Low-Level Software Security:

Attacks and Defenses;
Control Flow Integrity

System Security Seminar

Presenter: Cătălin Hrițcu

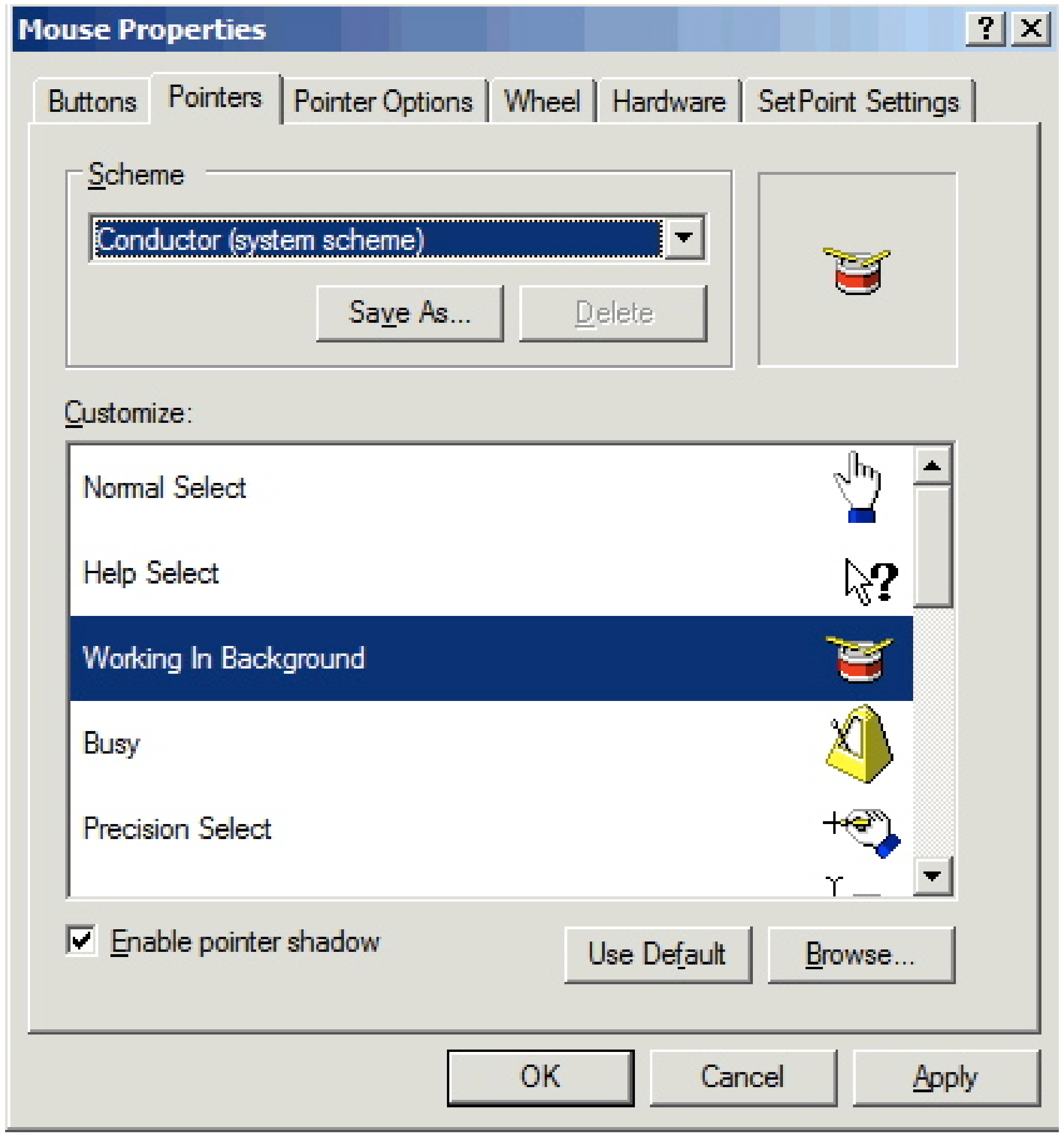
References

- ***Low-Level Software Security: Attacks and Defenses***, by Úlfar Erlingsson (FOSAD 2007)
- ***Control-flow integrity***, by Martín Abadi, Mihai Budiu, Úlfar Erlingsson, Jay Ligatti (CCS 2005)

- Many thanks to Úlfar Erlingsson from Microsoft Research and Reykjavk University
  - Many of the slides are from his FOSAD 2007 talk
  - Opinions and mistakes are still mine

A real-world attack

- Microsoft Windows animated cursor buffer overflow vulnerability (March 30, 2007)



Rated as “Extremely critical”

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Microsoft Windows Animated Cursor Buffer Overflow Vulnerability

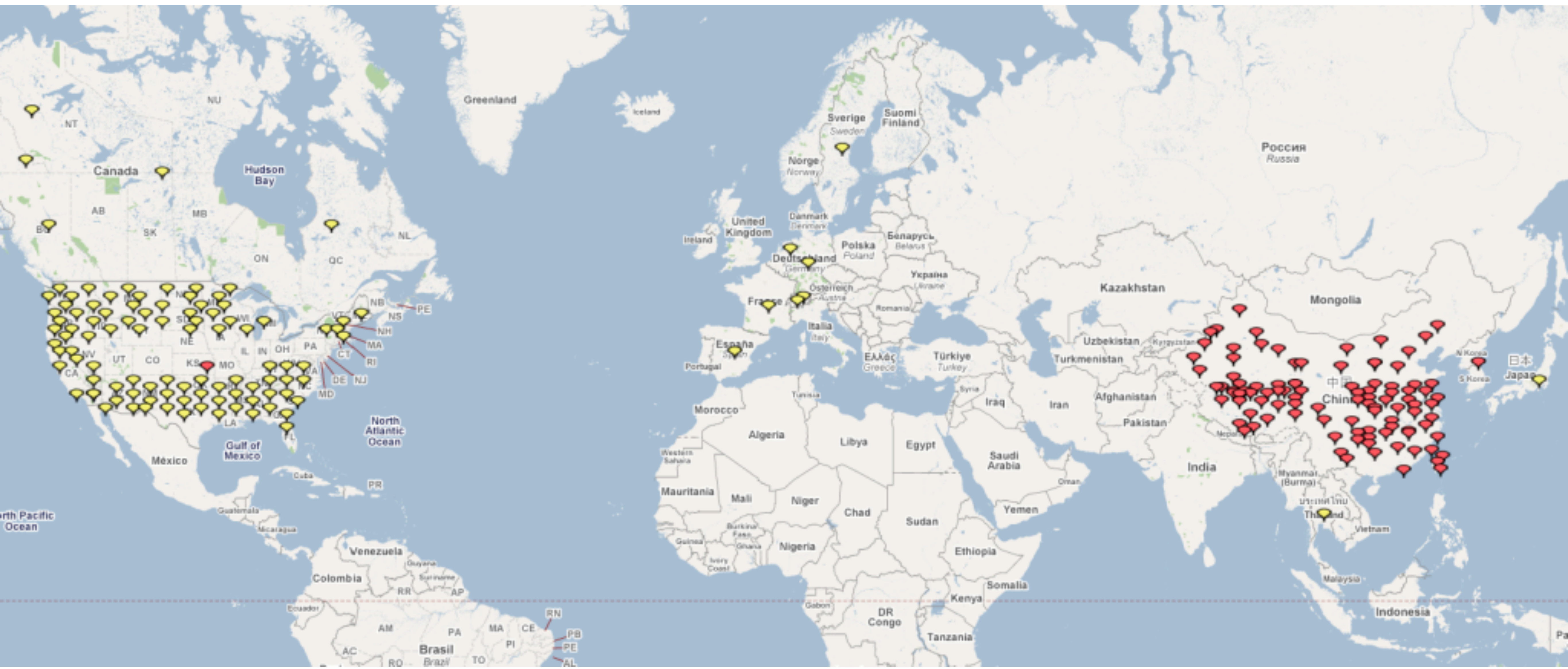
Secunia Advisory:	SA24659
Release Date:	2007-03-30
Last Update:	2007-05-09
Critical:	Extremely critical
Impact:	System access
Where:	From remote
Solution Status:	Vendor Patch
OS:	Microsoft Windows 2000 Advanced Server Microsoft Windows 2000 Datacenter Server Microsoft Windows 2000 Professional Microsoft Windows 2000 Server Microsoft Windows Server 2003 Datacenter Edition Microsoft Windows Server 2003 Enterprise Edition Microsoft Windows Server 2003 Standard Edition Microsoft Windows Server 2003 Web Edition Microsoft Windows Storage Server 2003 Microsoft Windows Vista Microsoft Windows XP Home Edition Microsoft Windows XP Professional

Exploited immediately in the wild

- Attack vectors:
  - HTML email / spam

From: Nude BritineySpeers.com [mailto:[redacted]]
Sent: Sunday, April 01, 2007 3:20 PM
To: [redacted]
Subject: Hot pictures of Britiney Speers
Importance: High

  - Browsers vulnerable - 2000+ different sites hosting exploit



Microsoft reacts fast

- Releases "out of band" patch (April 3)

Severity Ratings and Vulnerability Identifiers:

Vulnerability Identifiers	**Impact of Vulnerability**	**Windows 2000 Service Pack 4**	**Windows XP Service Pack 2**	**Windows Server 2003, Windows Server 2003 Service Pack 1, and Windows Server 2003 Service Pack 2**	**Windows Vista**
GDI Local Elevation of Privilege Vulnerability - CVE-2006-5758	Elevation of Privilege	Important	Important	Not Affected	Not Affected
WMF Denial of Service Vulnerability CVE-2007-1211	Denial of Service	Moderate	Moderate	Moderate	Not Affected
EMF Elevation of Privilege Vulnerability CVE-2007-1212	Elevation of Privilege	Important	Important	Important	Important
GDI Invalid Window Size Elevation of Privilege Vulnerability CVE-2006-5586	Elevation of Privilege	Important	Important	Not Affected	Not Affected
Windows Animated Cursor Remote Code Execution Vulnerability - CVE-2007-0038	Remote Code Execution	Critical	Critical	Critical	Critical
GDI Incorrect Parameter Local Elevation of Privilege Vulnerability - CVE-2007-1215	Elevation of Privilege	Important	Important	Important	Important
Font Rasterizer Vulnerability - CVE-2007-1213	Elevation of Privilege	Important	Not Affected	Not Affected	Not Affected
Aggregate Severity of All Vulnerabilities		**Critical**	**Critical**	**Critical**	**Critical**

- Unpatched systems are still being actively exploited

Low-level attacks

- Buffer overflows ~50% of all reported attacks
  - 1988: Robert Morris's Internet Worm
  - 2000: Code Red, SQL Slammer
  - 2007: Windows .ANI vulnerability

- Possible whenever compiling a high-level language into a low-level one without guaranteeing that the translation preserves the high-level abstractions

The legacy of C

- Millions of lines of security-critical code written in C
- C compilers do not guarantee any property of the translation
- Even if we ignore compilation, C is not type and memory safe
  - This often leads to exploitable vulnerabilities

- Safer low-level languages: Cyclone, CCured, SafeC, …
  - Most of them are safe dialects of C
  - Existing C code can be migrated with some changes

Advertisement: Deputy

- Promising safe C compiler from Berkeley
  - Designed to work on existing real-world C code
    - Including the Linux kernel itself!
  - Allows for incremental transition
    - Memory layout of data structures preserved
  - Dependent types (additional annotations)
    - Hybrid type checking (static + dynamic)
  - Low performance impact
    - Average of 10-20% for CPU-intensive tests
  - Low annotation burden
    - For the Linux kernel less than 1% of lines annotated
- Might be the subject of a future talk in this seminar

High-level languages

- e.g. Java, C#, Python, O'Caml, Standard ML, …
- Usually promise to be safer and more secure
- Their actual safety still depends on low-level details
  - Compiler and runtime-system need to be correct
  - Static checking is not enough
    - Most high-level properties need to be enforced at run-time
      - Safety vs. performance tradeoff
- Rewriting legacy code in a new language is in most cases out of the question
  - Even if the target language would be perfectly secure
  - And the run-time overhead negligible

Mitigation techniques

- The main subject of this talk
- Limited language-based defenses that
  - Work on legacy code
  - Are fully automatic
  - Operate at the lowest level (machine-code)
  - Involve no source-code changes (at most re-compilation)
  - Typically, runtime checks to guarantee high-level properties
  - Unobtrusive: close to **zero overhead** and zero false positives
  - Only prevent certain vulnerabilities / attacks
    - Often unclear what vulnerabilities are covered

Mitigations are a compromise

- Mitigations are limited, correct software is better
  - Wouldn't need any defenses if software was "correct"…
- So why not just fix all software?
  - Fixing software is difficult, costly, and error-prone
  - It is hard even to specify what "correct" should mean
  - Needs source, build environments, etc., and may interact badly with testing, debugging, deployment, and servicing
- Mitigations are not the optimal solution, but …
  - They can rule out many practical attacks
  - Some of the ones we will see are deployed in practice (e.g. Windows XP SP2 and Vista)

Outline

- A simple buffer overflow example
- Two simple mitigation techniques
  - Stack canaries and cookies
  - Preventing data execution (NXD)
- A more complex jump-to-libc attack
- A more powerful mitigation technique
  - Control-flow integrity

A concrete stack overflow example

```
int is_file_foobar( char* one, char* two )
{
    // must have strlen(one) + strlen(two) < MAX_LEN
    char tmp[MAX_LEN];
    strcpy( tmp, one );
    strcat( tmp, two );
    return strcmp( tmp, "file://foobar" );
}
```

- Attack overflows a (fixed-size) array on the stack
- The function return address points to the attacker's code
- The best known low-level attack
  - Used by the Internet Worm in 1988 and commonplace since

A concrete stack overflow example

address	content	
0x0012ff5c	0x00353037	; argument two pointer
0x0012ff58	0x0035302f	; argument one pointer
0x0012ff54	0x00401263	; return address
0x0012ff50	0x0012ff7c	; saved base pointer
0x0012ff4c	0x00000072	; tmp continues 'r' '\0' '\0' '\0'
0x0012ff48	0x61626f6f	; tmp continues 'o' 'o' 'b' 'a'
0x0012ff44	0x662f2f3a	; tmp continues ':' '/' '/' 'f'
0x0012ff40	0x656c6966	; tmp array: 'f' 'i' 'l' 'e'

- The above stack snapshot is normal w/o overflow
- The arguments here are “file://” and “foobar”

A concrete stack overflow example

- A stack snapshot with a benign overflow

address	content						
0x0012ff5c	0x00353037	; argument two pointer					
0x0012ff58	0x0035302f	; argument one pointer					
0x0012ff54	0x00666473	; return address	's'	'd'	'f'	'\0'	
0x0012ff50	0x61666473	; saved base pointer	's'	'd'	'f'	'a'	
0x0012ff4c	0x61666473	; tmp continues	's'	'd'	'f'	'a'	
0x0012ff48	0x61666473	; tmp continues	's'	'd'	'f'	'a'	
0x0012ff44	0x612f2f3a	; tmp continues	':'	'/'	'/'	'a'	
0x0012ff40	0x656c6966	; tmp array:	'f'	'i'	'l'	'e'	

- In the above, the stack has been corrupted
- The second (attacker-chosen) arg is "asdfasdfasdfasdf"
- Of course, an attacker might not corrupt in this way…

A concrete stack overflow example

- Now, a stack snapshot with a malicious overflow:

```
 address     content
0x0012ff5c  0x00353037  ; argument two pointer
0x0012ff58  0x0035302f  ; argument one pointer
0x0012ff54  0x0012ff48  ; return address: address of attack payload
0x0012ff50  0xXXXXXXXX  ; irrelevant
0x0012ff4c  0xXXXXXXXX  ; irrelevant
0x0012ff48  0xfeeb2ecd  ; attack payload
0x0012ff44  0xXX2f2f3a  ; tmp continues      ':' '/' '/' ...
0x0012ff40  0x656c6966  ; tmp array:          'f' 'i' 'l' 'e'
```

- In the above, the stack has been corrupted maliciously
- The args are "file://" and particular attacker-chosen data
- XX can be any non-zero byte value

Stack canaries

- Very simple defense
  - Assume a contiguous buffer overflow is used by attackers
  - And that the overflow is based on zero-terminated strings
  - Put canary with “terminator” values below the return address

address	content	
0x0012ff5c	0x00353037	; argument two pointer
0x0012ff58	0x0035302f	; argument one pointer
0x0012ff54	0x00401263	; return address
0x0012ff50	0x0012ff7c	; saved base pointer
0x0012ff4c	0x00000000	; *all-zero canary*
0x0012ff48	0x00000072	; tmp continues 'r' '\0' '\0' '\0'
0x0012ff44	0x61626f6f	; tmp continues 'o' 'o' 'b' 'a'
0x0012ff40	0x662f2f3a	; tmp continues ':' '/' '/' 'f'
0x0012ff3c	0x656c6966	; tmp array: 'f' 'i' 'l' 'e'

- Check canary integrity before using return address!

Stack cookies

- Can also use random, secret values: **cookies**
  - Defends against non-null-terminated overflows (e.g. via memcpy)

address	content	
0x0012ff5c	0x00353037	; argument two pointer
0x0012ff58	0x0035302f	; argument one pointer
0x0012ff54	0x00401263	; return address
0x0012ff50	0x0012ff7c	; saved base pointer
0x0012ff4c	**0xF00DFEED**	**; a secret, random cookie value**
0x0012ff48	0x00000072	; tmp continues 'r' '\0' '\0' '\0'
0x0012ff44	0x61626f6f	; tmp continues 'o' 'o' 'b' 'a'
0x0012ff40	0x662f2f3a	; tmp continues ':' '/' '/' 'f'
0x0012ff3c	0x656c6966	; tmp array: 'f' 'i' 'l' 'e'

- Check cookie integrity before using return address!
- Implemented in Windows (/GS compiler flag)

Stack canaries and cookies

- Stack canaries and stack cookies have very little cost
  - Only needed on functions with local arrays
  - Even so, not always applied: heuristics determine when
  - (Not a good idea, as shown by recent ANI attack on Vista)
- Widely implemented: /GS, StackGuard, ProPolice, etc.
  - Implementations typically combine with other defenses
- Main limitations:
  - Only protects against contiguous stack-based overflows
  - No protection if attack happens before function returns
  - For example, must protect function-pointer arguments
  - Do not prevent heap-based buffer overflows

Preventing data execution

- Simply prevent the execution of data as code
- This prevents both stack and heap-based attacks
- There is hardware support for this (NX bit on x86)
  - Can be done with pretty much zero overhead
  - But it breaks a lot of software:
    - Most Win32 GUI apps, CLR (and JITs)
- Can also be done in software (SMAC)
- Limitations:
  - Attackers don't always have to execute data as code
    - They can just corrupt data: data-only attacks
    - They can simply execute existing code: jump-to-libc

`Jump-to-libc`

- Any existing code can be executed by attackers
  - May be an existing function, such as `system()`
  - E.g., a function that is never invoked (dead code)
  - Or code in the middle of a function
- Can even be "opportunistic" code
  - Found within executable pages (e.g. switch tables)
  - Or found within existing instructions (long x86 instructions)
- Typically a step towards running attackers own shellcode

- These are *jump-to-`libc`* or *return-to-`libc`* attacks
- Allow attackers to overcome NX defenses

A new function to be attacked

- Computes the median integer in an input array
- Sorts a copy of the array and return the middle integer

```
int median( int* data, int len, void* cmp )
{
    // must have 0 < len <= MAX_INTS
    int tmp[MAX_INTS];
    memcpy( tmp, data, len*sizeof(int) );  // copy the input integers
    qsort( tmp, len, sizeof(int), cmp );   // sort the local copy
    return tmp[len/2];                     // median is in the middle
}
```

- If `len` is larger than `MAX_INTS` we have a stack overflow

An example bad function pointer

- Many ways to attack the `median` function
- The `cmp` pointer is used before the function returns
  - It can be overwritten by a stack-based overflow
  - And stack canaries or cookies are not a defense
- Using jump-to-`libc`, an attack can also foil NX
- Use existing code to install and jump to attack payload
  - Including marking the shellcode bytes as executable
- Example of *indirect code injection*
- (As opposed to *direct code injection* in previous attacks)

Concrete jump-to-libc attack example

- A normal stack for the `median` function
- Stack snapshot at the point of the call to `memcpy`
- MAX_INTS is 8
- The `tmp` array is empty, or all zero

stack address	normal stack contents	
0x0012ff38	0x004013e0	; cmp argument
0x0012ff34	0x00000001	; len argument
0x0012ff30	0x00353050	; data argument
0x0012ff2c	0x00401528	; return address
0x0012ff28	0x0012ff4c	; saved base pointer
0x0012ff24	0x00000000	; tmp final 4 bytes
0x0012ff20	0x00000000	; tmp continues
0x0012ff1c	0x00000000	; tmp continues
0x0012ff18	0x00000000	; tmp continues
0x0012ff14	0x00000000	; tmp continues
0x0012ff10	0x00000000	; tmp continues
0x0012ff0c	0x00000000	; tmp continues
0x0012ff08	0x00000000	; tmp buffer starts
0x0012ff04	0x00000004	; memcpy length argument
0x0012ff00	0x00353050	; memcpy source argument
0x0012fefc	0x0012ff08	; memcpy destination arg.

Concrete jump-to-libc attack example

- A **benign** stack overflow in the median function
- Not the values that an attacker will choose …

stack address	benign overflow contents	
0x0012ff38	0x1111110d	; cmp argument
0x0012ff34	0x1111110c	; len argument
0x0012ff30	0x1111110b	; data argument
0x0012ff2c	0x1111110a	; return address
0x0012ff28	0x11111109	; saved base pointer
0x0012ff24	0x11111108	; tmp final 4 bytes
0x0012ff20	0x11111107	; tmp continues
0x0012ff1c	0x11111106	; tmp continues
0x0012ff18	0x11111105	; tmp continues
0x0012ff14	0x11111104	; tmp continues
0x0012ff10	0x11111103	; tmp continues
0x0012ff0c	0x11111102	; tmp continues
0x0012ff08	0x11111101	; tmp buffer starts
0x0012ff04	0x00000040	; memcpy length argument
0x0012ff00	0x00353050	; memcpy source argument
0x0012fefc	0x0012ff08	; memcpy destination arg.

Concrete jump-to-libc attack example

- A **malicious** stack overflow in the median function
- The attack doesn't use the return address (e.g., to avoid stack canary or cookie defenses)
- Control-flow is redirected in qsort
- Uses jump-to-libc to foil NX defenses

stack address	malicious overflow contents	
0x0012ff38	0x7c971649	; cmp argument
0x0012ff34	0x1111110c	; len argument
0x0012ff30	0x1111110b	; data argument
0x0012ff2c	0xfeeb2ecd	; return address
0x0012ff28	0x70000000	; saved base pointer
0x0012ff24	0x70000000	; tmp final 4 bytes
0x0012ff20	0x00000040	; tmp continues
0x0012ff1c	0x00003000	; tmp continues
0x0012ff18	0x00001000	; tmp continues
0x0012ff14	0x70000000	; tmp continues
0x0012ff10	0x7c80978e	; tmp continues
0x0012ff0c	0x7c809a51	; tmp continues
0x0012ff08	0x11111101	; tmp buffer starts
0x0012ff04	0x00000040	; memcpy length argument
0x0012ff00	0x00353050	; memcpy source argument
0x0012fefc	0x0012ff08	; memcpy destination arg.

Concrete jump-to-libc attack example

- Below shows the context of cmp invocation in qsort
- Goes to a 4-byte *trampoline* sequence found in a library

```
...
push    edi             ; push second argument to be compared onto the stack
push    ebx             ; push the first argument onto the stack
call    [esp+comp_fp]   ; call comparison function, indirectly through a pointer
add     esp, 8          ; remove the two arguments from the stack
test    eax, eax        ; check the comparison result
jle     label_lessthan  ; branch on that result
...
```

address	machine code opcode bytes	assembly-language version of the machine code
0x7c971649	0x8b 0xe3	mov esp, ebx ; change the stack location to ebx
0x7c97164b	0x5b	pop ebx ; pop ebx from the new stack
0x7c97164c	0xc3	ret ; return based on the new stack

The intent of the jump-to-libc attack

- Perform a series of calls to existing library functions
- With carefully selected arguments

```
// call a function to allocate writable, executable memory at 0x70000000
VirtualAlloc(0x70000000, 0x1000, 0x3000, 0x40); // function at 0x7c809a51

// call a function to write the four-byte attack payload to 0x70000000
InterlockedExchange(0x70000000, 0xfeeb2ecd);     // function at 0x7c80978e

// invoke the four bytes of attack payload machine code
((void (*)())0x70000000)();                      // payload at 0x70000000
```

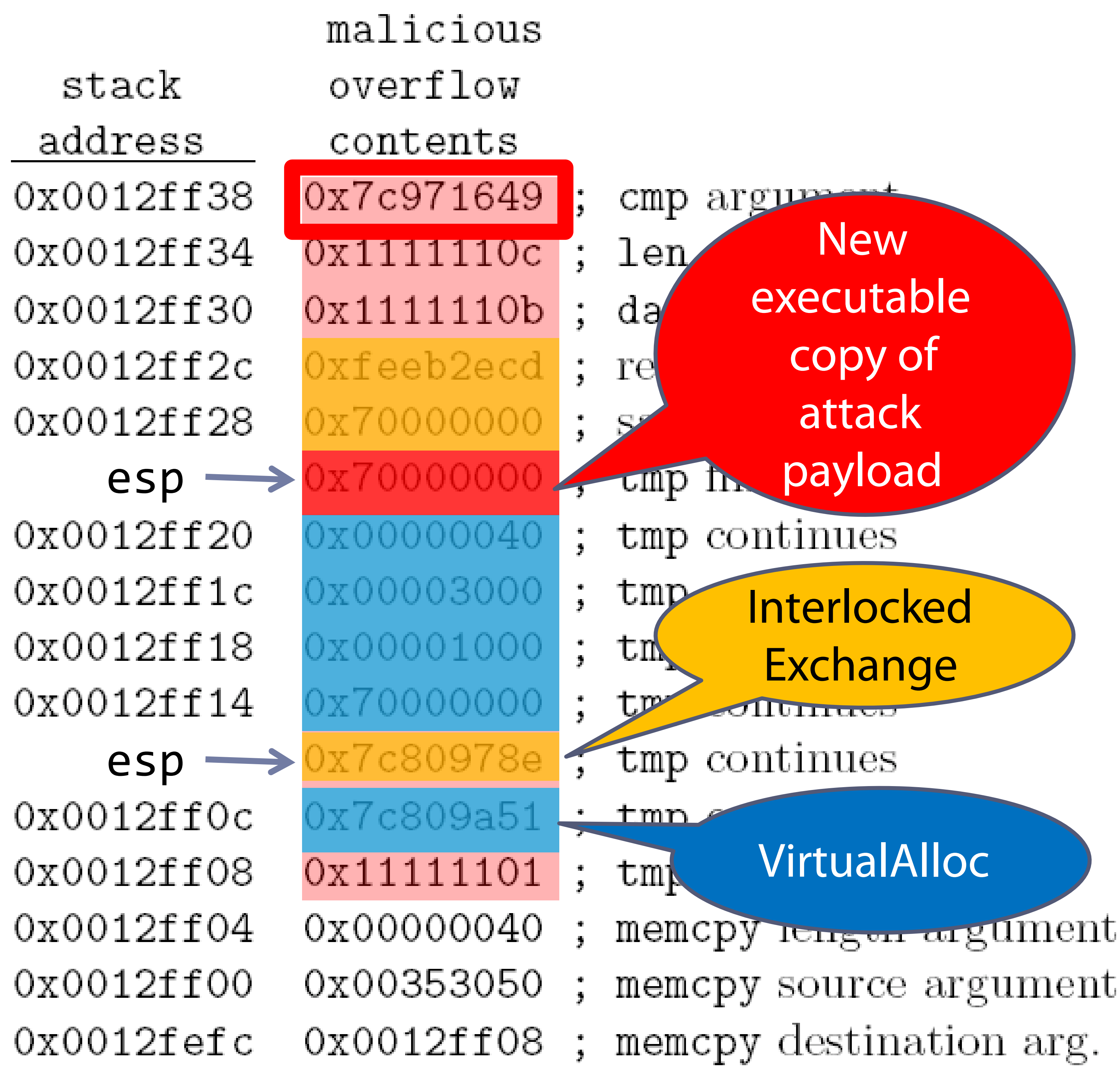
- The effect is to install and execute the attack payload

x86 __cdecl function-call convention

- Push parameters onto the stack, from right to left
- Call the function
- Save and update the %ebp
- Allocate local variables
- Perform the function's purpose
- Release local storage
- Restore saved registers
- Restore the old base pointer
- Return from the function
  - The RET instruction pops the old %EIP from the stack and jumps to that location. This gives control back to the caller function. Only the stack pointer and instruction pointers are modified by a subroutine return.
- Clean up pushed parameters

How the attack unwindes the stack

- First invalid control-flow edge goes to trampoline
- Trampoline returns to the start of VirtualAlloc
- Which returns to the start of the InterlockedExch. function
- Which returns to the copy of the attack payload



Where to find useful trampolines?

- In Linux `libc`, one in 178 bytes is a `0xc3` `ret` opcode
- One in 475 bytes is an opportunistic, or unintended, `ret`

```
f7 c7 07 00 00 00    test  edi, 0x00000007
0f 95 45 c3          setnz byte ptr [ebp-61]
```

Starting one byte later, the attacker instead obtains

```
c7 07 00 00 00 0f    movl  edi, 0x0f000000
95                   xchg  eax, ebp
45                   inc   ebp
c3                   ret
```

- All of these may be useful somehow

`Generalized jump-to-libc attacks`

- Recent demonstration by Shacham [upcoming CCS'07]
  - Possible to achieve anything by only executing trampolines
  - Can compose trampolines into "gadget" primitives
  - Such "return-oriented-computing" is Turing complete
  - Practical, even if only opportunistic `ret` sequences are used

- Confirms a long-standing assumption:

  if arbitrary jumping around within existing, executable code is permitted

  then

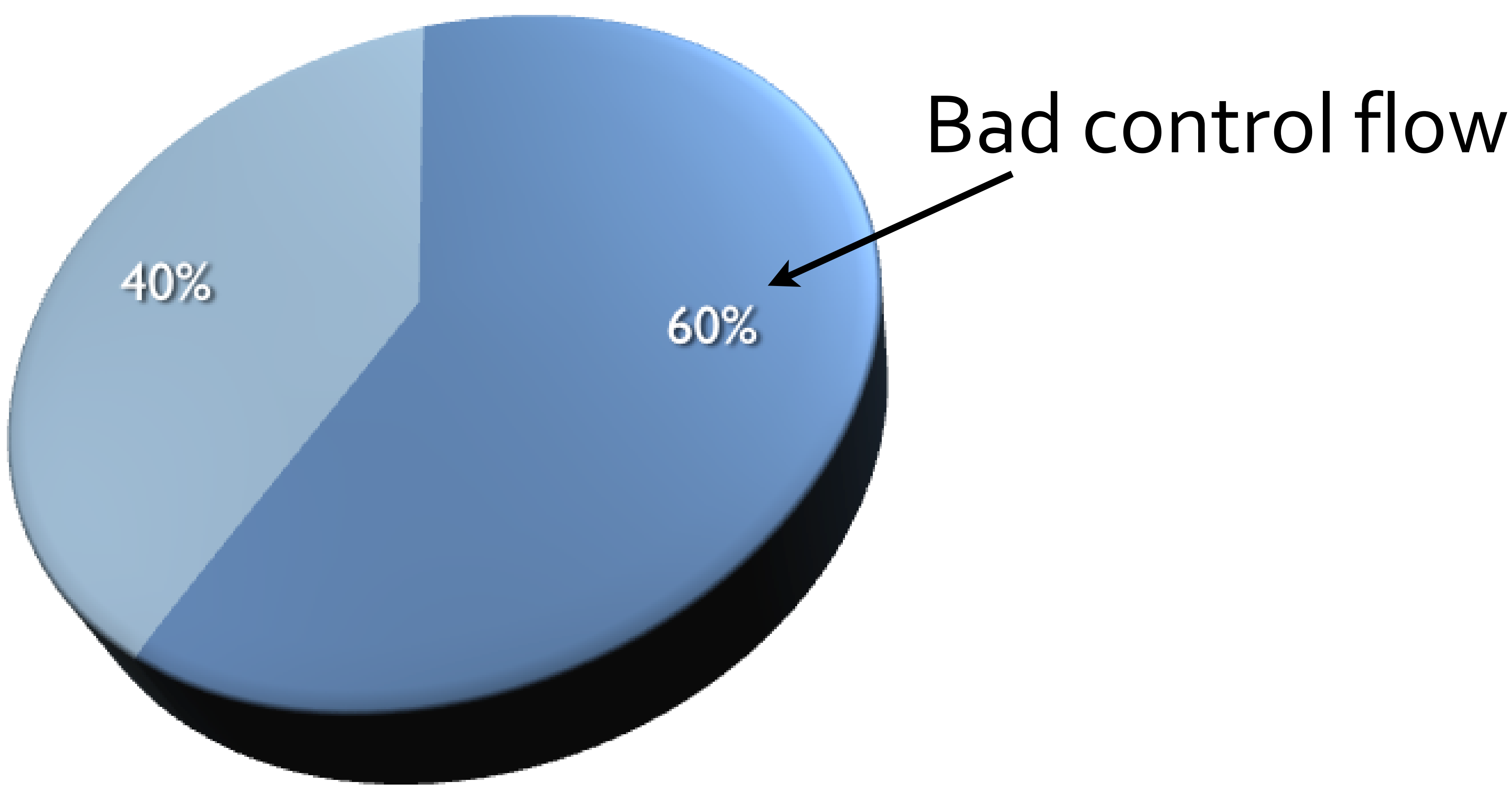
  an attacker can cause any desired, bad behavior

`Jump-to-libc attacks`

- Jump-to-libc attacks are of great practical concern
  - For instance, recent ANI attack on Vista is similar to `median`
- Traditionally, return-to-`libc` with the target `system()`
  - Removing `system()` is neither a good nor sufficient defense
    - Generality of trampolines makes this a unarguable point
  - Anyway difficult to eliminate code from shared libraries
- Based on knowledge of existing code, and its addresses
  - Attackers must deal with natural software variability
  - Increasing the variability can be a good defense
- Best defense is to lock down the possible control flow
  - Other, simpler measures will also help

Control-flow integrity

- ~60% of attacks subvert the expected control flow
  - Enforcing control-flow integrity would prevent such attacks



Assumptions about control flow

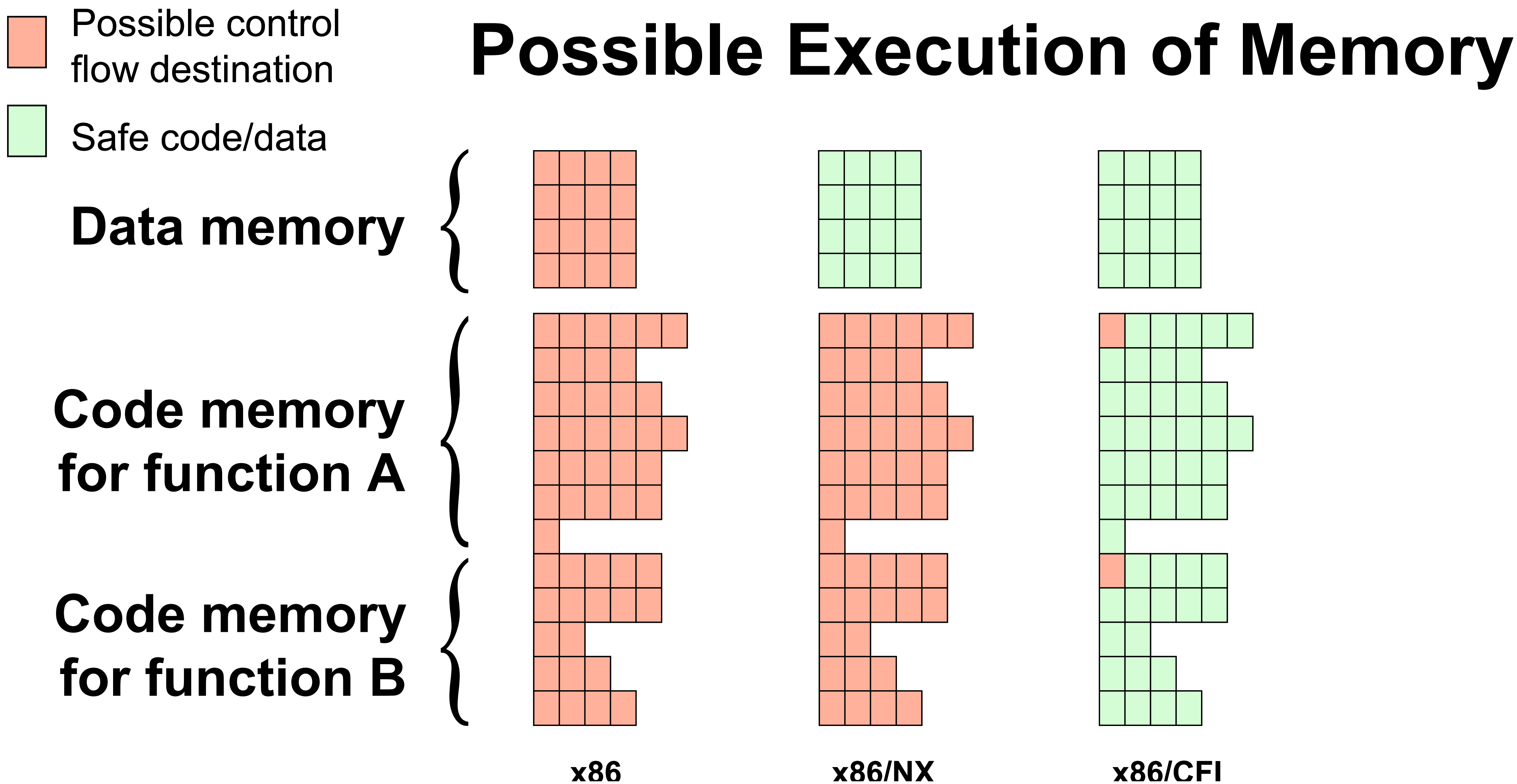
- We write our code in high-level languages
- Naturally, our execution model assumes:
  - Functions start at the beginning
  - They (typically) execute from beginning to end
  - And, when done, they return to their call site
  - Only the code in the program can be executed
  - The set of executable instructions is limited to those output during compilation of the program

Assumptions about control flow

- We write our code in high-level languages
- **But, actually, at the level of machine code**
  - Can start in the middle of functions
  - A fragment of a function may be executed
  - Returns can go to any program instruction
  - All the data has usually been executable
  - On the x86, can start executing not only in the middle of functions, but middle of instructions!

What bytes will the CPU interpret?

- Hardware places few constrains on control flow
- A call to a function-pointer can lead many places:



Enforcing control-flow integrity

- Only certain control-flow is possible in software
  - Even in C there are function and expression boundaries
  - Should also consider who-can-go-where, and dead code

- Control-flow integrity means that execution proceeds according to a specified control-flow graph (CFG).

  ⇒ Reduces gap between machine code and high-level languages
- Can enforce with CFI mechanism, which is simple, efficient, and applicable to existing software.

- CFI enforces a basic property that thwarts a large class of attacks— without giving "end-to-end" security.

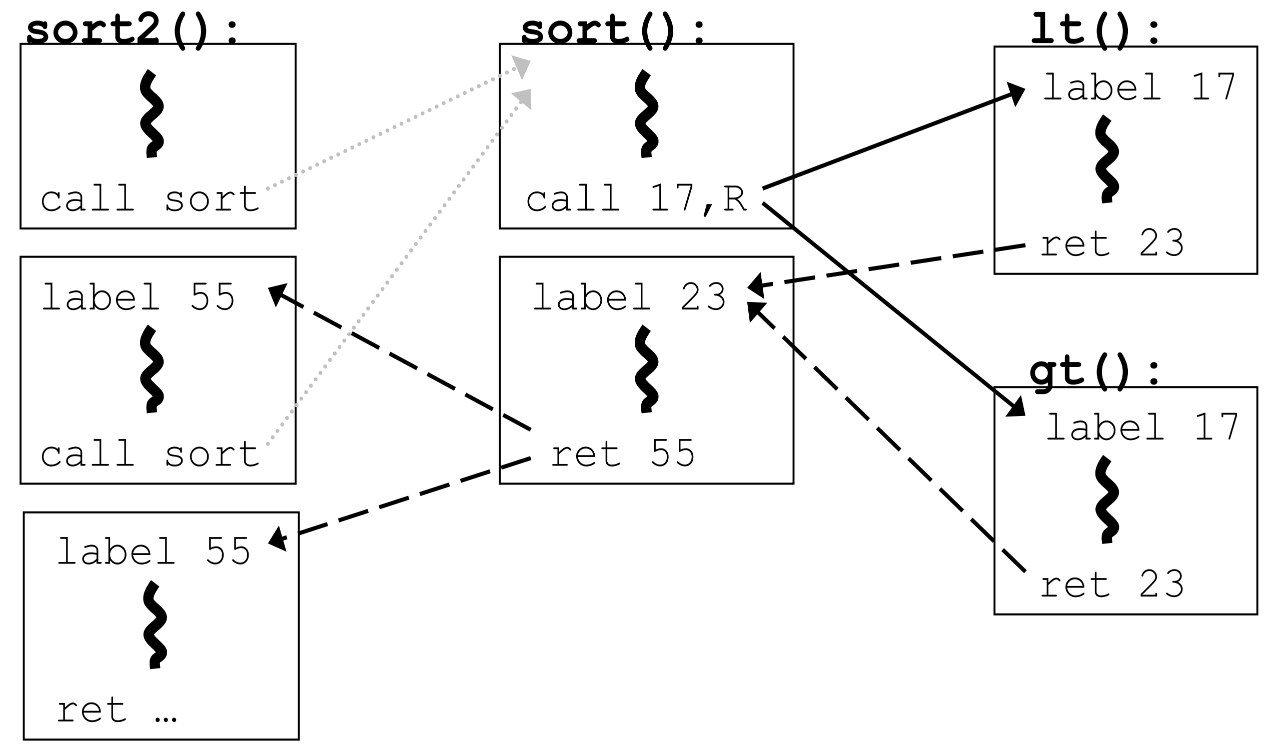
Guards for control flow integrity

- CFI guards restrict computed jumps and calls
  - Calls through function pointers (e.g. virtual methods in C++)
  - All return, exception and switch statements
- Direct calls are unaffected
- CFI guard matches label at source and target
  - Labels are constants embedded in machine-code
  - Labels are not secret, but must be **unique**
- Two destinations are equivalent when the CFG contains edges to it from the same set of sources
  - Equivalent destinations are labeled the same
  - i.e. a label uniquely identifies a CFG equivalence class

A simple example

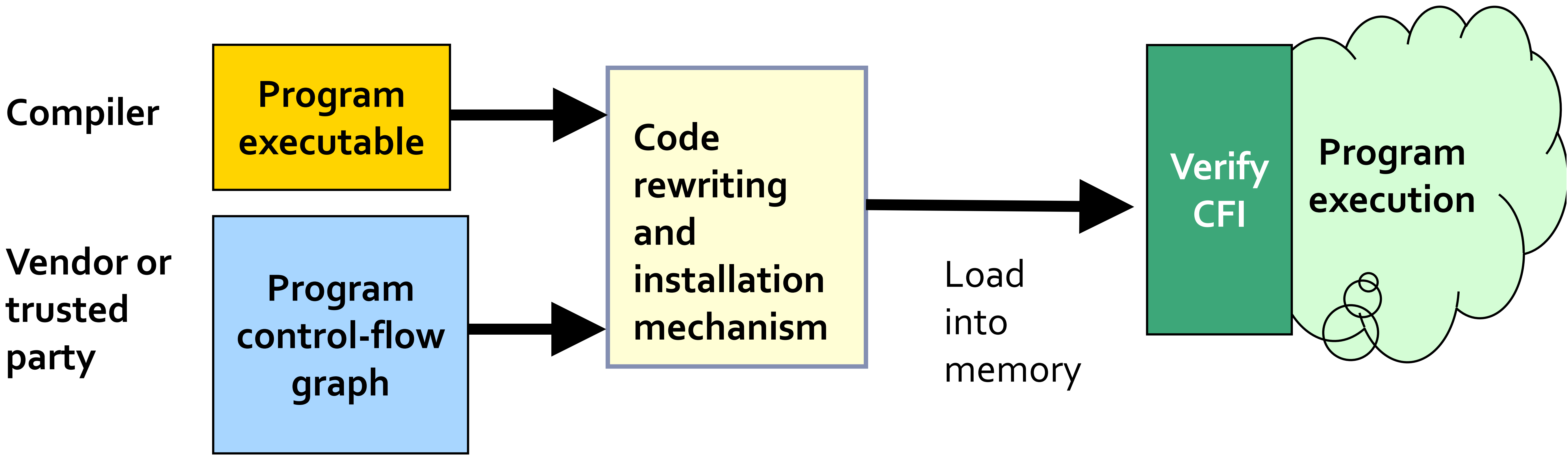
```
bool lt(int x, int y) {
    return x < y;
}
bool gt(int x, int y) {
    return x > y;
}

sort2(int a[], int b[], int len)
{
    sort( a, len, lt );
    sort( b, len, gt );
}
```



- Ensure "labels" are correct at load- and run-time
  - Bit patterns identify different points in the code
  - Indirect control flow must go to the right pattern
- Can be enforced using software instrumentation
  - Even for existing, legacy software

Overview of a system with CFI



- Machine code rewriting using instrumentation tool
  - Applies to legacy Windows x86 executables
  - Code rewriting need not be trusted, because of the verifier
  - The verifier is simple (2 KLoC, mostly parsing x86 opcodes)

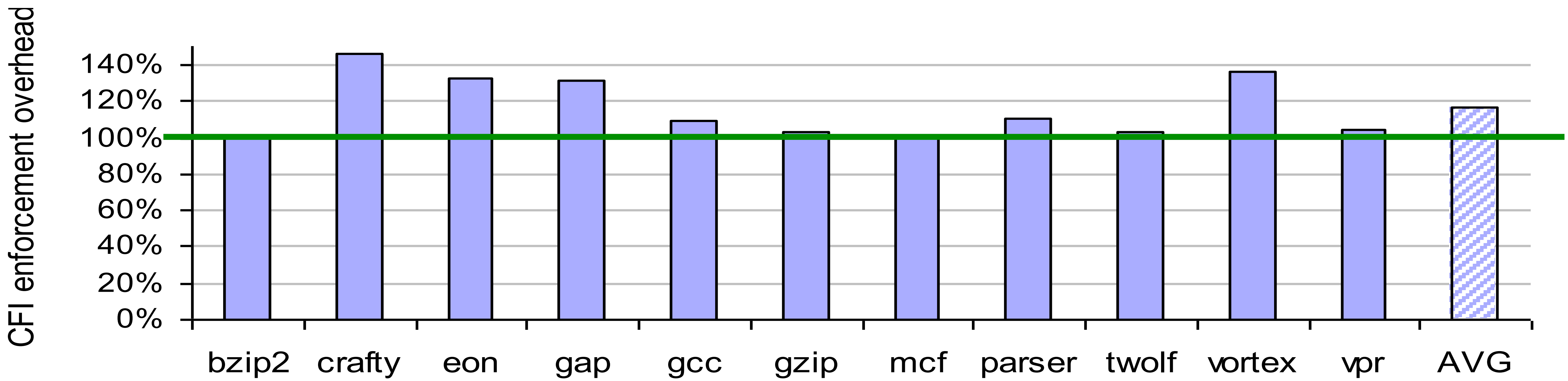
CFI formal study [ICFEM’05]

- Formally validated the benefits of CFI
  - Defined a machine code semantics
  - Powerful attacker model
    - Attacker can arbitrarily control all of data memory
  - Proved that, with CFI, execution always follows the CFG, even when under attack
- Assumptions
  - NXD: Data cannot be executed (hardware or software)
  - NWC: Code cannot be modified (hardware, already used)
  - We can rely on values in distinguished registers
  - Jumps cannot go into the middle of instructions
    - A convenient simplification to make the proof manageable

CFI as foundation for other prop.

- CFI can be used as a foundation for efficiently enforcing more sophisticated security properties
- Software fault isolation (e.g. sandboxing)
  - Dynamically check memory accesses to emulate traditional memory protection
- Software memory access control
  - Stronger than software fault isolation: isolated data memory regions accessible only from particular code
  - Removes NXD assumption, but adds extra overhead
- Protected shadow call stack
  - ID checks on return replaced by the use of a call stack
  - Very little extra overhead (at least with x86-specific tricks)

Cost and Benefits



SPECINT 2K reference runs, XP SP2, Safe Mode w/CMD, Pentium 4, no HT, 1.8GHz

- CFI overhead: ~16% in synthetic CPU-bound benchmarks
  - Is this really unobtrusive (close to zero overhead) ?
- Effectively stops most jump-to-libc attacks
  - No trampolining, even if CFI enforces a very coarse CFG
  - E.g., may have two labels -- for call sites and start of functions
- Limitation: Data-only attacks

Conclusion

- Mitigation techniques
  - Automatic defenses that work on legacy code
  - Operate at the machine-code level
  - Involve no source-code changes
  - Have close to zero overhead
  - Only prevent certain kinds of attacks
  - May provide a false feeling of security ... like a Volvo
  - Are not substitutes for correct code or safer languages
  - Do not protect against denial-of-service attacks
- Control-flow integrity
  - Particularly powerful mitigation technique
  - Prevents many kinds of attacks, including jump-to-libc