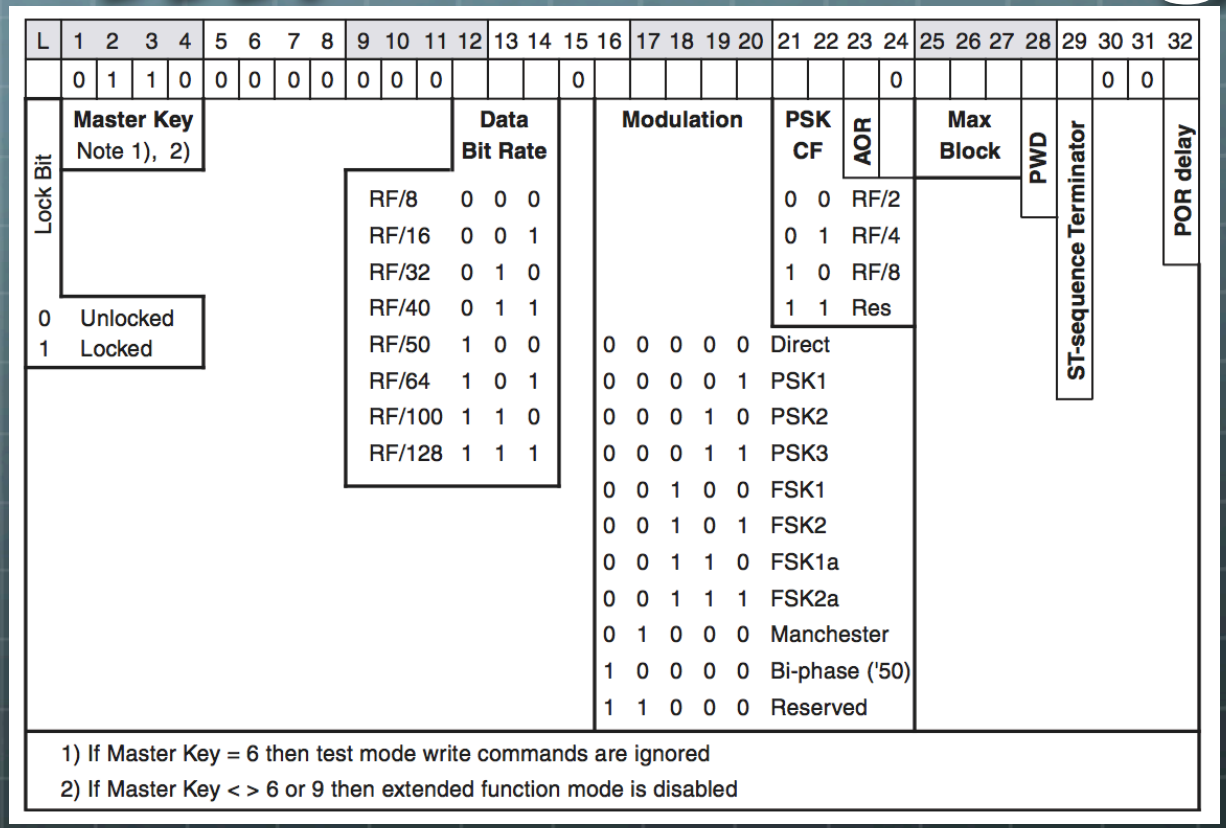
- On/Off Keying

LF Cloning (T55xx)

- Low-Frequency tag with configurable properties
  - Modulation: FSK/PSK/ASK
  - Encoding: Manchester/Biphase
  - 8 4-byte storage blocks
    - 1 Config Block (0)
    - 7 Bitstream Blocks (1-7)



T5557 Block 0 Config



L	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
	0	1	1	0	0	0	0	0	0	0	0				0									0						0	0	

Lock Bit

0	Unlocked
1	Locked

Master Key Note 1), 2)

Data Bit Rate

RF/8	0	0	0
RF/16	0	0	1
RF/32	0	1	0
RF/40	0	1	1
RF/50	1	0	0
RF/64	1	0	1
RF/100	1	1	0
RF/128	1	1	1

Modulation

0	0	0	0	0	Direct
0	0	0	0	1	PSK1
0	0	0	1	0	PSK2
0	0	0	1	1	PSK3
0	0	1	0	0	FSK1
0	0	1	0	1	FSK2
0	0	1	1	0	FSK1a
0	0	1	1	1	FSK2a
0	1	0	0	0	Manchester
1	0	0	0	0	Bi-phase ('50)
1	1	0	0	0	Reserved

PSK CF

0	0	RF/2
0	1	RF/4
1	0	RF/8
1	1	Res

AOR

Max Block

PWD

ST-sequence Terminator

POR delay

1) If Master Key = 6 then test mode write commands are ignored

2) If Master Key < > 6 or 9 then extended function mode is disabled

T5557 Block 0 (from datasheet)

Proxmark: lf search

Identify unknown tag

```
proxmark3> lf search
Reading 30000 bytes from device memory
```

- lf search : Automated LF Tag Detection
  - Step 1: lf read s
  - Step 2: data samples 30000
  - Step 3..n: Test each data *demod command until success

Proxmark: lf search

Identify unknown tag

```
proxmark3> lf search
Reading 30000 bytes from device memory

Data fetched
Samples @ 8 bits/smpl, decimation 1:1
NOTE: some demods output possible binary
  if it finds something that looks like a tag
False Positives ARE possible


Checking for known tags:

HID Prox TAG ID: 0deadbeef (57207) - Format Len: 37bit - FC: 3562 - Card: 450423

Valid HID Prox ID Found!
```

Proxmark Demodbuffer

Extract Tag Bitstream

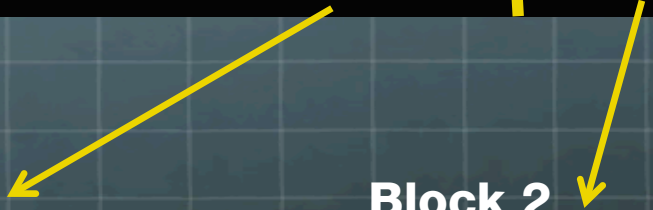
```
proxmark3> data printdemodbuffer x
DemodBuffer: 1D555555A6A999A69AA9A9AA
```

- DemodBuffer is the raw demodulated tag data
- Data can be split into 4-byte blocks for T55xx
- Bitstream starts with block 1

Proxmark Demodbuffer

Print Tag's Demodulated Bitstream

```
proxmark3> data printdemodbuffer x
DemodBuffer: 1D555555A6A999A69AA9A9AA
```



Block 1
0x1D555555

Block 2
0xA6A999A6

Block 3
0x9AA9A9AA

Setting T55xx Config

- Option 1: Determine block 0 manually via datasheets
- Option 2: Refer to excellent thread at proxmark.org
  - http://www.proxmark.org/forum/viewtopic.php?id=1767
- HID Tag uses: 0x00107060
  - 3 Blocks
  - FSK 2a Modulation
  - RF/50 Data Rate

Proxmark: T55xx Writes

Programming a T5557 Card with HID 37 deadbeef

```
proxmark3> lf t55xx write 0 0x00107060
Writing to block: 0  data  : 0x00107060
proxmark3> lf t55xx write 1 0x1D555555
Writing to block: 1  data  : 0x1D555555
proxmark3> lf t55xx write 2 0xA6A999A6
Writing to block: 2  data  : 0xA6A999A6
proxmark3> lf t55xx write 3 0x9AA9A9AA
Writing to block: 3  data  : 0x9AA9A9AA
```

Proxmark: HID Reading

Trust But Verify (with lf hid fskdemod)

```
proxmark3> lf hid fskdemod
#db# TAG ID: 0deadbeef (57207) - Format Len: 37bit - FC: 3562 - Card: 450423
#db# TAG ID: 0deadbeef (57207) - Format Len: 37bit - FC: 3562 - Card: 450423
#db# TAG ID: 0deadbeef (57207) - Format Len: 37bit - FC: 3562 - Card: 450423
#db# TAG ID: 0deadbeef (57207) - Format Len: 37bit - FC: 3562 - Card: 450423
#db# TAG ID: 0deadbeef (57207) - Format Len: 37bit - FC: 3562 - Card: 450423
#db# TAG ID: 0deadbeef (57207) - Format Len: 37bit - FC: 3562 - Card: 450423
#db# TAG ID: 0deadbeef (57207) - Format Len: 37bit - FC: 3562 - Card: 450423
#db# TAG ID: 0deadbeef (57207) - Format Len: 37bit - FC: 3562 - Card: 450423
#db# TAG ID: 0deadbeef (57207) - Format Len: 37bit - FC: 3562 - Card: 450423
#db# Stopped
```

What is Mifare?

- MiFare is a family of tags not just a single tag type
  - MiFare Classic
  - MiFare Ultralight (and variations)
  - MiFare DESFire (and variations)
  - Others?
- Tags support encryption in various capacities
  - All tags have a UID and sometimes that's all that matters
- Mifare is used everywhere (trains, payment cards, hotels, smartphone tags, etc)

Mifare Classic Cracking

Processes exist to recover keys from Mifare Classic

Once any key is known, nested attacks are possible

The result is complete key pwn in under 1 minute

“Magic” Cards

- Normally read-only UID is read-write instead
  - www.CloneMyKey.com (fast and reliable)
  - eBay “UID Changeable” (one vendor took 6+ weeks)
- Allows complete duplication of some card types
  - I have succeeded with Classic 1K and Ultralight cards
- This is why UID must not be used as a secure token

libNFC Cloning Example

- NXP PN533 w/ libNFC and “Magic” Mifare Ultralight
- nfc-mfultralight r dump.mfd
  - Create Mifare dump of target card
- nfc-mfultralight w source.mfd
  - Write contents of source.mfd to changeable tag
- Tested with key from CloneMyKey.com

Cloneable Stuff



- Hotel Contactless Key Cards
  - Several hotels are using insecure MIFARE variants
- EMV Legacy Transactions (Peter Fillmore, BH US 2015)
  - Due to support for contactless ‘legacy’ modes
- Android ‘Smart Unlock’ tags & some home NFC locks
  - Systems only validate UID which is easy to spoof

Hotel Card Clone Demo

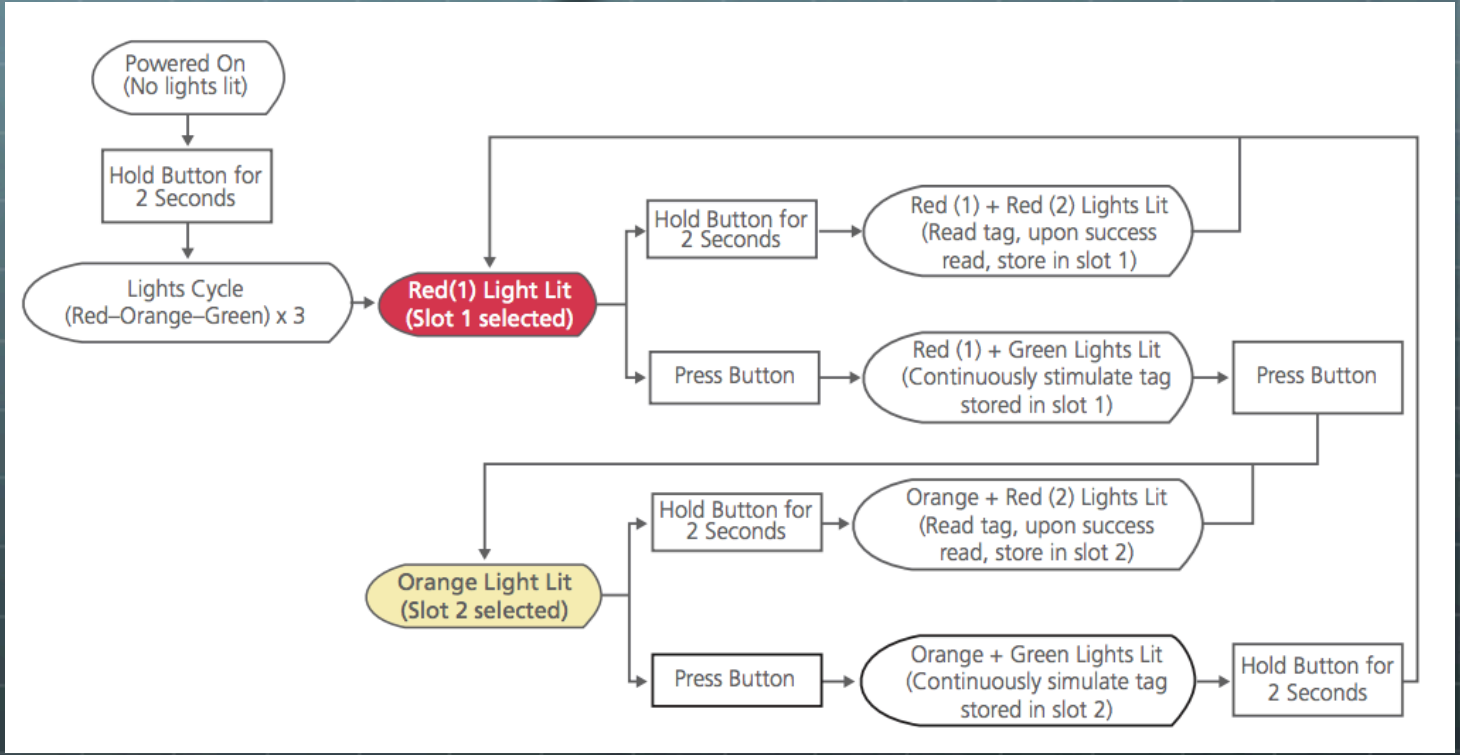


Firmware Hacking

Stand-Alone NFC

- Capture Tags
- Clone UID
- Replay UID

Proxmark3 LF Stand-Alone



Default PM3 standalone operation flow from ProxBrute whitepaper

Stand-Alone Design

Using ARM CPU for independent operation

- armsrc/appmain.c runs after init
- SamyRun() is invoked based on BUTTON_HELD(1000)

CmdHIDdemodFSK and related functions used

- Capture/Replay/T55x7 Clone toggle with button
- Visual indication through LED changes

Proxmark3 HF Stand-Alone

- Goal is reproducing the LF/HID functions for HF
  - Focus is on the popular Mifare card formats
- Initial support for UID value only
  - Demonstrates insecure use of UID for authentication
- Cloning to changeable (magic) Mifare Classic only
  - Support for other tags can be added easily

Offline HF Read (code)

iso14443a_setup(FPGA_HF_ISO14443A_READER_MOD)

iso14443a_select_card(uid, NULL, &cuid)

Return true means that a card select succeeded

Offline HF Sim (code)

UID is split into 2 4 byte values with valid byte order

SimulateIso14443aTag(1,uid_1st,uid_2nd,NULL)

UID only simulation (i.e. data support later?)

Offline HF Clone

Goal is to just set recorded UID on new tag

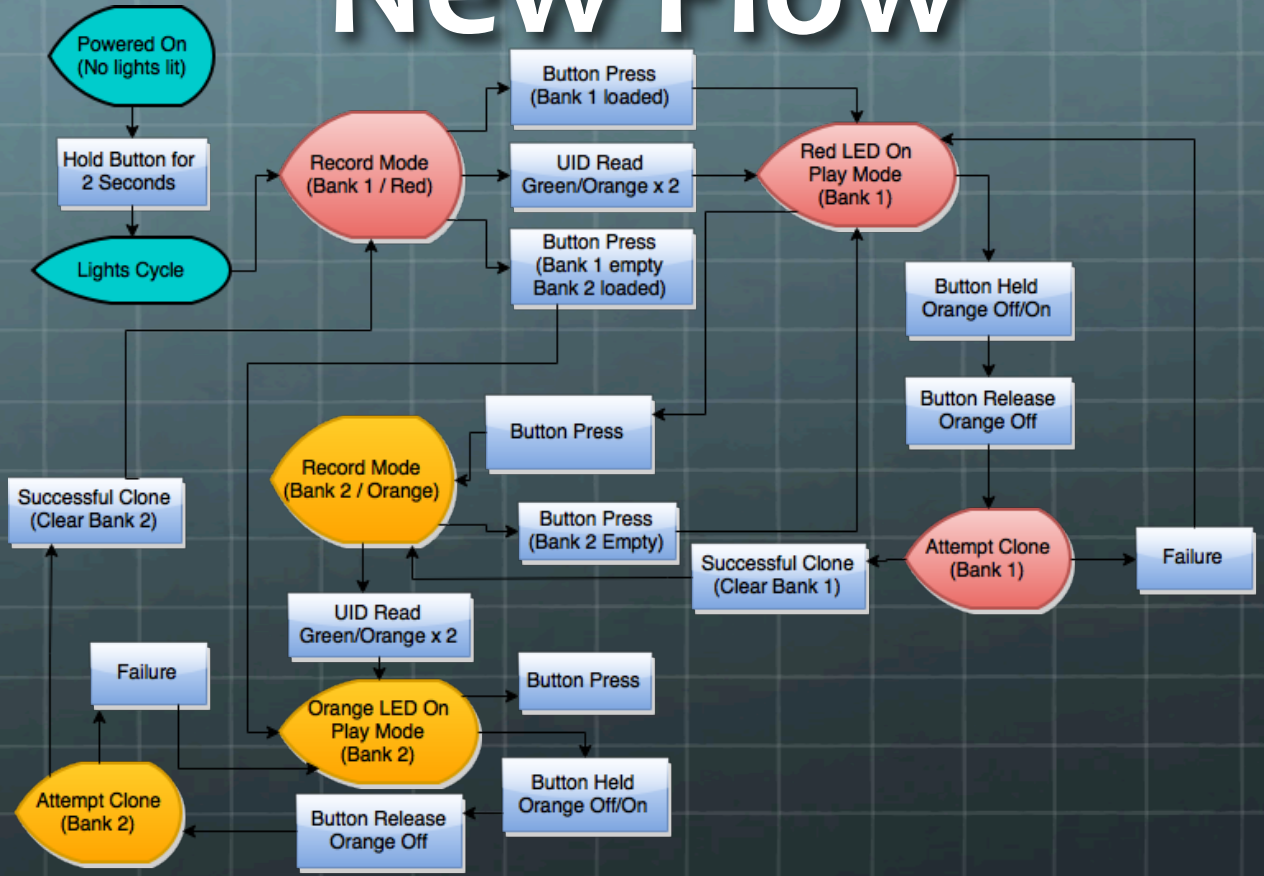
MiFare Classic support only initially

- hf mf csetuid <UID>

Useful for systems relying on UID for auth

- Samsung NFC locks, Smartphone unlock tags, etc.

New Flow


Powered On
(No lights lit)
Hold Button for
2 Seconds
Lights Cycle
Record Mode
(Bank 1 / Red)
Button Press
(Bank 1 loaded)
UID Read
Green/Orange x 2
Button Press
(Bank 1 empty
Bank 2 loaded)
Red LED On
Play Mode
(Bank 1)
Button Held
Orange Off/On
Button Release
Orange Off
Button Press
Record Mode
(Bank 2 / Orange)
Button Press
(Bank 2 Empty)
Successful Clone
(Clear Bank 2)
Successful Clone
(Clear Bank 1)
Attempt Clone
(Bank 1)
Failure
UID Read
Green/Orange x 2
Failure
Button Press
Orange LED On
Play Mode
(Bank 2)
Button Held
Orange Off/On
Attempt Clone
(Bank 2)
Button Release
Orange Off

HF Stand-Alone Demo!



Firmware Hacking

Extending AWID

- Reader Mode
- Sim from IDs
- Clone from IDs

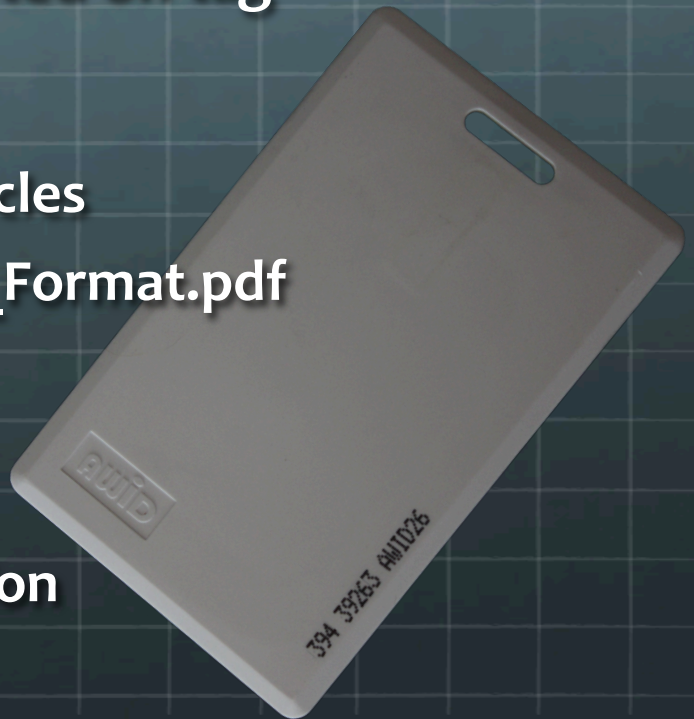
Adding PM3 Commands

- Target: ‘lf awid’ Proxmark3 context
  - fskdemod – Real-time demodulation for AWID tag
  - clone – Prepare T55xx card based on specified ID
  - sim – Tag emulation based on ID
- PM3 had no AWID26 code until this year
  - fskawiddemod added 2015
  - No lf awid context was added
  - Looked like a good place to contribute



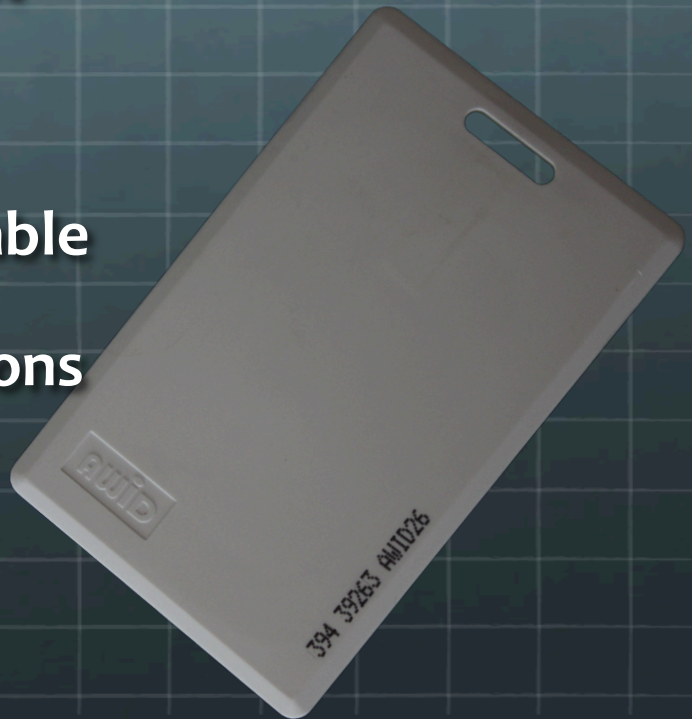
AWID26

- 8-bit Facility & 16-bit card number printed on tag
- 125kHz FSK2a (RF/50 data rate)
  - FSK Logic 0: 8 cycles, FSK Logic 1: 10 cycles
  - www.proxclone.com/pdfs/AWID_FSK_Format.pdf
- 96-bit transmission
  - Every 4th bit is a parity bit
  - 2 more parity bits for wiegand validation



Command Structure

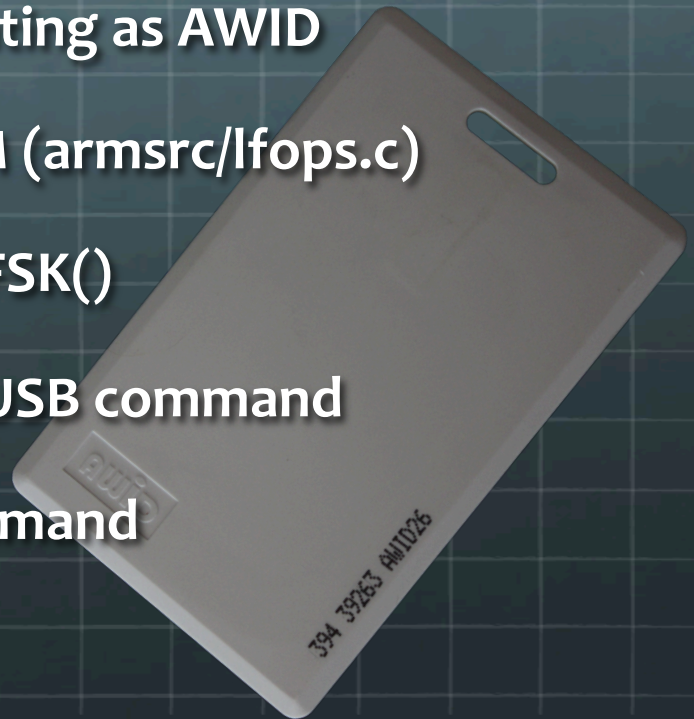
- Commands live in the proxmark3 client
- client/cmdlf.c for LF commands
- New commands added to CommandTable
- client/cmdlfawid.c created for definitions
  - Prepare & send UsbCommand to PM3



lf awid fskdemod

```
proxmark3> lf awid fskdemod
#db# AWID Found - BitLength: 26, FC: 1, Card: 31337 - Wiegand: 2f4d3, Raw: 011d8114eb2b281111111111
```

- Loop collecting samples and demodulating as AWID
- Runs as CmdAWIDdemodFSK() on ARM (armsrc/lfops.c)
- Structure copied from CmdHIDdemodFSK()
- CMD_AWID_DEMOD_FSK defined for USB command
- Logic in cmdlfawid.c exposes new command



AWID26 BitStream

- Added getAWIDBits() utility function on client side
  - Translate facility-code and card number into bits
  - Card data stored as array of 12 uint8_t
  - Logic via AWID PDF
  - parityTest() via lfdemod.h
  - Hardcoded for 26-bit Wiegand



If awid clone

- Programs T55x7 as specified AWID26
- Uses getAWIDBits() to determine BitStream
- Block 0 is static rate/modulation config
- Bitstream split into blocks 1-3
  - Cmd = CMD_T55XX_WRITE_BLOCK
  - Args: (data, block num, password)



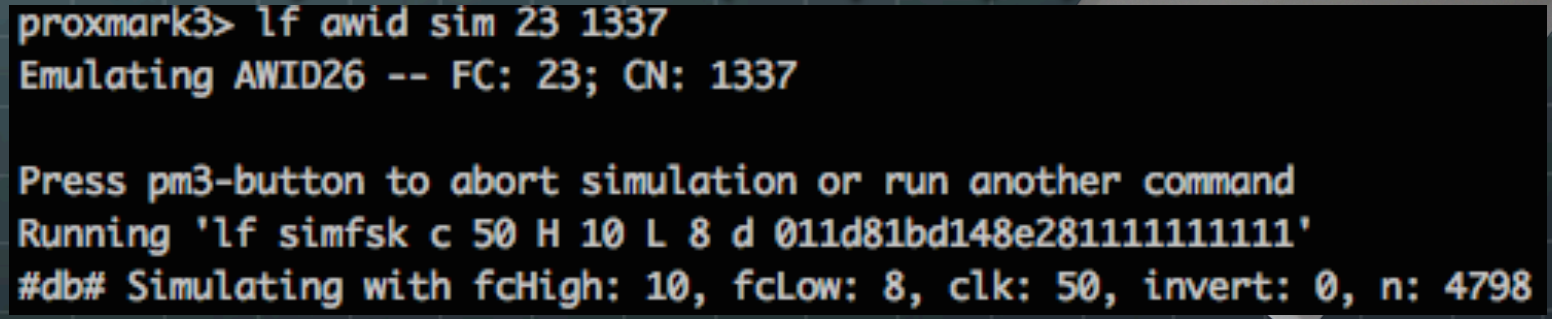
lf awid clone

```
proxmark3> lf awid clone 123 45678
Preparing to clone AWID26 to T55x7 with FC: 123, CN: 45678 (Raw: 011db7de722bd81111111111)
Block 0: 0x00107060
Block 1: 0x011db7de
Block 2: 0x722bd811
Block 3: 0x11111111
proxmark3> lf search
Reading 30000 bytes from device memory

Data fetched
Samples @ 8 bits/smpl, decimation 1:1
NOTE: some demods output possible binary
  if it finds something that looks like a tag
False Positives ARE possible


Checking for known tags:

AWID Found - BitLength: 26, FC: 123, Card: 45678 - Wiegand: 2f764dd, Raw: 011db7de722bd81111111111

Valid AWID ID Found!
```

lf awid sim

Calculates/displays ‘lf simfsk’ parameters for AWID26

- cmd = CMD_FSK_SIM_TAG
- arg[0] = fcHigh<<8 + fcLow = (10<<8)+8
- arg[1] = CLK & Invert = 50
- arg[2] = Length = 96 (bits)
- d.asBytes = BitStream (1 bit per byte)



Antenna Construction

- The Problem
  - Traditional DIY involves a lot of trial and error
  - The outcome is not always ideal for practical attacks
- My Solution: 3D Printing
  - Create forms with precise measurements easily
  - Make coils that blend in

Supplies

- High AWG magnet wire (e.g. 40AWG)
- Utility knife (to remove enamel from wire ends)
- Soldering iron
- Heat shrink tubing (optional)
- Inductance meter (optional)

The Math of Tuning

- The antenna coil is an inductor (L)
- An LC circuit is formed by pairing it with a capacitor
- Goal is to match the coil's L with the capacitor @ F

$$F = \frac{1}{2\pi\sqrt{CL}}$$

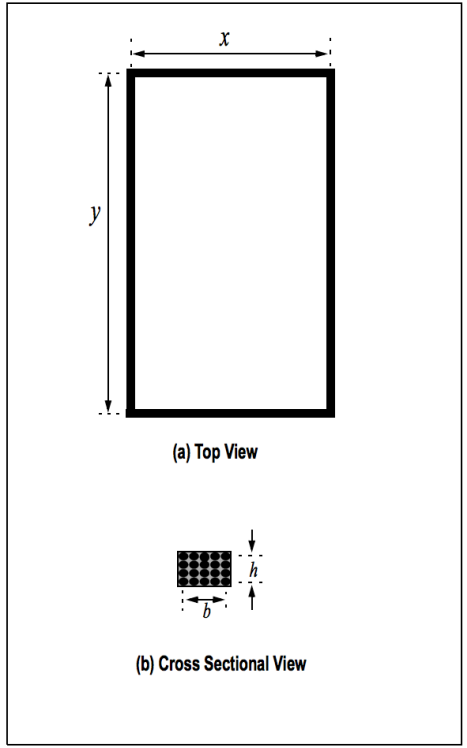
The Math of Tuning

- Microchip AN170
  - Coil induction equations
- Organized by coil shape
- For my ‘multilayer rectangular loop coil’:

$$L = \frac{0.0276(CN)^2}{1.908C + 9b + 10h}(\mu H)$$

WHERE➔

FIGURE 11: N-TURN SQUARE LOOP COIL WITH MULTILAYER



Making a Fake Badge

- Started with D18c7db's LF design
  - Constructed with CD jewel cases cut to size
- Rectangular "badge-like" 70x40mm coil is perfect
  - Drew with CAD and exported for printing
  - Add an ID sticker for an extra convincing look
  - Lanyard clip allows route for discrete wiring

Winding the Coil

- Coil inductance is matched to capacitor for resonance
- First calculate L based on F and C

$$L = \frac{1}{4\pi^2 C F^2}$$

- Calculate turns required for L based on shape
  - For my Proxmark3: ~87 turns
  - For my RFIDler: ~57 turns
- Calculations only give guideline due to natural variance

Winding the Coil

- Wind more turns than you expect to need
- Removing extra turns is easy
  - Making up for not enough turns – NOT SO EASY
- Count and watch for wire getting caught on edges

First Antenna Attempt







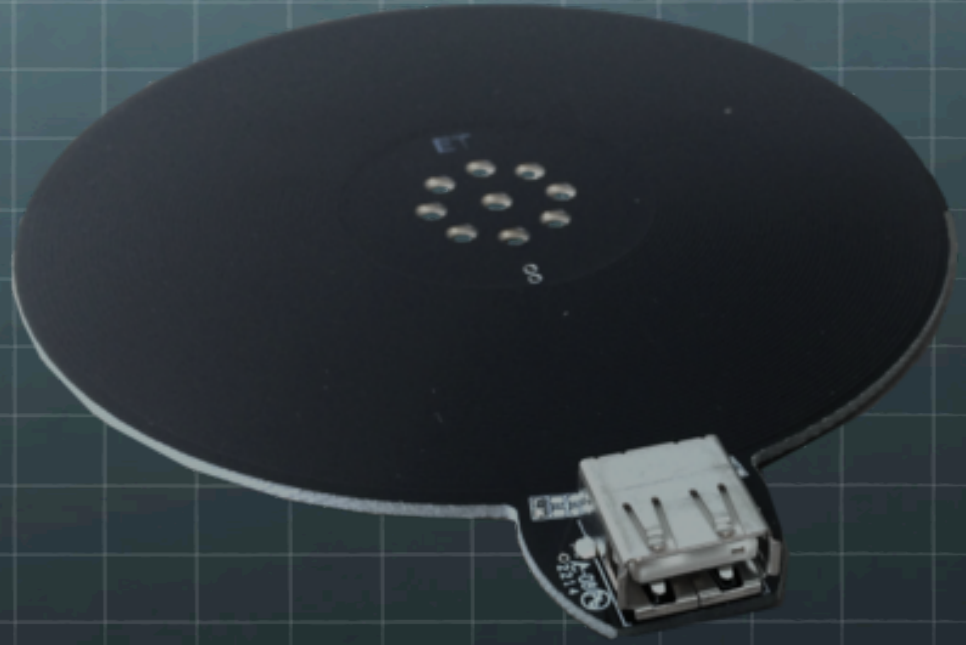
```
proxmark3> hw tune

Measuring antenna characteristics, please wait...
# LF antenna: 31.21 V @   125.00 kHz
# LF antenna: 18.29 V @   134.00 kHz
# LF optimal: 31.21 V @   125.00 kHz
# HF antenna:  2.23 V @    13.56 MHz
# Your HF antenna is unusable.
Displaying LF tuning graph. Divisor 89 is 134khz, 95 is 125khz.
```

DIY vs. Off-the-Shelf

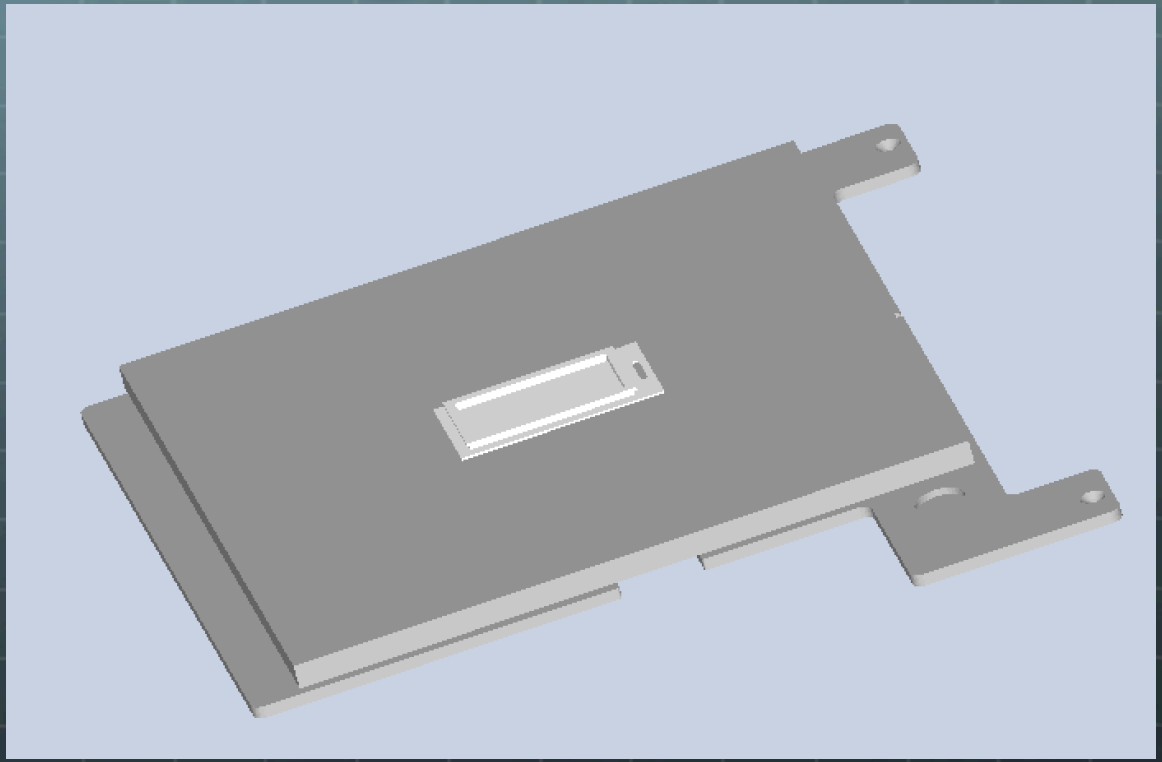
```
# LF antenna: 31.21 V @   125.00 kHz
# LF antenna: 18.29 V @   134.00 kHz
# LF optimal: 31.21 V @   125.00 kHz
```



```
# LF antenna: 14.85 V @   125.00 kHz
# LF antenna: 26.95 V @   134.00 kHz
# LF optimal: 29.43 V @   131.87 kHz
```



Badge Revision



BADge-tenna

- $7.68 + $4.99 shipping for flexible white plastic
  - Suitable alternative for those without a 3d printer
- With CubePro: about $4 filament
  - Print costs below $1 with generic filament
- Cable hidden in black lanyard
- Scavenged RCA cable for length



Clipwned



Storage clipboards are great cover!

They blend well with room for toys!

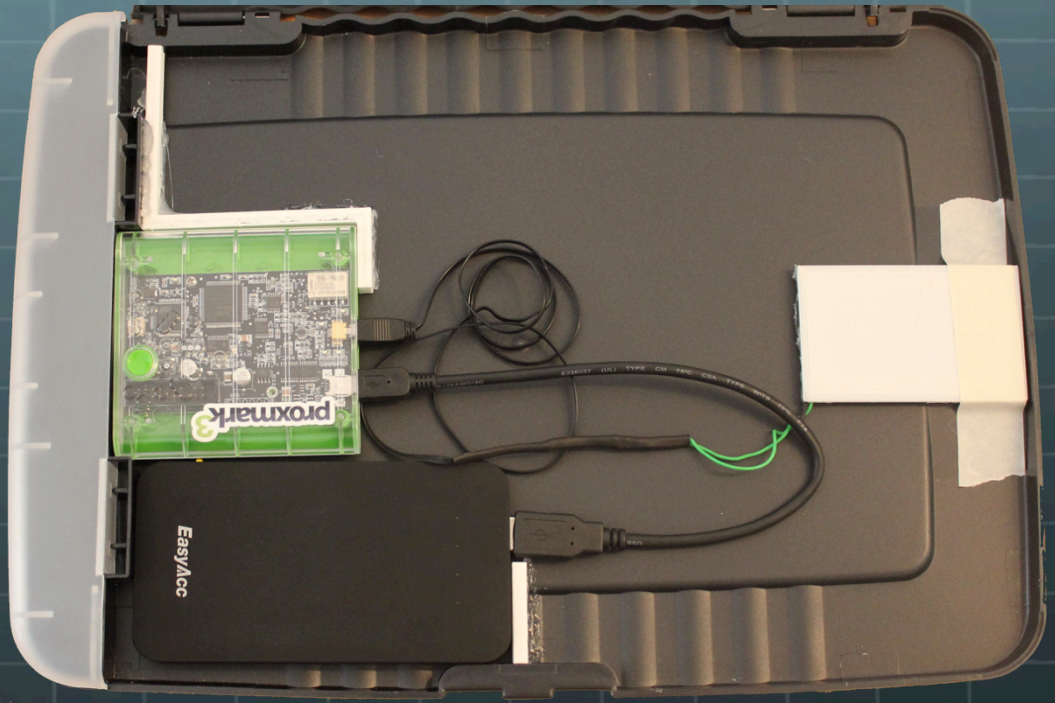
Printed spacers hold the gear tight.

An official sticker seals the deal…



Clipboards lend authority, it’s up to you to take it!

What is Clipwned



“Could I just grab that badge one second to make sure I’ve got your name right?”

Clipwned Supplies

Amazon is full of “Storage Clipboards”

Step 1 is finding one with the depth needed (3/4” minimum, 1” is great)

- Check dimensions of tools going into clipwned

3D printed parts provide guides to keep components in place

- Tape, wood, and other materials work as well

Making Clipwned 2.0

Attach battery to embedded computer for power

- Proxmark client compiles easily on many platforms
- libNFC supports major distros
- The RFIDler USB serial is almost universally supported

Connect embedded computer to RFID tool of choice via USB

Cover stash with legitimate forms or blank pages

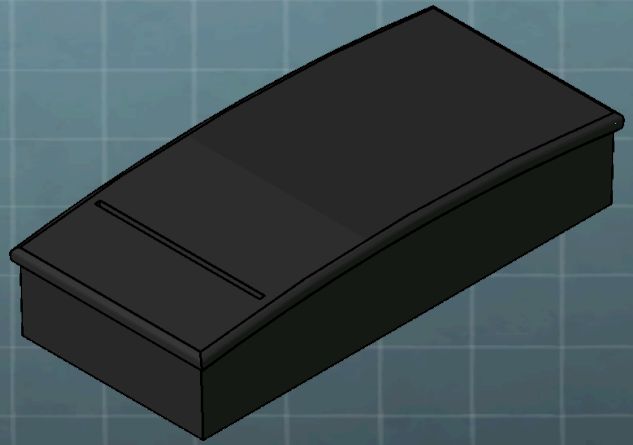
Make clipwned look like something a pro uses (notes, pens, etc.)

Making Fake Readers

- Building Information Modeling
  - Models available for common building components
  - This includes access control readers
  - Models are suited for modification and printing



Fake Readers



- Models via BIM make 3D printed readers possible
- Add an antenna inside for a hostile reader

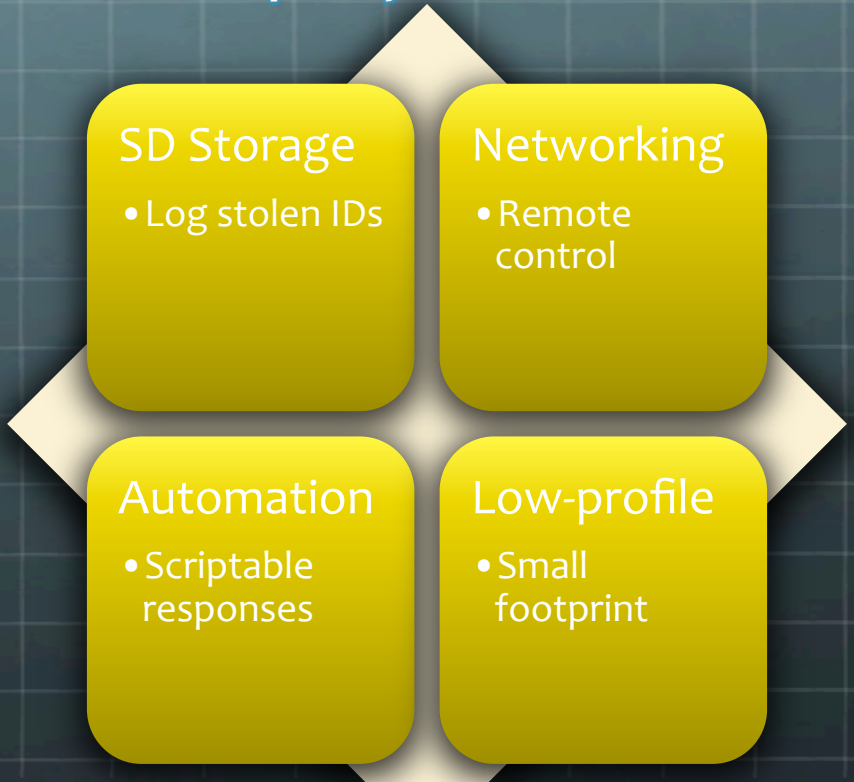
- Place it over an existing reader and relay/record badge scans for a day
- Install rogue readers in unexpected places and see who scans
  - “Badge for the elevator? Cool upgrade!!!”

Phone Case Snooper

- Phone based NFC payment is being hailed for security
  - What is possible by having a coil hidden in a case?
    - Snooping on transactions for research?
    - Stealthy relay attacks?
    - Android Beam/NDEF attacks?
- Phone case models readily available on web
  - Cube even includes an iPhone case as a test file

More Embedded Help

Pairing the RFIDler with a Raspberry Pi enables stealth & advanced attacks.



Thanks!

Special thanks to:

- Marshmellow42, Iceman, & the rest of the PM3 collaborators
- To my family for putting up with all the crazy hours leading up to DC23!

Much more info will is included in the whitepaper.

Please direct questions to:

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