

DOTA2024:9

Defense of the Ancients

Ninth topic - Machine architecture

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Important times/dates

Work this week...

Thursday 18th, 10am: In the seminar room we will have a 40 minute, 20 question MCQ test. Samples sent to you this morning.

Thursday 18th, 2pm: Last time for the free poster printing. However, you can of course get it printed elsewhere, although it will cost about \$20.

Friday 19th, 10pm: Submission of paper, poster, and video to me (via "Canvas/DOTA/Assignment") on Friday). Let's look at some sample videos.

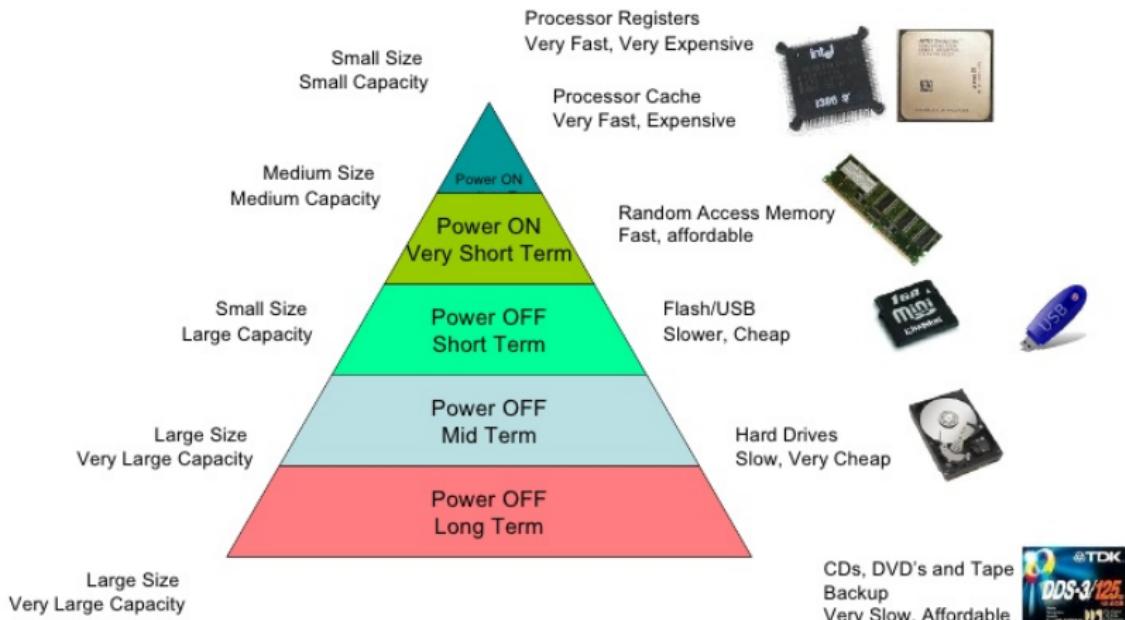
Saturday 20th, 9am: Poster showcase 09:00 to 13:00

- You will have your poster, and a table if needed, and random visitors.
 - Prepare a 10 second presentation (for anyone), and a 1 minute presentation (for colleagues), and then...
 - At least one person at your poster at all times, so perhaps a roster?
 - I will be passing out assessment sheets for assessing the other groups.
-

Saturday 20th, evening: Ceremony and awards.

Memory...

Computer Memory Hierarchy



Outline

1 Attacks on machine architecture...

- Memory, the buffer overflow attack
- General advice for safe practice

2 Hiding secrets: data and algorithms

- Hiding secrets
- Security hardware



How programs use memory for data

Storing a C string will come back to haunt us...

In C, a string like `Hello` is stored in six successive bytes, the five characters, and a NULL terminating character. This allows compact representation, and fast access to a string.

In Java for contrast, a string is stored as an object. For a five character string, the storage takes up 48 bytes: An object containing the actual characters; an integer offset into the array at which the string starts; the length of the string; and another int. This results in non-compact representation, and slow access.

When memory is needed for a program, the OS allocates memory:

- The calls to access memory are `malloc()` and `free()`.
- Java maintains its own heap, separate from the system heap.
- When lots of allocations and deallocations are being made, the heap may become fragmented, and the OS will run a `garbage collector` to fix up the heap from time to time.

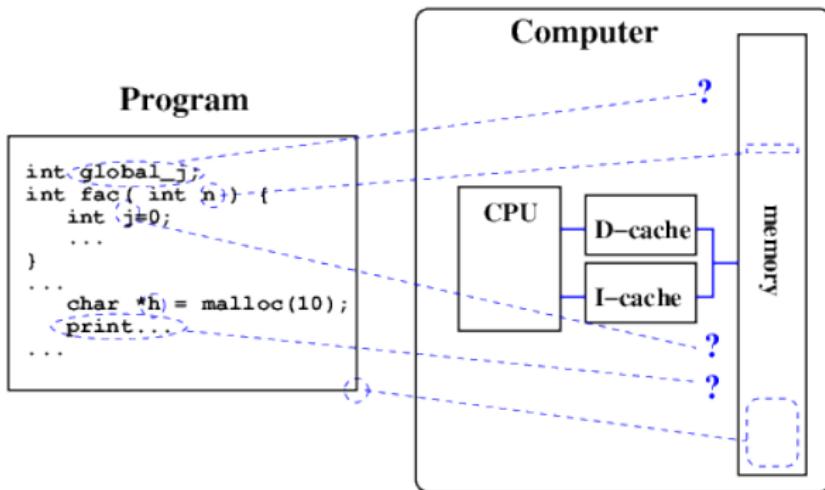
Machine architecture: visualizing memory

Location of “variables”?

```
int global_j;
int fac( int n ) {
    int j=0;
    if n=0 then
        return 1
    else
        return n*fac(n-1)
}
...
char *h=malloc(10);
global_j=5;
print(fac(global_j));
...
```

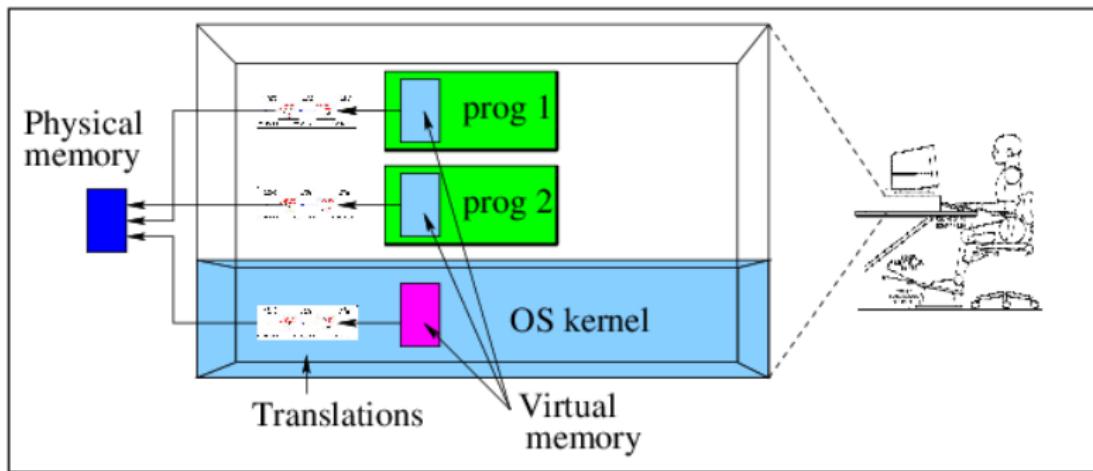
Machine architecture: visualizing memory

Location of “variables”?



Process use of memory

Virtual memory, physical memory, and translations...



The processes, and the OS kernel, each have their [own view of memory](#), somehow mapped/translated to the real (physical) memory.

Virtual memory addressing

Overview

Modern operating systems and hardware give **each process** an **individual address space** - starting at **0x0**.

A translation unit maps this *virtual* address to a real *physical* address, in fixed size pages.

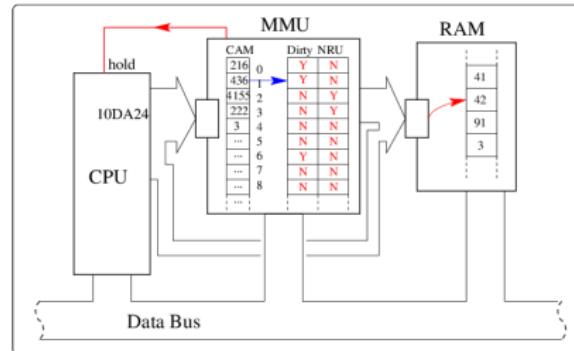
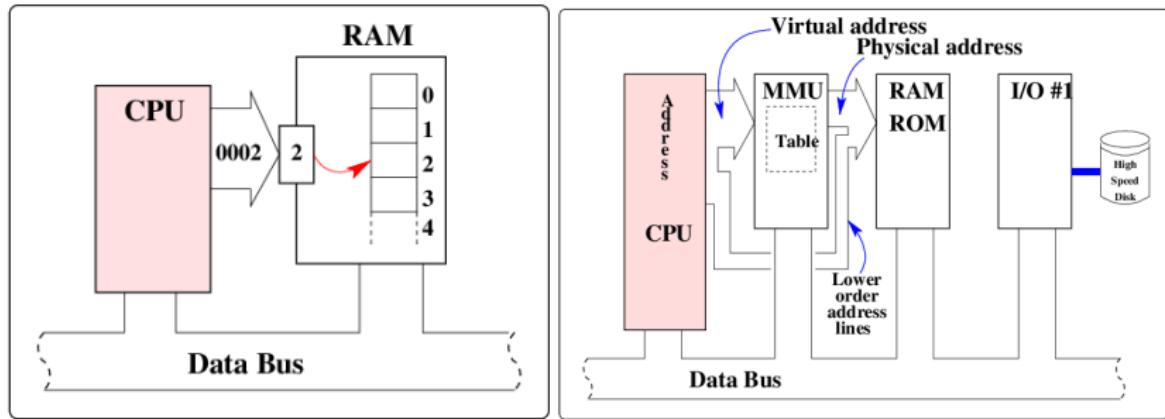
From the world of Intel...

On the Intel chips, there are 32/64 address lines. For a 32-bit system each process could have a virtual address space of up to 2^{32} bytes - or 4 gigabytes.

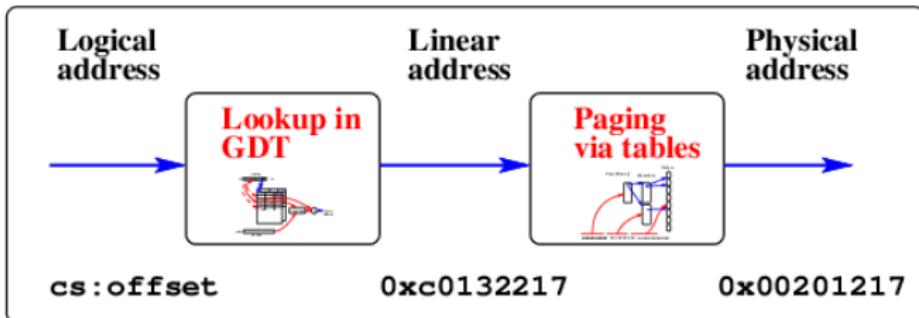
In a paged system, if our page size was 4096 bytes, the address bus would be split, with the bottom 12 bits going directly to the memory and the upper address bits to the translation unit.

Memory

Simple (embedded systems) and VM



VM=paging+segments (+disk)...



Disk can be used to store contents of memory

The part of the disk used in this way is called the '**swap**' - it may be either a file used for the purpose, or a partition of disk.

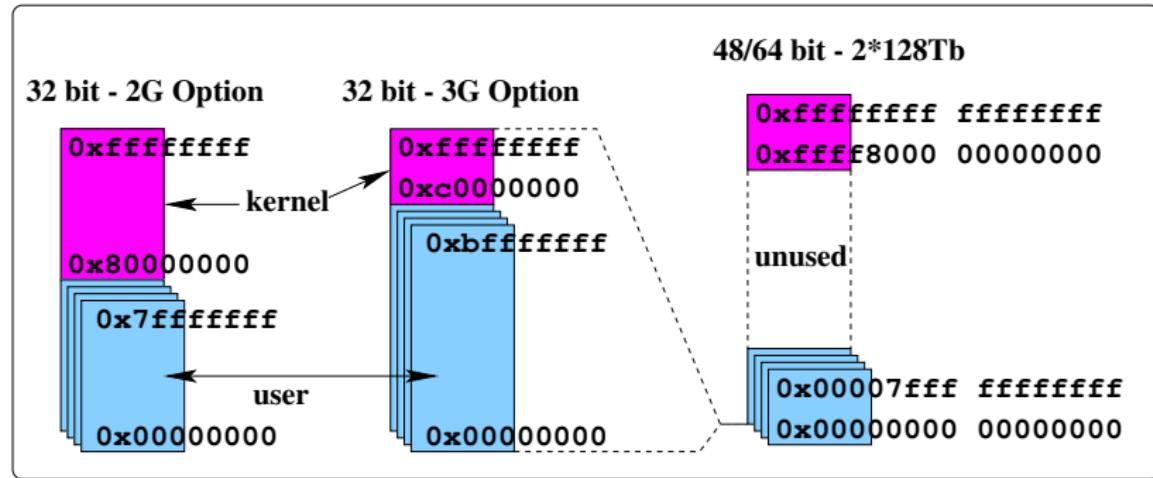
Page fault

When a VM system attempts to find a page, and does not find one, it is known as a **page fault**.

When a page fault occurs, the OS must *replace* a page in memory, efficiently, with the new one.

Windows (32/64-bit) X86 memory allocation

Several space options

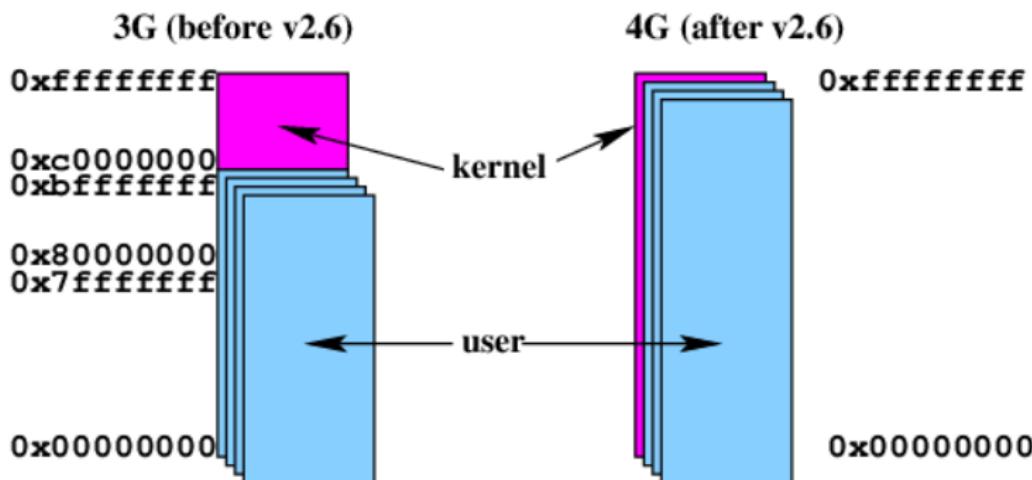


For 32-bit addressing, the “Kernel” area of memory has the HAL, drivers, page tables. The “User” area contains your exe code, dlls, stacks...

For 64-bit addressing, 64 bits is a **HUGE** space (more than 16 million terabytes). The top 128TB is used for the kernel, the bottom 128 TB for user processes.

Linux (32/64-bit) X86 memory allocation

3G before kernel v2.6, 4G afterwards (32-bit)

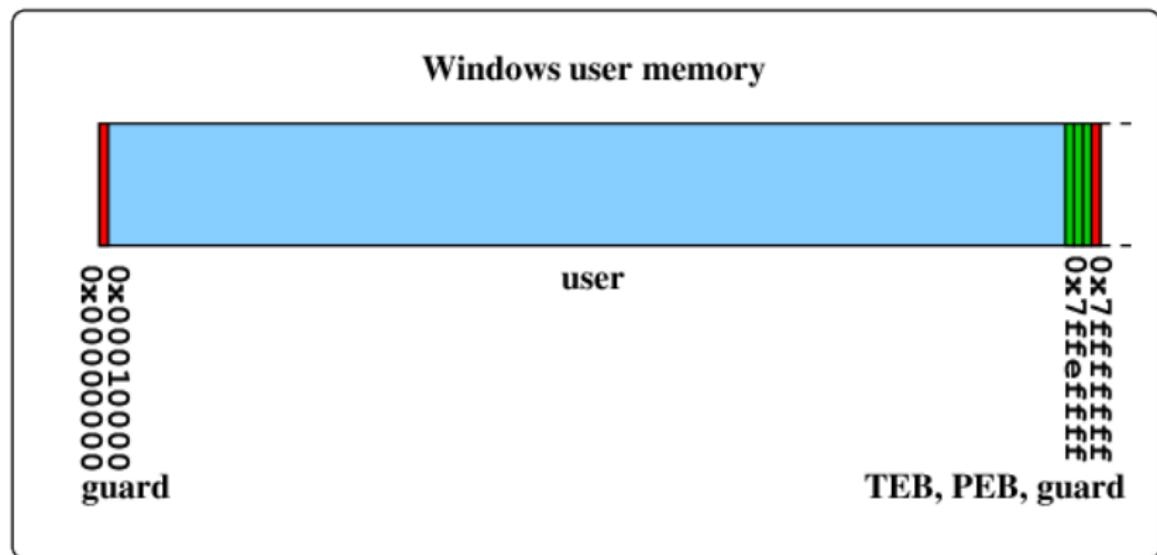


For 32-bit addressing, the “Kernel” area of memory has drivers, system stacks, page tables. The “User” area contains executable code, libraries, stacks...

For 64 bit addressing, the top half of memory is for the kernel, the lower half for user processes.

Windows process memory allocation

...for 2G model...

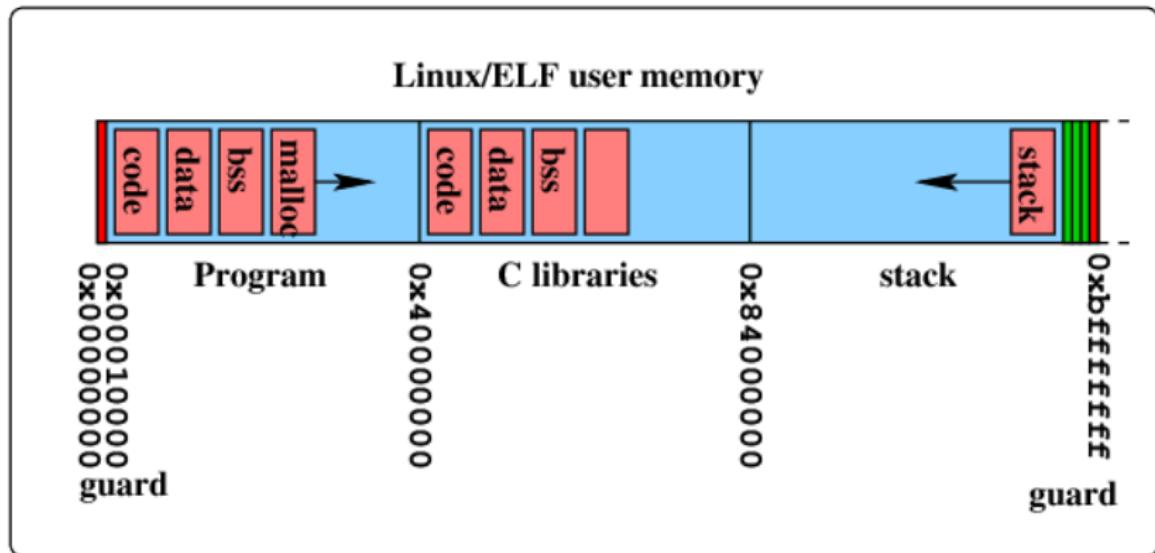


TEB and PEB are thread and process environment blocks.

The 64K guard blocks are sacrificial... against bad pointer references.

Linux ELF format user segments

Program, shared libraries, stack...



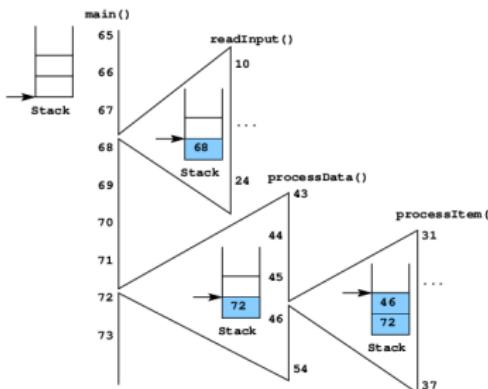
The malloc'ed memory is “above” the program.

As always, the stack grows downwards.

How programs use memory for return addresses

Return addresses need to be nested, so we use a stack:

```
10 readInput() {  
...  
24 } // Return to the most recent saved away address  
...  
31 processItem() {  
32 ...  
37 } // Return to the most recent saved away address  
...  
43 processData() {  
44 ...  
45   processItem(); // Save away 46 and call processItem()  
46 ...  
54 } // Return to the most recent saved away address  
...  
65 main() {  
66 ...  
67   readInput(); // Save away 68 and call readInput()  
68 ...  
70 ...  
71   processData(); // Save away 72 and call processData()  
72 ...  
73 }
```



A little warning...

Later, we will use **stacks** that are **upside down**, because that is how computers use stacks - they grow towards lower/smaller addresses.

Memory attack 1: simple Program

A pretty simple program...

CODE LISTING

vulnerable.c

```
void
main (int argc, char *argv[])
{
    char buffer[512];

    printf ("Argument is %s\n", argv[1]);
    strcpy (buffer, argv[1]);
}
```

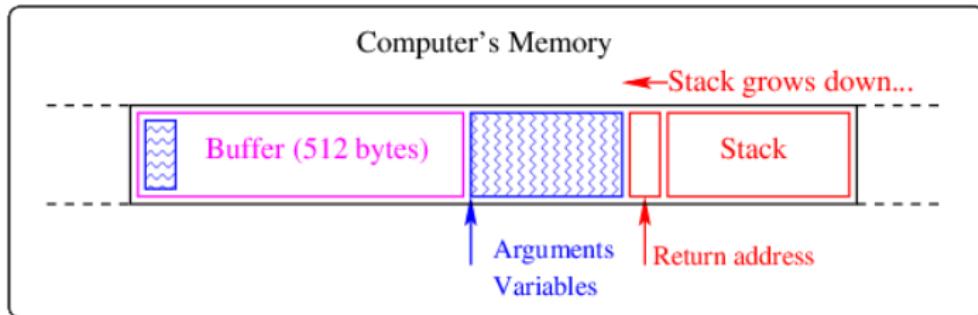
When we run it:

```
[hugh@pnp176-44 programs]$ ./vulnerable test
Argument is test
[hugh@pnp176-44 programs]$
```

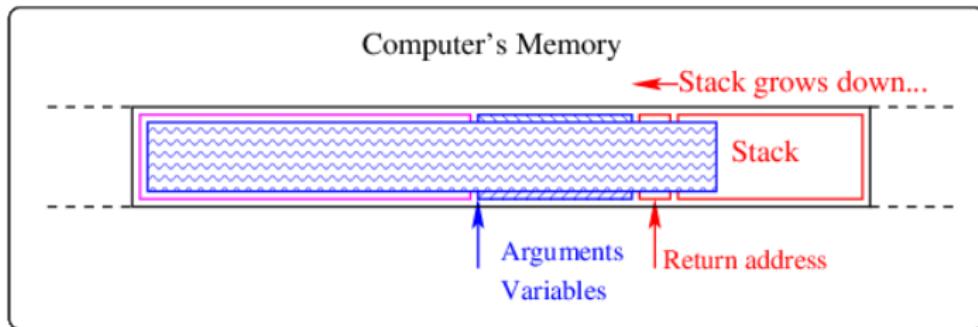
but...

Memory attack 1: stack buffer overflow

Normal operation

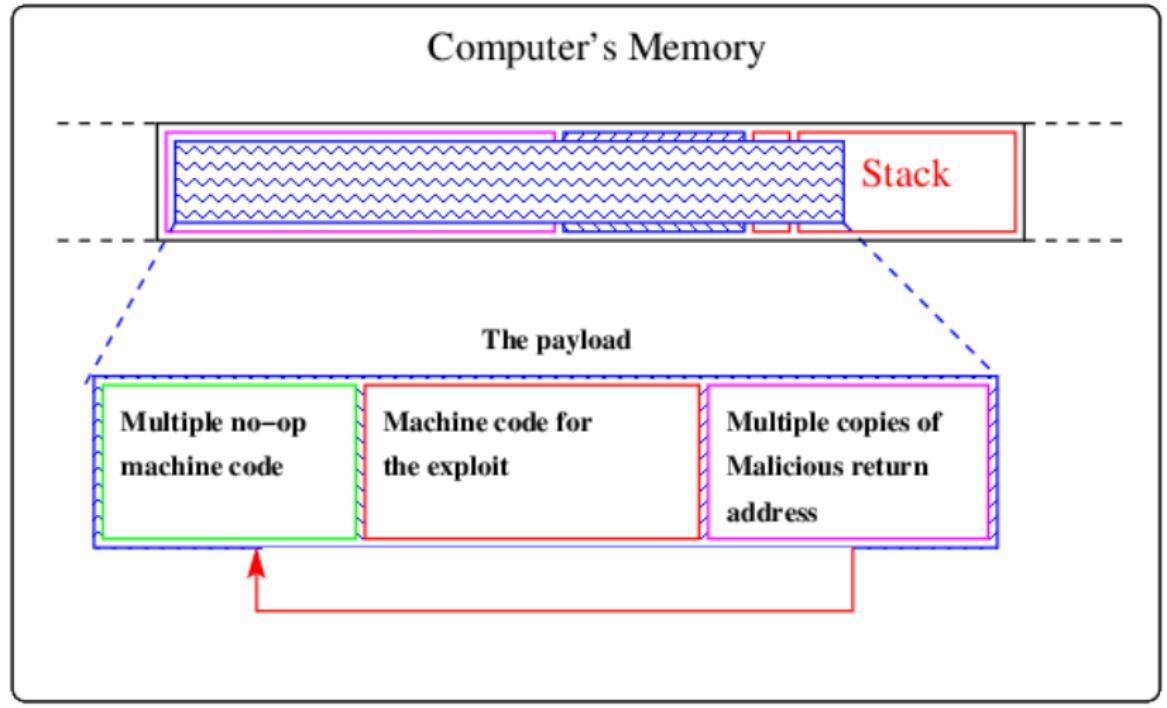


Overwrite the end of an array, with an "EGG"



Smashing the stack - the payload!

Contents of the payload



Payload code for an exploit

A C program which calls a shell...

```
#include <stdio.h>
void main() {
    char *nm[2];
    nm[0] = "/bin/sh";
    nm[1] = NULL;
    execve(nm[0], nm, NULL);
}
```

```
movl string, string_addr
movb $0x0, null_byte
movl $0x0, null_addr
movl $0xb, %eax
movl string, %ebx
leal string, %ecx
leal null_string, %edx
int $0x80          // OS call
"/bin/sh" string goes here.
```

At the left we see some C source code for running the program /bin/sh. On the right we see assembler code with extra OS nonsense removed.

Note that the binary code program has “zeroes” in it, and these will have to be removed if strcpy is to copy the program onto the stack. We can use translations like:

movb \$0x0, null_byte	xorl %eax, %eax
	movb eax, null_byte

Using the buffer overflow attack

3 examples of situations in which we can use it

- ① A **server** (say a web server) that expects a query, and returns a response. The demo buffer overflow attack done in class is one of these.
- ② A CGI/ASP or perl **script** inside a web server
- ③ A **SUID root** program on a UNIX system

Find a program that has a **buffer**, ... and that does not check its **bounds**. Then deliver an **EGG** to it to overflow the buffer.

Overwrite **stack** return address with address of **OUR** code.
The program then runs **OUR** code.

Example attack

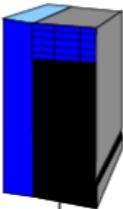
Many attacks on Microsoft systems are based on various buffer overflow problems. [CA-2003-20 W32/Blaster worm](#):

The W32/Blaster worm exploits a vulnerability in Microsoft's DCOM RPC interface as described in VU#568148 and CA-2003-16. Upon successful execution....

Memory attack 1: example

Consider the following scenario...

VM Honeypot on Hugh's mac



(Virtual) web server

Hugh's mac



(hack from here)

The Virtual machine running on the mac is running GNU+Linux, and a (cut down) version of an old version of Apache web server

Memory attack 1: web server code...

And in the web server we have this code:

```
void process(int newsockfd) {  
    char line[512];  
    ...  
    ...NEXT BIT DOESNT CHECK ARRAY SIZE! i.e. n<511  
    while (n>0 && c!='\n') {  
        n = read (newsockfd, &c, 1);  
        ... add it to line[idx++]...  
    }  
    ...  
    return;  
}
```

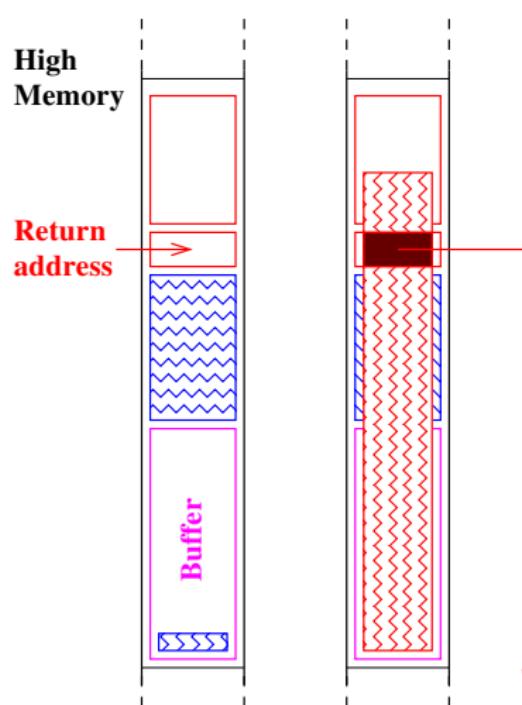
The general operation of this web server is hackable...

It matches our attack mechanism: A web server receives a file spec (index.html), and does not properly check a buffer that it puts the spec into.

We replace the file spec with **EGG**. Note that we will have to use a specialized **program** to deliver the EGG (i.e. not firefox)

Memory attack 2: return to libc!

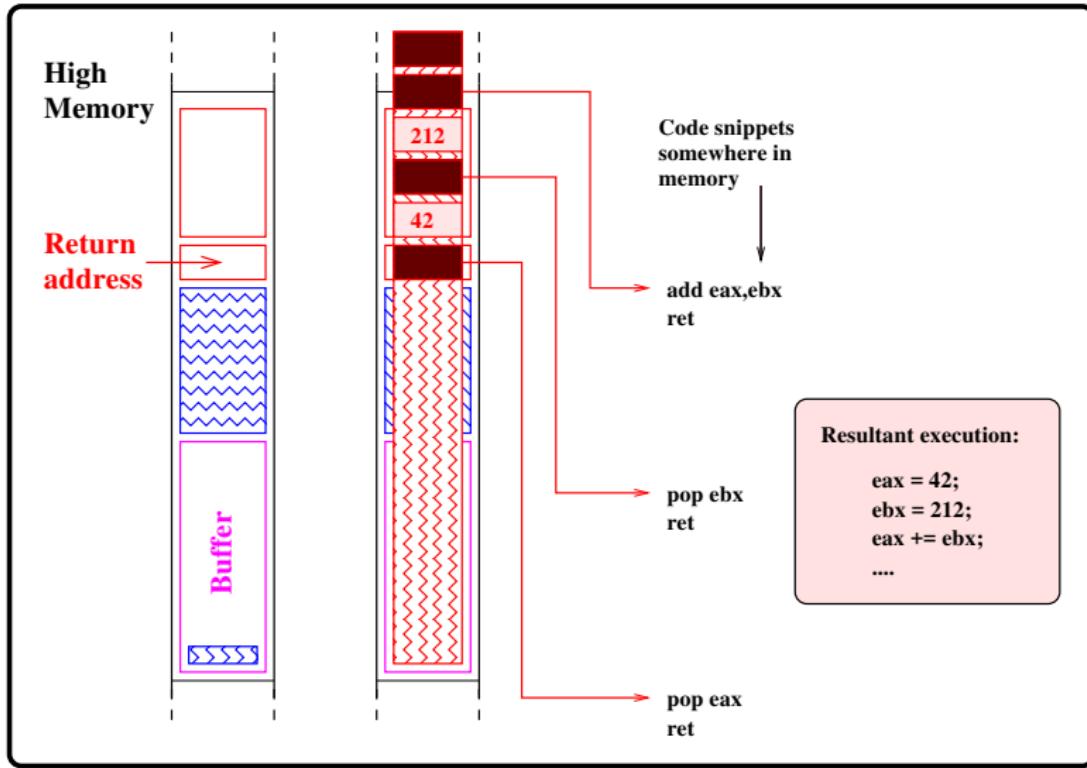
Run code already in libc...



This has the address of
the libc system call system().
You still need to provide an
argument to the system call...
so you get system("/bin/sh")

Memory attack 3: return oriented programming

Even with DEP: find code snippets, and overwrite stack...



Memory attack 4: heap overflow

The younger sibling of the buffer overflow

The **heap** is managed by the OS as a **doubly linked data structure**, containing a header, and the memory to be allocated.

The attacker starts by constructing/coding something that results in the OS allocating and deallocating memory from the heap. Then:

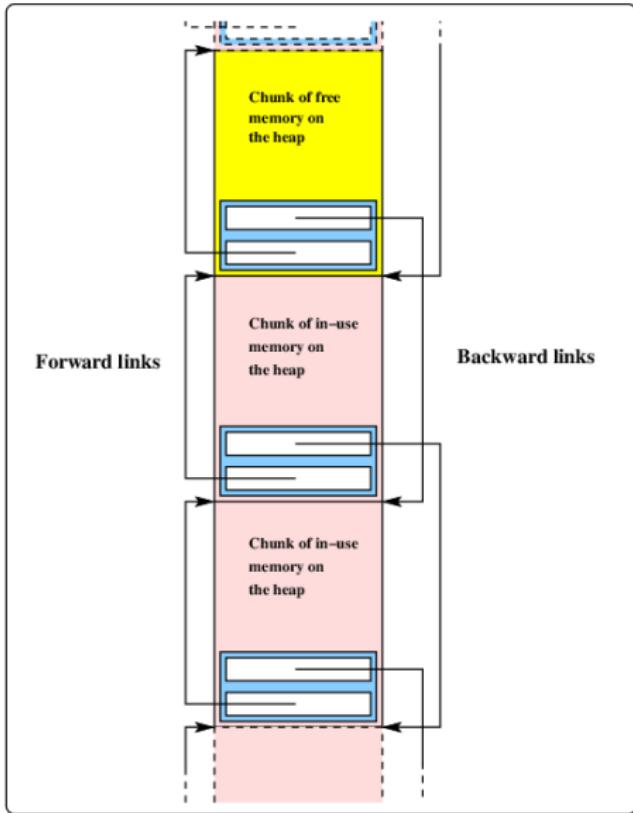
- After the `malloc()`, the program writes to the memory, and then returns it using `free()`. By careful choice of what we write to the memory, we can overwrite the NEXT header in the heap.
 - The **OS** then merges this *freed-up* memory, manipulating the headers in order to do so. It rewrites values in the previous headers that are dependent on the values in the next headers.
 - If the next header is modified to point to some place where a return address is being kept, then we can run crafted code.
-

Background reading:

<https://web.archive.org/web/20230401153759/http://www.h-online.com/security/features/A-Heap-of-Risk-747161.html>

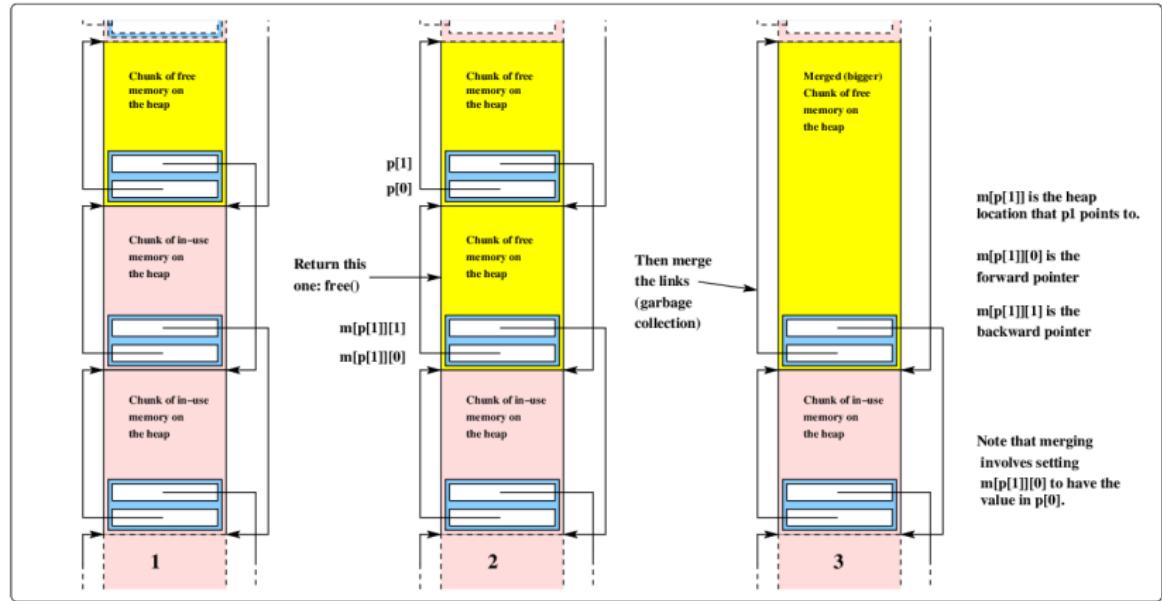
Memory attack 4: heap overflow

Consider the following part of a heap...



Memory attack 4: heap overflow

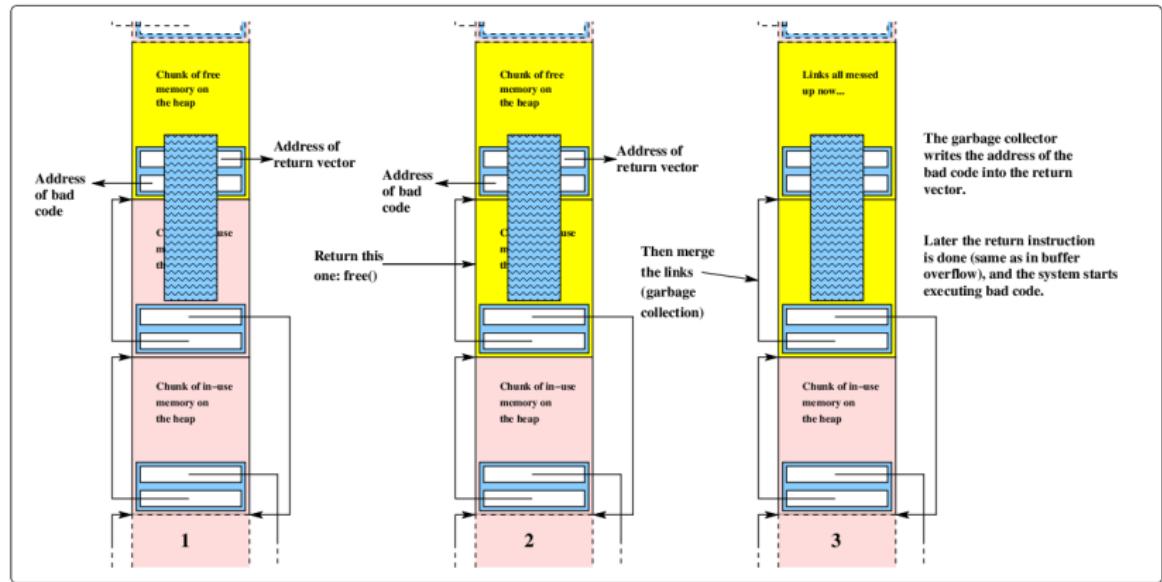
The normal free() and merge...



The OS heap management software automatically rewrites the values of the forward and backward links, using the values in the *next* links.

Memory attack 4: heap overflow

Consider the scenario where attacker changes pointers...



The attacker uses the OS GC to [write the address of malicious code into a *return-address* location](#), as for the buffer overflow.

Stack protection

Three methods to make overflow attacks harder:

- ① Not allow execution of code in the stack segment (as in MacOSX/openBSD) - but ROP still can get through.
- ② Randomly move the starting stack for processes.
- ③ Put a value just below the return address (a [canary](#)), and check it before doing a return from subroutine. It is hard to overwrite the return address without overwriting the canary.

Windows 7 and more recent versions include a wide range of protection against stack/heap overflows: They include the removal of commonly targeted data structures, heap entry metadata randomization, the heap header is more complex, there are randomized heap base addresses, function pointer are encoded, as well as the normal DEP and ASLR.

Memory attack 5: OpenSSL Heartbeat

What is a heartbeat in openssl?

A heartbeat is an extension to TLS, to allow a client to check if a TLS server is still alive (rather than tearing down a connection and renegotiating). It is described in <https://tools.ietf.org/html/rfc6520>.

The general idea is that clients can request a heartbeat, sending a heartbeat_request message with this structure:

```
struct {
    HeartbeatMessageType type;
    uint16 payload_length;
    opaque payload[payload_length];
    ...
} HeartbeatMessage;
```

The server will send back the payload in a matching heartbeat_response.

What is the issue?

What if the client lied about the payload_length?

Memory attack 5: OpenSSL Heartbeat

Request and response different...

The screenshot shows a browser window with the URL filippo.io/Heartbleed/www.borderlinx.com. The page title is "Heartbleed test". On the right, there's a large red heart icon with the text "Fork me on GitHub" above it. A blue banner at the top says "There should not be false results anymore, only "Uh-Oh"s." and "If there are problems, head to the FAQ". Below the banner, a text input field contains "www.borderlinx.com" and a green "Go!" button. A pink box below the input field displays the text "www.borderlinx.com IS VULNERABLE.". Underneath, it says "Here is some data we pulled from the server memory: (we put YELLOW SUBMARINE there, and it should not have come back)". A dark blue box shows a hex dump of memory starting with the byte sequence: 02 00 79 68 65 61 72 74 62 6c 69 65 64 2e 66 69. The text "filippo.ioYELLOW SUBMARINEo....." is visible in the dump.

```
(uint8) {
    00000000 02 00 79 68 65 61 72 74 62 6c 69 65 64 2e 66 69  [.._yellowbleed.FI]
    00000010 6c 69 78 79 6f 2e 69 6f 59 45 4c 4c 4f 57 28 53  [filippo.ioYELLOW SI]
    00000020 55 42 4d 4l 52 49 4e 45 6f ef 18 2c 0b bf cf 88  [SUBMARINEo.....]
    00000030 9b 9b 48 c8 29 e7 4e 84 93 dd de 47 bd 7e 2e 00  [..H.)N,...0.-..]
    00000040 05 90 05 01 00 00 00 00 00 0a 00 00 08 00 06 00 17  [.....]
    00000050 00 18 00 19 00 0b 00 02 01 00 00 0d 00 00 00 00 08  [.....]
    00000060 04 01 04 03 02 01 02 03 ff 01 00 01 00 00 04 01  [.....]
    00000070 00 01 85 00 00 00 17 00 15 00 00 12 a2 59 fe e5  [.....P..]
    00000080 01 45 69 94 e1 c4 c0 13 55 43 fd 42  [..E1.....U.BI]
}
```

Memory attack 5: OpenSSL Heartbeat

Original openssl-1.0.1f/ssl/d1_both.c...

```
/* Read type and payload length first */
hbtype = *p++;
n2s(p, payload);
pl = p; ...
```

The original source gets the type from the record that p points to, and puts it into hbtype. It then copies the next two bytes into the variable payload. This is the length of the payload, and is done without checking. The variable pl is the actual payload, which is later echoed, using the length value without any more checking.

Fixed openssl-1.0.1g/ssl/d1_both.c...

```
/* Read type and payload length first */
hbtype = *p++;
n2s(p, payload);
if (1 + 2 + payload + 16 > s->s3->rrec.length)
    return 0; /* silently discard */
pl = p; ...
```

(There is a little more, but that is the general idea).

Memory attack 6: Memory after reset

After a hardware reset...

If you press the **reset** button on the computer...

the memory of the computer retains the same values it had just before the reset.

If you are careful, it is possible to

- **bypass** the memory test (which destroys some values in memory).
 - **boot** a small OS (such as DOS) which will not change any of the important memory contents.
 - use a DOS application to **extract** the raw contents of memory, rebuilding the paging and segment tables, and then
 - **re-create** the memory for each process.
-

The memory may contain (for example) secrets that had been left in memory.

Memory attack 7: Malloc hack

The scenario...

In 1999, Microsoft fixed a security error in the login “password” software in the Windows login.

The error (it is not a “bug”) went something like this:

- The **software allocated space** in memory for the user to type in the password using **malloc()**.
- Then the **user typed in the password** (and it ended up in the memory of the computer), and it was used and then
- the **memory** used was **returned** to the OS using **free()**:

```
// ... Allocate some memory for the password:  
buffer = malloc( MaxPasswordSize );  
// ... Put the password into this buffer,  
// ... and use it to log in.  
// ...  
// ... Then return the memory to the OS:  
free( buffer );
```

Memory attack 7: Malloc hack

The error...

The problem with this scenario, was that the password was [left in clear text](#) in the memory of the computer, and the NEXT user of the computer could search the heap of the computer and discover it.

The fix was to clear the buffer using bzero():

```
// ... Zero out all the contents of the buffer:  
bzero( buffer, MaxPasswordSize );  
// ... Then immediately return the memory to the OS:  
free( buffer );
```

The error returns...

In 2001 hackers discovered that (after *improvements* made to the Microsoft compilers) the [password was back](#) in clear text in memory!

What can possibly be wrong with this [obviously correct](#) code?

Memory attack 7: Malloc hack

Error returns to haunt Microsoft...

The problem lay with the compiler:

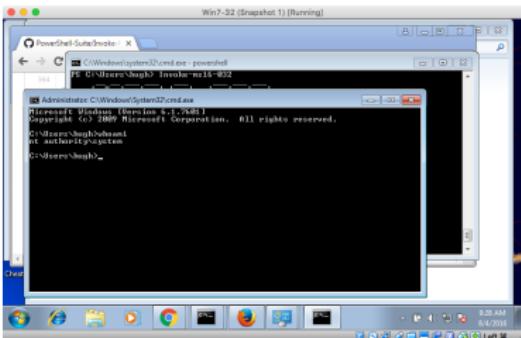
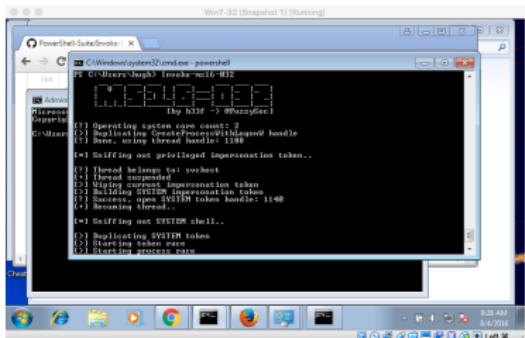
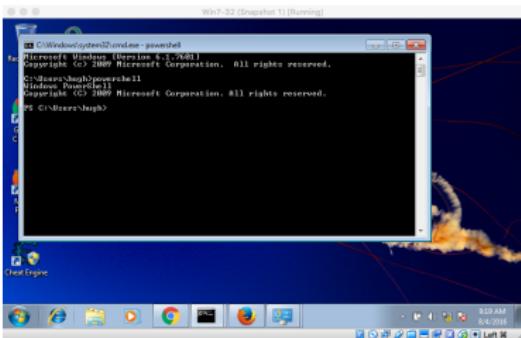
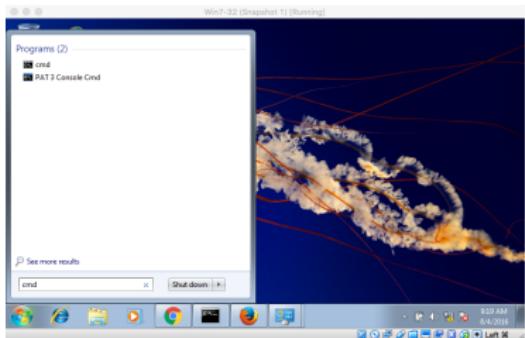
- The newer compiler did a lot of optimization, and
 - recognized that the buffer was not used again after setting all its values to zero, so
 - the `bzero()` was (silently) removed!
-

Score 10 for the compiler, and simultaneously, 0 for the compiler.

Surface 7 attack, privilege escalation...

A recipe...

Login to Windows and run powershell. Run `Invoke-ms16-032.ps1...`



Some useful practices

For system developers or coders...

- Check for use of safe memory technologies (in OS, compiler, libraries...)
- Check the use of parameters and buffers/arrays
- Overwrite secrets as soon as possible (and watch for compiler optimization)
- White hat approach: code conservatively -
 - Make interfaces explicit rather than implicit.
 - Minimize interfaces.
 - Check and recheck safety properties.
 - Requires, ensures and invariants.
- Wear a black hat

Safe memory technologies

As a system designer or coder...

You should be aware of the **environment** within which you are working.

For example:

- Your compiler - does it implement some sort of stack protection (such as StackGuard). Is there a better system available?
- The library routines you use (especially in Microsoft). Do they implement good stack protection technology?
- Your compiler - what sort of optimizations does it do?
- Your runtime system - does it use the OS heap or its own? What known attacks are there with this runtime system/heap?
- Your OS - is it recent? Are there any known attacks on it?
- Your language - does it have many security weaknesses? Is it C, C++, C#?
- Your code - have you used safer library routines? For example `strncpy()` versus `strcpy()`.

Parameters and buffers/arrays

Consider your source code. Ask yourself..

- Is there any way at all that your program takes **input** from outside (In 99% of programs the answer is YES BTW).
 - Do you ensure that the **input** is **constrained** to be within the range of values you expect? As early as possible?
-

Can an **index** can be **outside the range** you have specified?

```
idx=10;  
while (idx>0) {  
    ... body ...  
}
```

Consider the above code - does the body of the while loop get executed at least once? (i.e. Ensure **no indirect interfaces** between code segments.)

There is no way of avoiding secrets in memory...

...but once you have used a secret, you should **immediately overwrite** it. This will reduce a **window of opportunity** to an attacker.

Conservative code: modularity

Software design, modular programming...

Modular design is an effective way of designing, building, and coding large software projects:

http://en.wikipedia.org/wiki/Modular_programming

In a good modular design concerns are separated such that

- modules are more or less stand alone, and that
 - when they do depend upon other modules of the system the interfaces are explicit (i.e. easily visible in the code).
-

The system designer/coder should reduce or minimize the dependencies.

Conservative code: explicit interfaces

Do not hide away interaction between modules...

If two modules share a variable, this should be explicit, and not hidden:

```
var x;
module1() {
    manipulate x...
}
...
module42() {
    manipulate x...
}
```

In the above code - two modules both rely on the shared variable, but if you read the code for `module1()`, there is no clear indication that it is also being manipulated by `module42()`. When you reason to yourself about the correctness of `module1()`, you may forget the effect of `module42()`.

It is possible to reason about *tiny* segments of code in a program, but ...
... even the fanciest designer or coder cannot correctly `reason` about *small* programs, let alone *large* ones.

Conservative code: interfaces

If variables are being used across modules...

Make their use explicit:

- ... as parameters (even though you may believe this to be inefficient),
 - ... by using modules (classes/objects) correctly,
 - ... by documentation and warnings.
 - ... revisit your code and review it for good programming practices.
-

Minimize them ... make sure you actually do need them, and if not, remove them.

Conservative code: design by contract

Software design, design-by-contract, code-contracts...

An approach to [defensive programming](#).

Design-by-contract is an effective way of [checking and rechecking safety properties](#): http://en.wikipedia.org/wiki/Design_by_contract

In a good design-by-contract design, the [components and interfaces](#) between them are precisely [defined](#) using

- [preconditions \(requires\)](#). What does the component expect?
 - [postconditions \(ensures\)](#). What does the component guarantee?
 - [invariants](#). What does the component maintain?
-

These definitions are called [contracts](#). Bertrand Meyer coined the design-by-contract term when developing the language [Eiffel](#).

There is at least some support for contracts in some languages, including [Java](#), [Spec#](#), [.NET](#).

Conservative code: requires, ensures

A useful idea

In Eiffel, `requires` and `ensures` are part of the language and are checked at the beginning (for `requires`) and the end (for `ensures`):

```
my_list.do_all (agent (s: STRING)
    require
        not_void: s /= Void
    do
        s.append_character (',')
    ensure
        appended: s.count = old s.count + 1
    end)
```

In the above code, if either contract is broken, the run time system traps to some handler for the error.

If there is no handler, the program exits, with the name of the broken part of the contract.

Conservative code: invariants

When you want to ensure a safety property is always kept

```
class interface
    ACCOUNT
feature -- Access
    balance: INTEGER          -- Current balance
    deposit_count: INTEGER     -- Number of deposits
feature -- Element change
    deposit (sum: INTEGER)    -- Add 'sum' to account.
        require
            non_negative: sum >= 0
        ensure
            one_more_deposit: deposit_count = old deposit_count + 1
            updated: balance = old balance + sum
invariant
    consistent_balance: balance = all_deposits.total
end -- class interface ACCOUNT
```

(Eiffel) In the above code, if any contract is broken, the run time system traps to some handler for the error.

If there is no handler, the program exits, with the name of the broken part of the contract.

Wear a black hat...

... from time to time ...



Cautious, conservative programming is the main defense, but occasionally you need to put on your **black hat**, and find out what the attackers have discovered recently...

Testing and finding flaws

Still theoretical...

One aspect in engineering the security of software is that even one flaw in software may lead to a security issue. This leads to everything weighted on the side of the attacker:

- Lets say people find one flaw in 100 hours of testing/use.
- Let us also assume that there are 100,000 errors in a large software product. A company employs testers for 100,000 hours, and discover 1000 flaws.

Unfortunately:

An attacker discovers one flaw, in 100 hours, and the likelihood that the testers have found this specific error is only 1%.

The math favours the attacker.

S/W development for security

A sub species of S/W development...

Aspects of engineering the security of software may include extra work in areas such as design reviews and testing, along with administrative duties such as system and configuration management and post mortems.

Design and code review:

One study suggested that security flaws are found in a large software project at the following times:

- 17% found when doing system design inspection
- 19% found when doing component design inspection
- 15% found when looking at the code
- 30% found when doing integration testing
- 16% found afterwards during general testing.

Of course we have no idea how many errors are left in the code.

Secrets come in lots of flavours

Not just secret keys...

We have seen how [secrets](#) can be useful, particularly for keeping [keys](#) for cryptography.

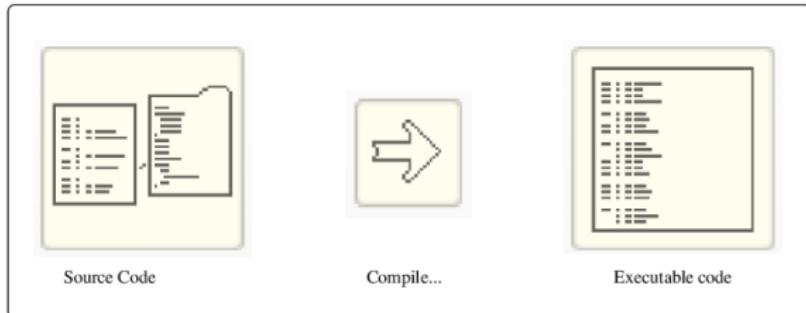
Secrets may also be [algorithmic](#)...

- An encryption algorithm
 - A particular protocol (sequence of communications).
 - A hashing algorithm.
-

These secrets are programs, not data. [How do we keep these sorts of secrets?](#)

Applications running on PCs, phones, ...

Consider the compilation process...



Often, the **executable** is distributed, not the source. RMS points out many reasons why this is **most likely a bad idea**.

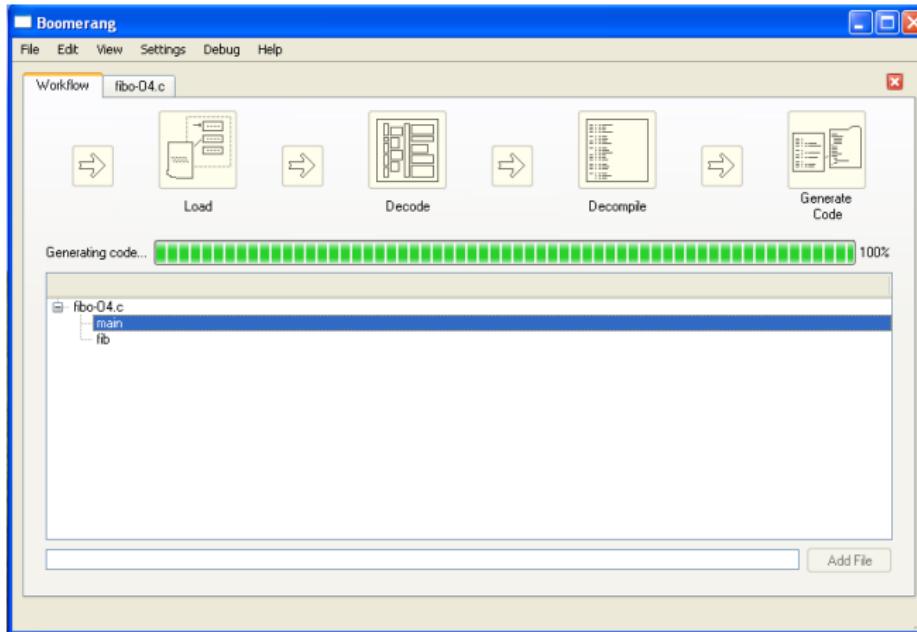
But, in a *security* scenario, you may think that by only distributing your executable code, you can **hide your source code secrets**.

This is a **silly idea**. You should keep no secrets in source code.

- You should not have source code secrets (remember the notion of **open design**), and
- you cannot hide things by using compilation.

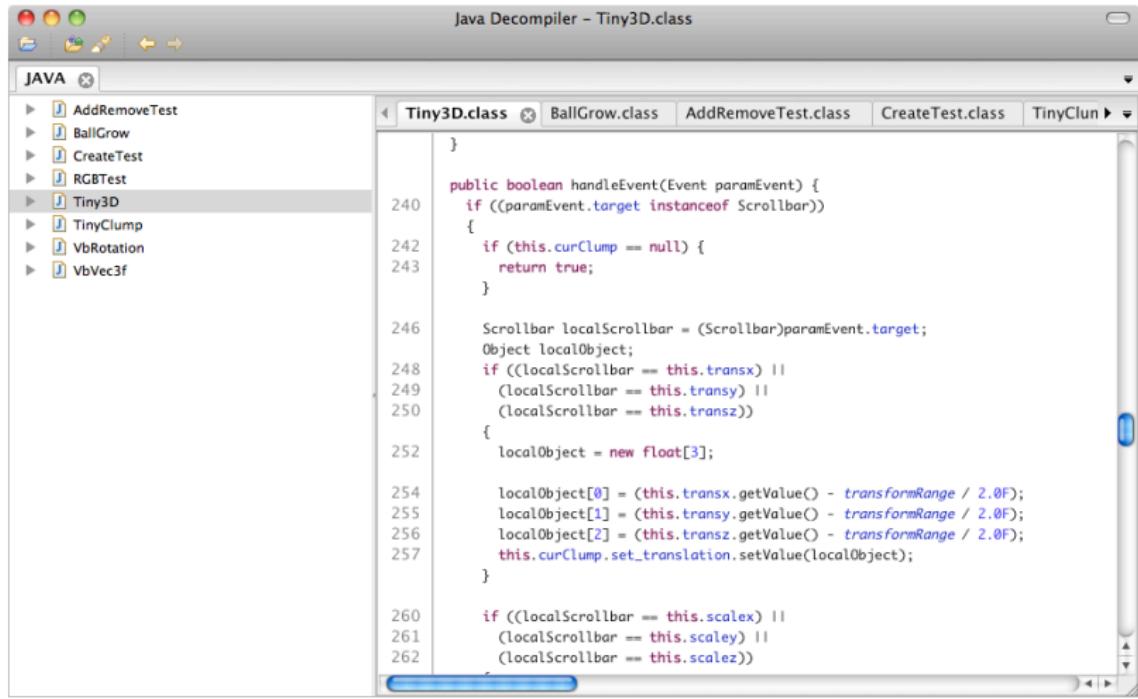
Why?

Decompilation is reverse of compilation...



Note that really good decompilation may take user input, but it is possible.

Java decompilation is particularly easy...



The screenshot shows a Java decompiler interface with the title "Java Decomplier - Tiny3D.class". On the left, there's a tree view under a "JAVA" tab containing various class names: AddRemoveTest, BallGrow, CreateTest, RGBTest, Tiny3D (which is selected), TinyClump, VbRotation, and VbVec3f. The main pane displays the decompiled Java code for the Tiny3D class. The code handles scroll events and updates transformation values.

```
public boolean handleEvent(Event paramEvent) {
    if ((paramEvent.target instanceof Scrollbar))
    {
        if (this.curClump == null)
            return true;
    }

    Scrollbar localScrollbar = (Scrollbar)paramEvent.target;
    Object localObject;
    if ((localScrollbar == this.transx) ||
        (localScrollbar == this.transy) ||
        (localScrollbar == this.transz))
    {
        localObject = new float[3];
        localObject[0] = (this.transx.getValue() - transformRange / 2.0F);
        localObject[1] = (this.transy.getValue() - transformRange / 2.0F);
        localObject[2] = (this.transz.getValue() - transformRange / 2.0F);
        this.curClump.set_translation.setValue(localObject);
    }

    if ((localScrollbar == this.scalex) ||
        (localScrollbar == this.scaley) ||
        (localScrollbar == this.scalez))
```

Applications...

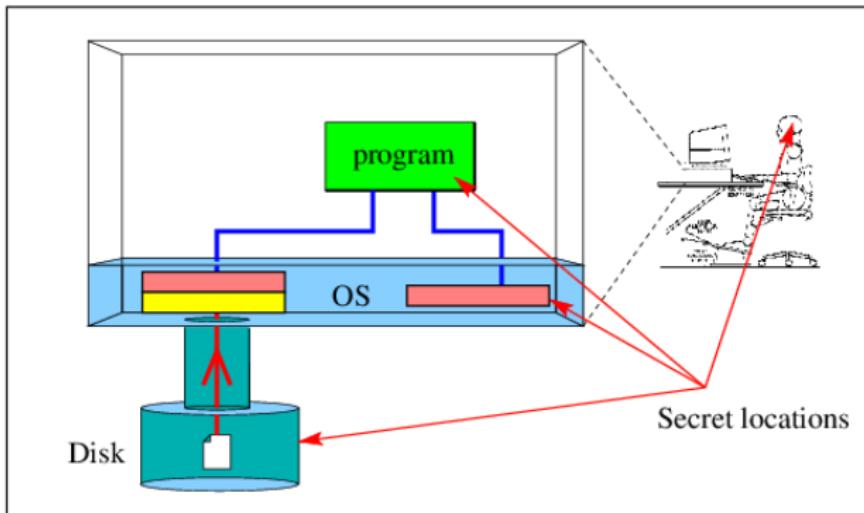
...are, essentially, an open book...

If the platform is sufficiently complex (e.g, Windows, GNU+Linux, Android, Symbian), then it is likely that **sources for any application could be generated easily**, so if you intend to distribute your application to other users, and it relied on some secret in the code, that secret is unsafe.

Of course - **you can still have secrets**. They must be kept separately. (Do I detect an example of **Least common mechanism**: Minimize the amount of mechanism common to more than one user and depended on by all users?)

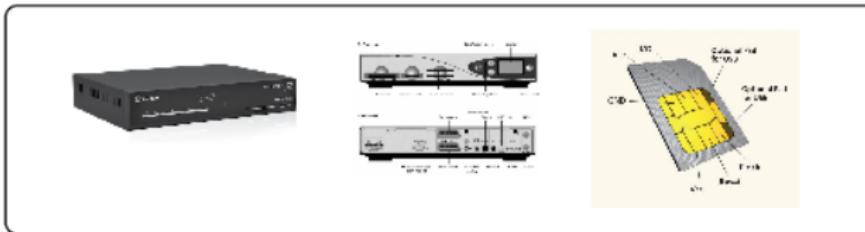
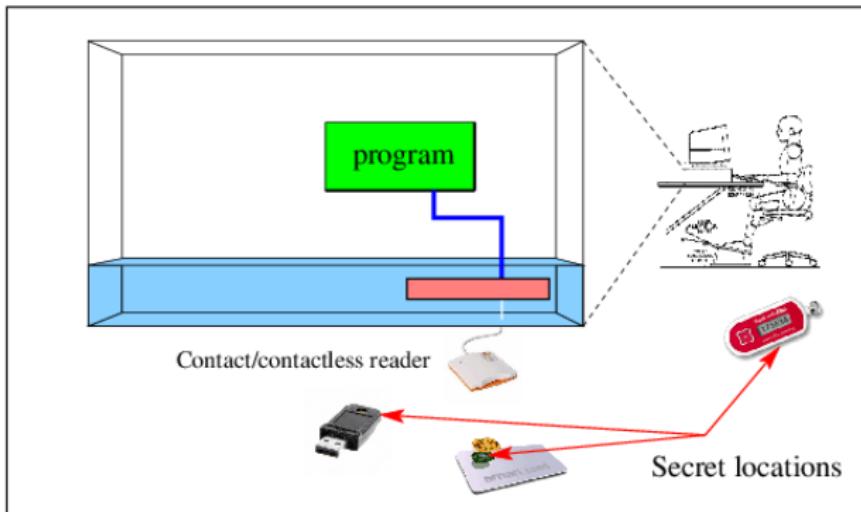
Possible locations for secrets

Disk (file), program, OS, brain...



Other locations for secrets

Dongles, smart cards, 2-factor devices...



Summary...

There is no such thing as a safe PC...

Secrets may be data, or algorithmic.

Complex platforms are unsuitable for hiding secrets - they are open to attacks:

- **physical** (someone breaks open a box and steals a disk containing secrets), or
 - **software based** (someone manages to install or otherwise hack either an application or a whole OS).
-

A strategy for getting around this is to somehow install the secret on a **portable computer system** that is harder to attack (more resistant to tampering), and possibly, resistant to theft.

- Examples of this approach are found everywhere (smart cards, SIM cards...).
- Such external devices typically contain small computers with small amounts of memory.

Classes of attackers for security hardware

For tamper-resistant portable devices...

Anderson outlines this classification:

- **Class 1 attackers:** Clever **outsiders**, who may not have detailed knowledge of the inner workings of the system
 - **Class 2 attackers:** **Insiders**, with detailed system knowledge.
 - **Class 3 attackers:** **Governments**, the Mafia - who may have money and time to burn. May also have strong motivation.
-

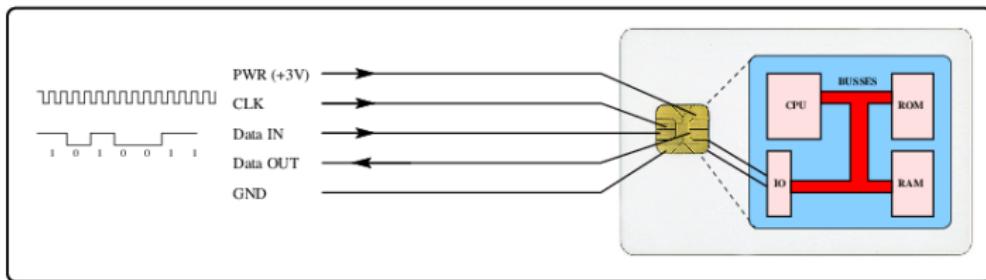
Anderson points out that **persistence and cunning** are some of the hallmarks of an effective attacker, and that sometimes the class 1 attacker can do things that the class 3 attacker failed to do.

We have both invasive and non-invasive attacks:

- **Invasive:** the semiconductor chip is decapsulated, and direct attacks made on the circuitry. Some of these attacks require expensive equipment.
- **Non-invasive:** we manipulate the device without decapsulation. May need only inexpensive equipment.

Typical hardware on a Smart/SIM card

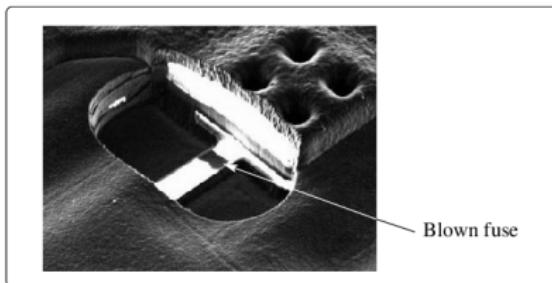
A high-security Smart/SIM card controller



- CPU, memory and IO are under the (gold) **connector**. They are all in **one chip**, and the components are connected by (internal) busses.
- Reader must **supply power** and a **clock** to operate the CPU.
- Only external signaling is a **single line IN** and a **single line OUT**.
- **Data bits are serialized.** 1010011 above might correspond to the byte (hex) 0x53, perhaps corresponding to the ASCII letter S.

Fuses: sample security-specific feature

For devices like these...



The **chips** come from the factory **all the same**, and need to be programmed.

- When the devices are manufactured, the **memory** (PROM) can be **read and written from outside** using the serial port.
- Once the device has been uniquely programmed, a **fuse** is blown. This fuse is just a track in the IC, and is blown by providing too much current.

A blown fuse means **no more (external) reading and writing.**

Fuses: Class 3 attacker hack: rewiring

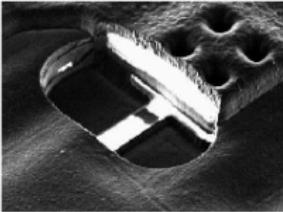
Assuming you happen to have some fancy equipment

Recipe: Take a common household electron microscope, a focused ion beam tool, and various other items. And then...

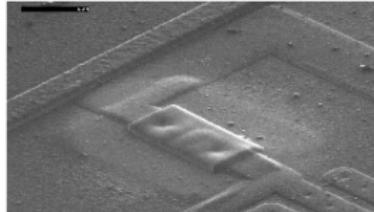
- Expose chip using chemical and/or laser cutting (decapsulation).
- Re-connect the fuse using deposition or tiny probes.
- Read the memory using the serial port.



Decapsulation
(Nitric acid...)



Discover blown fuse
(May need FIB to
expose layer)



Deposit new material over fuse

Summary...

Only a brief outline here...

- Invasive and non-invasive attacks possible on security hardware.
- It is an arms race, and I have not even begun to cover techniques like encryption of memory, light sensitive fusing and so on.
- Invasive attacks may include
 - Decapsulation followed by imaging, reconnecting blown fuses, or probing.
 - Introducing faults, rewiring.
- Non-invasive attacks may include
 - Introducing glitches, or uncovering protocol/software flaws
 - Timing attacks.
- Software based techniques to reduce these effects include
 - Constant time loops
 - Reducing the likelihood of a single-glitch attack, by making code reliant on two independent tests.

Memory attack 6: Historical TENEX password hack

A secure password scheme?

- The TENEX operating system had a handy utility which could **display page faults** for you.
- Programmers found that if you wrote a program which attempted to check a password with just its **first letter before a page boundary** and the second letter after...
- The program would either
 - **fail** because the first letter was wrong, or
 - **display a page break and then fail** because the second letter was wrong.
- All the letters A-Z were tried and then the password was moved back by one byte and the second letter searched.
 - This technique could discover a ten letter password in about 130 tries (normally it would be 26 to the power of 10).

Memory attack 6: Historical TENEX password hack

At the core of the password routine:

- Does this look peculiar?

```
void testPW( char buf[] ) {  
    int i=0;  
    while ( i<PWDSize ) {  
        if ( buf[i]!=password[i] ) {  
            return NOMATCH;  
        }  
        i=i+1;  
    }  
    return MATCH;  
}
```

On this bad code we can do a timing attack...

Memory attack 6: Historical TENEX password hack

Fix?

- The fix just involved a [tiny change](#) to the password scanning routine.

```
void testPW( char buf[] ) {  
    int i=0;  
    bool match=TRUE;  
    while ( i<9 ) {  
        if ( buf[i]!=password[i] ) {  
            match=FALSE;  
        }  
        i=i+1;  
    }  
    return match;  
}
```

The “page fault” attack is no longer possible
...but a timing attack may still be possible.

Memory attack 6: Swap after reset

After a hardware reset...

- If you press the [reset](#) button on the computer...
 - the [swap](#) space (on disk) is unchanged.
- If you are careful, it is possible to
 - [bypass](#) the memory test (again).
 - [boot](#) a small OS (such as GNU+Linux), without swap, so it will not change any of the swap partition contents.
 - use a GNU+Linux application to [extract](#) the raw contents of the swap partition of the disk, and then
 - [re-create](#) the memory for each process.
- The memory may contain (for example) secrets that had been left in memory.

This [attack is limited](#), because the page tables are unlikely to be swapped. As a result it is difficult to correctly rebuild the memory with each page in order. However it still may be [possible to extract secrets](#).

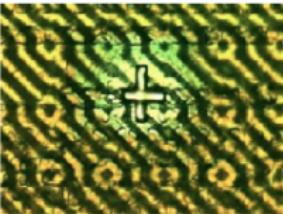
Fuses: Class 3 attacker hack 3: probing

If you have microprobes...

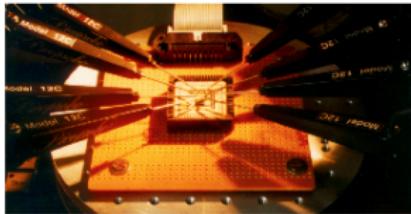
- **Recipe:** Take a common household electron microscope, a focused ion beam tool, and various other items. And then...
 - Expose chip using chemical and/or laser cutting (decapsulation).
 - Expose internal wiring (FIB), and construct landing pads for probes.
 - Observe internal busses and hence anything about the system.



Decapsulation



Expose critical circuitry
(Use FIB to do surgery on chip,
constructing landing pads for probes)



Connect probes

Fuses: Class 1 attacker (the outsider) hack 1

Only a little equipment needed...

- The outsider does not have electron microscopes or FIB units, or even Nitric acid! Life is tough sometimes.
- The outsider notices that when power is first applied, the smart card outputs an identification string on the serial OUT line:

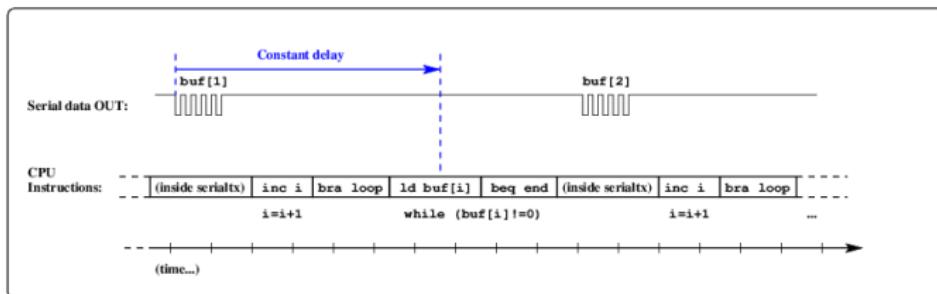
Vsn 0.97

- The outsider knows that the software is very small, and probably stores strings like “Vsn 0.97” in 9 bytes of memory, the 8 bytes of the string, terminated by a null (a byte with all zeroes in its bits).
- The outsider surmises that the code is probably like this:

```
void printit( char buf[] ) {  
    int i=0;  
    while ( buf[i]!=0 ) {  
        serialtx(buf[i] );  
        i=i+1;  
    }  
}  
...  
printit( "Vsn 0.97" );
```

Fuses: Class 1 attacker hack 1

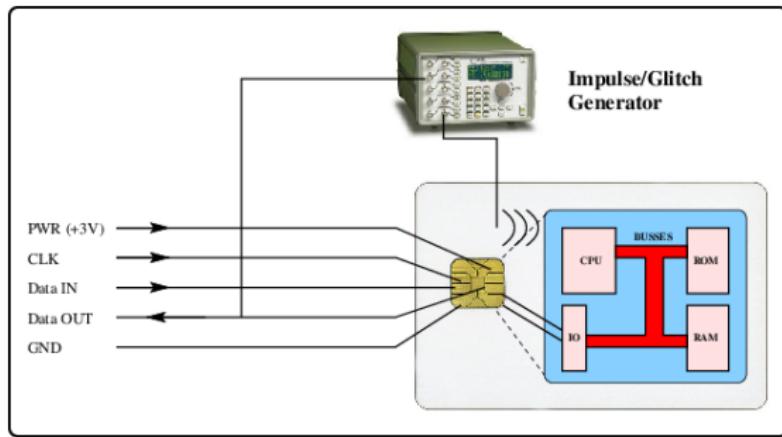
Timing diagram for the printit() while loop...



- The **instructions** executed by the CPU are **predictable**. After transmitting the serial character for `buf[1]` :
 - The `i` variable is incremented (`inc i`)
 - The CPU branches to the beginning of the while loop (`bra loop`)
 - The value in `buf[i]` is loaded (`ld buf[i]`)
 - If it is equal to 0, then branch to the end of the loop (`beq end`)
 - Otherwise transmit the next character...
- There is a **constant delay** between the character and these instructions.

Fuses: Class 1 attacker hack 1: glitch

A "glitch" attack...



- By timing a **pulse/glitch** to occur exactly **when the software checks** the test at the beginning of the while loop, (it is always a fixed time after the previous character), attacker can make the **test always succeed**.
- i.e. `buf[i] != 0` will always be **TRUE**.
- A **glitch** may be a **spark**, a **variation** of the **power supply**, or some other activity. Hardware to do this is cheaply available (e.g. in most EE labs).

Fuses: Class 1 attacker hack 1: glitch

A "glitch" attack...

- If `buf[i] != 0` is always TRUE...
- The code acts like this:

```
void printit( char buf[] ) {  
    int i=0;  
    while ( TRUE ) {  
        serialtx(buf[i] );  
        i=i+1;  
    }  
}
```

...

- As a result, the serial data line continues to output serial data corresponding to the entire memory of the processor (program and data).
- Note that in small systems like this, memory is not protected, and `buf[0] ... buf[65536]` is ALL of memory.

Protecting from this attack?

Consider this crazy code...

```
void printit( char buf[] ) {  
    int i=0;  
    while ( buf[i]!=0 AND buf[i]!=0 ) {  
        serialtx(buf[i] );  
        i=i+1;  
    }  
}  
...  
    printit( "Vsn 0.97" );
```

- Can you see why this code may be better than the previous code?
- Can you understand why a compiler might undermine this solution?

PK space attack

Smart cards are slow...

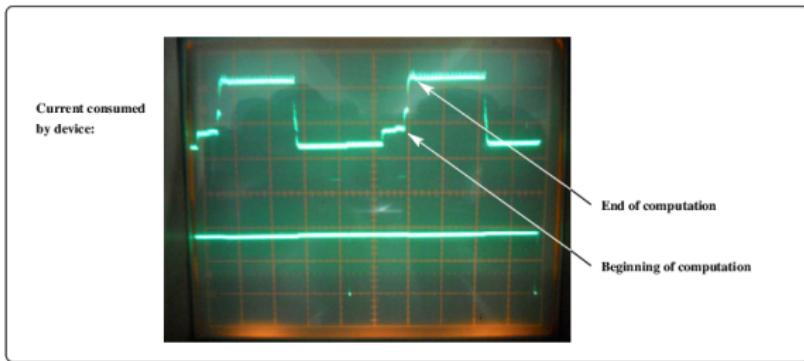
- Sometimes people implement PK encryption or authentication on smartcards, but the processors are really slow, and...
- An exponentiation operation required takes time proportional to the number of bits that are 1 in a large (1024) bit random prime number.
- A 1024 bit random number should on average have bits set to a 1.
- However, this might make the smartcard unacceptably slow. So instead...
 - Developers select large (1024) bit prime numbers that only have a small number (3-5) bits set to a 1.
 - Smartcard is now fast, but open to attack.

What is the attack?

- Consider how few large (1024) bit primes there are, if only 5 bits are set to a 1!

Timing attacks

Observe behaviour externally by measuring current...



- Current trace gives **evidence** about computation - **type** and **timing**.

What is the attack?

- Accurate measure of time of computation leads to an attack.
- The **tutorial** has an example of a timing attack.

Tutorial timing attack...

Just a reminder...

- The case of a function to test an 8-digit PIN number:

```
void testPIN( char buf[] ) {  
    int i=0;  
    while ( i<9 ) {  
        if ( buf[i]!=password[i] ) {  
            return NOMATCH;  
        }  
        i=i+1;  
    }  
    return MATCH;  
}
```

- Instead of requiring $10^8 = 100,000,000$ attempts at the password, our attack algorithm only required 80.
- The attack involved precise measurement of the time for the function while trying out PINs.

Tutorial timing attack...

Possible solution...

- A constant-time function to test an 8-digit PIN number:

```
void testPIN( char buf[] ) {  
    int i=0;  
    bool match=TRUE;  
    while ( i<9 ) {  
        if ( buf[i]!=password[i] ) {  
            match=FALSE;  
        } else {  
            match=match;  
        }  
        i=i+1;  
    }  
    return match;  
}
```

- No timing attack possible.
- Routine always takes a fixed amount of time.