Where's the FEEB? Effectiveness of Instruction Set Randomization

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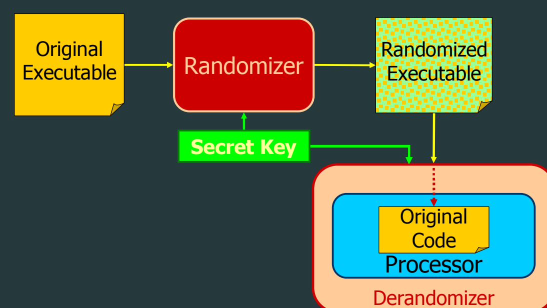
Security Through Diversity

- Today's Computing Monoculture
  - Exploit can compromise billions of machines since they are all running the same software
- Biological Diversity
  - All successful species use very expensive mechanism (i.e., sex) to maintain diversity
- Computer security research: [Cohen 92], [Forrest+ 97], [Cowan+ 2003], [Barrantes+ 2003], [Kc+ 2003], [Bhatkar+2003], [Just+ 2004]

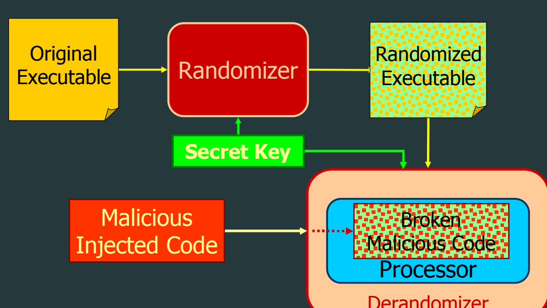
Instruction Set Randomization
[Barrantes+, CCS 03] [Kc+, CCS 03]

- Code injection attacks depend on knowing the victim machine's instruction set
- Defuse them all by making instruction sets different and secret
  - Its expensive to design new ISAs and build new microprocessors

Automating ISR



ISR Defuses Attacks



ISR Designs

	Columbia [Kc 03]	RISE [Barrantes 03]
Randomization Function	XOR or 32-bit transposition	XOR
Key Size	32 bits (same key used for all locations)	program length (each location XORed with different byte)
Transformation Time	Compile Time	Load Time
Derandomization	Hardware	Software (Valgrind)

How secure is ISR?

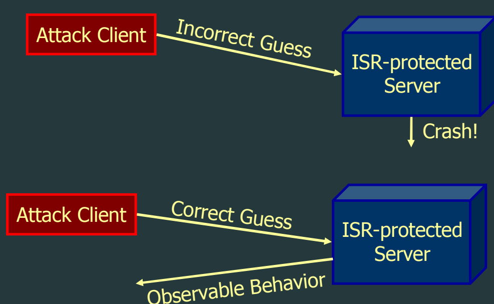
Slows down an attack about 6 minutes!

Under the right circumstances…

Memory Randomization Attack

- Brute force attack on memory address space randomization (Shacham et. al. [CCS 2004]): 24-bit effective key space
- Can a similar attack work against ISR?
  - Larger key space: must attack in fragments
  - Need to tell if partial guess is correct

ISR Attack



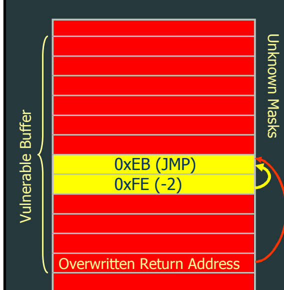
Server Requirements

- Vulnerable: buffer overflow is fine
- Able to make repeated guesses
  - No rerandomization after crash
  - Likely if server forks requests (Apache)
- Observable: notice server crashes
- Cryptanalyzable
  - Learn key from one ciphertext-plaintext pair
  - Easy with XOR

Two Attack Ideas

- RET (0xC3): return from procedure
  - 1-byte instruction: up to 256 guesses
  - Returns, leaves stack inconsistent
    - Only works if server does something observable before crashing
- JMP -2 (0xEBFE): jump offset -2
  - 2-byte instruction: up to 2^{16} guesses
  - Produces infinite loop
- Incorrect guess usually crashes server

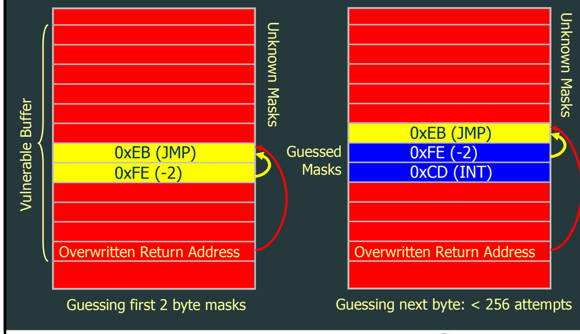
Jump Attack



2^{16} possible guesses for 2-byte instruction

Correct guess produces infinite loop

Incremental Jump Attack



Guess Outcomes

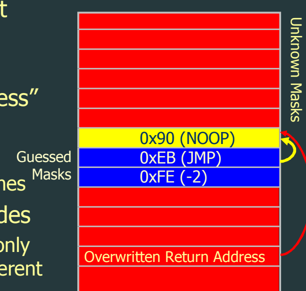
	Observe "Correct" Behavior	Observe "Incorrect" Behavior
Correct Guess	Success	False Negative
Incorrect Guess	False Positive	Progress

False Positives

- Injected bytes produce an infinite loop:
  - JMP -4
  - JNZ -2
- Injected bytes are "harmless", later executed instruction causes infinite loop
- Injected guess causes crash, but timeout expires before remote attacker observes

False Positives – Good News

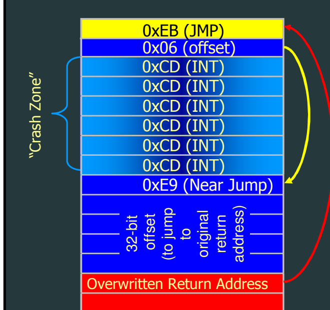
- Can distinguish correct mask using other instructions
- Try injecting a "harmless" one-byte instruction
  - Correct: get loop
  - Incorrect: *usually* crashes
- Difficulty: dense opcodes
  - No pair that differs in only last bit are reliably different in harmfulness



False Positives – Better News

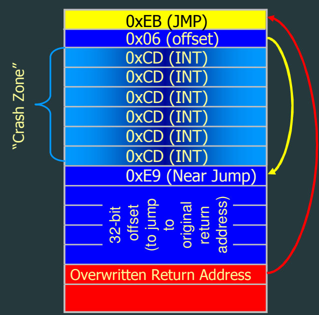
- False positives are not random
  - Conditional jump instructions
  - Opcodes **0111**0000-**0111**1111
- **All** are complementary pairs: $0111xyza$ not taken $\Leftrightarrow$ $0111xyz\bar{a}$ is!
- 32 guesses always find an infinite loop
- About 8 additional guesses to determine correct mask

Extended Attack



- Near jump to return location
  - Execution continues normally
  - No infinite loops
- 0xCD 0xCD is interrupt instruction guaranteed to crash

Expected Attempts

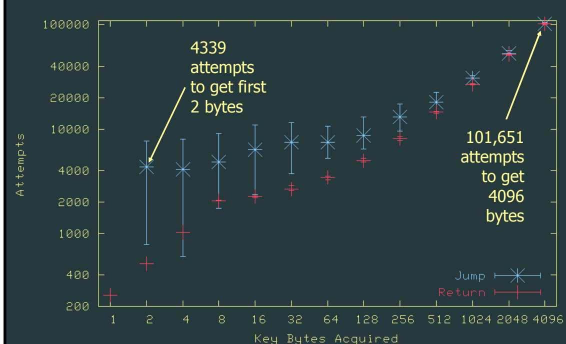


~ 15½ to find first jumping instruction
+ ~ 8 to determine correct mask
23½ expected attempts per byte

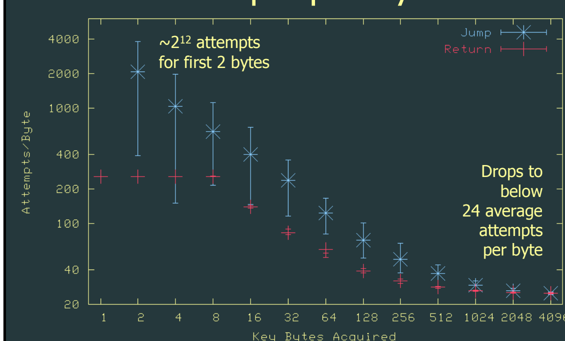
Experiments

- Implemented attack against constructed vulnerable server protected with RISE [Barrantes et. al, 2003]
  - Memory space randomization works!
    - Turned of Fedora's address space randomization
  - Needed to modify RISE
    - Ensure forked processes use same randomization key (other proposed ISR implementations wouldn't need this)
- Obtain correct key over 95% of the time

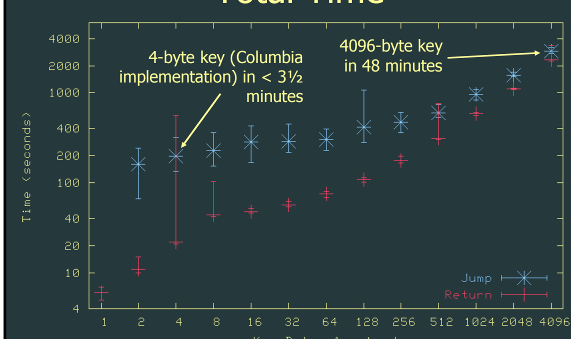
Attempts Required



Attempts per Byte



Total Time



Attacker: "Is this good enough?" Defender: "Is this bad enough?"

How many key bytes needed?

- Inject malcode in one ISR-protected host
  - Sapphire worm = 376 bytes
- Create a worm that spreads on a network of ISR-protected servers
  - Space for FEEB attack code: 34,723 bytes
  - Need to crash server ~800K times

Maybe less…?

- VMWare: 3,530,821 bytes
- Java VM: 135,328 bytes
- Minsky's UTM: 7 states, 4 colors

- **MicroVM: 100 bytes**

Entire MicroVM Code

```
  push dword ebp   mov ebp, WORM_ADDRESS + WORM_REG_OFFSET
  pop dword [ebp + WORM_DATA_OFFSET]
  xor eax, eax        ; WormIP = 0 (load from ebp + eax)
read_more_worm: ; read NUM_BYTES at a time until worm is done
  cld      xor ecx, ecx           mov byte cl, NUM_BYTES
  mov dword esi, WORM_ADDRESS     ; get saved WormIP
  add dword esi, eax              mov edi, begin_worm_exec
  rep movsb                       ; copies next Worm block into execution buffer
  add eax, NUM_BYTES              ; change WormIP
  pushad                          ; save register vals
  mov edi, dword [ebp]            ; restore worm registers
  mov esi, dword [ebp + ESI_OFFSET]     mov ebx, dword [ebp + EBX_OFFSET]
  mov edx, dword [ebp + EDX_OFFSET]     mov ecx, dword [ebp + ECX_OFFSET]
  mov eax, dword [ebp + EAX_OFFSET]
begin_worm_exec:                  ; this is the worm execution buffer
   nop nop nop nop nop nop nop nop nop nop nop nop
   nop nop nop nop nop nop nop nop nop nop nop nop
   mov [ebp], edi     ; save worm registers
   mov [ebp + ESI_OFFSET], esi         mov [ebp + EBX_OFFSET], ebx
   mov [ebp + EDX_OFFSET], edx         mov [ebp + ECX_OFFSET], ecx
   mov [ebp + EAX_OFFSET], eax
   popad              ; restore microVM register vals
   jmp read_more_worm
```


MicroVM

76 bytes of code
\+ 22 bytes for execution
\+ 2 bytes to avoid NULL
= 100 bytes is enough
> 99% of the time

Learned Key Bytes:

- save worm address in **ebp**
- move stack frame pointer
- WormIP ← 0
- copy worm code into buffer
- update WormIP
- save MicroVM registers
- load worm registers
- 22-byte worm execution buffer
- save worm registers
- load MicroVM registers
- jmp to read next block

saved registers
worm code
host key masks
guessed (target) masks
other worm data

Worm code must be coded in blocks that fit into execution buffer (pad with noops so instructions do not cross block boundaries)

Making Jumps

- Within a block - short relative jump is fine
- Between worm blocks
  - From end of block, to beginning of block
  - Update the WormIP stored on the stack
  - Code conditional jump, **JZ target** in worm as:

  JNZ +5 *; if opposite condition, skip*
  MOV [ebp + WORMIP_OFFSET] **target**

Deploying a Worm

- Learn 100 key bytes to inject MicroVM
  - Median time: 311 seconds, 8422 attempts
  - Fast enough for a worm to spread effectively
- Inject pre-encrypted worm code
  - XORed with the known key at location
  - Insert NOOPs when necessary to avoid NULLs
- Inject key bytes
  - Needed to propagate worm

Preventing Attack: Break Requirement

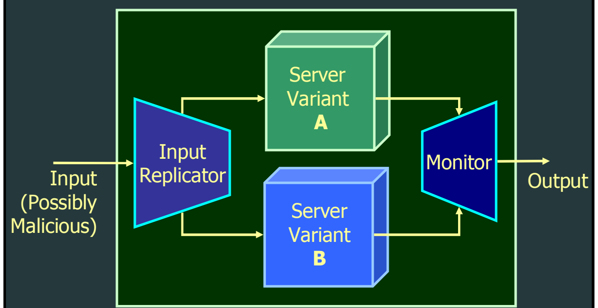
- Vulnerable: eliminate vulnerabilities
  - Rewrite all your code in a type safe language
- Able to make repeated guesses
  - Rerandomize after crash
- Observable: notice server crashes
  - Maintain client socket after crash?
- Cryptanalyzable
  - Use a strong cipher like AES instead of XOR

Better Solution

- Avoid secrets!
  - Keeping them is hard
  - They can be broken or stolen
- Prove security properties without relying on assumptions about secrets or probabilistic arguments

Secretless Security Structure

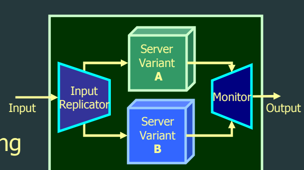
work with Jack Davidson, Jonathan Hill, John Knight & Anh Nguyen-Tuong



Disjoint Variants

- Any attack that succeeds against Variant A must cause Variant B to crash
- Monitor observes crash and recovers

Examples:
Instruction Sets
Memory Addresses
Schedule Interleaving



Making Disjoint Variants

JMP
CALL
JO
JNO
JB
JNB
JZ
JNZ
…

Variant A Variant B

Challenges

- Engineering
  - Input replicator and monitor
  - Shared state (databases, files)
  - Nondeterminism (session state)
- Security
  - Proving variants are disjoint
  - Multi-stage attacks
  - Achieving high-level disjoint properties

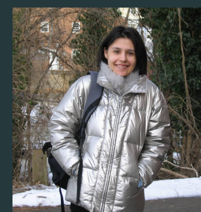
Diversity depends on your perspective

Slide from my USENIX Security 2004 Talk, *What Biology Can (and Can't) Teach us about Security*

Summary

- Diversity defenses defeat undetermined adversaries
- Determined adversaries may be able to determine secrets
  - Break ISR-protected server in < 6 minutes
- Secretless diversity designs promise provable security against classes of attack

Credits



Nora “NORAndomizer” Sovarel

Nate “Byte Annihilator” Paul

Genesis Project: Jack Davidson, Adrian Filipi, Jonathan Hill, John Knight, Anh Nguyen-Tuong, Chenxi Wang (CMU)
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Questions?