N-Variant Systems

A Secretless Framework for Security through Diversity

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Attacks Require Knowledge

Heat (1995)

Artificial Diversity Methods

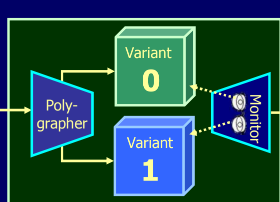
Attack Class	Assumptions	Diversity
Code Injection	Instruction Set	Instruction Set Randomization [Barrantes+ 2003], [Kc+ 2003]
Memory Corruption	Address Space Layout	Address Space Randomization [Forrest+ 97], [Bhatkar+2003]
Return to Lib-C	Calling Convention	Calling Sequence Diversity
Time Of Check To Time Of Use	Process Scheduling	???
⋮	⋮	⋮

Limitations of Diversity Methods

- Requires high entropy
  - Difficulty scales with the number of possibilities
  - Low entropy broken by brute force [Shacham+, CCS 04]
- Attacker can learn the diversity key
  - Incremental attacks [Sovarel+, USENIX Sec 05]
  - Side channels
- Security assurance difficult
  - Vulnerability changed, not removed
  - Assumes secrets can be kept

N-Variant System Framework

- Run variants in parallel with identical inputs
- Variants designed to vary assumptions
- Check behavior of variants is equivalent



Redundant Execution

- Debugging [Knowlton 68]
  - Rearrange code and memory segments of program and run in parallel
- Robustness [Berger & Zorn 06]
  - Dynamically randomize layout of heap and run multiple versions in parallel comparing output
- Security [Reynolds+ 03, Totel+ 05, Gao+ 05]
  - Design diversity with rough comparison

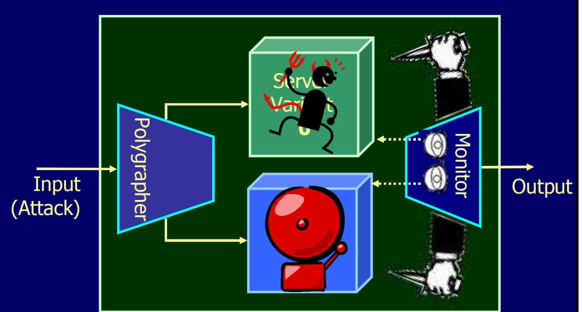
Proving Detection

- Detection property
  - Attack causes states between variants to diverge noticeably
  - If one variant is compromised another must enter alarm state
- Normal equivalence
  - Before attack, variants must be in equivalent states
  - Deterministic behavior

Example Variations

- Address space partitioning
  - Detection property: access injected address
  - Normal equivalence: addresses identical except for high order bit
- Instruction set tagging
  - Detection property: run injected code
  - Normal equivalence: instructions in variants are same except for tags

Thwarting Attacks



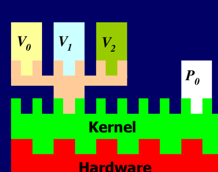
Implementation Requirements

- Polygrapher
  - Identical inputs to variants at same time
- Monitor
  - Continually examine variants completely
- Variants
  - Fully isolated, behave identically on normal inputs

Too expensive for real systems

Implementation

- Modified Linux 2.6.11 kernel
- Run variants as processes
- Create 2 new system calls
  - `n_variant_fork`
  - `n_variant_execve`
- Wrap existing system calls
  - Replicate input
  - Monitor system calls



Wrappers

- Check consistency
- I/O wrappers (e.g., read(), write())
  - Perform system call once
  - Return same result to all variants
- Reflective (e.g., setuid(), signal())
  - Perform corresponding system call on all variants
  - Check identical result

```
sys_write_wrapper(int fd, char __user * buf, int len){
  if (!IS_VARIANT(current)) { Perform System Call }
  else {
    if (!inSystemCall(current->nv_system)) {
      Save Parameters
      Sleep
      Return Result Value
    } else if (currentSystemCall(current->nv_system) !=SYS_WRITE) {
      DIVERGENCE – different system calls
    } else if (!Parameters Match) {
      DIVERGENCE – different parameters
    } else if (!isLastVariant(current->nv_system) {
      Sleep
      Return Result Value
    } else {
      Perform System Call
      Save Result
      Wake Up All Variants
      Return Result Value
    }
  }}
```

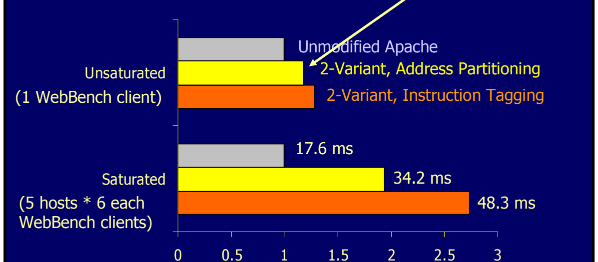

Constructing Variants

- Address Space Partitioning
  - Specify segments' start addresses and sizes
  - OS detected injected address as segmentation fault
- Instruction Set Tagging
  - Use Diablo [De Sutter+ 03] to insert tags into binary
  - Use Strata [Scott+ 02] to check and remove tags

Results

Latency increase from 2.35 to 2.77 ms

Normalized Latency



Apache 1.3 on Linux 2.6.11

Implementation Limitations

- Expensive for CPU-bound servers
- Requires deterministic behavior
  - Most sources of nondeterminism removed
  - Timing can be a problem (see poster)
- Dangerous system calls
  - `execve()`, `mmap()`
- Variants lack complete isolation
- Does not address recovery

Fundamental Limitation

- Only protects against attacks whose assumptions are broken by variations
- Opportunities
  - Low entropy variations (e.g., calling conventions, timing, root uid, …)
  - High-level variations
    - Requires knowledge of application semantics

Summary

N-Variant systems employ artificial diversity techniques to provide provable resilience against certain classes of attacks without needing secrets.

www.cs.virginia.edu/nvariant

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