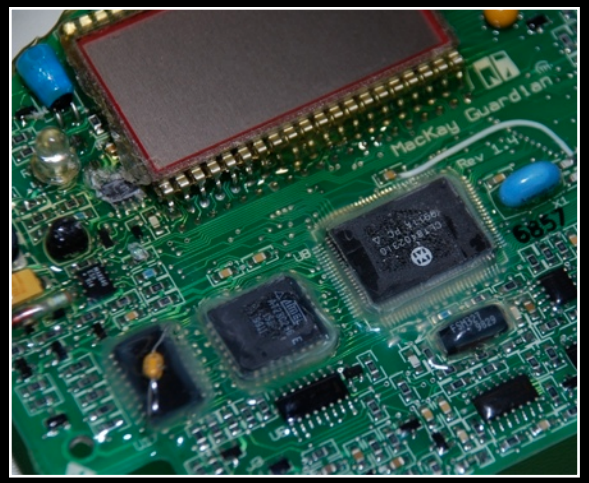
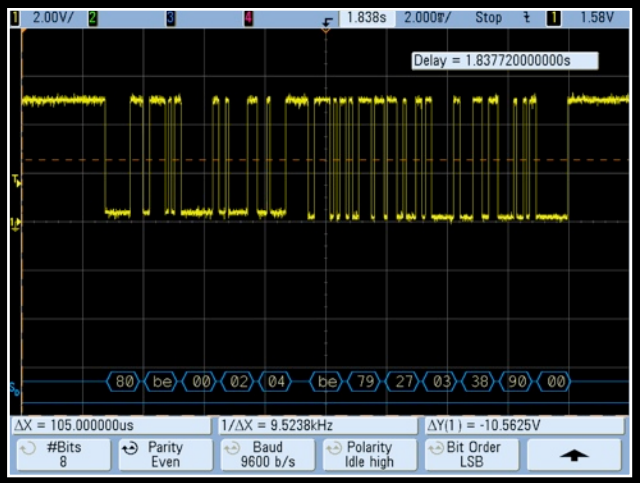
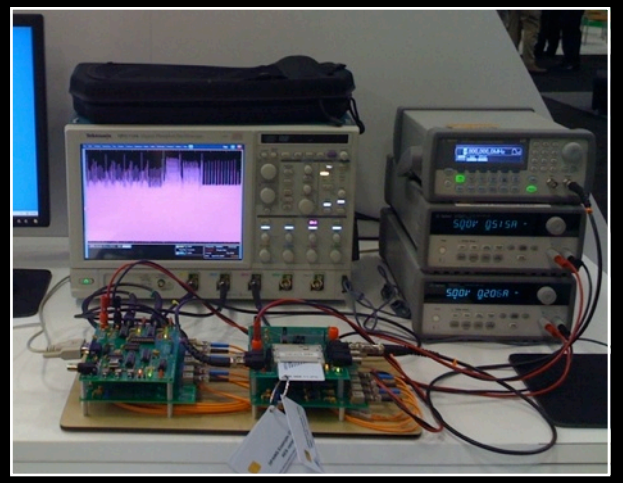
Hardware is the New Software







Joe Grand aka KINGPIN, Grand Idea Studio, Inc.

/me

- Electrical engineer
- Hardware hacker
- Product designer
- Member of the L0pht hacker think-tank in 1990s
- Co-host of Prototype This on Discovery Channel
- Security work includes breaking smart parking meters, authentication tokens, and early PDAs

We Are Controlled By Technology

- Electronics are embedded into nearly everything we use on a daily basis
- Often taken for granted and inherently trusted
  - H/W is not voodoo, but people treat it that way
- Hardware has largely been ignored in the security field
  - Many products susceptible to compromise via simple, practical classes of attack
  - Vendors mostly respond to security problems by blowing them off (like S/W in the 90s!)
    - ...or it is blown completely out of proportion

The Time is Now...

- The tools are available
- The information is available
- All you need is the confidence to approach the problem...

Why Hardware Hacking? For Good?

- Security competency
  - Test hardware security schemes for failures/weaknesses
- Consumer protection
  - I don't trust glossy marketing materials...do you?
- Military intelligence
  - What is that hardware? How was it designed? By whom?
- Education and curiosity
  - To simply see how things work
  - Do something new, novel, and/or unique

Why Hardware Hacking?
For Evil?

- Theft of service
  - Obtaining a service for free that normally costs $$$
- Competition/cloning
  - Specific theft of information/data/IP to gain a marketplace advantage
- User authentication/spoofing
  - Forging a user's identity to gain access to a system

Easy Access to Tools

- Cost of entry can be less than setting up a software development environment!
- Pre-made, entry-level packages available
  - Ex.: Ladyada's Electronics Toolkit, `www.adafruit.com/index.php?main_page=product_info&cPath=8&products_id=136`
  - Ex.: Deluxe Make: Electronics Toolkit, `www.makershed.com/ProductDetails.asp?ProductCode=MKEE2`

Easy Access to Tools 2

- Soldering Iron
  - From a simple stick iron to a full-fledged rework station (~$10 to $5k)
  - Fine tip, 700 degree F, > 50W soldering stick iron is recommended
  - Ex.: Weller WP25 or W60P Controlled-Output, $67.95

Easy Access to Tools 3

- Soldering accessories
  - Solder: No-clean flux, thin gauge (0.032" or 0.025" diameter), ~60/40 Rosin core or Lead-free
  - Desoldering Tool ("Solder Sucker"): Manual vacuum device that pulls up hot solder, useful for removing components from circuit boards (Radio Shack #64-2098, $7.99)
  - Desoldering Braid: Wicks up hot solder (Radio Shack #64-2090, $3.99)
  - IC Extraction Tool: Helps lift ICs from the board during removal/desoldering (Radio Shack #276-1581, $8.39)

Easy Access to Tools 4

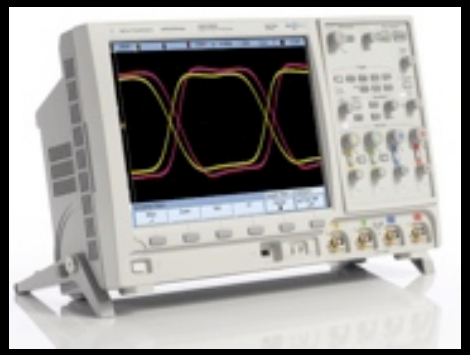
- Soldering accessories (continued)
  - ChipQuik SMD Removal Kit: Allows the quick and easy removal of surface mount components
  - Tip cleaner: Helps to keep the solder tip clean for even heat distribution. Ex.: Sponge, lead-free tip tinner

Easy Access to Tools 5

- Multimeter
  - Provide a number of precision measurement functions: AC/DC voltage, resistance, capacitance, current, and continuity
  - Ex.: Fluke Model 115, $129.00

Easy Access to Tools 6

- Oscilloscope
  - Provides a visual display of electrical signals and how they change over time
  - Available in analog, digital, and mixed-mode versions
  - Good introductory guide: XYZs of Oscilloscopes, `www.tek.com/Measurement/App_Notes/XYZs/index.html`
  - Approximate price range $100 (used) - $20k US
  - Ex.: USBee, $295-$1495, `www.usbee.com`
  - Ex.: PicoScope, $250-$1500, `www.pico-usa.com`

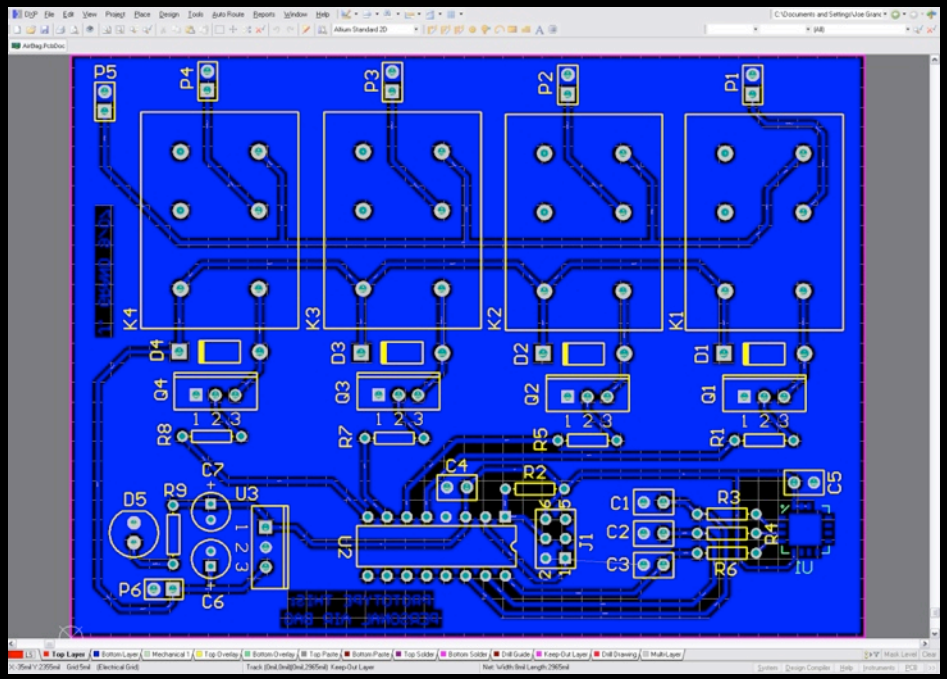


Easy Access to Tools 7

- Microscope
  - Useful for careful inspection of circuit boards, reading small part numbers, etc.
  - Human hands have more resolution than the naked eye can resolve
    - Greatly aids in soldering surface mount devices
    - You'll be amazed at what fine-pitch components you can solder when using a decent microscope!
  - Approximate price range $100 - $5k US
  - Ex.: Vision Engineering, `www.visioneng.com`
  - Ex.: AmScope/Precision World, `http://stores.ebay.com/Precision-World`

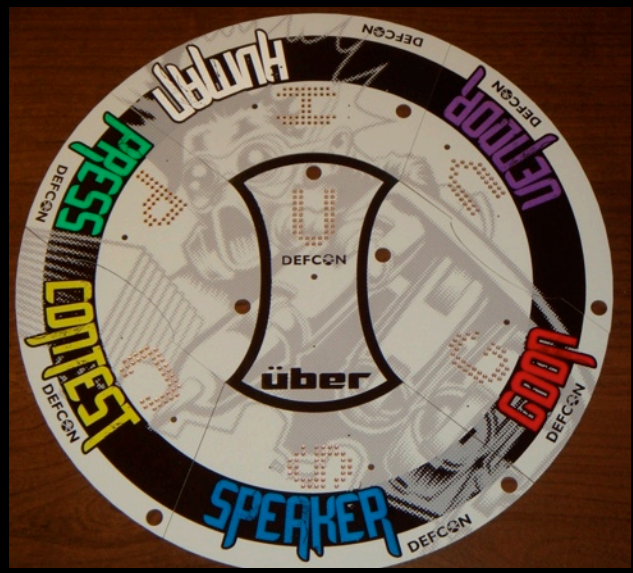
Easy Access to Tools 8

- PCB Design
  - Many low-cost, open source, or captive solutions
  - Ex.: EAGLE, `www.cadsoftusa.com`
  - Ex.: gEDA, `http://geda.seul.org`
  - Ex.: Kicad, `www.lis.inpg.fr/realise_au_lis/kicad`
  - Ex.: PCB123, `www.sunstone.com/PCB123.aspx`



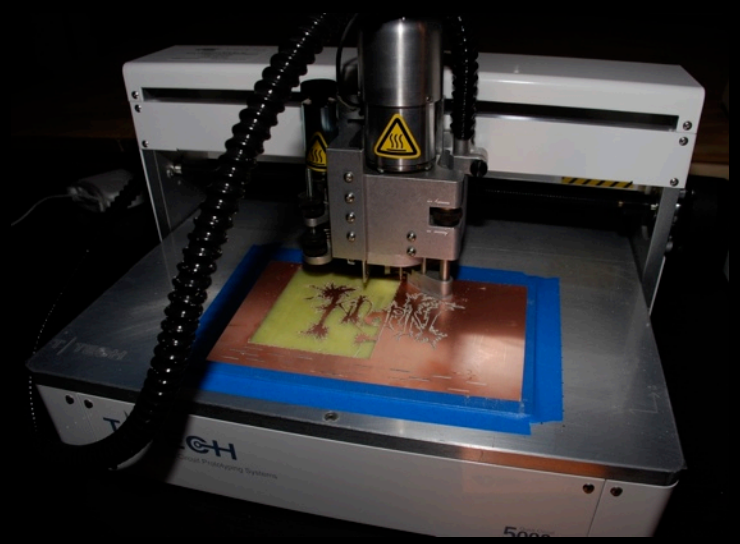
Easy Access to Manufacturing

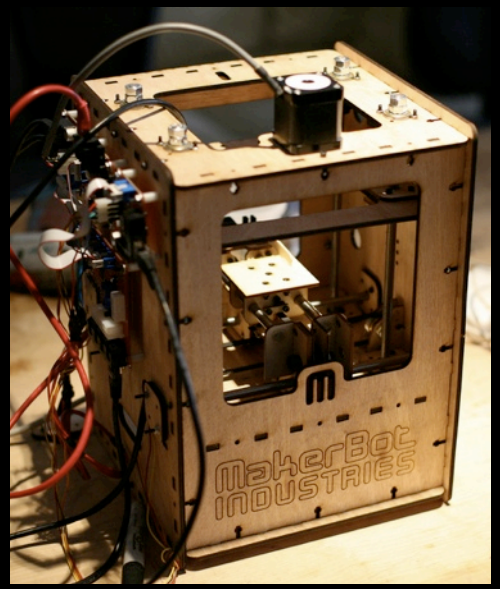
- PCB Fabrication
  - Can get professional prototype PCBs for ~$20 US each
  - Many production houses available online
  - Ex.: Advanced Circuits, `www.4pcb.com`
  - Ex.: BatchPCB, `www.batchpcb.com`
  - Ex.: e-Teknet, `www.e-teknet.com`
- PCB Assembly
  - Have someone else build your complicated surface-mount boards
  - Ex.: Advanced Assembly, `www.aapcb.com`
  - Ex.: Screaming Circuits, `www.screamingcircuits.com`



Easy Access to Manufacturing 2

- Rapid Prototyping
  - Laser cutter
  - CNC
  - PCB prototype machine
    - Ex.: T-Tech, LPKF
  - 3D printing
    - Open-source solutions now exist
    - Ex.: MakerBot, `www.makerbot.com`
    - Ex.: RepRap, `www.reprap.org`
    - Ex.: Fab@home, `www.fabathome.org`





Easy Access to Information

- Open source hardware and DIY sites becoming commonplace
- People are publishing their new work daily
  - Pictures, videos, source code, schematics, Gerber plots
- G00gle & YouTube
- hack a day, `www.hackaday.com`
- Instructables, `www.instructables.com`
- Adafruit Industries, `www.adafruit.com`
- Harkopen, `http://harkopen.com`

Easy Access to Other People

- You don't have to live in a bubble anymore (if you don't want to)
- Can outsource tasks to people with specific/ specialized skills
- Hackerspaces
  - Local venues for sharing equipment and resources
  - Much different than the hacker groups of the 80s and 90s that paved the way
  - Hundreds exist all over the world
  - Ex.: HackerspaceWiki, `http://hackerspaces.org`
  - Ex.: HacDC, `www.hacdc.org`
  - Ex.: Noisebridge (SF), `www.noisebridge.net`

Easy Access to Other People 2

- Workshops
  - Public, membership-based organizations (like a health club)
  - Classes and training available
  - Like hackerspaces, but more focused/directed to serve a specific purpose
  - Ex.: Techshop, `www.techshop.ws`
  - Ex.: The Crucible, `www.thecrucible.org`
- Various Forums & Cons
  - Black Hat, DEFCON, ToorCon, HOPE, ShmooCon, CCC, HAR, Hack in the Box, etc.

Hardware Hacking Methodology

- There's never only *one* correct process
- Major subsystems:
  - Information gathering
  - Hardware teardown
  - External interface analysis
  - Silicon die analysis
  - Firmware reversing

Hardware Hacking Methodology 2

- General guidelines:
  1. Research the product
  2. Obtain the product
  3. Examine product for external attack areas
  4. Open the product
  5. Reverse engineer circuitry, silicon, and/or firmware
  6. Identify potential attack areas
  7. Perform attack
  8. If not successful, repeat steps 6-7

Information Gathering

- Crawling the Internet for specific information
  - Product specifications, design documents, marketing materials
  - Check forums, blogs, Twitter, Facebook, etc.
- Acquire target hardware
  - Purchase, borrow, rent, steal, or ask the vendor
  - Ex.: eBay, surplus
- Dumpster diving
- Social engineering

Hardware Teardown

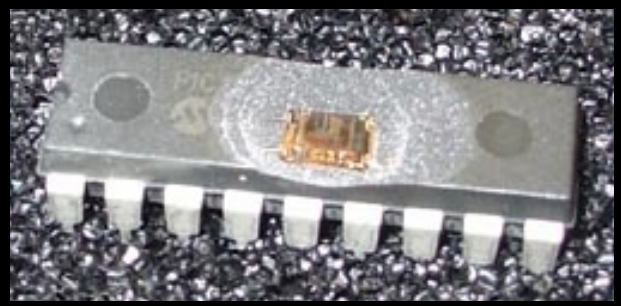
- Hardware and electronics disassembly and reverse engineering
- Get access to the circuitry
- Component and subsystem identification
- Gives clues about design techniques, potential attacks, and system functionality
- Typically there are similarities between older and newer designs
  - Even between competing products

External Interface Analysis

- Communications monitoring
- Protocol decoding and/or emulation
- Ex.: Smartcard, Serial, USB, JTAG, I2C, SPI, Ethernet, CAN
- Any interface accessible to the outside world may be an avenue for attack
  - Especially program/debug connections: If a legitimate designer has access to the interface, so do we
- Using oscilloscope, logic analyzer, dedicated sniffers, software tools, etc.
  - Ex.: Bus Pirate, `http://buspirate.com`

Silicon Die Analysis

- Supremely useful depending on attack goals
  - Simple imaging to gather clues
  - Key/algorithm extraction from ICs
  - Retrieve contents of Flash, ROM, FPGAs, other non-volatile devices
  - Cutting or repairing silicon structures (security fuses, traces, etc.)
- Like reversing circuitry, but at a microscopic level



Silicon Die Analysis 2

- "Real" equipment still fairly expensive, but can find in academic environment, get from surplus, or go low-tech:
  - Fuming Nitric Acid (HNO3)
  - Acetone
  - Microscope
  - Micropositioner w/ sewing needle

Wired.com, Hack a Sat-TV Smart Card

Silicon Die Analysis 3

- Required reading/viewing:
  - "Hack a Sat-TV Smart Card," `www.wired.com/video/hack-a-sattv-smart-card/1813637610`
  - Chris Tarnovsky/Flylogic Engineering's Analytical Blog, `www.flylogic.net/blog`
  - "Hacking Silicon: Secrets from Behind the Epoxy Curtain," Bunnie Huang, ToorCon 7, `www.toorcon.org/2005/slides/bunnie-hackingsilicon.pdf`
  - "Hardware Reverse Engineering," Karsten Nohl, 25C3, `http://tinyurl.com/ya3s56r`
  - "Deep Silicon Analysis," Karsten Nohl, HAR 2009, `har2009.org/program/events/149.en.html`

Firmware Reversing

- Extract program code/data from on-board memory devices
  - Using off-the-shelf device programmer or product-specific tool
  - You'll end up with a binary or hex dump
  - Ex.: Flash, ROM, RAM, EEPROM, FPGA
- Quick run through w/ *strings* and hex editor to pick most interesting area to begin with
- Gives clues to possible entry/access points to administrative menus or ideas of further attacks

Firmware Reversing 2

- Disassembly and reverse engineering using IDA, etc.
- Modify, recompile, and reprogram device, if desired
- Now pure software hackers can get into the game
  - Using tools and techniques they are already familiar with
  - Electronic/embedded systems are typically nothing more than a general purpose computer programmed to perform a specific task

Common Themes

- Most product design engineers not familiar with security
- Many products based on publicly available reference designs provided by chip vendors
- Components easy to access, identify, and probe
- Engineers and manufacturers want easy access to product for testing and debugging
- Even the simplest attacks can have huge repercussions

Lots of High Profile Attacks

- e-Voting Machines
  - Massive security problems with devices around the world
  - Casting multiple votes, tampering with election configurations and data, easily changing firmware, remote detection of voting via TEMPEST monitoring
  - Ex.: `www.eff.org/issues/e-voting/`
  - Ex.: `www.avirubin.com/vote/`
  - Ex.: `http://wijvertrouwenstemcomputersniet.nl/English/`
- ATM "cash dispensing" bug (pulled from Black Hat US 2009)
  - Ex.: `www.wired.com/threatlevel/2009/06/atm-vendor-halts-talk/`

Lots of High Profile Attacks 2

- Smart power meters
  - Wireless and peer-to-peer capabilities, no authentication for in-the-field firmware updates, can sever customer from power grid
  - Ex.: `www.blackhat.com/presentations/bh-usa-09/MDAVIS/BHUSA09-Davis-AMI-SLIDES.pdf`
  - Ex.: North County Times, Jan. 10, 2010 `http://tinyurl.com/yattkae`

www.flickr.com/photos/adrianpritchett/2440979828/

Source unknown

Lots of High Profile Attacks 3

- Boston MBTA Fare Collection
  - Stored value and/or time-based pass (unlimited rides during a given time period)
  - CharlieTicket: Magnetic stripe, can be rewritten for value up to $655.36 by changing 16-bits corresponding to value
  - CharlieCard: RFID-based smartcard using MIFARE Classic
    - Weak encryption leading to key recovery and full access to card
    - MIFARE Classic proprietary Crypto-1 algorithm previously broken by Karsten Nohl, et. al. 2007-2008
  - MBTA launched assault on researchers to try and squelch release of information (only temporarily successful)
  - Ex.: `http://tech.mit.edu/V128/N30/subway.html`
  - Ex.: `www.eff.org/cases/mbta-v-anderson`

Smart Parking Meters

- Parking industry generates $28 billion annually worldwide
- Where there's money, there's risk for fraud and abuse
- Attacks/breaches can have serious fiscal, legal, and social implications
- Collaboration w/ Jake Appelbaum and Chris Tarnovsky to analyze San Francisco implementation
- Full details at `www.grandideastudio.com/portfolio/smart-parking-meters/`

Parking Meter Technology

- Pure mechanical replaced with hybrid electromechanical in early 1990s
  - Mechanical coin slot
  - Minimal electronics used for timekeeping and administrator access (audit, debug, programming?)
- Now, we're seeing pure electronic "smart" systems
  - Microprocessor, memory, user interface
  - US is late to the game, other countries have been doing this for years

Parking Meter Technology 2

- User Interfaces
  - Coin
  - Smartcard
  - Credit card
- Administrator Interfaces
  - Coin
  - Smartcard
  - Infrared
  - Wireless (RF, GPRS)
  - Other (Serial via key, etc.)

Prior Problems and/or Failures

- New York City reset via infrared (universal remote control), 2001, `http://tinyurl.com/mae3g8`
- San Diego stored value card by H1kari, 2004, `www.uninformed.org/?v=1&a=6&t=txt`
- Chicago multi-space failures, June 2009
  - Firmware bug or intentional social disobedience?
  - `http://tinyurl.com/nt7g19`
- Lots of other smartcard hacking has been done in the past
  - Ex.: Dutch phone cards (Hack-Tic), FedEx/Kinko's, satellite TV (DirecTV/DISH)

San Francisco MTA

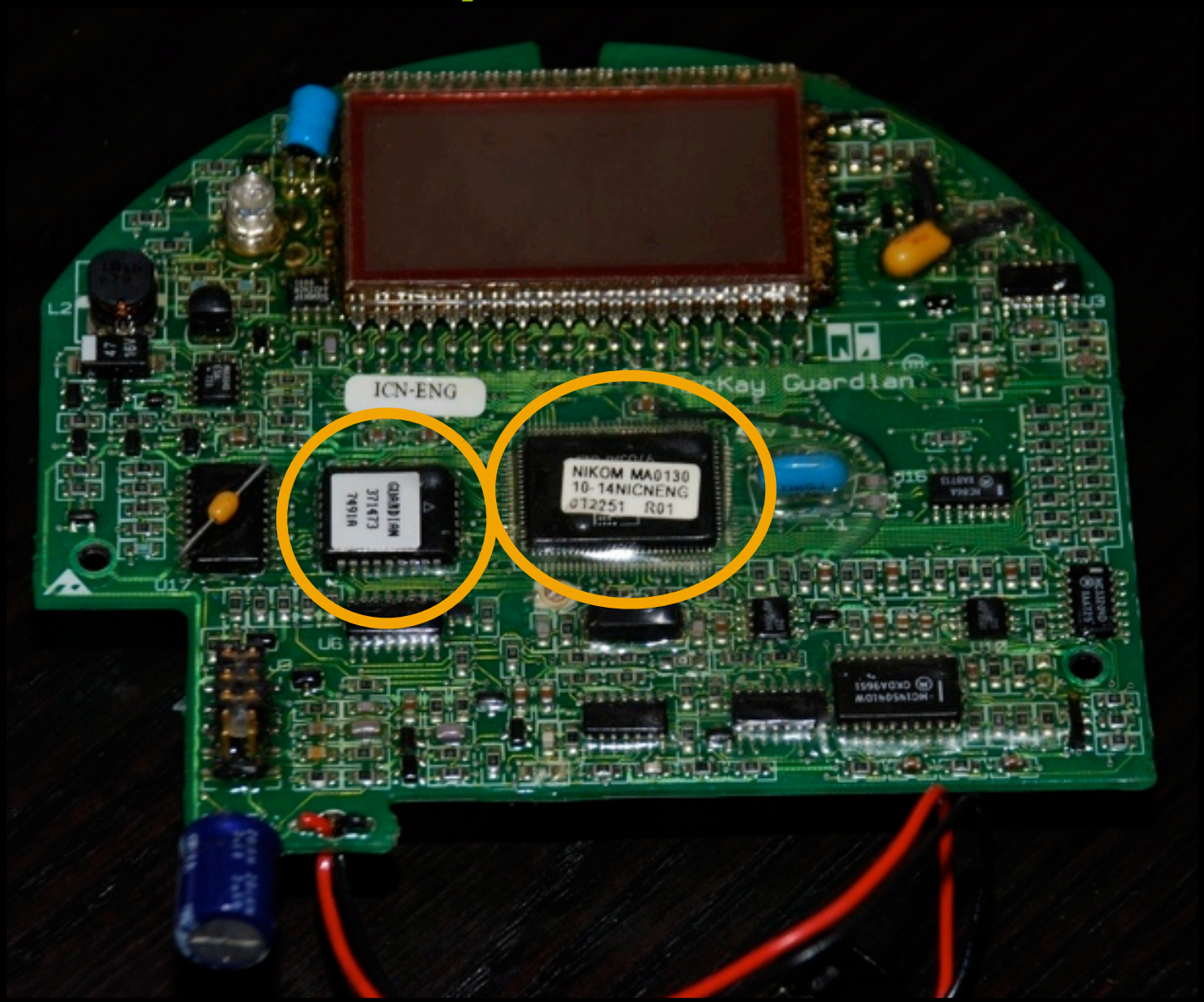
- Part of a $35 million pilot program to replace 23,000 mechanical meters with "smart" parking meters in 2003
- Infrastructure currently comprised of MacKay Guardian XLE meters
- Stored value smart card
  - $20 or $50 quantities
  - Can purchase online with credit card or in cash from selected locations

San Francisco MTA 2

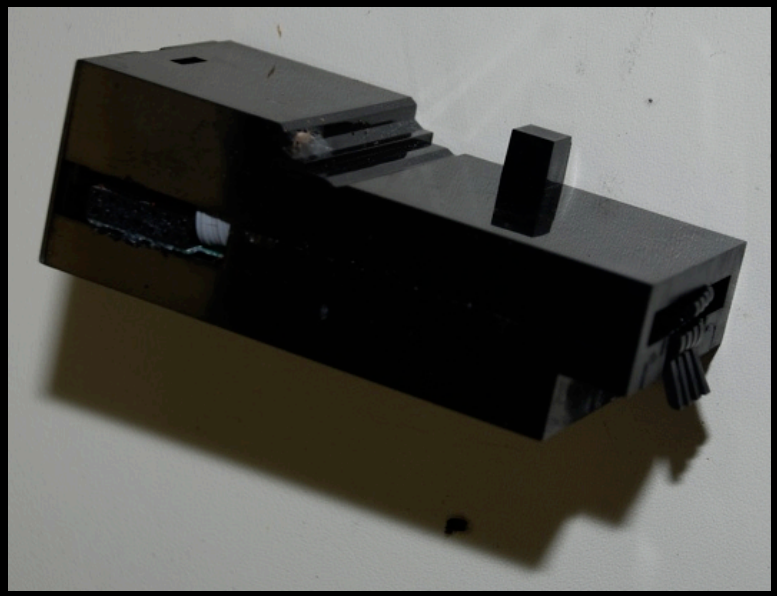
- Easy to replay transaction w/ modified data to obtain unlimited parking
  - Determined solely by looking at oscilloscope captures of smartcard transactions
  - Succeeded in three days

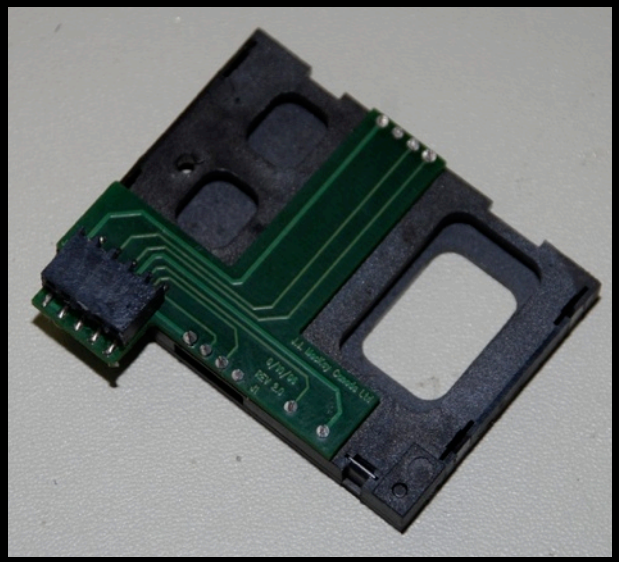
Meter Disassembly: MacKay Guardian

Meter Disassembly: MacKay Guardian 2

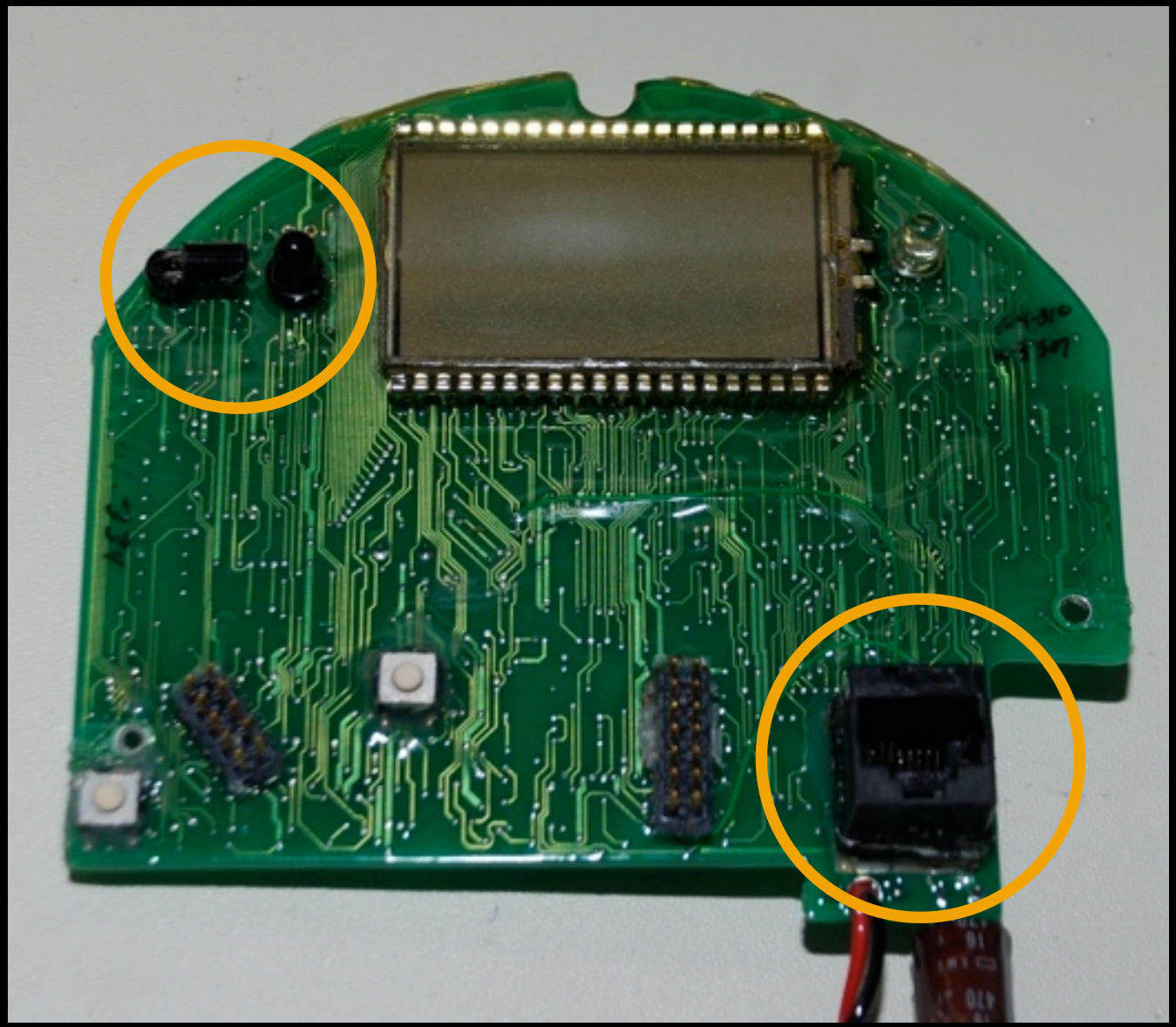


Meter Disassembly: MacKay Guardian 3

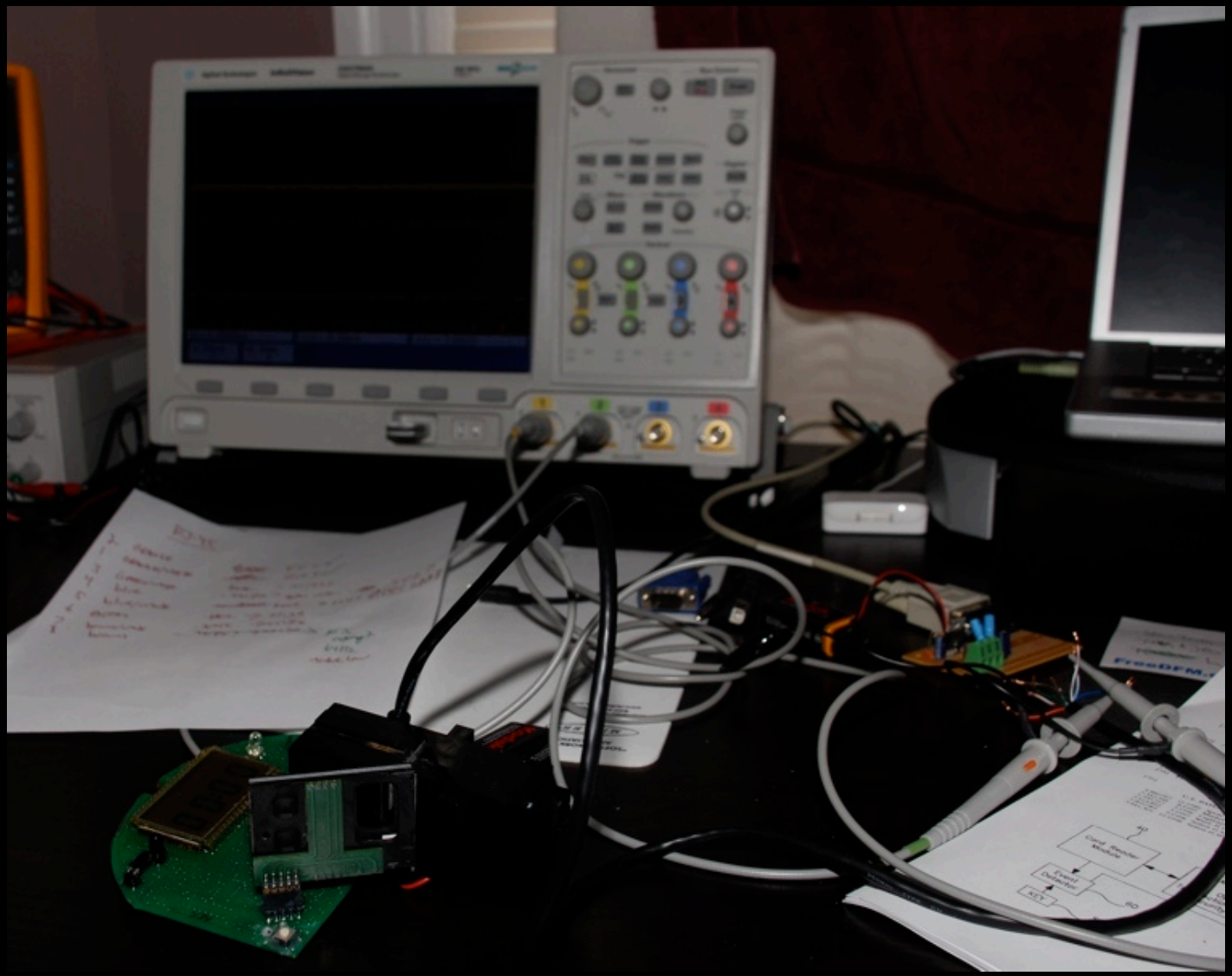




Meter Disassembly: MacKay Guardian 4



Meter Disassembly: MacKay Guardian 5



Information Gathering

- A chance encounter w/ Department of Parking & Transportation technician on the streets of SF
  - Ask smart, but technically awkward questions to elicit corrections
- Crawling the Internet for specific information
  - Product specifications, design documents, etc.
  - What is the core business competency?
  - Do they have technical troubles?

Information Gathering 2

```
# From: xxx <xxx at jjmackay dot ca>
# Date: Wed, 14 Mar 2001 10:27:29 -0400

I am learning how to use CVS and as part of this process I set up a test
repository to 'play' with.

D:\src\working\epurse\cvstest>cygcheck -s -v -r -h

Cygnus Win95/NT Configuration Diagnostics
Current System Time: Wed Mar 14 09:39:50 2001

Win9X Ver 4.10 build 67766446  A

Path:   /cygdrive/c/NOVELL/CLIENT32
        /cygdrive/c/WINDOWS
        /cygdrive/c/WINDOWS/COMMAND
        /usr/bin
        /cygdrive/c/JJMACKAY/MET_TALK
        /cygdrive/c/JJMACKAY/UTILITY


GEMPLUS_LIB_PATH = `C:\WINDOWS\GEMPLUS'

Found: C:\cygwin\bin\gcc.exe
Found: C:\cygwin\bin\gdb.exe


xxx, Sr. Software Designer
```

http://www.cygwin.com/ml/cygwin/2001-03/msg00842.html

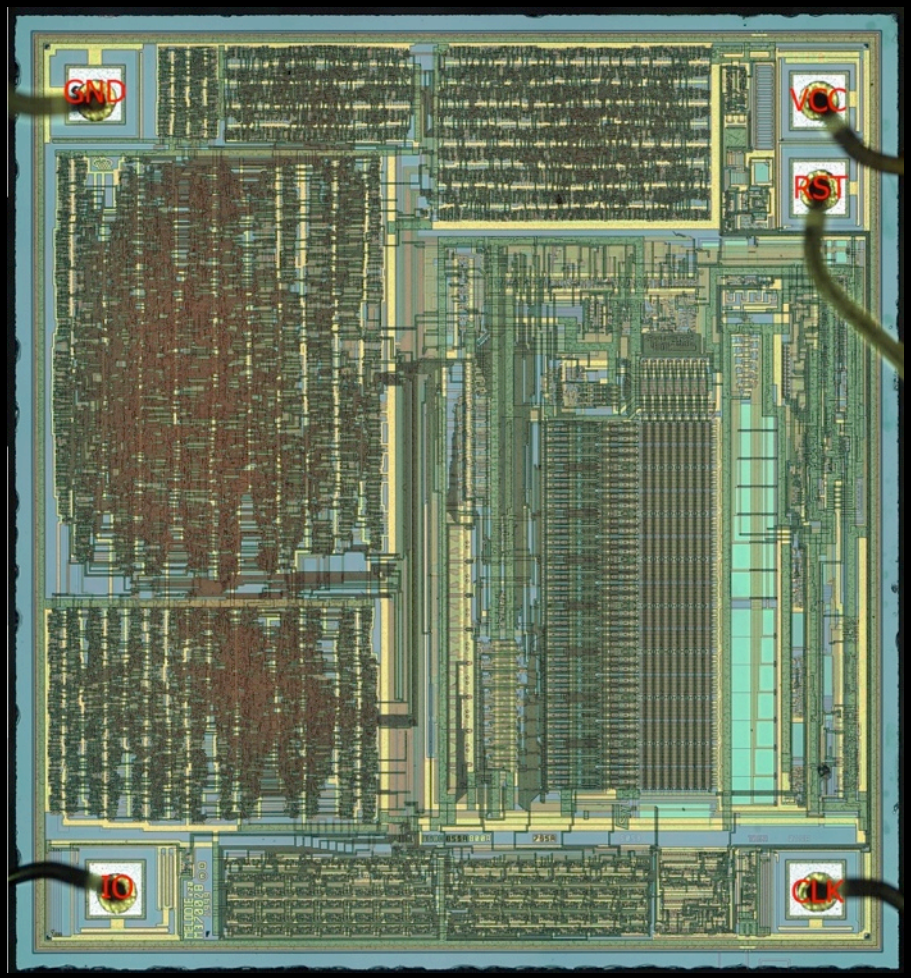
Smartcard Die Analysis

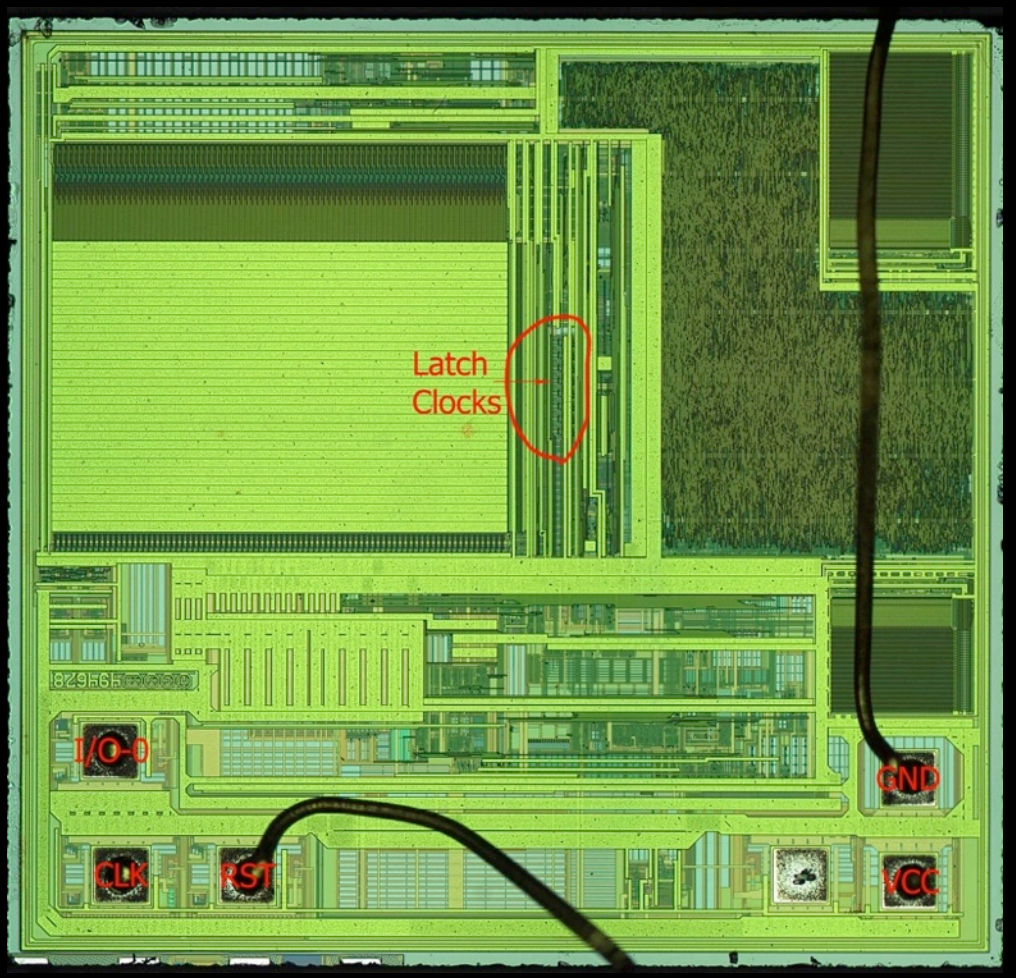
- Purchased and decapsulated multiple cards to look for clues of manufacturer and functionality
- Decapsulation process for smartcards
  1. Remove plastic surrounding the die (usually w/ acetone)
  2. Throw die into small Pyrex of heated Fuming Nitric Acid (HNO3)
  3. Rinse in acetone
  4. Glue die into a ceramic DIP package (for probing)
  5. If part is for analysis, prevent scratching!

Smartcard Die Analysis 2

- Visually identified that two different smartcard types exist
  - Gemplus GemClub-Memo (ASIC)
  - 8051 microcontroller *emulating* GemClub-Memo
- Dependent on card serial number
  - Older cards are ASIC, newer cards are MCU
- Microcontroller has potential for hidden/ undocumented commands
  - One could retrieve the code from the card and reverse engineer (we didn't)

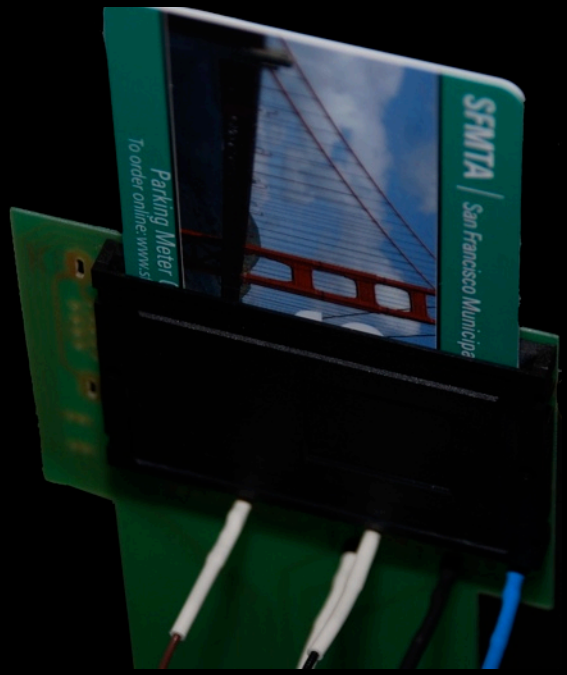
Smartcard Die Analysis 3



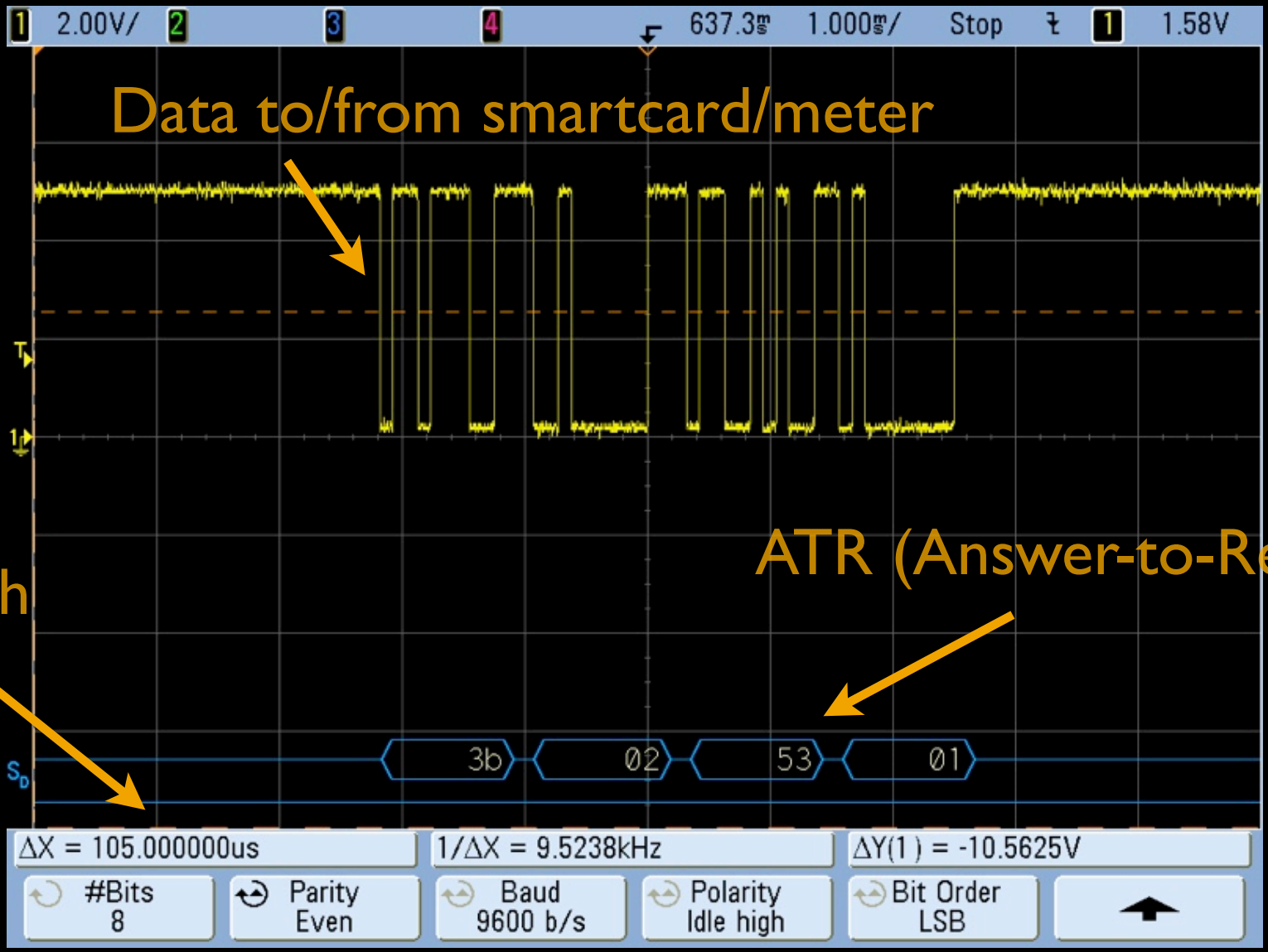


Smartcard Communications Monitoring

- Used "shim" between smartcard and meter
  - Unpopulated Season 2 Interface
- Monitored I/O transaction w/ digital oscilloscope
- Asynchronous serial data @ 9600, 8E1 captured and decoded
  - Correct baud rate determined by measuring bit width on scope



Smartcard Communications Monitoring 2

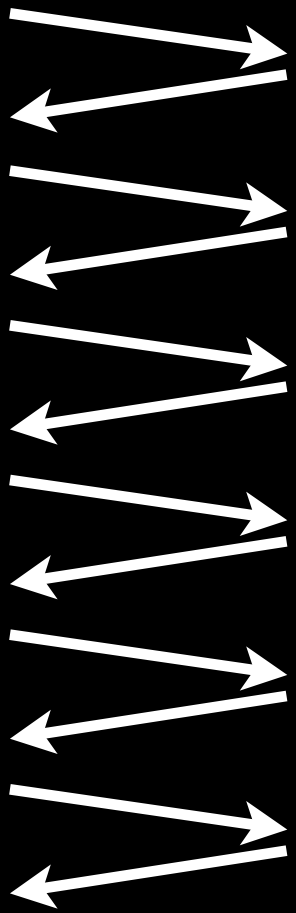


Smartcard Protocol Decoding

- Captured multiple transactions to gather clues on operation
  - Different valued cards
  - Different serial numbers
- Based on what values changed per transaction & per card, could narrow down what data meant what
- Decoded transaction functionality by hand, no computer needed!

Initialization

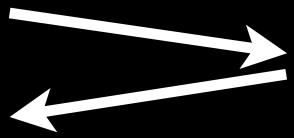
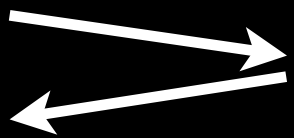
Meter		*Card*
Reset		[4 byte responses unless noted]
		ATR
Read Address 0		
		Manufacturer ID
Read Address 1		
		Serial #
Read Address 2		
		Constant
Read Address 3		
		Unknown (8) [Used for meter to calculate CSC1 password?]
Read Address 4		



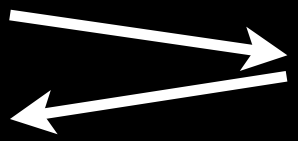
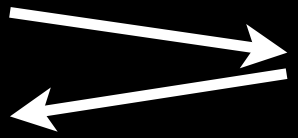
Initialization 2

Meter		*Card*
		[4 byte responses unless noted]
Read CSC1 Ratification Counter	→	
	←	0
CSC1 Password [Password calculated by meter and sent to card for authentication]	→	
	←	Password OK (2)
Read Address 14	→	
	←	0
Read CTC1 Card Transaction Counter	→	
	←	CTC1 [value varies]

Initialization 3

Meter		*Card*
Read Balance 2		[4 byte responses unless noted] Maximum Card Value Ex.: 0xFF FF F0 AF = $20 Ex.: 0xFF FF F1 27 = $50
Read CTC1 Card Transaction Counter		CTC1 [value varies]

Deduction of Single Unit ($0.25)

Meter		*Card*
		[4 byte responses unless noted]
Update Balance 1 Current Value A1		OK (2)
Update Balance 1 Current Value A2		OK (2)

- By updating the Balance 1 Value (8 bytes), CTC1 automatically increments
- CTC1 is the only value that changes during the entire transaction!

Computation of Card Value

- Maximum card value = (Balance 2 - 95d)
  - Ex.: $0AF (175d) - 95d = 80 units
    - 80 * 0.25 = $20
  - Ex.: $127 (295d) - 95d = 200 units
    - 200 * 0.25 = $50

Protocol Emulation

- First attempt to replay exact transaction captured w/ scope
  - Microchip PIC16F648A
  - Written in C using MPLAB + CCS PIC-C
  - Challenge for code to be fast enough and incorporate required short delays while still be readable/useful C

Protocol Emulation 2

card.c

card.c:5 <No selected symbol>

```c
#include "card.h"

void main (void)
{
    port_b_pullups(FALSE); // disable port B pull-ups

    atr();
    manufacturer();
    issuer();
    current_value();

    while(1)
    {
        issuer();
        deposit_coin();
    }
}

void atr(void)
{
    delay_ms(1);

    putc(0x3B);delay_us(170); // guard time
    putc(0x02);delay_us(170);
    putc(0x53);delay_us(170);
    putc(0x01);
}

void manufacturer(void)
{
    output_float(SIO);
    while (getc() != 0x80);
    while (getc() != 0xBE);
    while (getc() != 0x00);
    while (getc() != 0x00);
    while (getc() != 0x04);
    delay_us(500);
    putc(0xBE);delay_us(170); // guard time
    putc(0x7A);delay_us(170);
    putc(0x11);delay_us(170);
    putc(0x11);delay_us(170);
    putc(0xFF);delay_us(170);
    putc(0x90);delay_us(170);
    putc(0x00);
}
```

Code snippet

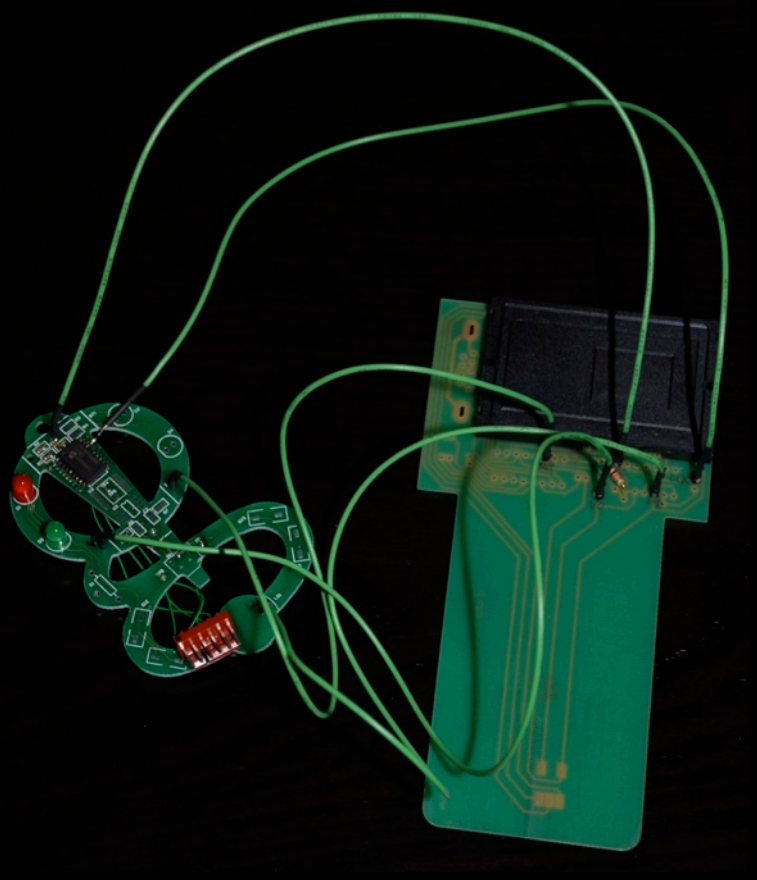
Protocol Emulation 3

- Then, modified code to change various values until success
  - Knowing how "remaining value" is computed, what happens if we change Balance 2 to $FFF?
    - Ex.: $FFF (4095d) - 95d = 4000 units?
  - Meter believes card has the maximum possible value
  - Could also have the code never increment CTC1 so stored value never decreases

Protocol Emulation 4

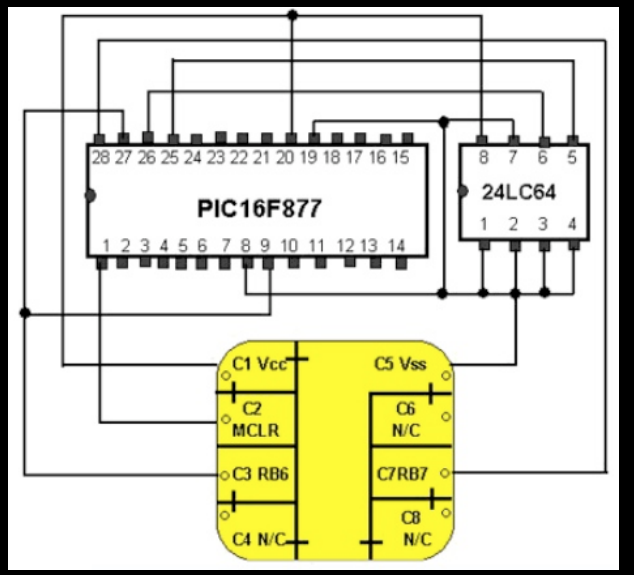
- Ported code to Silver Card (PIC16F877-based smart card)
  - PIC-based smartcards have been popular for satellite TV hackers for years, so required equipment is readily available
    - Ex.: `http://interesting-devices.com`

Hardware Evolution



1) Custom PCB + shim

2) MM2 card w/ external PIC



3) Silver Card PIC16F877 smartcard

San Francisco MTA Results

Final Thoughts

- Hardware is now more accessible to hackers than ever before
- The line is now blurred between HW & SW
- Simplest attacks known for decades still work
- New skills and techniques continually being developed and shared
- The time is right to get involved
- The media likes it, too!

Q & A

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