Morpheus
A Vulnerability-Tolerant Secure Architecture

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Presented by Miles Dai
6.888, Fall 2020
Motivation

A vulnerability-agnostic secure system can be created by defending against exploitation of undefined semantics.

- Control flow exploits are still prevalent!
- New threats use more execution-level information to bypass defenses
- A systematic approach is needed to future-proof processors
Intuition

- We can think of program execution as occurring on multiple levels
  - Language level: we create some pointer to some memory
  - Execution level: where is that memory located? How do I dereference the pointer? What is the memory initialized to? Where is the stack?

- **Moving target defenses**: since benign programs are (mostly) agnostic to execution-level details, what if we randomize them?

- Strengthen existing moving target defenses through layering defenses and continuous randomization.
  - Ensembles of Moving Target Defenses (EMTD)
  - Churn
Threat Model

• A trusted but vulnerable victim processes untrusted inputs

• Trusted
  • Physical system
  • Boot sequence
  • Random number generator
  • Morpheus hardware
  • Loader and OS scheduler

• Attacker exploits memory errors to hijack control flow

• Currently does not protect against DoS and side-channel attacks
Discussion

What are some strengths and weaknesses of Morpheus?
Evaluation

Strengths

• Systematic approach to memory safety
• Low execution and adoption overhead

Weaknesses

• More discussion on tag propagation and attack detector logic: implementation and area overheads
• Application to non-64-bit architectures might have reduced security guarantees
Domain Tagging

• Memory falls into 4 Domains: code (C), code pointers (CP), data pointers (DP), data (D)
• Compiler tags memory objects in two passes
• Microarchitectural support
  • Each register gets two additional bits
  • All tag information sits together in DRAM and are cached
  • Pipeline propagates tags
• Domain tagging allows for moving target defenses (MTDs)
Pointer Displacement – MTD 1

• Present a Displaced Address Space (DAS) offset by up to $2^{60}$ to the program
• Code and Data segments receive different offsets
Pointer Displacement Defense
Domain Encryption – MTD 2

• Code, code pointers, and data pointers are encrypted with distinct keys. Variable-sized non-pointer data values are not encrypted.

• Data is encrypted/decrypted on the L1-L2 boundary; L2 and DRAM only contain encrypted information.

• Physical address is encrypted with corresponding key and XOR’ed with value.
Domain Encryption Defense
Churn

• Creates new offset for data and code segments
• Re-encrypts all encrypted data with new keys
• Steps: Pipeline flush, key generation, register updates, memory update using threshold register
Attack Detector

- Domain tagging allows for policy enforcement
- Program can be ABORTed or suspicious behavior can trigger CHURN

<table>
<thead>
<tr>
<th>&lt;OP&gt;</th>
<th>Check Condition</th>
<th>Rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABORT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Execute</td>
<td>Instr.tag != C</td>
<td>Only execute C</td>
</tr>
<tr>
<td>ANY</td>
<td>R1/R2.tag == C</td>
<td>No C in the pipeline</td>
</tr>
<tr>
<td>JAL(R)</td>
<td>R1.tag != CP</td>
<td>Jump target must be CP</td>
</tr>
<tr>
<td>LD/ST</td>
<td>R1.tag != DP</td>
<td>Address must be a DP</td>
</tr>
<tr>
<td>COMPARE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANY (not JAL(R))</td>
<td>R1.tag != R2.tag</td>
<td>No inter-domain compares</td>
</tr>
<tr>
<td>ANY (not LD/ST)</td>
<td>R1.tag == CP</td>
<td>CP arithmetic suspicious</td>
</tr>
<tr>
<td></td>
<td>R2.tag == DP</td>
<td>DP arithmetic suspicious, except add/sub D</td>
</tr>
<tr>
<td>CHURN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANY</td>
<td>Overflow Occurs</td>
<td>Overflows are undefined</td>
</tr>
<tr>
<td>SHIFT</td>
<td>Shift &gt; RegWidth</td>
<td>Invalid shift is undefined</td>
</tr>
</tbody>
</table>
Attack Detector Defense

1. Make a pointer go out of bounds
2. Use pointer to write or free
3. Modify a data pointer
4. ... to the attacker specified code
5. Use pointer by indirect call/jump
6. Execute available gadgets / functions

- Code corruption attack
- Control-flow hijack attack
- Data-only attack
- Information leak

- Code Integrity
- Code Pointer Integrity
- Address Space Randomization
- Control-Flow Integrity
- New Instruction Set Randomization

- V1. Memory Safety
- V1.A. Code Integrity
- V2. Data Space Randomization
- V2.A. Data Integrity
- V3. Interpret the output data
- V3.A. Data Variable

- Attack Detector Defense
Evaluation – EMTD Effectiveness

• Stacking defenses (ensemble) has clear benefits
• Attack probe time increases with more defenses applied
  • $E = \text{encryption}, \ P = \text{pointer displacement}$
Performance Impact of Churn

• Large data segments, more pointers, and large codebases cause more work for the churn unit

• For long churn periods (200 ms), churn very slightly improves performance as it acts as a prefetcher
Evaluation – Adoptability

Based on the criteria outlined in the SoK paper\(^1\):

- Performance overhead
- Compatibility
  - Software toolchain based on LLVM compiler extensions
  - Displacement preserves physical memory alignment
  - Extensive hardware modifications needed
- Robustness
  - More robust than many existing solutions to currently unknown attacks
- Dependencies
  - Toolchain does not appear to be publicly available currently

\(^1\)SoK: Eternal War in Memory. Laszlo Szekeres et al.
Comparison with Existing Solutions

• Displacement (e.g. ASLR)
  • Insufficient randomness
  • Single address leakage discloses all code and data locations

• Encryption
  • Morpheus generally has lower overhead with HW support and stronger encryption

• Software-based MTD (e.g. Shuffler)
  • Morpheus shows lower overhead and more entropy

• Tagged Architectures
  • Full labeling of code is hard and other hardware-based tags lead to high false-positives
Discussion Questions - Security

• Does the fact that pointers are all linearly displaced by a constant amount (rather than being truly shuffled) make this scheme vulnerable to attack?
• Is it possible to avoid triggering churn by exfiltrating data through side channels?
• How could Morpheus be extended to consider DoS attacks in its threat model?
Discussion Questions - Applications

• How does "data" become code safely? (In the sense of a downloaded program being executed for the first time, or really anything being loaded from disk, or JIT programs)

• Are there legitimate uses of reading pointers as data that Morpheus will make impossible? E.g. debugging with stack traces will be very difficult though potentially possible.
Discussion Questions - Performance

• Can continuous churn cause performance issues or battery life reduction (denial of service rather than control flow attack)? Is it just exchanging one attack for another?

• Are there legitimate programs that Morpheus hinders?