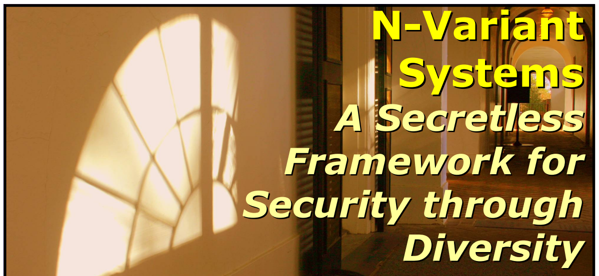

N-Variant Systems
A Secretless Framework for Security through Diversity

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29 May 2006

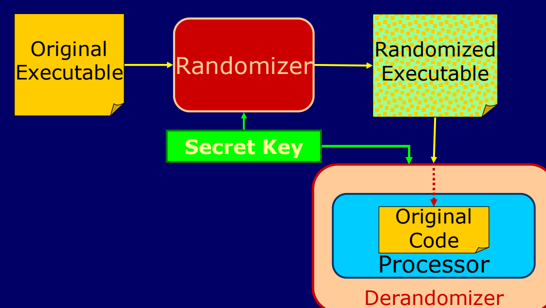
Security Through Diversity

- Today's Computing Monoculture
  - Exploit can compromise billions of machines since they are all running the same software
- Biology's Solution: Diversity
  - Members of a species are different enough that some are immune
- Computer security research: [Cohen 92], [Forrest+ 97], [Cowan+ 2003], [Barrantes+ 2003], [Kc+ 2003], [Bhatkar+2003], [Just+ 2004], [Bhatkar, Sekar, DuVarney 2005]

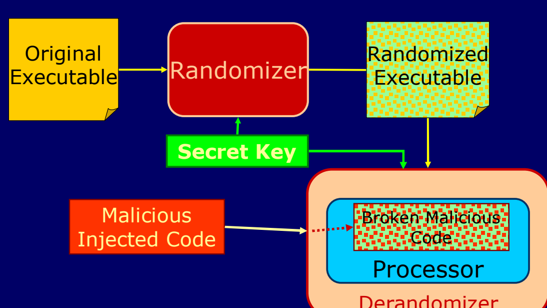
Instruction Set Randomization
[Barrantes+, CCS 03] [Kc+, CCS 03]

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

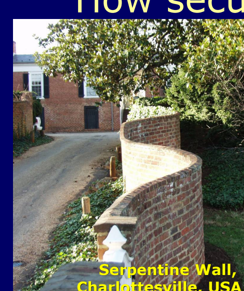
Automating ISR

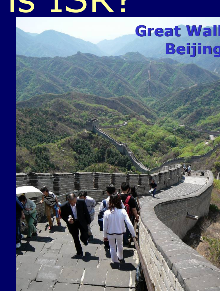


ISR Defuses Attacks



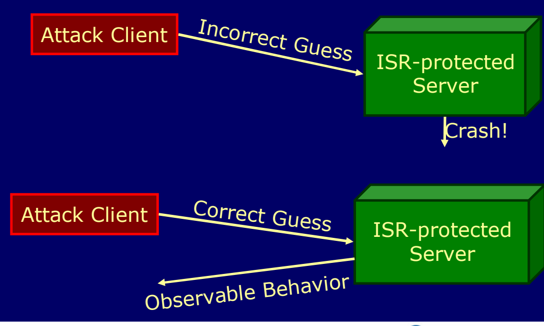
How secure is ISR?





Where's the FEEB? Effectiveness of Instruction Set Randomization. Ana Nora Sovarel, David Evans and Nathanael Paul. *USENIX Security Symposium*, August 2005.

ISR Attack



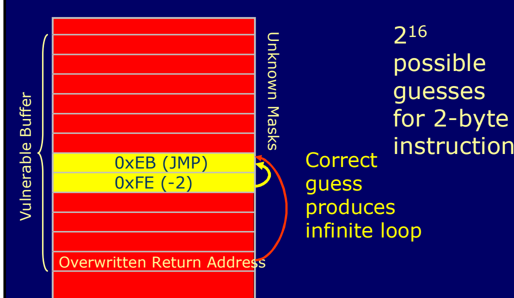
Server Requirements

- 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

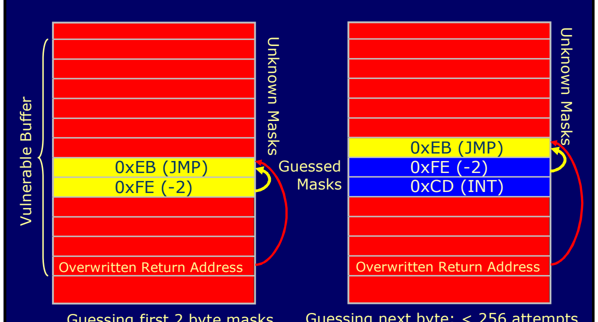
Jump Attack

- JMP -2 (0xEBFE): jump offset -2
  - 2-byte instruction: up to 2^{16} guesses
  - Produces infinite loop
- Incorrect guess usually crashes server

Jump Attack



Incremental Jump Attack



Guess Outcomes

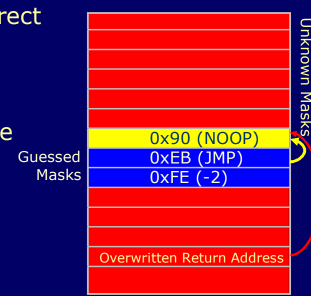
	Observe "Correct" Behavior	Observe "Incorrect" Behavior
Correct Guess	Success	False Negative
Incorrect Guess	False Positive	Progress

False Positives

- Injected bytes produce an infinite loop:
  - JMP -4
  - JNZ -2
- Injected bytes are "harmless", later instruction causes infinite loop

False Positives – Good News

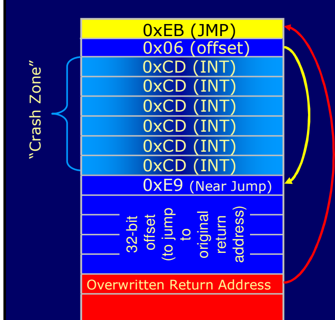
- Can distinguish correct mask using other instructions
- Try injecting a "harmless" one-byte instruction
  - Correct: get loop
  - Incorrect: *usually* crashes
- Difficulty: dense opcodes



False Positives – Better News

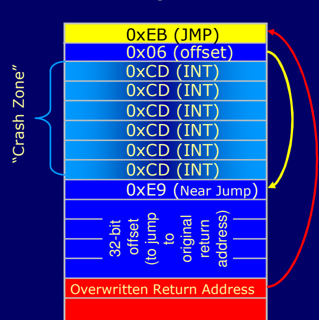
- False positives are not random
  - Conditional jump instructions
  - Opcodes **0111**0000-**0111**1111
- **All** are complementary pairs:
  0111*xyz*a not taken ⇔ 0111*xyz*$\bar{a}$ is!
- 32 guesses must find an infinite loop, about 8 more guesses to learn correct mask

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]
  - Need to modify RISE to ensure child processes have same key
- Obtain correct key over 95% of the time
  - 4 byte key in 3½ minutes
  - 4096 bytes in 48 minutes (>100,000 guess attempts)
- Is this good 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 our code: 34,723 bytes
  - Need to crash server ~800K times

Maybe less…?

- VMWare: 3,530,821 bytes
- Java VM: 135,328 bytes
- **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

Learned Key Bytes

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

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)

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 to avoid NULLs
- Inject key bytes
  - Needed to propagate worm

Preventing Attack: Break Attack Requirements

- 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

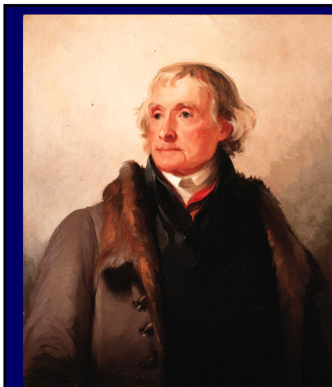
- Avoid secrets!
  - Keeping them is hard
  - They can be broken or stolen
- Prove security properties without relying on assumptions about secrets or probabilistic arguments

N-Variant Systems: A Secretless Framework for Security through Diversity

To appear in *USENIX Security Symposium*, August 2006. Benjamin Cox, David Evans, Adrian Filipi, Jonathan Rowanhill, Wei Hu, Jack Davidson, John Knight, Anh Nguyen-Tuong, and Jason Hiser.

Lie Detector Polygraph

Thomas Jefferson's Polygraph



Thomas Jefferson

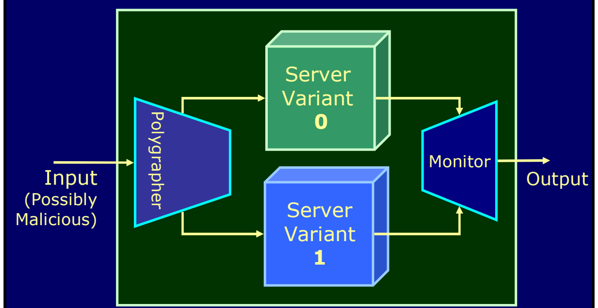
- Author of "Declaration of Independence"
- 3rd President of United States
- Cryptographer, scientist, architect

Computer Science at UVa

- Strong research groups in:
  - Security (me, Jack Davidson, Anita Jones, Alf Weaver)
  - Software Engineering (me, Mary Lou Soffa, John Knight)
  - Architecture (Gurumurthi, Skadron)
  - Sensor Networks (Stankovic)
  - Theory (Mishra)
  - Graphics (Humphreys)
- 75 PhD students

www.cs.virginia.edu

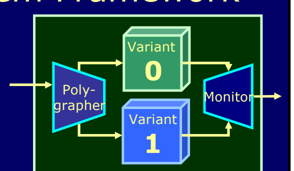
2-Variant System



N-Version Programming [Avizienis & Chen, 1977]	**N-Variant Systems**
• Multiple teams of programmers implement same spec	• Transformer automatically produces diverse variants
• Voter compares results and selects most common	• Monitor compares results and detects attack
• No guarantees: teams may make same mistake	• Guarantees: variants behave differently on particular input classes

N-Variant System Framework

- Polygrapher
  - Replicates input to all variants
- Variants
  - *N* processes implement the same service
  - Vary property you hope attack depends on: memory locations, instruction set, file names, system call numbers, scheduler, calling convention, …



- Monitor
  - Observes variants
  - Delays effects until all variants agree
  - Starts recovery if variants diverge

Variants Requirements

- *Detection* Property
  Any attack that compromises Variant 0 causes Variant 1 to "crash" (behave in a way that is noticeably different to the monitor)
- *Normal Equivalence* Property
  Under normal inputs, the variants stay in equivalent states:

$$\mathcal{A}_0(S_0) \equiv \mathcal{A}_1(S_1)$$

Actual states are different, but abstract states are equivalent

Memory Partitioning

- Variation
  - Variant 0: addresses all start with **0**
  - Variant 1: addresses all start with **1**
- Normal Equivalence
  - Map addresses to same address space
- Detection Property
  - Any *absolute* load/store is invalid on one of the variants

Instruction Set Tagging

- Variation: add an extra bit to all opcodes
  - Variation 0: tag bit is a **0**
  - Variation 1: tag bit is a **1**
  - At run-time check bit and remove it
    - Low-overhead software dynamic translation using Strata [Scott, et al., CGO 2003]
- Normal Equivalence: Remove the tag bits
- Detection Property
  - Any (tagged) opcode is invalid on one variant
  - Injected code (identical on both) cannot run on both

Implementing N-Variant Systems

- Competing goals:
  - Isolation: of monitor, polygrapher, variants
  - Synchronization: variants must maintain normal equivalence (nondeterminism)
  - Performance: latency (wait for all variants to finish) and throughput (increased load)
- Two implementations:
  - Divert Sockets (prioritizes isolation over others)
  - Kernel modification (sacrifices isolation for others)

Kernel Modification Implementation

- Modify process table to record variants
- Create new fork routine to launch variants
- Intercept system calls:
  - 289 calls in Linux
  - Check parameters are the same for all variants
  - Make call once

Wrapping System Calls

- I/O system calls (process interacts with external state) (e.g., open, read, write)
  - Make call once, send same result to all variants
- Process system calls (e.g, fork, execve, wait)
  - Make call once per variant, adjusted accordingly
- Dangerous:
  - mmap: each variant maps segment into own address space, only allow MAP_ANONYMOUS (shared segment not mapped to a file) and MAP_PRIVATE (writes do not go back to file)
  - execve: cannot allow

System Call Wrapper Example

```
ssize_t sys_read(int fd, const void *buf, size_t count) {
  if (hasSibling (current)) {
    record that this variant process entered call
    if (!inSystemCall (current->sibling)) { // this variant is first
       save parameters
       sleep // sibling will wake us up
       get result and copy *buf data back into address space
       return result;
    } else if (currentSystemCall (current->sibling) == SYS_READ) {
       // I'm second variant, sibling is waiting
       if (parameters match) { // match depends on variation
          perform system call
          save result and data in kernel buffer
          wake up sibling
          return result;
       } else {
         DIVERGENCE ERROR! }
    } else { // sibling is in a different system call!
       DIVERGENCE ERROR! } }
  ...
}
```


Overhead

Results for Apache running WebBench 5.0 benchmark

	Description	Unmodified Apache, unmodified kernel	2-variant system, *address space partitioning*	2-variant system, *instruction tagging*
Unloaded	Throughput (MB/s)	2.36	2.04	1.80
Unloaded	Latency (ms)	2.35	2.77	3.02
Loaded	Throughput (MB/s)	9.70	5.06	3.55
Loaded	Latency (ms)	17.65	34.20	48.30

Latency increases ~18%

Throughput 36% of original

Summary

- Producing artificial diversity is easy
  - Defeats undetermined adversaries
- Keeping secrets is hard
  - Remote attacker can break ISR-protected server in < 6 minutes
- N-variant systems framework offers provable (but expensive) defense
  - Effectiveness depends on whether variations vary things that matter to attack


Diversity depends on your perspective
From my USENIX Security 2004 Talk, *What Biology Can (and Can't) Teach us about Security*
www.nvariant.org
43
Computer Science
at the University of Virginia


Questions?
Links: http://www.cs.virginia.edu/nvariant
Contributors: Ben Cox, Jack Davidson, Adrian Filipi, Jason Hiser, Wei Hu, John Knight, Ana Nora Sovarel, Anh Nguyen-Tuong, Nate Paul, Jonathan Rowanhill
Funding: National Science Foundation, DARPA