Protecting Consumer Electronics

Benjamin Jun | Cryptography Research, Inc. | 8 April 2008 | HT1-108

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Protecting consumer electronics

- Consumer electronics threats
- Learning from open-source

- Probing tools
- Information leakage
- Fault induction
- Boot attacks

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Consumer electronics threats

- Obtain “unauthorized” access to asset
  - Pirated digital content

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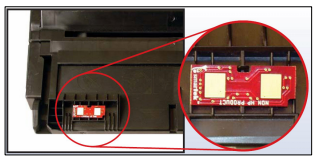
Consumer electronics threats

- Obtain “unauthorized” access to asset
  - Pirated digital content
- Interact with “unauthorized” device/service
  - Use of non-authentic peripheral

“RAZR V3” Battery



Unauthorized toner chip

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Consumer electronics threats

- Obtain “unauthorized” access to asset
  - Pirated digital content
- Interact with “unauthorized” device/service
  - Use of non-authentic peripheral
- Make device execute “unauthorized” code
  - Enable unauthorized features, linux

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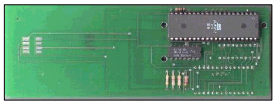
Consumer electronics threats

- Obtain “unauthorized” access to asset
  - Pirated digital content
- Interact with “unauthorized” device/service
  - Use of non-authentic peripheral
- Make device execute “unauthorized” code
  - Enable unauthorized features, linux
- Clone a device
  - Unauthorized copy



Pay TV smartcard emulator

Starting car w/ DST simulator

Source: “Security Analysis of a Cryptographically-Enabled RFID Device”, Bono, Green, Stubblefield, Juels, Rubin, Szydlo, 1/29/2005

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Who am I? What do I do?

- Cryptography Research, Inc.
  - Solve fraud, piracy problems
  - R&D emphasis on applied security issues
- Design and evaluation services
- License security technologies

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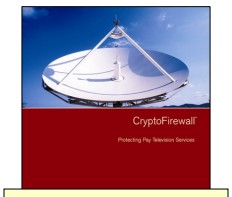
DPA:
Tamper Resistance



CryptoFirewall:
Pay-TV Security

SPDC / BD+:
Renewable Security
for Digital Content

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Try this at home!

Learn from open-source embedded projects

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Looking to open-source embedded projects

- Not (really) a security compromise…
  - Learn about techniques to gain control of and use HW
  - Reverse engineering is a key part of project efforts
- Good engineering lessons
  - Fast way to explore deployed embedded environments
  - Good fun! Good return on $ + time.

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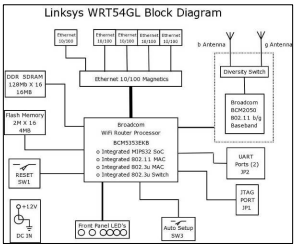
Linksys WRT54GL

- $60 home wireless router
  - Linksys released open source SW (2003)
- Why modify?
  - Modify operating parameters (xmit power, etc.)
  - Add more firewall setttings, mesh networking, QoS, use metering, etc.
  - Linux on cheap, low power platform
- Thriving hobbyist community
  - DD-WRT (www.dd-wrt.com)
  - OpenWRT (www.openwrt.org)
  - Note: buy the WRT54GL



Linksys (Cisco Systems)
The Consolidated Hacking Guide For The Linksys WRT54GL, "ByteEnable", www.linuxelectrons.com

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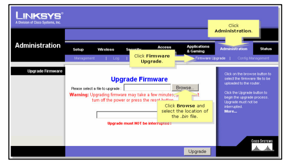
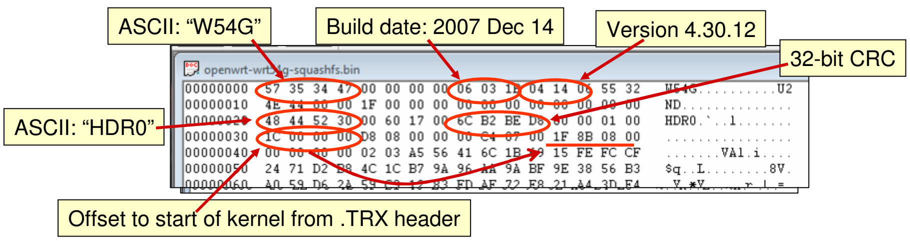
FW reflash of Linksys WRT54GL

- Example: Upgrade to OpenWRT firmware
  - Download OpenWRT whiterussian rc5, squash fs
    http://downloads.openwrt.org/whiterussian/rc5/bin/openwrt-wrt54g-squashfs.bin
  - Use (unsecured) firmware update mechanism
  - Router reboots, use www interface to set root pw
  - SSH in!



Stock Linksys FW: "4.30.12 1/10/2008" **OpenWRT FW: whiterussian rc5, squash FS**



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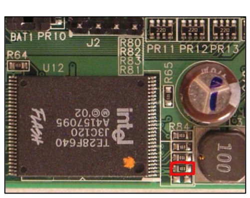
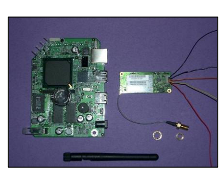
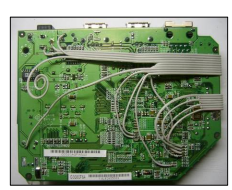
Try this: NSLU2

- Linksys NSLU2
  - Ethernet SMB (Windows) fileserver for USB disks ($70)
- NSLU-linux project (www.nslu2-linux.org)
  - Unslung distribution keeps stock Linksys functionality
  - Disk makes it easy to experiment with
- HW mods
  - Overclocking, serial port, RAM upgrade, debug ports, etc.







http://www.nslu2-linux.org/wiki/HowTo/AddAThirtyFourPinUniversalConnector http://www.nslu2-linux.org/wiki/HowTo/OverClockTheSlug David Hicks, http://www.nslu2-linux.org/wiki/HowTo/AddInternalWireless

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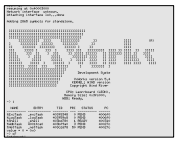
No surprise to embedded developers…

- Nearly all products based on commodity cores, reference designs
  - WRT54GL: Broadcom BCM5352E
  - NSLU2: Intel IXP420 XScale (ARM)
- Small number of widely used embedded development environments
  - Linux, uC Linux, VxWorks
  - Good development, cross-compilation, debugging tools
- Hardware is incrementally "free"
  - Differentiating features governed by software
  - Software modifications have interesting results!

µClinux



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Why follow these projects?

- Infrastructure type projects
  - "Boot linux on ____ platform."
  - Understand debugging, porting tools
- Patch type projects
  - "Get in, get system to do ____, get out."
  - SW reverse engineering
- Hardware extension projects
  - HW reverse engineering

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Probing

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Probing goals

- Goal: Gather enough information for analysis
  - Reverse engineering is about making hypotheses
  - … and finding ways to confirm them !
- Static analysis
  - Use disassemblers and static analysis tools
- Probe system as it responds to stimuli
  - In normal processing
  - In abnormal processing

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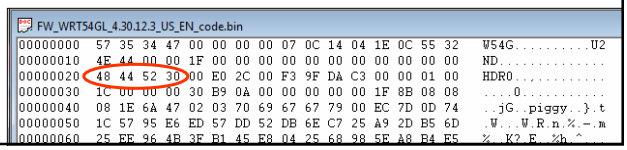
Static reading of flash / ROM

- For discrete parts, this is easy…
  - Use ROM reader
  - Tap data bus, drive address bus
- On-die ROM
  - Get software to read it!
- With a code dump…
  - Recognize processor type
  - Disassemble, probe for implementation weakness
  - Search for keys (high entropy)

Conitec GALEP-4 progammer/reader



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Probing tools

IC test clip (PLCC)

Emulation Technology Part 5281

SCSI Bus Analyzer

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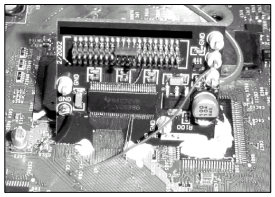
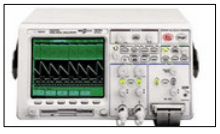


Custom FPGA Logic Analyzer

Bunnie Huang, http://www.xenatera.com/bunnie/proj/anatak/xboxmod.html



GPIB Oscilloscope + Logic Analyzer

Agilent Technologies, 1672G data page

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Countermeaures to probing

- Bury vias
  - "Production" mods harder, one-time probing still doable…
- Use "encrypted" memory
  - Use global or unique key
  - If keys managed by SW, this is essential
  - … but difficult to rely on with many copies of identical data
- Hardcode keys + algorithms + processing
  - Integrity + privacy benefits
  - Good: In SoC ROM
  - Better: In HW gates

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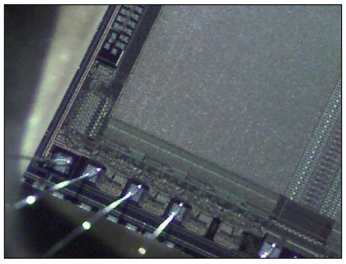
Die imaging: ROM

- Imaging on-die ROM
  - Optical microscope / FIB: Use automated tool to image ROM
  - Active probing: Tap data bus, drive address bus
  - Passive probing: Tap bus lines
- Responses
  - Shield metal layers
  - "Encrypted" memory
  - HW-based obfuscation



Memory image: Hector Vega
FIB: University of Cambridge Department of Materials Science Device Materials Group

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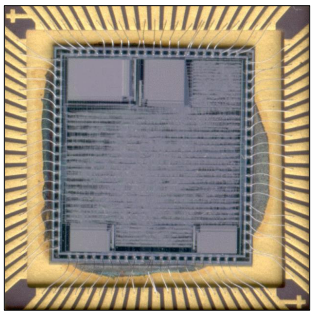
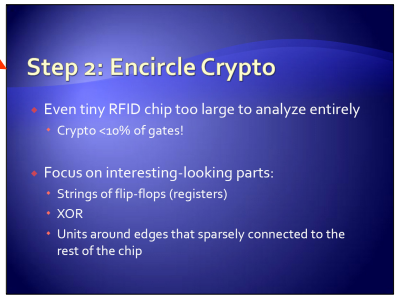
Die imaging: Gates

- Imaging attacks on gates
  - Automated tool to image + recover netlist
  - Easier if crypto area small, design has good structure
  - One reference: Nohl, Starbug, Plotz, *Mifare Security*, CCC 2007
- Responses
  - Shield layers
  - Camouflage libraries
  - If imaging not 100% accurate…





http://www.ece.cmu.edu/~koopman/stack_computers/binar_chip.jpg
Nohl, Starbug, Plotz, Mifare Security, CCC 2007

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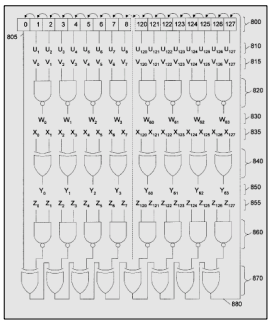
Example: Entropic Array

- State-of-the-art reverse engineering techniques are error-prone
  - Attacks involve human interpretation + correction
  - For normal circuits, attackers do fine w/buggy output
  - Example: AES with a few errors is obviously AES
- Goal: make imperfect reverse engineering results useless
  - Exact circuit required to perform crypto correctly
    - Attackers can't infer where they made mistakes
  - EA designed to be difficult to interpret
    - "Grown" from design rules and random seed
    - Internal entropy / lack of structure



Example EA

US patent 6,640,305

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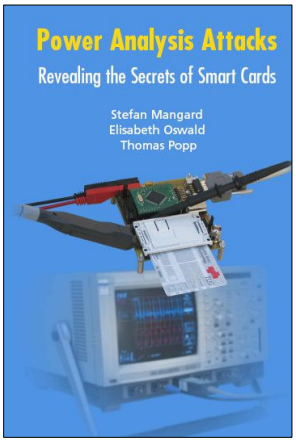
Information Leakage Attacks



Mangard, Oswald, Popp
www.dpabook.org

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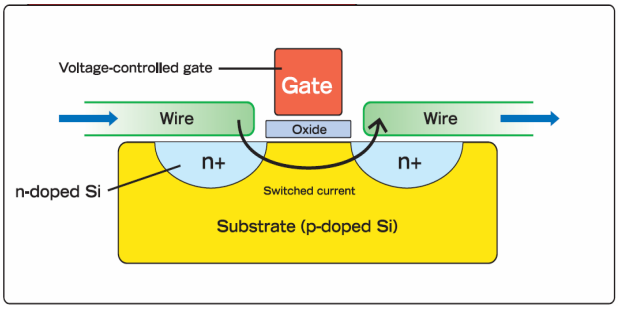
Information leakage

Integrated circuits consume power as they operate.



Typical MOS Transistor

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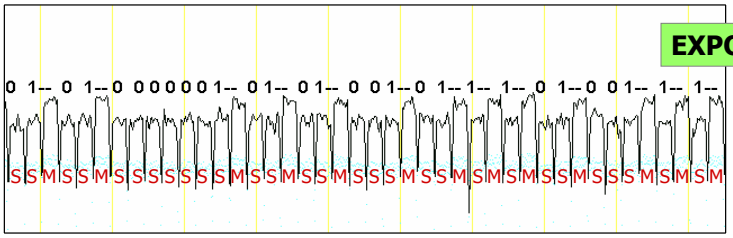
Simple Power Analysis (SPA)




```
Algorithm MODULAR_EXPONENTIATION (exponent e, base b, modulus n)
      Let A = 1
      Let X = b mod n
      Let k be the number of bits in e.  Then,
      For i = k downto 0, do
            A = (A * A) mod n
            Let e_i be the i'th bit of exponent e        ; bit 0 is LSB
            if (e_i == 1), do
                  A = (A * X) mod n
            Done
      Done
      Return A
End Algorithm
```

LOOP

SQUARE

CONDITIONAL MULT

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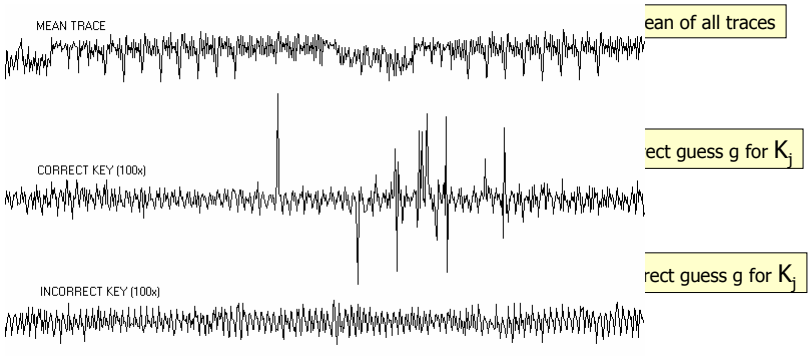
Differential Power Analysis (DPA)



- **To read more about DPA**
  - **www.cryptography.com/dpa**
  - **www.dpabook.org**

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Hybrid attacks

- Use power consumption as an output channel

  - Code insertion
    - Buffer overflow loads + executes target code
  - For each bit of data
    - Perform instruction A or instruction B 256 times
    - Dump memory via SPA activity

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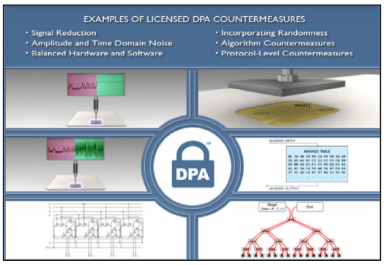
Defenses against power analysis

- Categories
  - Obfuscation
  - Leak Reduction
  - Balanced HW / SW
  - Amplitude & Temporal Noise
  - Incorporating Randomness
  - Protocol Level CM
- Certifications / Requirements
  - FIPS 140-3 draft
  - Common Criteria
  - CAC, E-Passport, HSPD-12
- Complicated!
  - Naïve CM can make things worse
  - Device evaluation is important



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Use of these countermeasures requires a license from Cryptography Research and is protected under US patents 6,278,783, 6,298,442, 6,304,658, 6,327,661, 6,510,518, 6,539,092, 6,654,884 and other patents issued and pending in the US and worldwide.

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Fault Induction Attacks

Van de Graff (left)

US Smithsonian Institution

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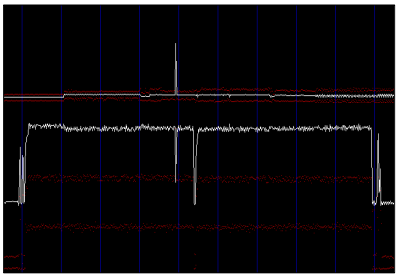
Why induce faults?

- Security code (generally) assumes that platform is reliable
  - What if it isn't?
- Why do this?
  - Induce a computational fault
  - Change value being read/stored
  - Break into/out of an execution loop
  - Change program counter (PC)
- Surprises
  - More repeatable than you think…



Glitch impulse & power trace during successfully-glitched RSA CRT

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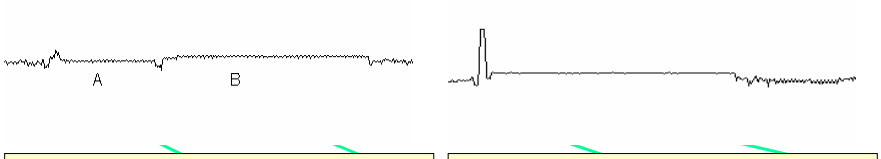
Tearing nonvolatile memory writes

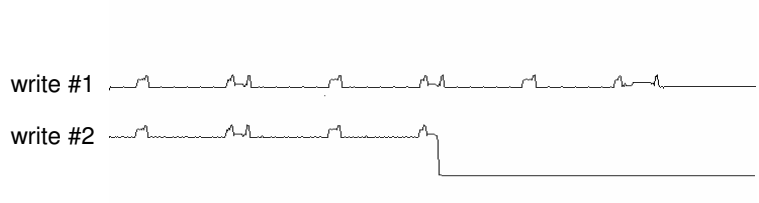
- Typical EEPROM write/clear cycles



Device 1: Bit Clearing Phase (A) and Bit Setting Phase (B)

Device 2: Bit Setting Phase (A) and Bit Clearing Phase (B)

- Tearing example



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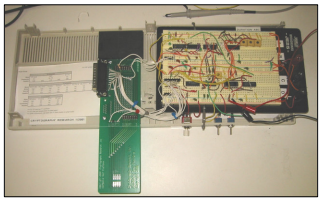
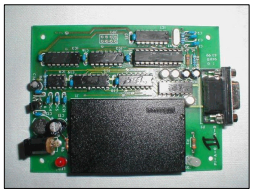
Glitching tools





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Glitching examples

- Glitch instruction to extend output loop
  - Example: DJNZ instruction

```
; This routine is used to output a 4-byte result
; DPTR points to first byte of data
result_out:  MOV R0, 3              ; set loop counter
result_loop: CALL #putch            ; call UART routine
             INC DPTR               ; increment pointer
             DJNZ R0, #result_loop  ; conditional loop
             RET
```

- Glitching program counter
  - "Serpent's tail": NOP sled followed by target code

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Example glitch defenses (SW)

- Check your work!
  - Verify private key computations
- Preincrement error flags

Before

```
// check password
result = secureMemCmp(passwordLen, userPin, userInput);
if (result)
  nvmErrorCount = 0;
else if (++nvmErrorCount > errorMax)
  lockOut();
return (result);
```

After

```
if (nvmErrorCount++ > errorMax)
  lockOut();
result = secureMemCmp(passwordLen, userPin, userInput);
if (!result)
  nvmErrorCount = 0;
return (result);
```

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Example glitch defenses (HW)

Canaries used to detect CO gas in mines
(Hollinger Mine, Ontario, 1928)

- Environmental sensors
  - Monitor clock, voltage
  - Not available in all silicon processes
- Independent votes
  - Independent modules vote before enabling output, unlock
- Canary logic (CryptoFirewall)
  - Cumulative hash of system control state on every clock
  - Hardware design element designed to be on critical path
  - Example: Gate output unless canary logic permits operation

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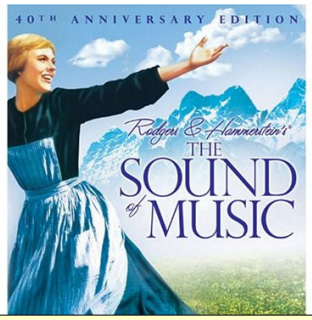
Boot Attacks



"Let's start at the very beginning
A very good place to start
When you read you begin with A-B-C
When you sing you begin with do-re-mi"
– Maria

Rodgers, Hammerstein, The Sound of Music (1965)

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Taking over a device

- Step 1: Understand how device operates
- Step 2: Get (malicious) code on the device
- Step 3: Get control of program counter (PC)

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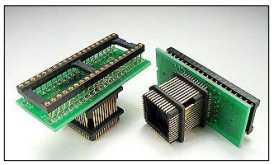
Getting to execution – ROM/flash replacement

- Socketed flash/ROM

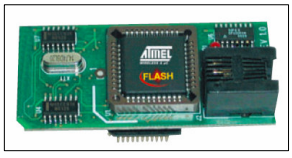
BIOS socket (X-Box)
Bunnie Huang, xenatera.com



DIP to PLCC adaptor
Logical systems, www.logicalsys.com

- ROM / flash emulator

ROM emulator
Transtronics Pocket ROMulator



Flash emulator
MSC AT51Flash-Emulator

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Getting to execution – debug tools

- JTAG analyzer
  - Full debug interface
  - Boot code replacement
  - In-target flash/ROM reading + programming

EJTAG In-target analyzer

First Silicon Solutions, ISA-MIPS

ARM JTAG debugger interface

Olimex Ltd., ARM-USB-OCD

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Getting to execution – taking over control

- Take over control directly
  - Buffer overflow, glitch to executable code, protocol errors, …
  - Suspend/resume with memory image change
- Bypass authentication in bootloader
  - Bypass authentication process (CRC, signature)
    - Common problem: bad authentication protocol
  - Ex: “Savegame” buffer overflow in “007” Xbox game (2003)
    - Modifies public key, makes modulus divisible by 3
    - Signature forgery, clean start sequence!

```
BE00000080          mov esi, 80000000
AD                  lodsd                       ; 0x00000032
81EE03000000        sub esi, 00000003
3DBD1B4BA4          cmp eax, A44B1BBD
75F2                jne 00000032                ; scan RAM for public key
8176FFD68BD72D xor dword ptr [esi-0], 2DD78BD6  ; modify last 4 bytes of public key
```

http://xbox-linux.sourceforge.net/docs/007analysis.html

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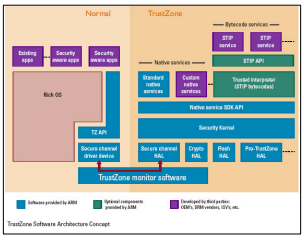
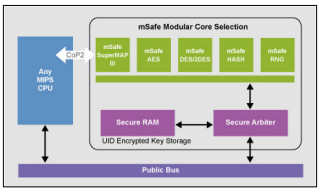
HW tools for boot protection

- ARM TrustZone
  - Lightweight hardware extensions for security
    - S-Bit added to CP15 register
    - SMI (Secure monitor interrupt) instruction
  - Only privileged OS can issue SMI
  - Non-secure processes have limited privileges



ARM TrustZone Architecture

- MIPS Safe-SOC
  - Peripheral on MIPS coprocessor bus
  - Crypto accelerator with access to memory space



MIPS Safe-SOC Architecture

- Cautions
  - Monitor and secure kernel should be small
  - Watch out for complexity!

ARM, MIPS product literature

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Example: Bootloader with code signatures

- Boot ROM with code authentication
  - Reset vector jumps to boot ROM
  - Verify RSA cert (hash of PK can be hard-coded)
  - Hash and verify payload, FAIL on error
  - Decrypt + decompress payload to RAM
  - Clear all other RAM
  - Jump to payload

- HW requirements
  - Force jump to internal boot ROM on reset
  - JTAG and other execution vectors should be off on boot
  - Development/test: skip bootloader if fuse unblown

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Example: Continuous code checking

- Continuous verification
  - Boot ROM starts watchdog timer
  - Background code scanning process
    - Steps through program RAM & computes hash
    - Restart timer if code check passes
  - Code scanning is interruptible
    - Halt & restart completely if interrupted
    - Can work on smaller chunks of code
      - Verify one branch of a hash tree at a time

- HW requirements
  - Watchdog that can only be started by code in boot ROM area
  - Requires protected RAM or dirty bit that is set on interrupt

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Bootloader challenges

- Challenges
  - Enabling development environment
  - Support for powerdown / sleep modes
  - MMU behavior as system boots

- "Cat and mouse"
  - Example: smartcard code hashing and emulators

Checkpoint Charlie (1986)

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Where do we go from here?

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Conclusion

- Most consumer electronics devices:
  - Are in physical possession by attacker
  - Have flat memory architectures
  - Are used offline
- Developer tools == attacker tools
  - Most systems use standard platforms + tools
  - Good debuggers and debugging interfaces
- HW and SW can't do this alone!
  - SW can enable functionality, handle updates
  - HW can enforce small set of rigid rules

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