CE 815 - Secure Software Systems

Lecture 1

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Acknowledgments: Some of the slides are fully or partially obtained from other sources. Reference is noted on the bottom of each slide, when the content is fully obtained from another source. Otherwise a full list of references is provided on the last slide.

Software Faults

- Software are developed by humans and therefore are not perfect
- A human error may introduce a bug (or fault)
- Are all software faults security bugs?

Software Insecurity

- A software bug or software fault may be a security bug or vulnerability
  - When the bug is triggered or exploited it compromises the security of the software system

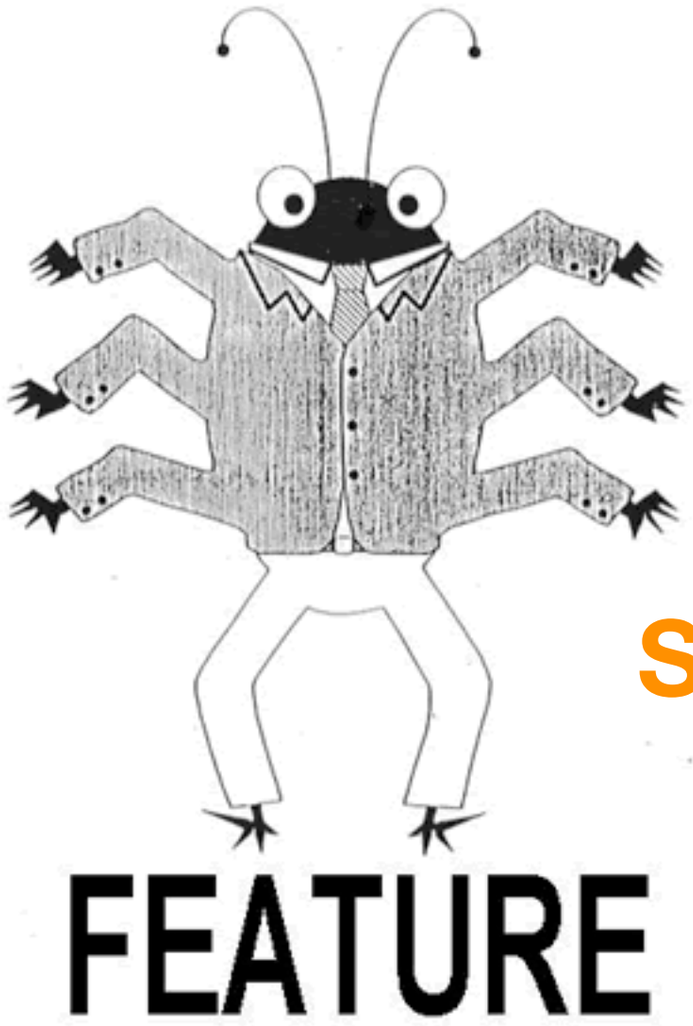
Software Security

- Easy, just write perfect software!
  - Is that actually enough?
- Easy, just write perfect software and have perfect users!
  - Is that actually enough?
- Easy, just write perfect software, have perfect users, and configure software perfectly!
  - Is that actually enough?
- Easy, just write perfect software, have perfect users, configure software perfectly, and use a perfect Operating System!

Software Security

- Easy, just write perfect software, have perfect users, configure software perfectly, use a perfect Operating System, use a perfect hypervisor, run on a system with perfect firmware, run on a system with perfect hardware, …

Really depend on how you look at it



Speculative Execution

Examples (CVE- 2009-4307)

```
groups_per_flex = 1 << sbi->s_log_groups_per_flex;
  /* There are some situations, after shift the value of 'groups_per_flex' can
  become zero and division with 0 will result in fixpoint divide exception */
if (groups_per_flex == 0)
  return 1;
flex_group_count = ... / groups_per_flex;
```

- X86 32bit, shift inst. truncates the shift amount to 5 bits. (32 shift becomes 0)
- PowerPC 32bit, shift inst. truncates the shift amount to 6 bits. (32 shift becomes 1)
- In C, shifting an n-bit integer by n or more bits is undefined behavior.
- Compiler thinks, groups_per_flex will never be zero
  - removed the check when compiling to optimize code

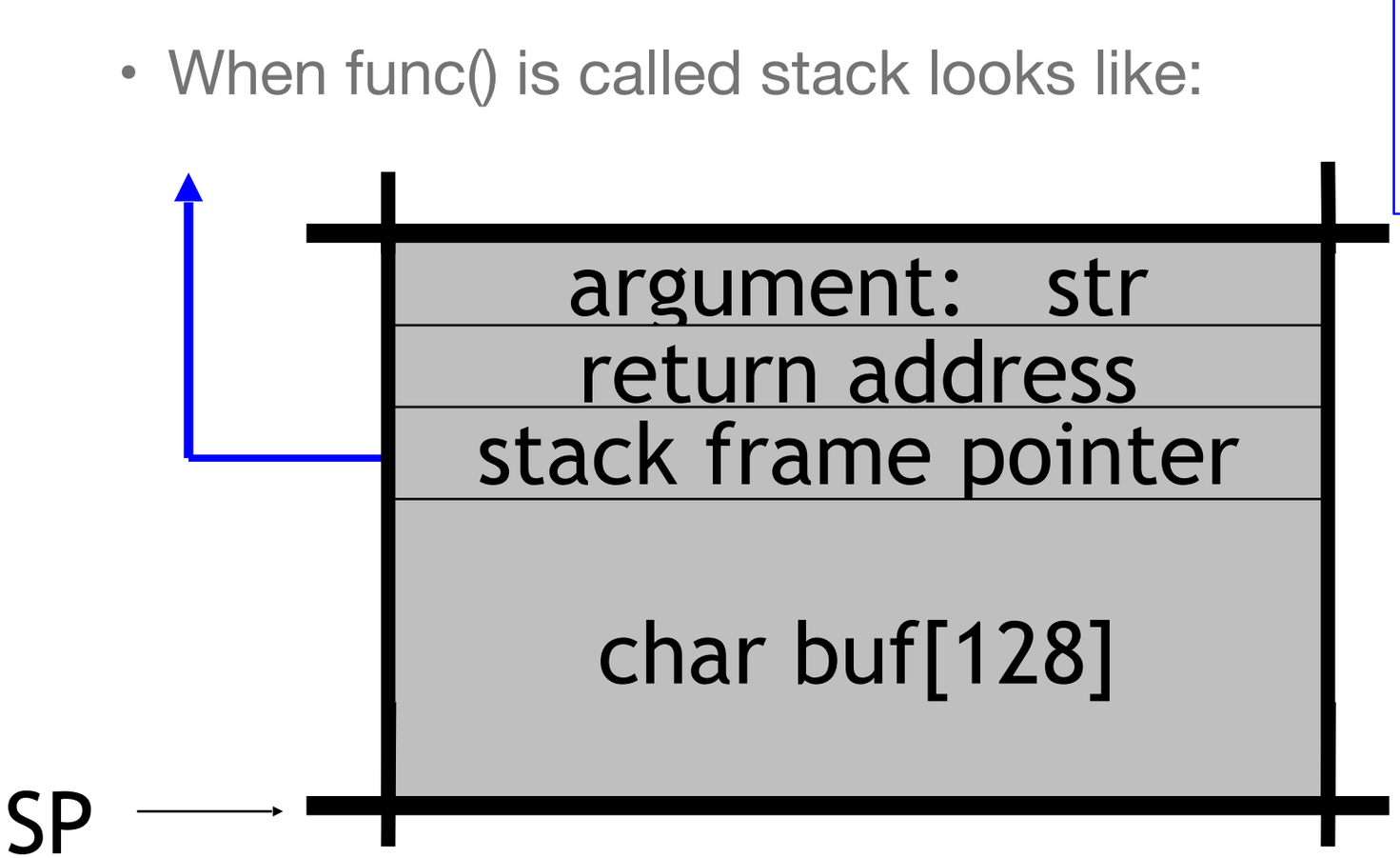
Buffer overflow

- Suppose a web server contains a function:

```
void func(char *str) {
    char buf[128];

    strcpy(buf, str);
     do-something(buf);
}
```

- When func() is called stack looks like:



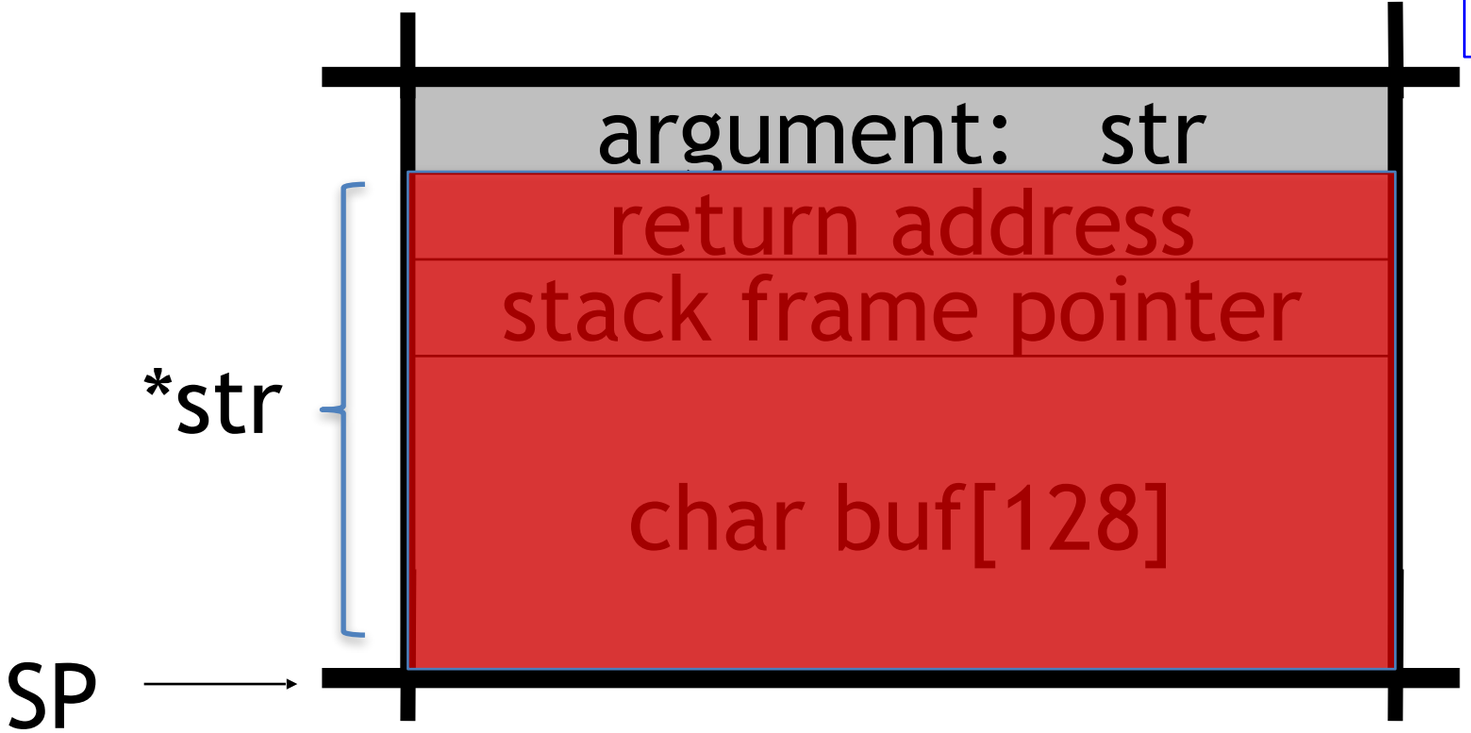
Buffer overflow

- What if *str is 136 bytes long?

```
void func(char *str) {
    char buf[128];

    strcpy(buf, str);
     do-something(buf);
}
```

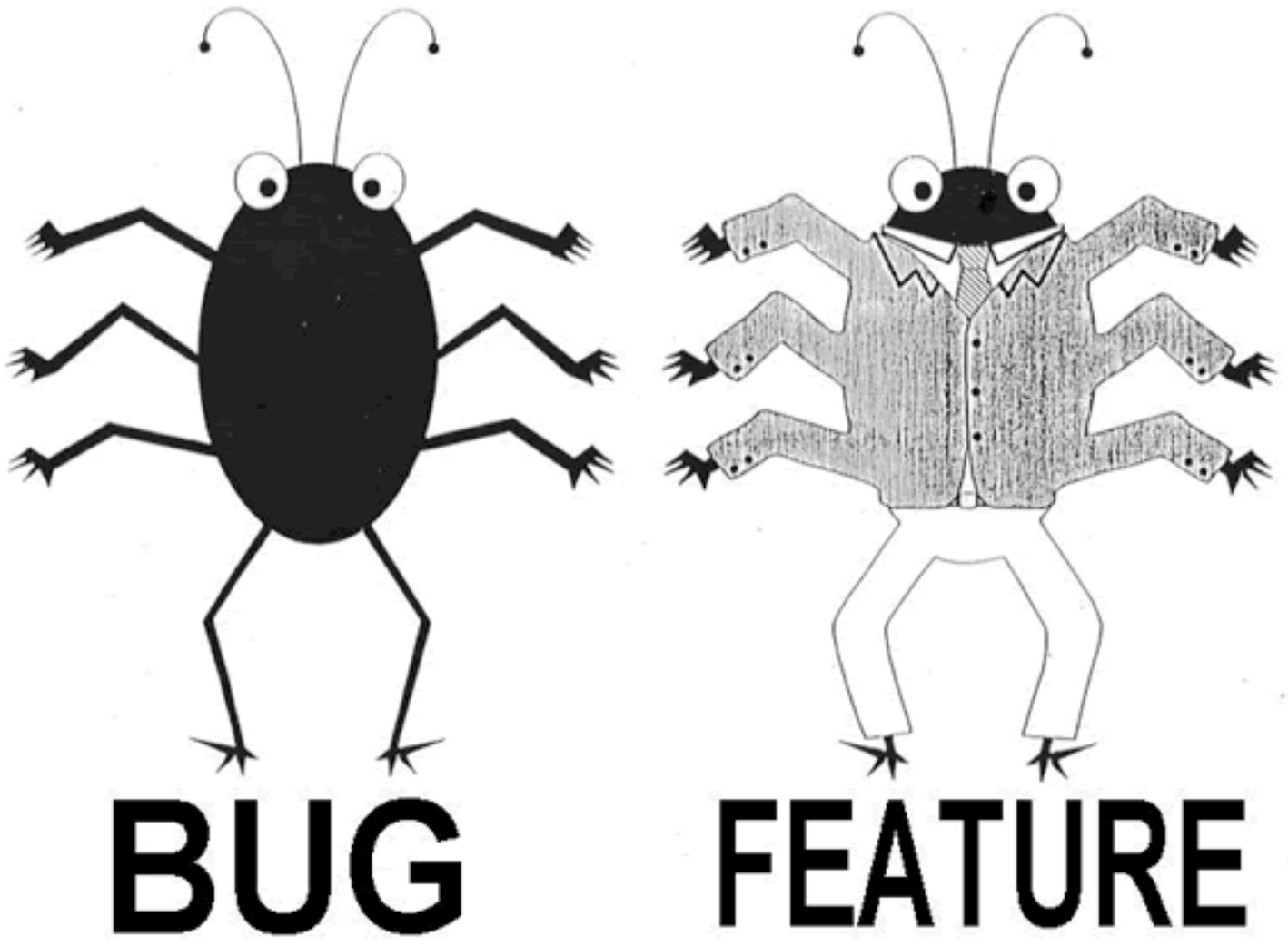
- After strcpy:



Problem:
no length checking in strcpy()

Other Examples

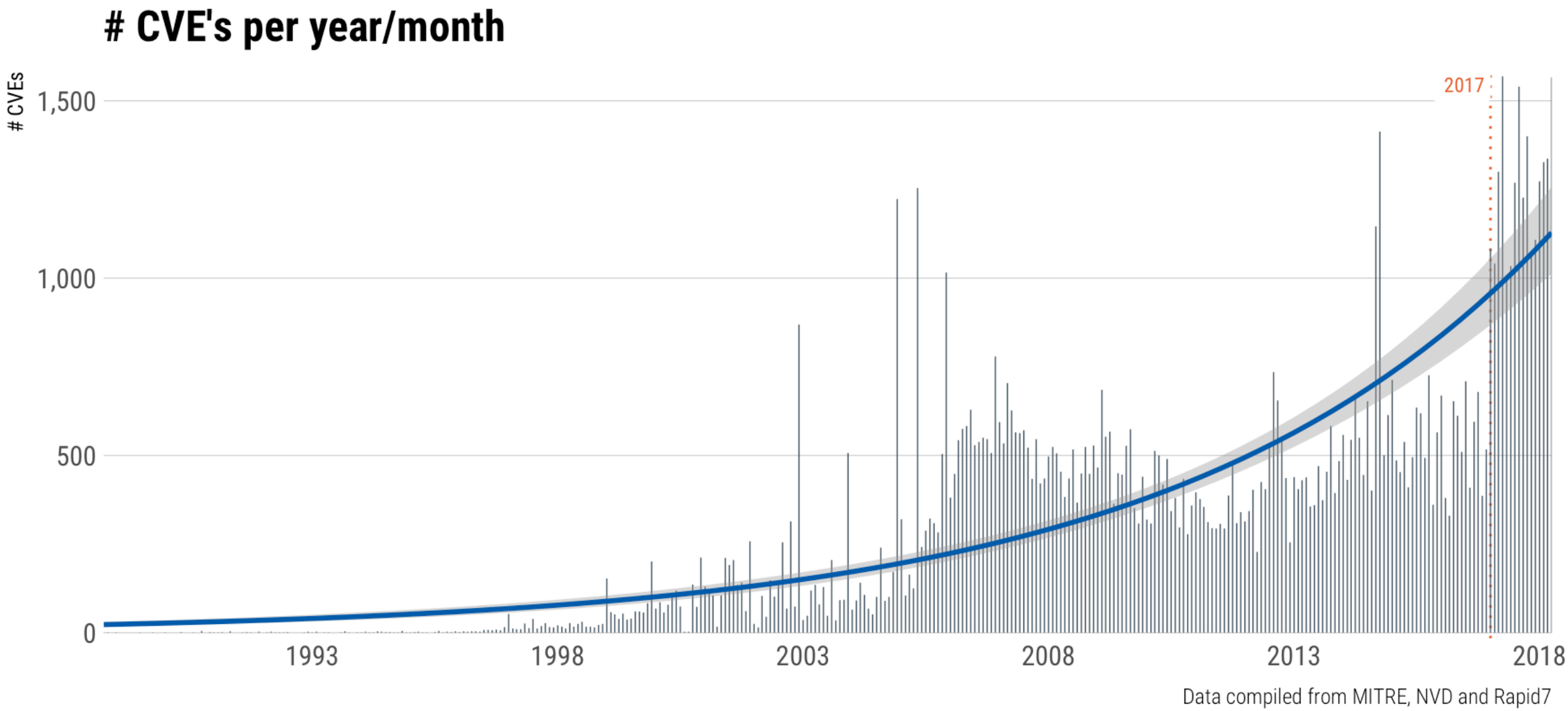
- Out of bound memory access
- Temporal Memory Safety Violations
- Integer overflow
- …..


BUG
FEATURE

Vulnerabilities ….

HeartBleed	CVE-2014-0160	Affected over 600,000 websites	
Shellshock	CVE-2014-6271	The impact is anywhere from 20 to 50% of global servers	 Shellshock
Dirty COW	CVE-2016-5195	Affects all Linux-based operating systems including Android	 DIRTY COW
VNOM	CVE-2015-3456	Affected all version of XEN and KVM	 VENOM
glib GHOST	CVE-2015-0235	A core component used in most Linux distributions	

CVE Growth


CVE's per year/month
CVEs
1,500
1,000
500
0
2017
1993
1998
2003
2008
2013
2018
Data compiled from MITRE, NVD and Rapid7

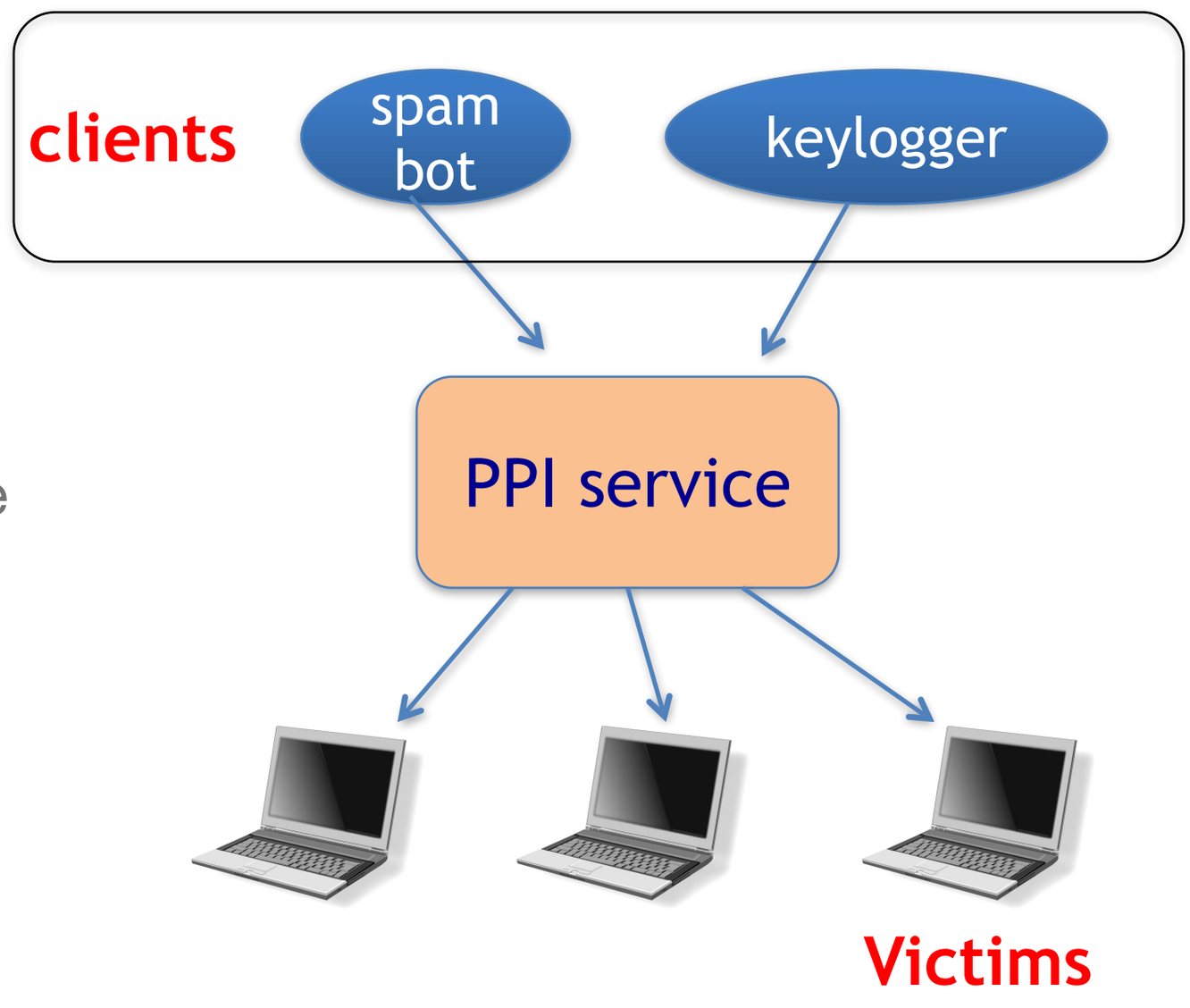
Who cares if there are vulnerabilities???

Marketplace for owned machines

Pay-per-install (PPI) services

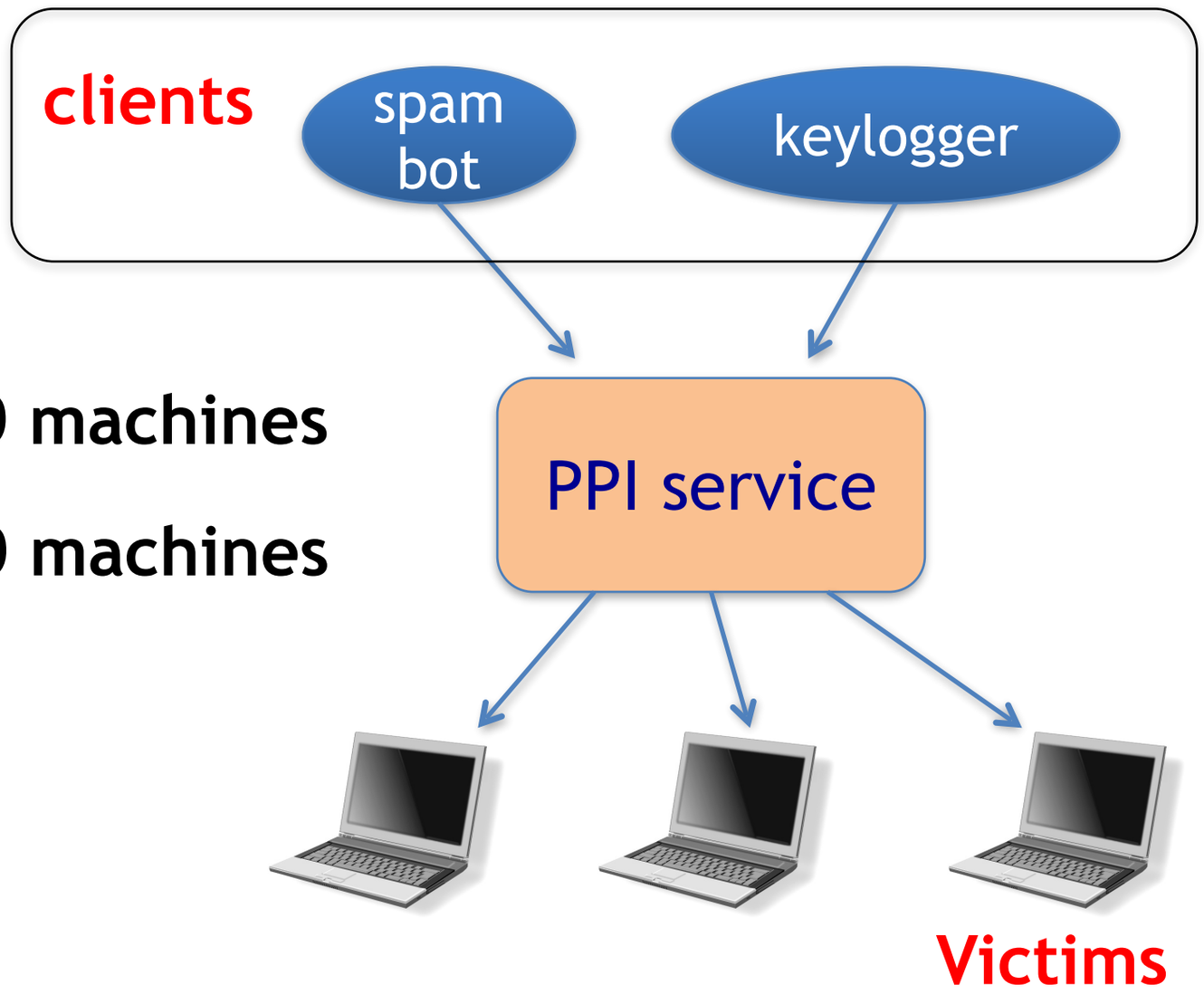
PPI operation:

1. Own victim's machine
2. Download and install client's code
3. Charge client



Source: Cabalerro et al. (www.icir.org/vern/papers/ppi-usesec11.pdf)

Marketplace for owned machines



Cost: **US - 100-180$ / 1000 machines**

Asia - 7-8$ / 1000 machines

Source: Cabalerro et al. (www.icir.org/vern/papers/ppi-usesec11.pdf)

Marketplace for Vulnerabilities

Option 1: bug bounty programs (many)

- Google Vulnerability Reward Program: up to $20K
- Microsoft Bounty Program: up to $100K
- Mozilla Bug Bounty program: $7500
- Pwn2Own competition: $15K

Option 2:

- Zero day initiative (ZDI), iDefense: $2K – $25K

Example: Mozilla

Novel vulnerability and exploit, new form of exploitation or an exceptional vulnerability	High quality bug report with clearly exploitable critical vulnerability$_1$	High quality bug report of a critical or high vulnerability$_2$	Minimum for a high or critical vulnerability$_3$	Medium vulnerability
$10,000+	$7,500	$5,000	$3,000	$500 - $2500

Marketplace for Vulnerabilities

Option 3: black market

ADOBE READER	$5,000–$30,000
MAC OSX	$20,000–$50,000
ANDROID	$30,000–$60,000
FLASH OR JAVA BROWSER PLUG-INS	$40,000–$100,000
MICROSOFT WORD	$50,000–$100,000
WINDOWS	$60,000–$120,000
FIREFOX OR SAFARI	$60,000–$150,000
CHROME OR INTERNET EXPLORER	$80,000–$200,000
IOS	$100,000–$250,000

Source: Andy Greenberg (Forbes, 3/23/2012)

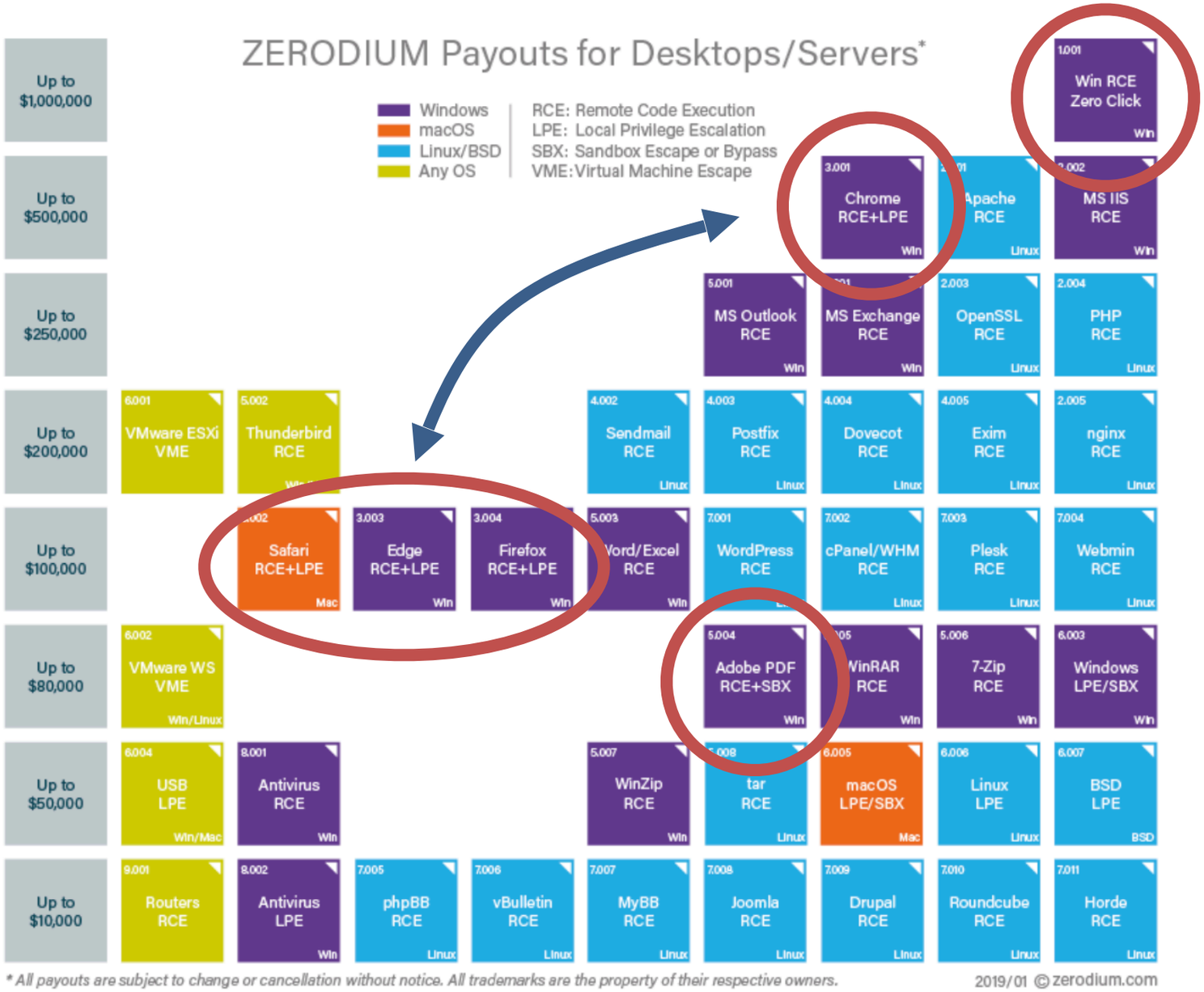
Marketplace for Vulnerabilities

RCE: remote code execution

LPE: local privilege escalation

SBX: sandbox escape

Source: Zerodium payouts



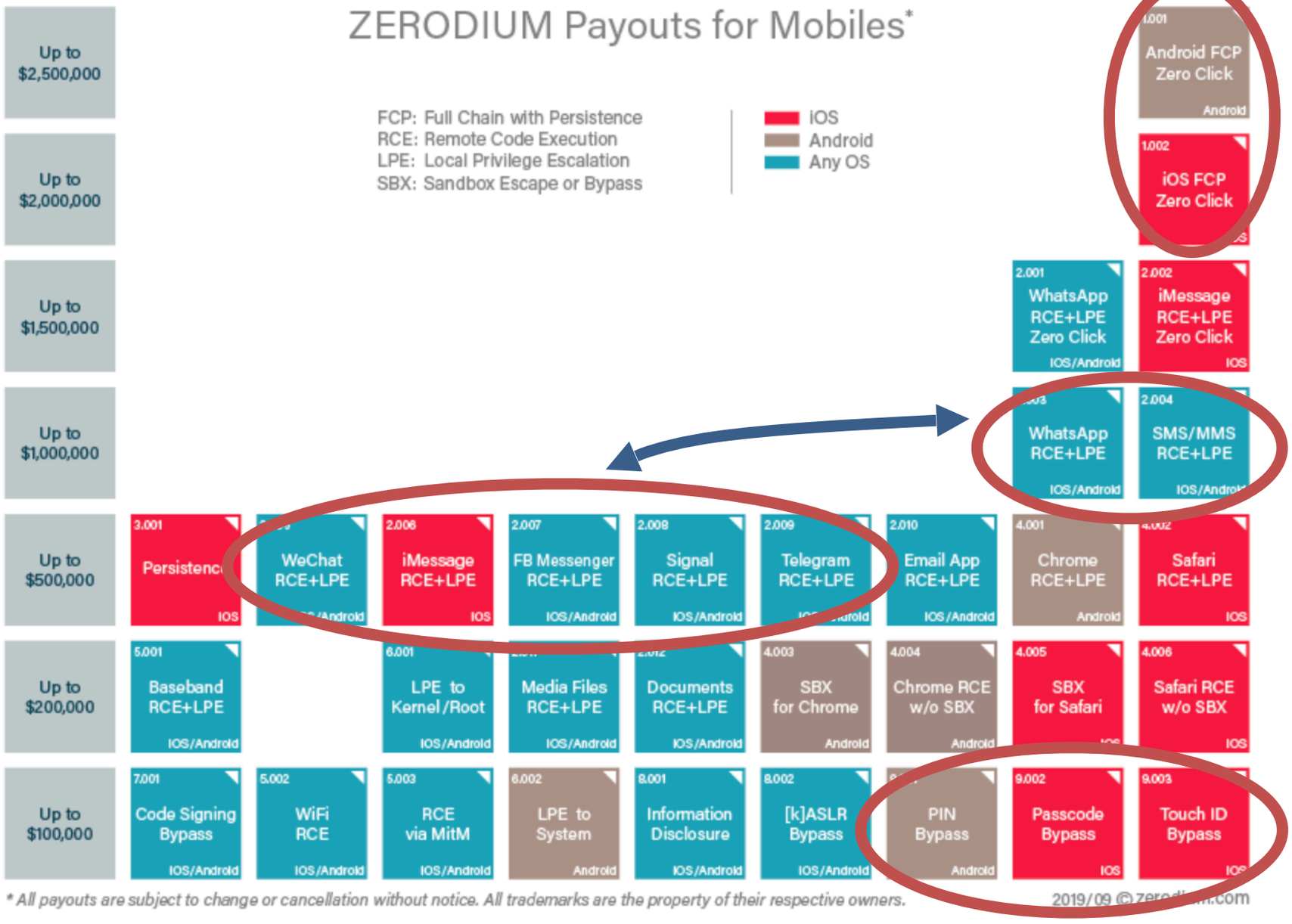
Dan Boneh

Marketplace for Vulnerabilities

RCE: remote code execution

LPE: local privilege escalation

SBX: sandbox escape



Source: Zerodium payouts

Dan Boneh

Ok, Important. How we find them?

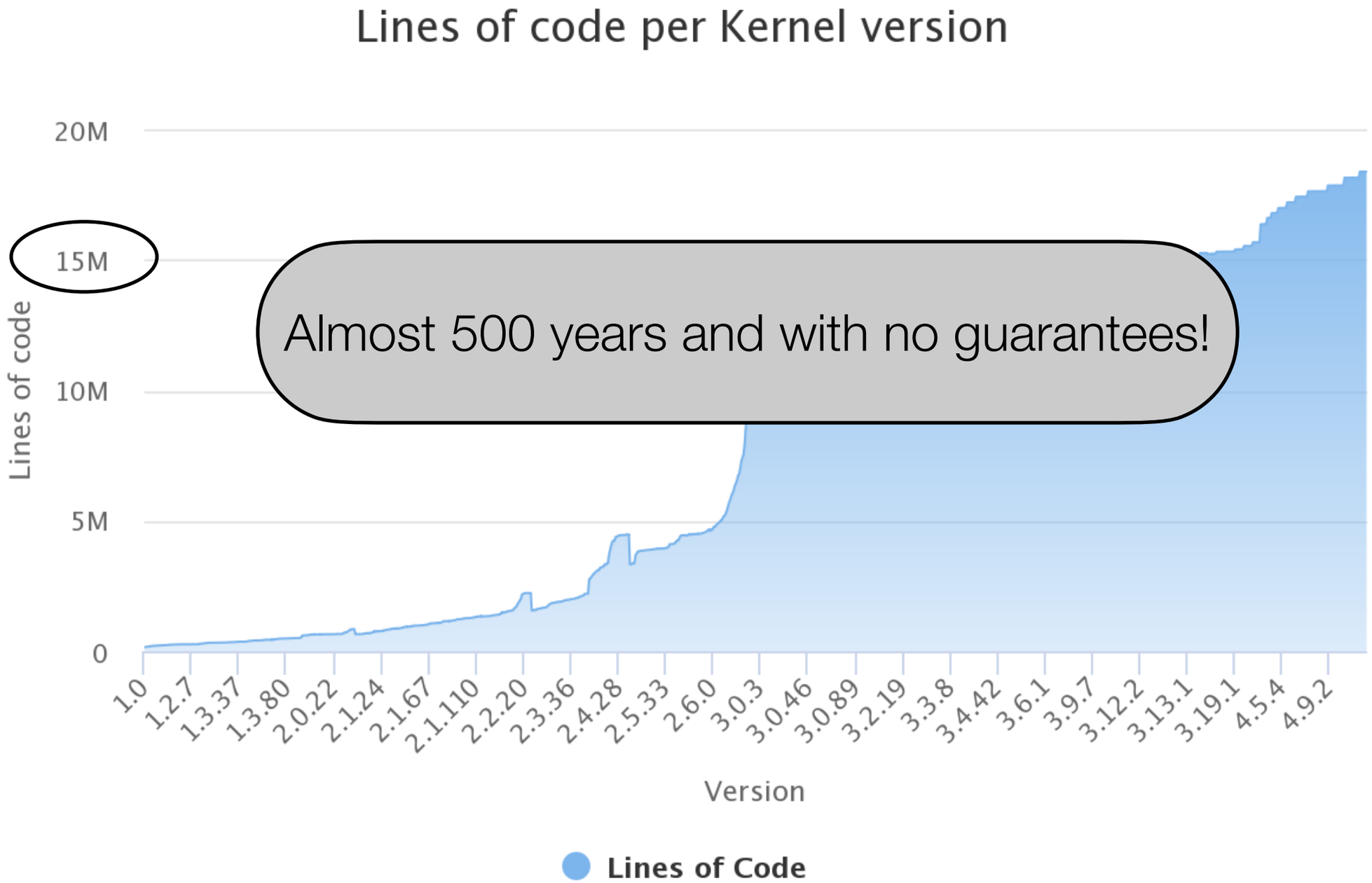
Audit it

- How much does it take to audit all available programs?

Language	files	blank	comment	code
C	53	12066	3945	46676
C++	28	2027	328	7189
C/C++ Header	114	1775	1351	6891

- It took 2 years to audit TrueCrypt (2013-2015)
- German Government + Cryptographers and Security researchers conducted the audit
- Audit finished April 2015
- CVE-2015-7358 and CVE-2015-7359 discovered September 2015 by Google Zero Project!

Too much code !



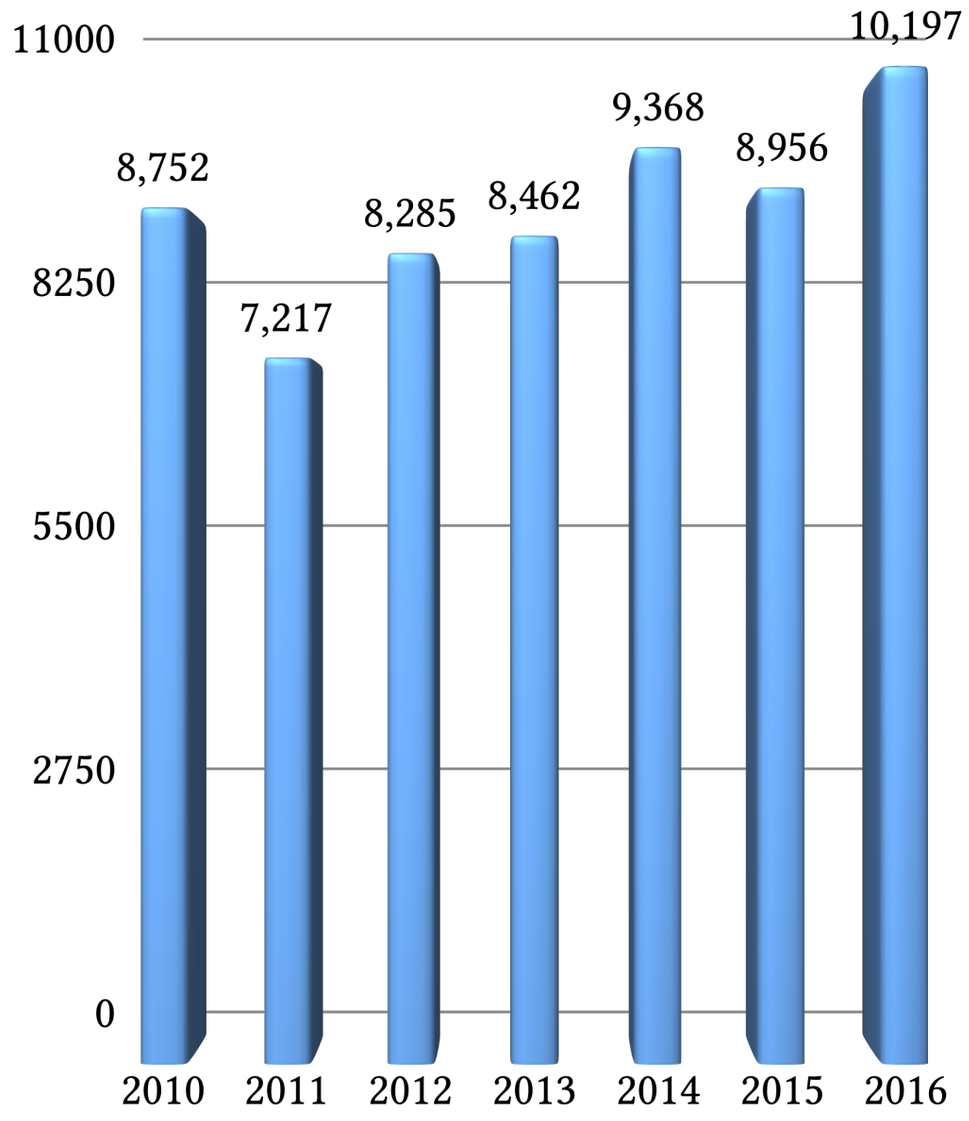
Almost 500 years and with no guarantees!

Too much code !!!

- 111 billion lines of new software code is created every year

- Each bug found by hackers first, will lead to a disaster

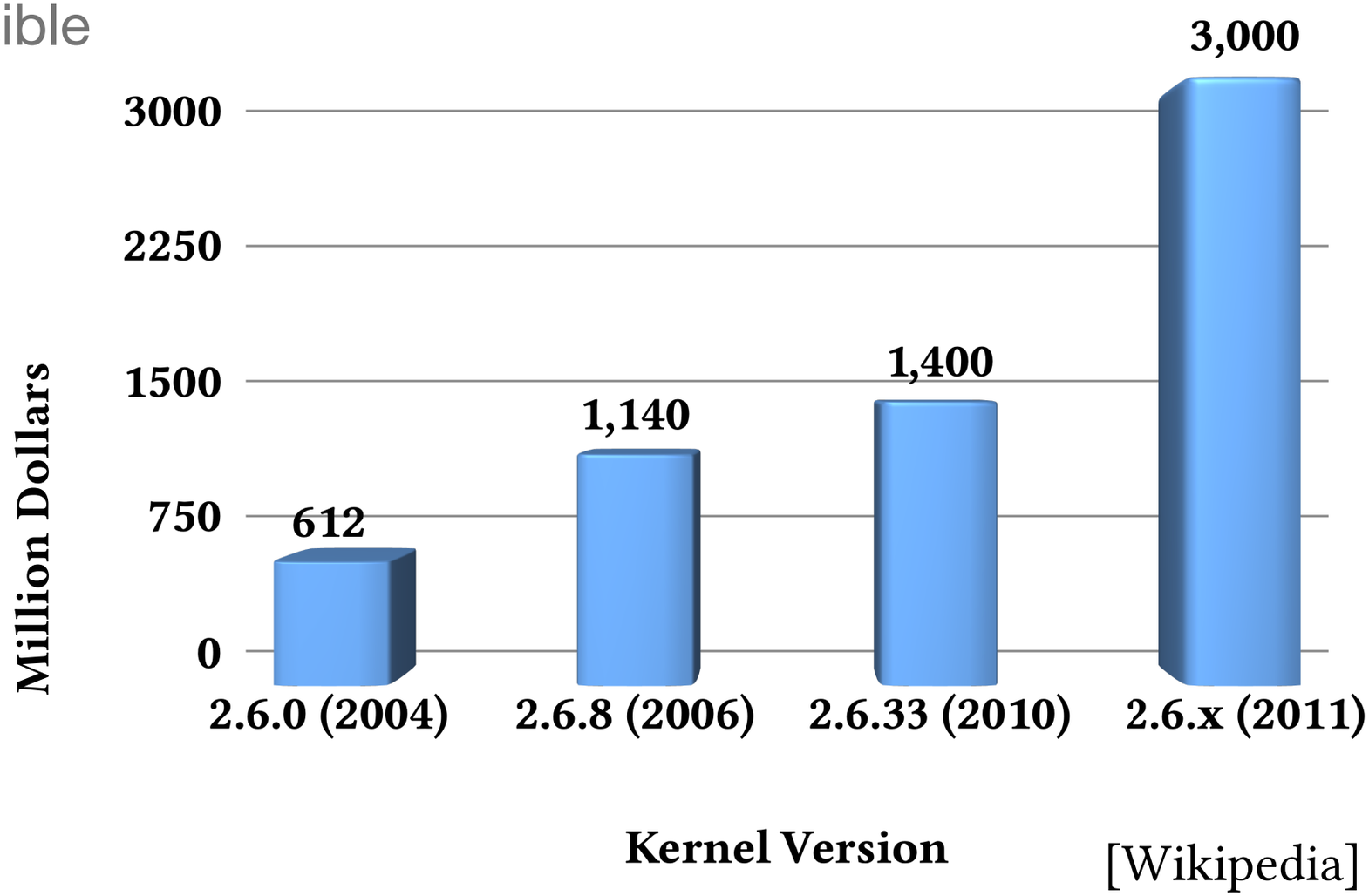
- Hackers are interested in Exploitable bugs!



- **Number of Vulnerabilities per year; IBM Report 2017**

Solutions

- Redevelop Linux Kernel and all other programs
  - Not feasible



[Wikipedia]

DARPA Cyber Grand Challenge

- “Cyber Grand Challenge (CGC) is a contest to build high-performance computers capable of Finding and Fixing Vulnerabilities
- Announced in 2013, and Final Contest held in 2016

- Teams build “Cyber Reasoning Systems” (CRS)
- CRS finds “Proof of Vulnerability” (POV) (automatically exploit)
- CRS fixes vulnerability

Who participated in CGC?

What happens if we don’t find them all?

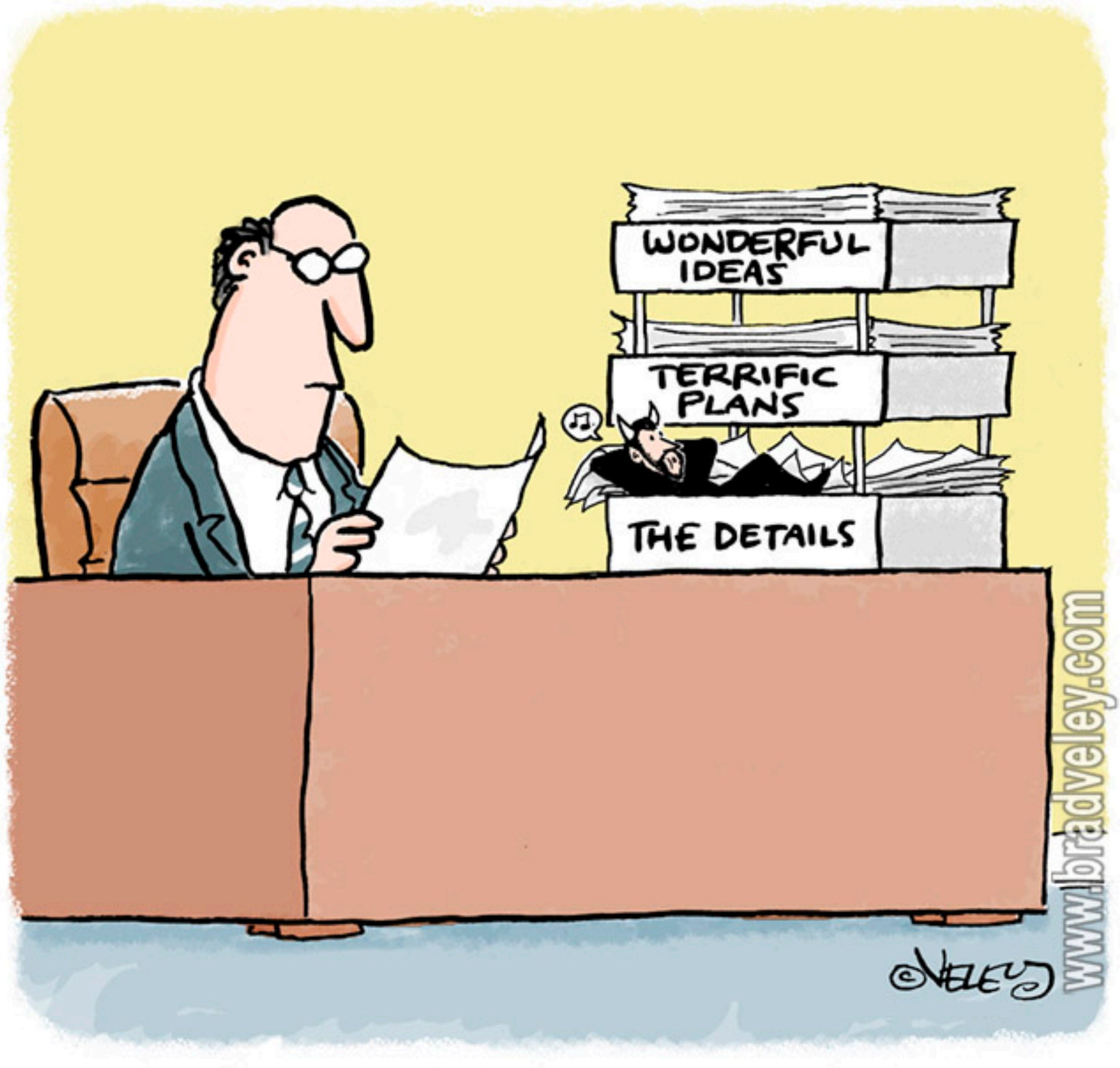
Multiple layers of defense

- How to mitigate the vulnerabilities?
  - run-time protection
- How do we look for vulnerabilities?
  - Program analysis
- How do we refrain from one vulnerabilities causing another one?
  - Better Architectures
- How do we refrain from future vulnerabilities?
  - Better programming languages

Survey

- How much familiar with?
  - Gdb, objectdump, rop
  - CFI, Taint
  - Symbolic Execution, Static Analysis
  - NLP Concepts: one hot, word2vec , skipgram, etc.
  - DL Concepts: LSTM, DNN, GNN, etc.

A quick review of some of the very basics!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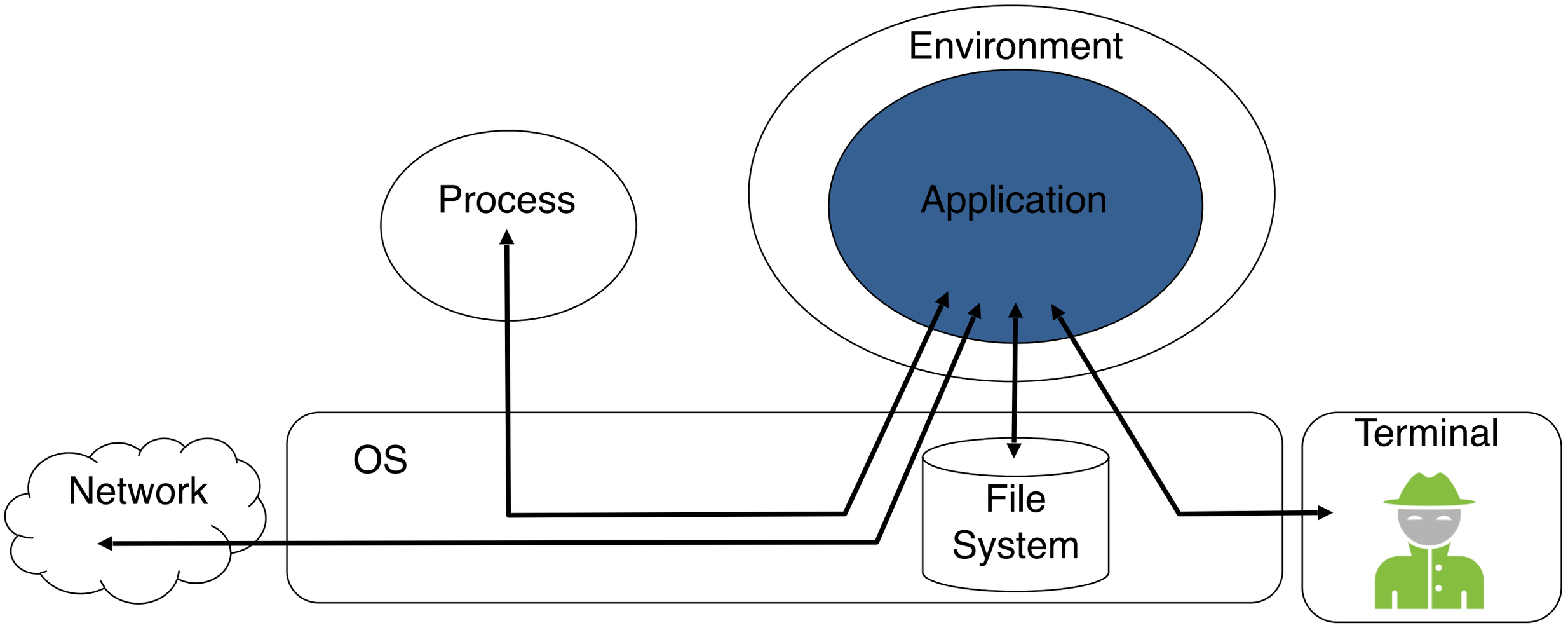
Application Model



Stages in which there could be a vulnerability

- Design vulnerabilities
  - Flaws in the overall logic of the application
    - Lack of authentication and/or authorization checks
    - Erroneous trust assumptions
- Implementation vulnerabilities
  - Application is not able to correctly handle unexpected events
    - Unexpected input, Unexpected errors/exceptions
    - Unexpected interleaving of events
- Deployment vulnerabilities
  - Incorrect/faulty deployment/configuration of the application
    - Installed with more privileges than the ones it should have
    - Installed on a system that has a faulty security policy and/or mechanism (e.g., a file that should be read-only is actually writeable)

The Life of an Application

- Author writes code in high-level language
- The application is translated in some executable form and saved to a file
  - Interpretation vs. compilation
- The application is loaded in memory
- The application is executed
- The application terminates

Interpretation

- The program is passed to an interpreter
  - The program might be translated into an intermediate representation
    - Python byte-code
- Each instruction is parsed and executed
- In most interpreted languages it is possible to generate and execute code dynamically
  - Bash: eval <string>
  - Python: eval(<string>)
  - JavaScript: eval(<string>)
  - …

Compilation

- The preprocessor expands the code to include definitions, expand macros
  - GNU/Linux: The C preprocessor is cpp
- The compiler turns the code into architecture-specific assembly
  - GNU/Linux: The C compiler is gcc
    - gcc -S prog.c will generate the assembly
    - Use gcc's -m32 option to generate 32-bit assembly

Compilation

- The assembler turns the assembly into a binary object
  - GNU/Linux: The assembler is as
  - A binary object contains the binary code and additional metadata
    - Relocation information about things that need to be fixed once the code and the data are loaded into memory
    - Information about the symbols defined by the object file and the symbols that are imported from different objects
    - Debugging information

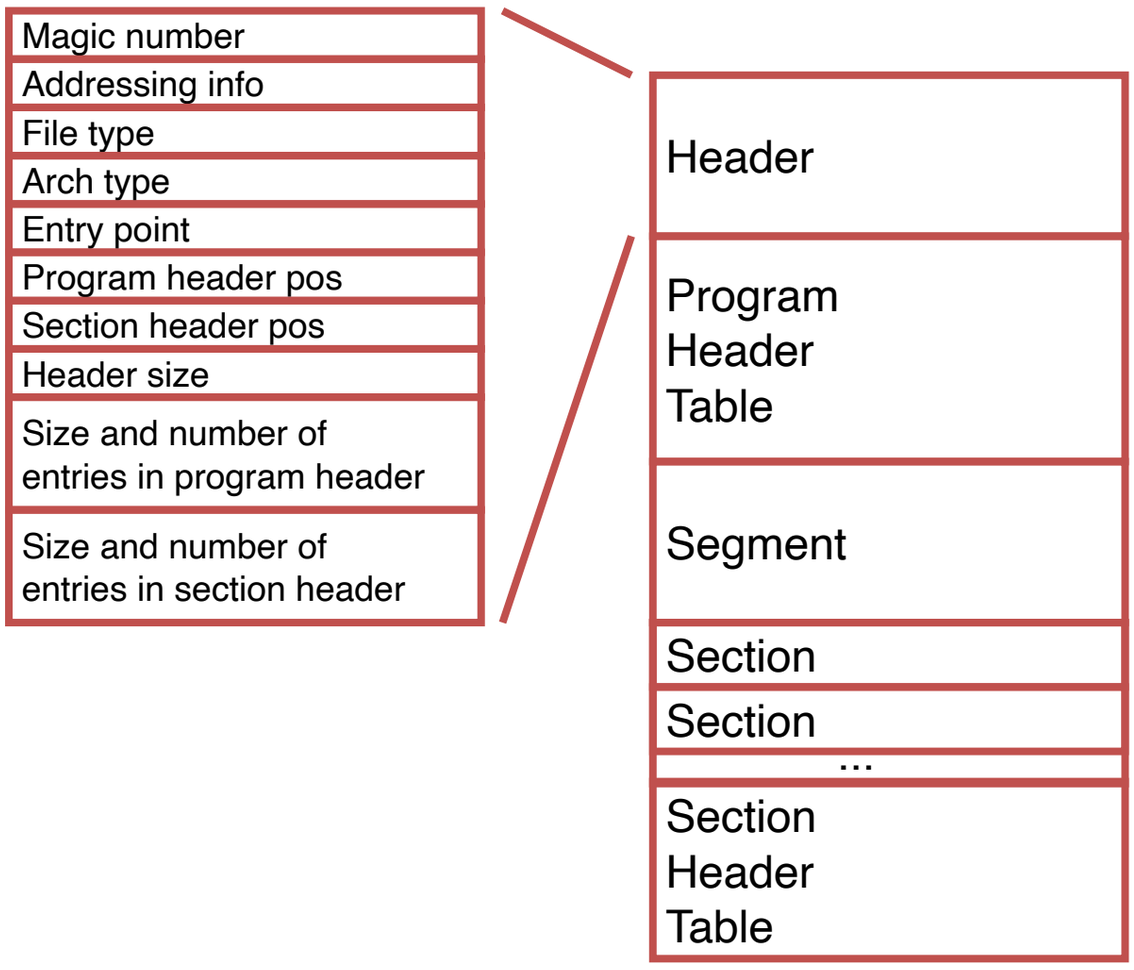
Compilation

- The linker combines the binary object with libraries, resolving references that the code has to external objects (e.g., functions) and creates the final executable
  - GNU/Linux: The linker is ld
  - Static linking is performed at compile-time
  - Dynamic linking is performed at run-time
- Most common executable formats:
  - GNU/Linux: ELF
  - Windows: PE

The ELF File Format

- The Executable and Linkable Format (ELF) is one of the most widely-used binary object formats
- ELF is architecture-independent
- ELF files are of four types:
  - Relocatable: need to be fixed by the linker before being executed
  - Executable: ready for execution (all symbols have been resolved with the exception of those related to shared libs)
  - Shared: shared libraries with the appropriate linking information
  - Core: core dumps created when a program terminated with a fault
- Tools: readelf, file

The ELF File Format



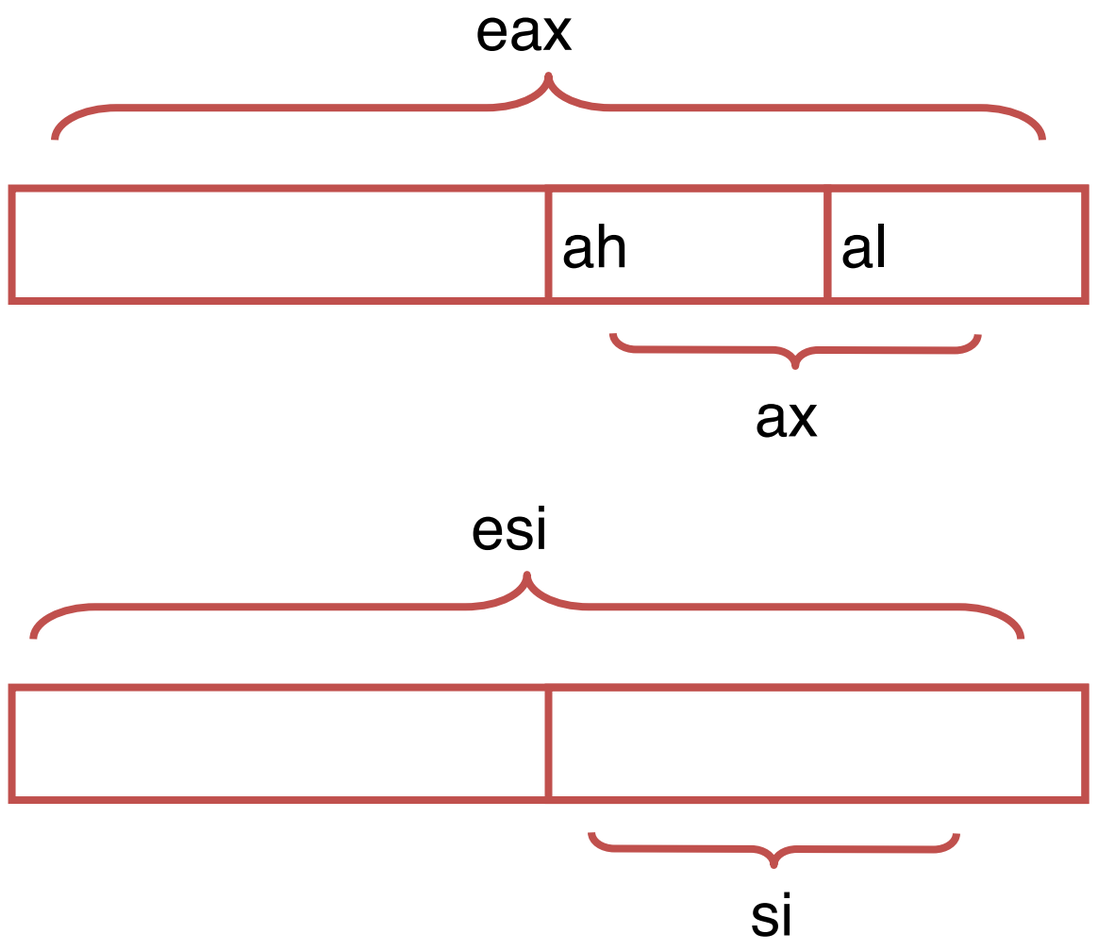
- A program is seen as a collection of segments by the loader and as a collection of sections by the compiler/linker
- A segment is usually made of several sections
- The segment structure is defined in the Program Header Table
- The section structure is defined in the Section Header Table

The PE File Format

- The PE file was introduced to allow MS-DOS programs to be larger than 64K (limit of .COM format)
- Also known as the “EXE” format
- The header contains a number of relocation entries that are used at loading time to “fix” the addresses (this procedure is called rebasing)
  - Programs are written as if they were always loaded at address 0
  - The program is actually loaded in different points in memory

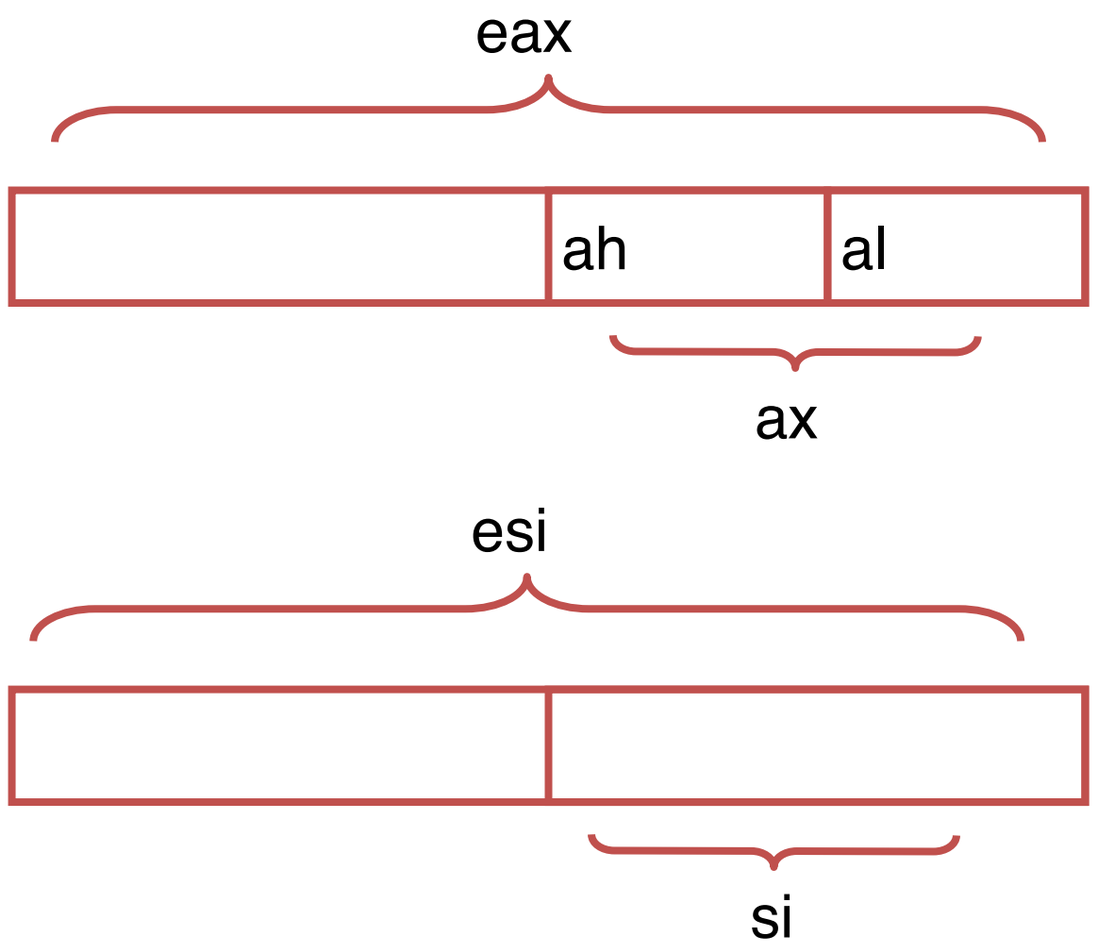
x86 Registers

- Registers represent the local variables of the processor
- There are four 32-bit general purpose registers
  - eax/ax, ebx/bx, ecx/cx, edx/cx
- Convention
  - Accumulator: eax
  - Pointer to data: ebx
  - Loop counter: ecx
  - I/O operations: edx



x86 Registers

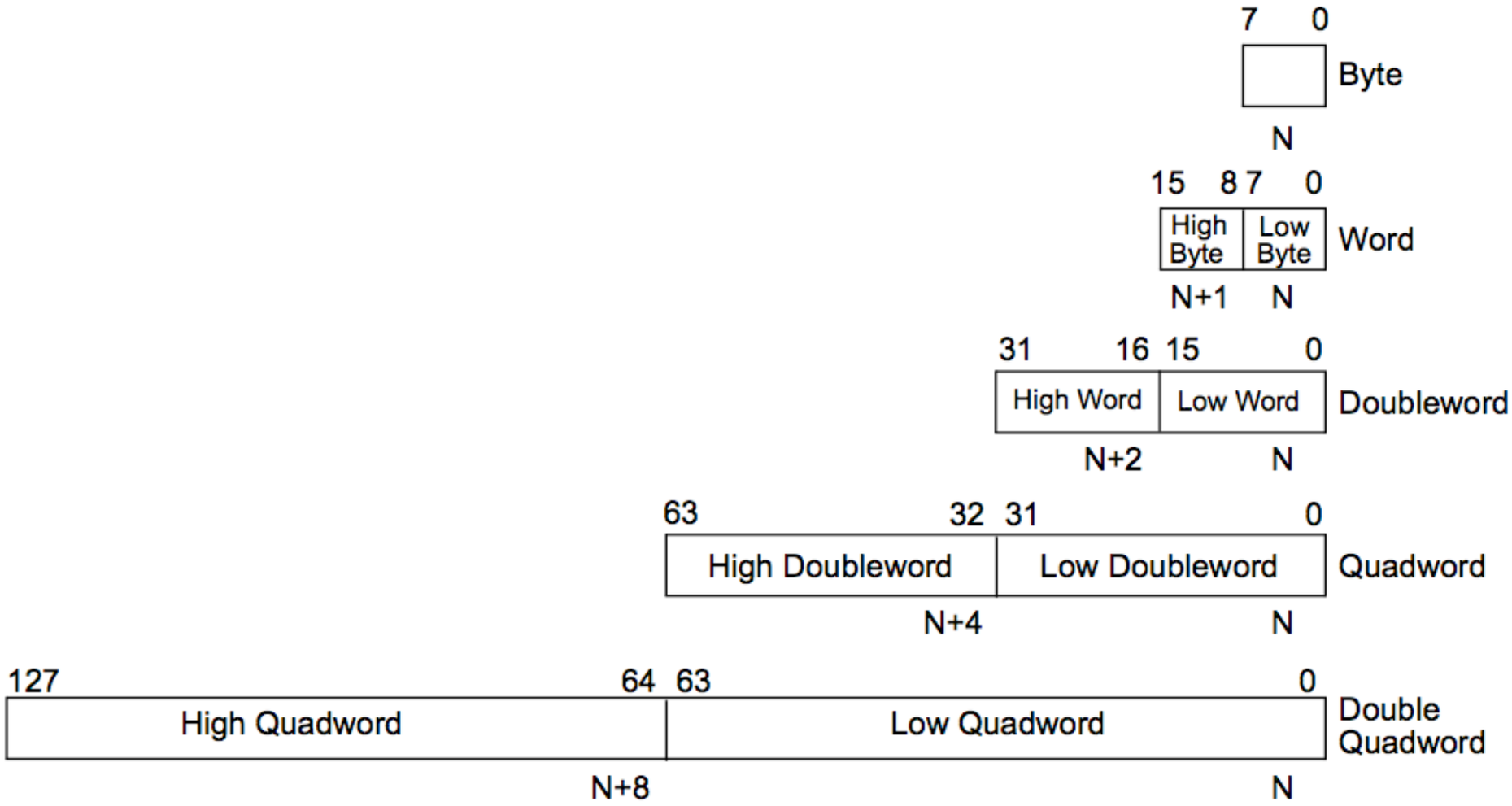
- Two registers are used for high-speed memory transfer operations
  - esi/si (source), edi/di (destination)
- There are several 32-bit special purpose registers
  - esp/sp: the stack pointer
  - ebp/bp: the frame pointer



x86 Registers

- Segment registers: cs, ds, ss, es, fs, gs
  - Used to select segments (e.g., code, data, stack)
- Program status and control: eflags
- The instruction pointer: eip
  - Points to the next instruction to be executed
  - Cannot be read or set explicitly
  - It is modified by jump and call/return instructions
  - Can be read by executing a call and checking the value pushed on the stack
- Floating point units and mmx/xmm registers

Data Sizes


7 0
Byte
N
15 8 7 0
High Byte
Low Byte
Word
N+1 N
31 16 15 0
High Word
Low Word
Doubleword
N+2 N
63 32 31 0
High Doubleword
Low Doubleword
Quadword
N+4 N
127 64 63 0
High Quadword
Low Quadword
Double Quadword
N+8 N

x86 Assembly Language

- (Slightly) higher-level language than machine language
- Program is made of:
  - directives: commands for the assembler
  - .data identifies a section with variables
  - instructions: actual operations
    - jmp 0x08048f3f
- Two possible syntaxes, with different ordering of the operands!
  - AT&T syntax (objdump, GNU Assembler)
    - mnemonic source, destination
  - DOS/Intel syntax (Microsoft Assembler, Nasm, IDA Pro)
    - mnemonic destination, source
  - In gdb can be set using: set disassembly-flavor intel/att

Data Definition

- Constants
  - Hexadecimal numbers start with `0x`
- Data objects are defined in a data segment using the syntax
  - `label  type  data1, data2, ...`
- Types can be
  - DB: Byte
  - DW: Word (16 bits)
  - DD: Double word (32 bits)
  - DQ: Quad word (64 bits)
- For example:

```
.data
  myvar     DD  0x12345678, 0x23456789   # Two 32-bit values
  bar       DW  0x1234                   # 16-bit data object
  mystr     DB "foo", 0                  # Null-terminated string
```

Addressing Memory

- Memory access is composed of width, base, index, scale, and displacement
  - Base: starting address of reference
  - Index: offset from base address
  - Scale: Constant multiplier of index
  - Displacement: Constant base
  - Width: (address suffix)
    - size of reference (b: byte, s: short, w: word, l: long, q: quad)
  - Address = base + index*scale + displacement
    - AT&T Syntax —> displacement(base, index, scale)
  - Example:
    - movl -0x20(%eax, %ecx, 4), %edx

Addressing Memory

- movl -8(%ebp), %eax
  - copies the contents of the memory pointed by ebp - 8 into eax
- movl (%eax), %eax
  - copies the contents of the memory pointed by eax to eax
- movl %eax, (%edx, %ecx, 2)
  - moves the contents of eax into the memory at address edx + ecx * 2
- movl $0x804a0e4, %ebx
  - copies the value 0x804a0e4 into ebx
- movl (0x804a0e4), %eax
  - copies the content of memory at address 0x804a0e4 into eax

Instruction Classes

- Data transfer
  - mov, xchg, push, pop
- Binary arithmetic
  - add, sub, imul, mul, idiv, div, inc, dec
- Logical
  - and, or, xor, not

Instruction Classes

- Control transfer
  - jmp, call, ret, int, iret
  - Values can be compared using the cmp instruction
    - cmp src, dest # subtracts src from dest without saving the result
    - Various eflags bits are set accordingly
      - jne (ZF=0), je (ZF=1), jae (CF=0), jge (SF=OF), …
    - Control transfer can be direct (destination is a constant) or indirect (the destination address is the content of a register)
- Input/output
  - in, out
- Misc
  - nop

Invoking System Calls

- System calls are usually invoked through libraries
- Linux/x86
  - int 0x80
    - eax contains the system call number

X86(32 bit) System Call Table

NR	syscall name	%eax	arg0 (%ebx)	arg1 (%ecx)	arg2 (%edx)
0	restart_syscall	0	-	-	-
1	exit	1	int error_code	-	-
2	fork	2	-	-	-
3	read	3	unsigned int fd	char *buf	size_t count
4	write	4	unsigned int fd	const char *buf	size_t count
5	open	5	const char *filename	int flags	umode_t mode
6	close	6	unsigned int fd	-	-
7	waitpid	7	pid_t pid	int *stat_addr	int options
8	creat	8	const char *pathname	umode_t mode	-
9	link	9	const char *oldname	const char *newname	-
10	unlink	A	const char *pathname	-	-
11	execve	B	const char *filename	const char *const *argv	const char *const *envp

Hello World!

```
.data
hw:
        .string "hello world\n"
.text
.globl main
main:
    movl    $4,%eax
    movl    $1,%ebx
    movl    $hw,%ecx
    movl    $12,%edx
    int     $0x80
    movl    $1,%eax
    movl    $0,%ebx
     int    $0x80
```

```
int main()
{
  printf("hello world!");
    return 0;
}
Return 0;

syscall(4, 1, “hello world!\n", 12);
syscall(1, 0);
```

Program Loading and Execution

- When a program is invoked, the operating system creates a process to execute the program
- The ELF file is parsed and parts are copied into memory
  - In Linux /proc/<pid>/maps shows the memory layout of a process
- Relocation of objects and reference resolution is performed
- The instruction pointer is set to the location specified as the start address
- Execution begins

Acknowledgments/References (1/2)

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