Software Protection: How to Crack Programs, and Defend Against Cracking
Lecture 8: Hardware
Moscow State University, Spring 2014

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Introduction
This lecture

1. Disk and dongle protection against software and media piracy.
   - Disk protection — distribute the program on a physical medium, such as a CD and make the CD hard to copy.
This lecture

Disk and dongle protection against software and media piracy.

- **Disk protection** — distribute the program on a physical medium, such as a CD and make the CD hard to copy.
- **Dongle protection** — the program refuses to run without a hardware token distributed with the program.
**This lecture...**

2. **Trusted Platform Module (TPM):**
   - Small chip soldered to the motherboard of a PC
   - Used to boot a trusted environment
   - IBM/Lenovo ThinkPad ships with a TPM chip
   - not used in practice
This lecture...

Crypto-processor:
- Can execute encrypted programs.
- Contains encryption key.
- Program is encrypted with processor’s public key.
- Only one computer can run the program!
This lecture... 

Attacks on tamperproof hardware:
- Physical attacks (shave off the top!)
- Side channel attacks (“listen” to the chip!)
Dongles and Tokens
Dongles

Dongles are hardware devices distributed with a program.
Dongles

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- Prevent piracy.
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- The dongle must be connected to the user’s computer,
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- The program periodically queries the dongle.
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- Prevent piracy.
- The dongle must be connected to the user’s computer,
- The program periodically queries the dongle.
- Is the dongle present? Genuine?
Today dongles are active devices with built-in processors.
Today dongles are active devices with built-in processors.
Sometimes backed up by a battery.
class Dongle {

    private static long count = 3;
    private static long memory[] = new long[127];
    private static String password = "heyahaya";
    private static final long ID = 2376423;
    private static final long KEY = 0xab0ab012;
    private static java.util.Random rnd;

    public static final byte LOGIN = 0;
    public static final byte ISPRESENT = 1;
    public static final byte ENCODE = 2;
    public static final byte DECODE = 3;
    public static final byte READ = 4;
    public static final byte WRITE = 5;
    public static final byte GETID = 6;
    public static final byte GETTIME = 7;
    public static final long PRESENT = 0xca75ca75;
}
```java
static long call(byte operation,
                 String pw,
                 long arg1, long arg2) {
    if (!pw.equals(password) || (count<0)) return -1;
    switch (operation) {
        case LOGIN : count--;
                     rnd=new java.util.Random(arg1)
                     return 0;
        case ISPRESENT : return PRESENT;
        case ENCODE : return arg1ˆKEY;
        case DECODE : return arg1ˆKEY;
        case READ : return memory[(int)arg1];
        case WRITE : memory[(int)arg1]=arg2;
                     return 0;
        case GETID : return ID;
        case GETTIME : return System.currentTimeMillis;
        default : return -1;
    }
}
```
Aladin HASP

- The dongle has a small amount of internal memory
Aladin HASP

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- a battery-backed internal realtime clock,
Aladin HASP

- The dongle has a small amount of internal memory
- a battery-backed internal realtime clock,
- an identifier unique to every dongle
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- a battery-backed internal realtime clock,
- an identifier unique to every dongle
- a counter,
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- a battery-backed internal realtime clock,
- an identifier unique to every dongle
- a counter,
- a password,
- a pseudo-random number generator
Aladin HASP

- The dongle has a small amount of internal memory
- a battery-backed internal realtime clock,
- an identifier unique to every dongle
- a counter,
- a password,
- a pseudo-random number generator
- an encryption engine with a hardcoded key.
public class Main {
    static String password = "heyahaya";
    static final long timeout = 1281964454908L;
    static final long seed = 260124545;
    static java.util.Random rnd;

    public static void main (String args[]) {
        Dongle.call(Dongle.LOGIN, password, seed, 0);
        rnd = new java.util.Random(seed);
        if (Dongle.call(Dongle.GETTIME, password, 0, 0) > timeout)
            System.exit(-1);
        ...
    }
}
Calling the dongle

```java
if (Dongle.call(Dongle.ISPRESENT,password,0,0)!=Dongle.PRESENT) {
    System.err.println("No dongle present");
    System.exit(-1);
}
...
long here = Dongle.call(Dongle.ISPRESENT,password,0,0);
...
boolean OK = here == Dongle.PRESENT;
...
if (!OK) System.exit(-1);
```

Obfuscate the challenge calls such that automatic removal becomes difficult.
Add bogus calls!

Dongle.call((byte)42, password, secret1, secret2);

• Sprinkle bogus calls to the dongle all over your code!
Problem with Dongles

- Contribute to the cost of distribution.
- If they contain a battery they will eventually have to be replaced.
- If they are lost, the owner will have to request a new copy.
- Today are only used to protect very expensive programs.
http://www.nodongle.com

We can make Emulators for any protection type, Hasp4, HaspHL, Sentinel Super Pro, Aladdin Hardlock, . . . , any protection.

Our emulators are 100% perfect, 100% guaranteed. 100% private, . . .

Dongle Emulator is a software to allow your program to run without any key attached.

We don't have fixed prices, our prices depend [sic] on protection, not program price dependent, this will be very cheap if compared with program price...

Send a email with some infos about your program, like name and protection, so we can give you a personalized answer.
Authenticated boot using a trusted platform module
Algorithm: Authenticated boot

We’ve assumed the program executes in an untrusted environment. The adversary can
1. examine (reverse engineer),
2. modify (tamper),
3. copy (pirate),

our program.
Algorithm: Authenticated boot

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our program.

Our techniques have been software based:
1. obfuscation (to make a program harder to examine),
2. tamperproofing (to make modification harder),
3. watermarking (to trace copying).
Algorithm: Authenticated boot

What if we could trust the client to run trusted
- hardware,
- operating system,
- applications?
Trusted Platform Boot
Trusted Platform Boot
Trusted Platform Boot
Trusted Platform Boot

- Trusted Server
- Untrusted Client
- Client
- Untrusted Client

Client

Client

SW/HW
Trusted Platform Boot

Trusted Server

Client SW/HW

Untrusted Client
Trusted Platform Boot

I want to buy a book!

Client SW/HW

Untrusted Client

Trusted Server
Trusted Platform Boot

Prove you are safe!

Trusted Server

Untrusted Client

Client SW/HW
Trusted Platform Boot

- Trusted Server
  - Here are hashes over all my code!

- Untrusted Client

- Client SW/HW
Algorithm: Authenticated boot

Before you agree to communicate with a system you ask it to prove to you that it won’t do anything bad.
Algorithm: Authenticated boot

Before you agree to communicate with a system you ask it to prove to you that it won’t do anything bad.

Anything that’s running on Bob’s computer could, potentially, affect whether you should trust it:

1. OS,
2. BIOS,
3. bootloader,
4. application programs,
5. firmware, . . .
Algorithm: Authenticated boot

- CRTM
- BIOS
- loader
- kernel
Secure boot vs. Authenticated boot

- **Secure boot**: only ever boot a system consisting of code that you trust.
- **Authenticated boot**:
  - Bob can boot whatever system he wants!
  - But, he cannot lie about what system he’s booted!
1. nonce ← RND()
   send nonce
1. \text{nonce} \leftarrow \text{RND}()
   \text{send nonce}

2. \text{receive nonce}

\begin{itemize}
  \item \text{SHA-1()}
  \item \text{EK}
  \item \text{PCR[0]}
  \item \text{PCR[1]}
  \item \ldots
  \item \text{PCR[15]}
\end{itemize}
1. nonce ← RND()
   send nonce

2. receive nonce
3. send (quote, SML)

\[
\text{quote} \leftarrow \text{sig}\{\text{PCR, nonce}\}^{EK_{priv}}
\]
1. nonce ← RND()
   send nonce
4. receive (quote, SML)

2. receive nonce
3. send (quote, SML)

Client

kernel

SML:

SH-1()
EK
PCR[0]
PCR[1]
...
PCR[15]
quote ← $\text{sig}\{\text{PCR, nonce}\}^{EK_{\text{priv}}}$

Server
Server

1. nonce ← RND()
   send nonce
2. receive nonce
3. send (quote, SML)
   receive nonce
4. receive (quote, SML)
   kernel

Client

5. \texttt{cert}(E_{K_{pub}}) \text{ OK?}

\begin{itemize}
  \item \texttt{SHA-1()}
  \item \texttt{EK}
  \item \texttt{PCR[0]}
  \item \texttt{PCR[1]}
  \item \texttt{...}
  \item \texttt{PCR[15]}
  \item \texttt{quote ← \texttt{sig}\{PCR, nonce\}^{E_{K_{priv}}}}
\end{itemize}

SML: kernel

15

\begin{itemize}
  \item \texttt{SML:0} \rightarrow \texttt{1} \rightarrow \texttt{2} \rightarrow \texttt{3}
\end{itemize}
Server

1. nonce ← RND()
   send nonce
4. receive (quote, SML)
5. \texttt{cert}(EK_{pub}) \texttt{ OK?}
6. \texttt{sig}\{PCR, nonce2\}EK_{priv} \texttt{ valid?}

Client

2. receive nonce
3. send (quote, SML)

\begin{itemize}
\item SHA-1()
\item EK
\item PCR[0]
\item PCR[1]
\item \ldots
\item PCR[15]
\end{itemize}

quote ← \texttt{sig}\{PCR, nonce\}EK_{priv}

\begin{itemize}
\item SML: 9
\item 15
\end{itemize}

\texttt{kernel}
1. nonce ← RND()
   send nonce
4. receive (quote, SML)
5. \texttt{cert(EK}_{pub}) \text{ OK?}
6. \texttt{sig}\{PCR, nonce2\}_{EK_{priv}} \text{ valid?}
7. nonce2 fresh?
   SML not tampered?
   measurements OK?

2. receive nonce
3. send (quote, SML)

\[
\begin{array}{c}
\text{kernel} \\
\text{quote ← } \texttt{sig}\{PCR, nonce\}_{EK_{priv}} \\
\text{SML: } 15
\end{array}
\]
IBM’s implementation

- Database of measurements for Redhat Fedora: 25000 measurements.
- A typical SML: 700-1000 measurements.
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- A typical SML: 700-1000 measurements.
- How to collect “good” measurements:
  1. boot a “trusted system”
  2. measure all modules, config files, scripts $\Rightarrow$ whitelist of hashes
**IBM’s implementation**

- Database of measurements for Redhat Fedora: 25000 measurements.
- A typical SML: 700-1000 measurements.

**How to collect “good” measurements:**
1. boot a “trusted system”
2. measure all modules, config files, scripts ⇒ whitelist of hashes

**How to collect “bad” measurements:**
1. boot a compromised system (root kits, trojans, …)
2. measure infected files ⇒ blacklist of hashes

How do we keep these lists up-to-date?!?!
Sealing

Disney encrypts Nemo with a special sealing key *Seal*. 
Sealing

Disney encrypts Nemo with a special **sealing key** \textit{Seal}.

\textit{Seal} depends on

- the values in the \textit{PCRs}
- the TPM itself.

\implies your friend with an identical computer can’t watch your copy of Nemo!
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⇒ your friend with an identical computer can’t watch your copy of Nemo!

If you reboot with slightly hacked OS
- the *PCR*s will have changed
  ⇒ the *Seal* will be different
  ⇒ you can’t decrypt Nemo!
Sealing

Disney encrypts Nemo with a special **sealing key** *Seal*.

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- the **PCR**s will have changed
  ⇒ the *Seal* will be different
  ⇒ you can’t decrypt Nemo!

Microsoft could do the same to protect Office.
Encrypted execution
Encrypted execution

Idea:
- Encrypt the program.
- Keep a (unique) secret key in the CPU.
- Decrypt inside the CPU.

Protect algorithms (privacy)!
Protect from tampering (integrity)!
Protect from cloning (piracy)!
Assume the CPU cannot be tampered with.
XOM Overview

\[ E_{K_{pub}}(K_{sym}) \]

\[ E_{K_{sym}}(P) \]
The XOM architecture

- Stanford design.
- Never implemented in silicon.
- Simulated in software.
- Operating system, XOMOS, runs on top of it.
The XOM architecture — Compartments

- Each process may run in different security mode.
- Encrypted programs are slow!
- Programs may switch between encrypted and cleartext execution.
- CPU has 4 Compartments:
  - logical containers
  - protect one process from being observed or modified by another process.
  - the OS is untrusted: runs in its own compartment!
The XOM architecture — Compartments

- **Compartment 0**: code runs unencrypted
- **ACTIVE register**: current executing compartment
- **Session key table**: Maps compartment ID to key.
- Each **register** is tagged with compartment key.
- Each **cache line** is tagged with compartment key.
- On-chip data is in cleartext.
- On cache flush: encrypt!
The XOM architecture — Example
**The XOM architecture — Example**

```
<table>
<thead>
<tr>
<th>addr</th>
<th>contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$B_{sym}(I_1 \parallel CRC(I_1))$</td>
</tr>
<tr>
<td>2</td>
<td>$A_{sym}(I_2 \parallel CRC(I_2))$</td>
</tr>
<tr>
<td>3</td>
<td>$B_{sym}(D_1 \parallel CRC(D_1))$</td>
</tr>
</tbody>
</table>
```
The XOM architecture — Example

The CPU tries to load data value $D_1$ at address 3 into register r0:

1. Look in the cache line: empty!
The XOM architecture — Example

The CPU tries to load data value $D_1$ at address 3 into register r0:

1. Look in the cache line: empty!
2. Cache miss, read $B_{sym}(D_1 \parallel CRC(D_1))$ from address 3.
The XOM architecture — Example

The CPU tries to load data value $D_1$ at address 3 into register r0:

1. Look in the cache line: empty!
2. Cache miss, read $B_{sym}(D_1 \| CRC(D_1))$ from address 3.
3. Look up key for the active compartment: $B_{sym}$. 
The XOM architecture — Example

The CPU tries to load data value $D_1$ at address 3 into register r0:

1. Look in the cache line: empty!
2. Cache miss, read $B_{sym}(D_1 \parallel CRC(D_1))$ from address 3.
3. Look up key for the active compartment: $B_{sym}$.
4. Decrypt the cache-line!
The XOM architecture — Example

Adversary could have swapped $D_1$ it for another encrypted value from some other part of the code!

- Store CRC hash of each cache line.
- If CRC doesn’t match $\Rightarrow$ exception!
- Otherwise, load $D_1$ into register $r0$
- Set $r0$’s tag to 2.
Attacks on Tamperproof Devices
Attacks on Tamperproof Devices

Assumption: Physical barrier isn’t broken!
This section:

1. Attacking the XBOX
2. Invasive attacks on smartcards
3. Non-invasive attacks on smartcards
The Microsoft XBOX hack

MIT Ph.D. student Andrew “bunnie” Huang got an XBOX game console from his fiance’ for Christmas.
The Microsoft XBOX hack

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He took it apart.
The Microsoft XBOX hack

MIT Ph.D. student Andrew “bunnie” Huang got an XBOX game console from his fiance’ for Christmas.

- He took it apart.
- He cracked the security.


- **X86 CPU, 64 MB of cheap RAM, northbridge and southbridge chips, IDE controllers, etc.**
The Microsoft XBOX hack

System startup:
1. boot block executes
The Microsoft XBOX hack

System startup:
1. boot block executes
2. boot block decrypts, verifies, and jumps to the bootloader
The Microsoft XBOX hack

System startup:
1. boot block executes
2. boot block decrypts, verifies, and jumps to the bootloader
3. bootloader decrypts, verifies, and jumps to the OS kernel
The Microsoft XBOX hack

Observations:

1. Key and decryptor in the southbridge.
The Microsoft XBOX hack

Observations:
1. key and decryptor in the southbridge.
2. the CPU decrypts
The Microsoft XBOX hack

Observations:

1. Key and decryptor in the southbridge.
2. The CPU decrypts
3. ⇒ Key/decryptor will travel in cleartext over two busses!
The Microsoft XBOX hack

1) decrypt bootloader
2) decryption OK?
3) call bootloader

128-bit RC/4 key
RC/4 decryptor

1) decrypt kernel
2) decryption OK?
3) call kernel

Which bus to tap?

north-southbridge bus: Only 8 bits wide!
The Microsoft XBOX hack

Which bus to tap?

1. north-southbridge bus: Only 8 bits wide!
2. solder a tap board onto the bus
The Microsoft XBOX hack

1) decrypt bootloader
2) decryption OK?
3) call bootloader

1) decrypt kernel
3) call kernel

Which bus to tap?
1. north-southbridge bus: Only 8 bits wide!
2. solder a tap board onto the bus
3. sniff the decryptor + key
The Microsoft XBOX hack

Which bus to tap?

1. north-southbridge bus: Only 8 bits wide!
2. solder a tap board onto the bus
3. sniff the decryptor + key
4. pattern match \(\Rightarrow\) RC/4 decryptor!
The Microsoft XBOX hack

Which bus to tap?
1. north-southbridge bus: Only 8 bits wide!
2. solder a tap board onto the bus
3. sniff the decryptor + key
4. pattern match ⇒ RC/4 decryptor!
5. try every 16 bytes from bootblock as key!
Hacking smartcards
Smartcards

- Mass transit, prepaid phone cards, identification cards, SIM cards, pay-TV set-top boxes, credit cards.
- Protected memory in which a secret can be stored.
**Smartcards**

- Gets power and clock from **Card Acceptance Device** (CAD).
- CAD and card communicate over 1-bit serial ylink.
**Invasive vs. non-invasive attacks**

- **Invasive attack**: expose the bare chip,
Invasive vs. non-invasive attacks

- **Invasive attack:**
  1. expose the bare chip,
  2. probe the surface to extract information
Invasive vs. non-invasive attacks

- **Invasive attack:**
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  3. poke the surface to modify the chip
Invasive vs. non-invasive attacks

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- **Non-invasive attack:**
  - monitor execution characteristics (power, radiation, execution time) etc.
**Invasive vs. non-invasive attacks**

**Invasive attack:**
1. expose the bare chip,
2. probe the surface to extract information
3. poke the surface to modify the chip

**Non-invasive attack:**
- monitor execution characteristics (power, radiation, execution time) etc.
- watch normal operations or induce faults
Smartcards — Invasive attacks

Chipworks can extract analog or digital circuits from semiconductor devices and deliver detailed easy-to-understand schematics that document a single functional block or all the circuits. . . . We decapsulate the chip and analyze the die to locate the circuit blocks of interest. Then, using our Image Capture and Imaging System (ICIS) we generate mosaics for each level of interconnect. Finally, advanced software and expertise is used to extract the circuits for analysis.
Smartcards — Invasive attacks — Depackaging

1. Remove the chip from the card itself by heating and bending it.
2. Remove the epoxy resin around the chip by dipping it in 60°C fuming nitric acid.
3. Clean the chip by washing it with acetone in an ultrasonic bath.
4. Mount the exposed chip in a test package and connect its pads to the pins of the package.
**Smartcards — Invasive attacks — Deprocessing**

5. Use an optical microscope to take large high-resolution pictures of the chip surface.

6. Identify major architectural features (ROM, ALU, EEPROM, etc.) and/or lower-level features such as busses and gates.

7. Remove the top metal track layer by dipping the chip in hydrofluoric acid in an ultrasonic bath.

8. Repeat from 5, for each layer.
Smartcards — Invasive attacks — Reverse Engineering

- Reverse engineer the chip
- Analyze the information collected
- Understand the functional units of the chip
To allow the probe contact with the chip, use a laser cutter mounted on the microscope to remove (patches of) the passivation layer that covers the top-layer aluminum interconnect lines.

Record the activity on a few of the bus lines (as many as you have probes) as you go through a transaction with the card.

Repeat from 10 until you’ve collected the bus activity trace from all of the bus lines.
Dish Network is accusing News Corp … of hiring hacker Christopher Tarnovsky to break into Dish’s network, steal the security codes, and use them to make pirated cards to flood the black market.

Tarnovsky admitted in court he was paid James Bond villain style, with $20,000 cash payments mailed from Canada hidden inside “electronic devices.”

Smartcards — Invasive attacks —

Summary

- Attacks get harder as features get smaller
- Rent a lab!
- User your university lab!
Smartcards — Non-invasive attacks

- **Passive attack**: Watch what comes out of the chip, ..., electromagnetic radiation, power consumption, execution time, ...

- **Active attack**: Feed carefully constructed data/power/clock/... to the chip, *then* measure the chip’s behavior.
Smartcards — Timing attacks

\[
s[0] = 1;
\]
\[
\text{for } (k=0; k<w; k++) \{ \\
\quad \text{if } (x[k] == 1) \\
\quad \quad R[k] = (s[k]*y) \mod n; \\
\quad \text{else} \\
\quad \quad R[k] = s[k]; \\
\quad s[k+1] = R[k]*R[k] \mod n \\
\}\n\]
\[
\text{return } R[w-1];
\]

- Ask card: “please encrypt this file with your secret key”
Boardlevel protection
IBM 4758 cryptographic coprocessor

- Physical protection hasn’t been broken!
- Costs about $4000.
- Vending machines that “sell money”: topping up mobile phones, adding money to smartcards, or printing postage stamps.
- Used by banks to protect electronic transfers from insider attacks.
IBM 4758 cryptographic coprocessor

- Sensors
  - radiation
  - power
  - temp
  - mesh

- PCI BOARD
  - 32KB RAM
  - 486 CPU
  - 4MB RAM
  - 3DES
  - RSA
  - SHA-1
  - 4MB FLASH
  - DATE
  - RND

- Power
- Temp
- Mesh

- 32 bit internal bus

- 4MB RAM

- PCI bus

- Vcc
IBM 4758 cryptographic coprocessor

- PCI card — plug in to a host computer.
- 486-type processor, 4MB of RAM, 4MB of FLASH, 32KB of battery backed RAM.
- Cryptographic facilities: DES, 3DES, RSA, true random number generation, SHA-1.
- Date and time unit.
IBM 4758 — Tamper-detection

When tamper-detection sensor triggers:

1. Turn off power to the battery backed RAM ⇒ zero secret code and data.
2. Reset the CPU ⇒ destroy RAM contents.
IBM 4758 — Attacks and Defenses

Penetration attacks:

⇒ “polyurethane mixture and a film with an imprinted circuit pattern to detect minute penetration and erosion attacks”
IBM 4758 — Attacks and Defenses

Penetration attacks:
- “polyurethane mixture and a film with an imprinted circuit pattern to detect minute penetration and erosion attacks”

Memory remanence attacks:
- Freeze/radiate, remove from computer, drill down to RAM
- temperature and radiation sensors
IBM 4758 — Attacks and Defenses

- Penetration attacks:
  - ⇒ “polyurethane mixture and a film with an imprinted circuit pattern to detect minute penetration and erosion attacks”

- Memory remanence attacks:
  - Freeze/radiate, remove from computer, drill down to RAM
  - ⇒ temperature and radiation sensors

- Fault-induction attacks:
  - Bring voltage abnormally high or low.
  - ⇒ low and high voltage sensors.
Power analysis attacks:

⇒ filter the power supply
IBM 4758 — Attacks and Defenses

- **Power analysis attacks**:
  - Filter the power supply

- **Electromagnetic analysis attacks**:
  - Shield the board in a metal enclosure (Faraday Cage)
No known attacks against the physical protection of the 4758.
IBM 4758 — Summary

- No known attacks against the physical protection of the 4758.
- **Lessons**: Must protect against
  - *any* kind of leakage of information
  - *any* injection of faulty code/data
  - *any* adverse environmental conditions
IBM 4758 — Summary

- No known attacks against the physical protection of the 4758.
- **Lessons**: Must protect against
  - *any* kind of leakage of information
  - *any* injection of faulty code/data
  - *any* adverse environmental conditions
- Can we build a device that is
  - efficient,
  - secure, and
  - cheap?
Discussion
Disadvantages

- **Deployment** — long time before new technology is on every PC.
- **Cost** — extra hardware is expensive.
- **Usability** —
  - Lose a dongle?
  - Upgrade to a faster CPU, with different key?
  - Software vendor goes out of business?
- **Security** — invasive attacks, side-channel attacks.
- **Performance** — crypto-processors are slower.
- **Engineering** — design complexity, ease of testing, . . .
Thank You!