Morpheus

A Vulnerability-Tolerant Secure Architecture

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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

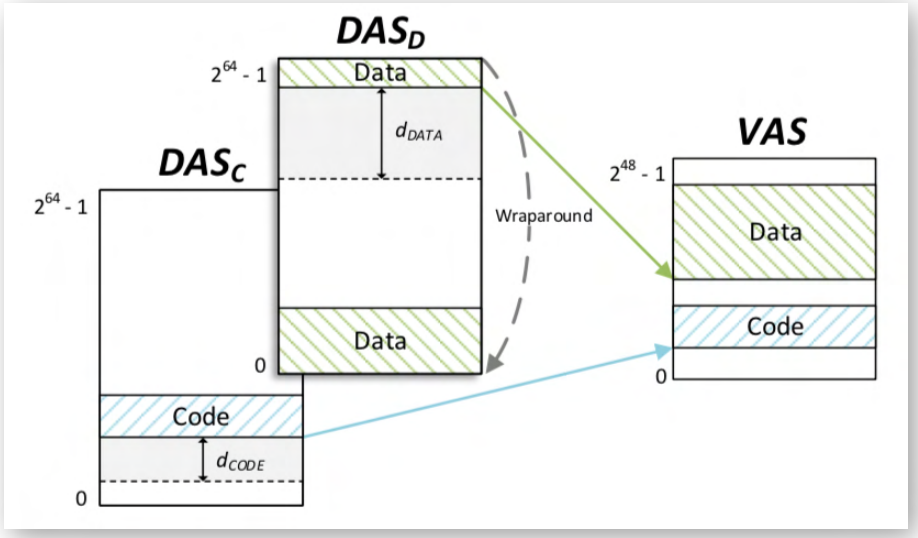
- More discussion on tag propagation and attack detector logic: implementation and area overheads
- Application to non-64-bit architectures might have reduced security guarantees

Domain Tagging

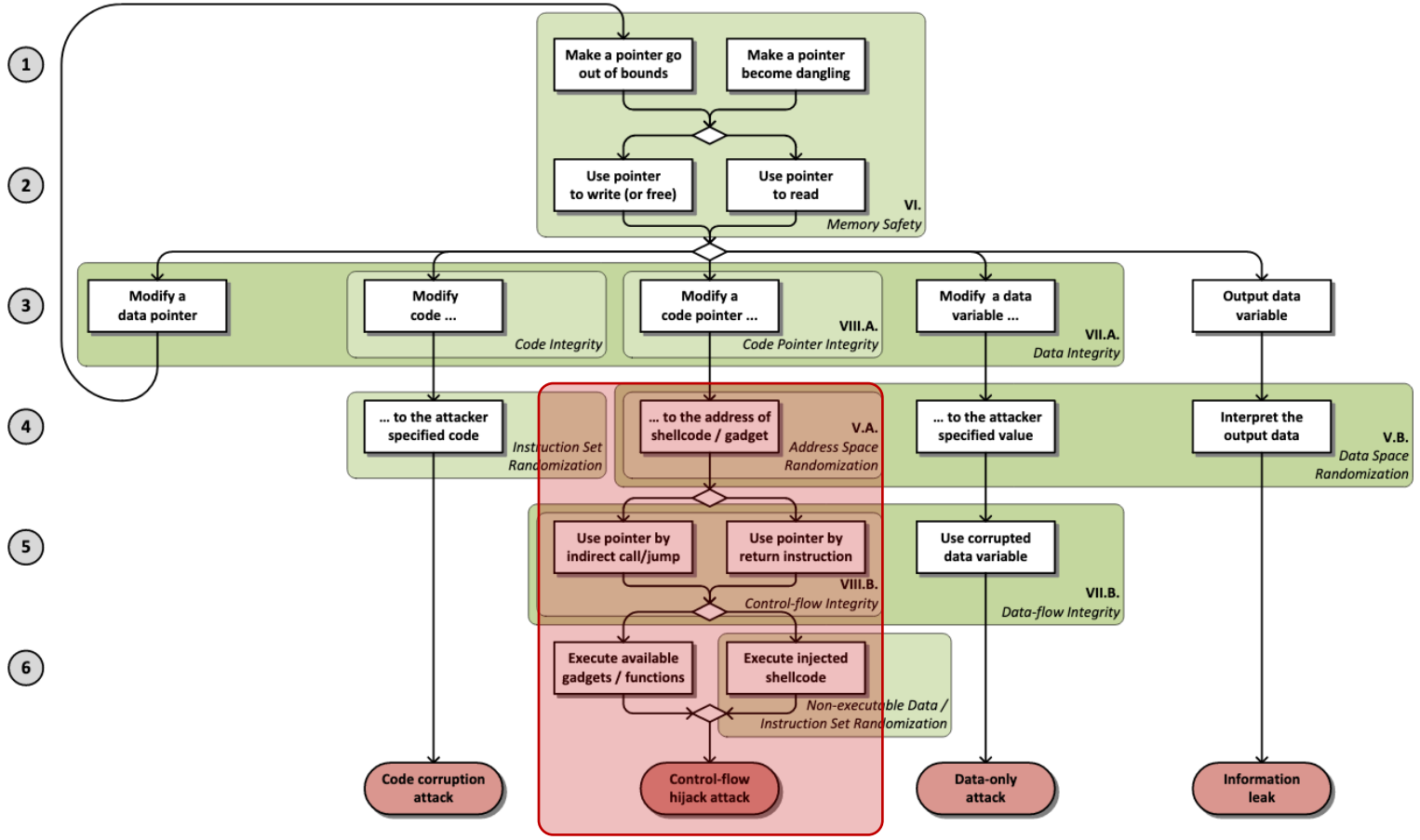
- Memory falls into 4 Domains: code (C), code pointers (CP), data pointers (DP), data (D)
- Compiler tags memory objects in two passes
- Microarchitectural support
  - Each register gets two additional bits
  - All tag information sits together in DRAM and are cached
  - Pipeline propagates tags
- Domain 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

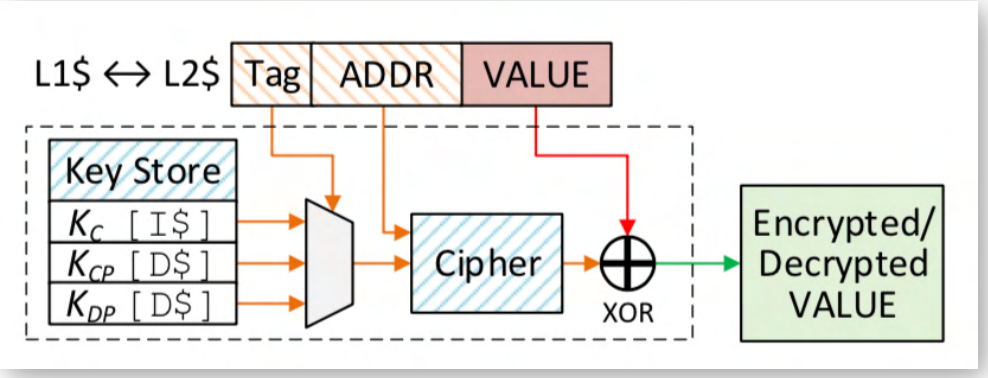


Pointer Displacement Defense

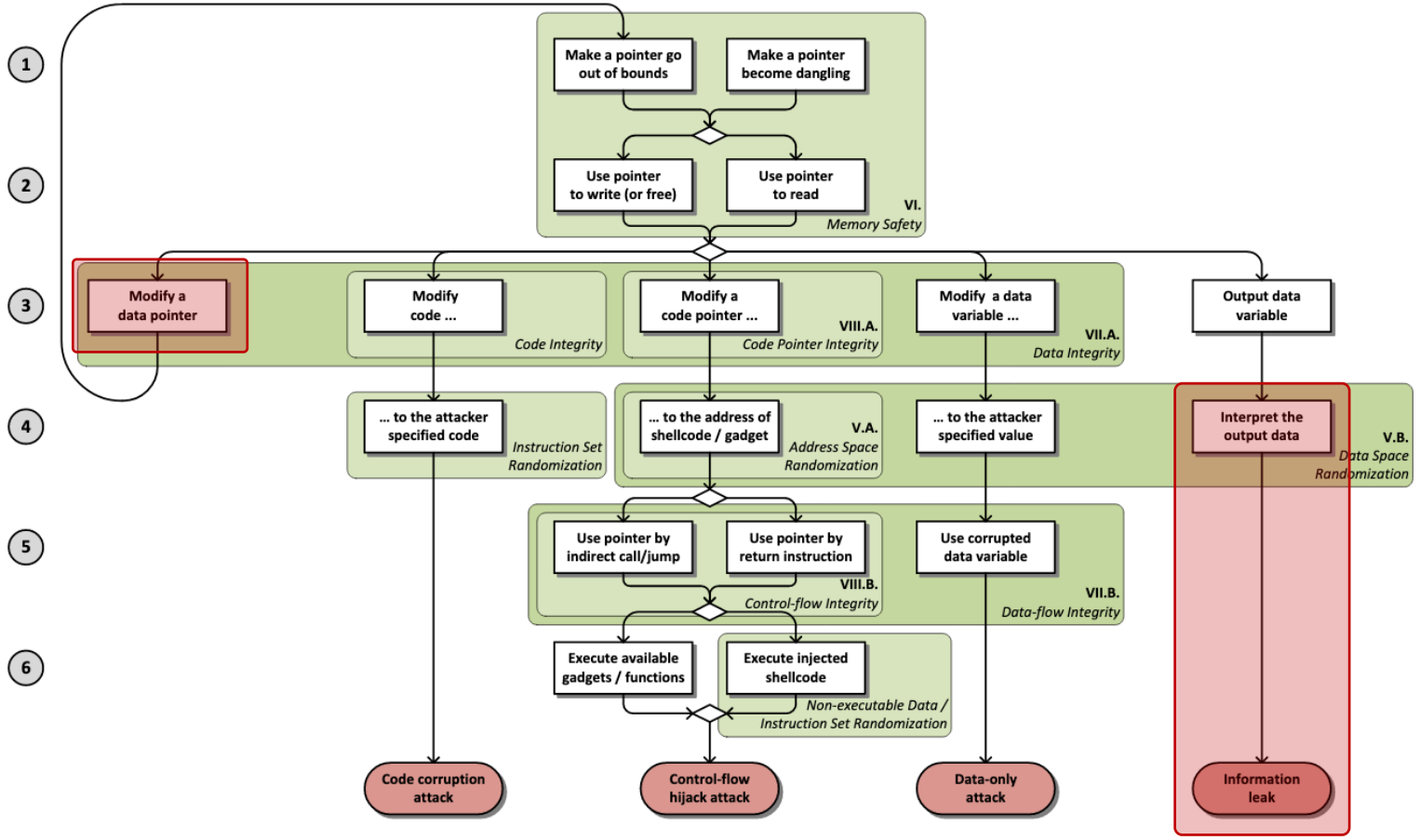


Domain Encryption – MTD 2

- 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

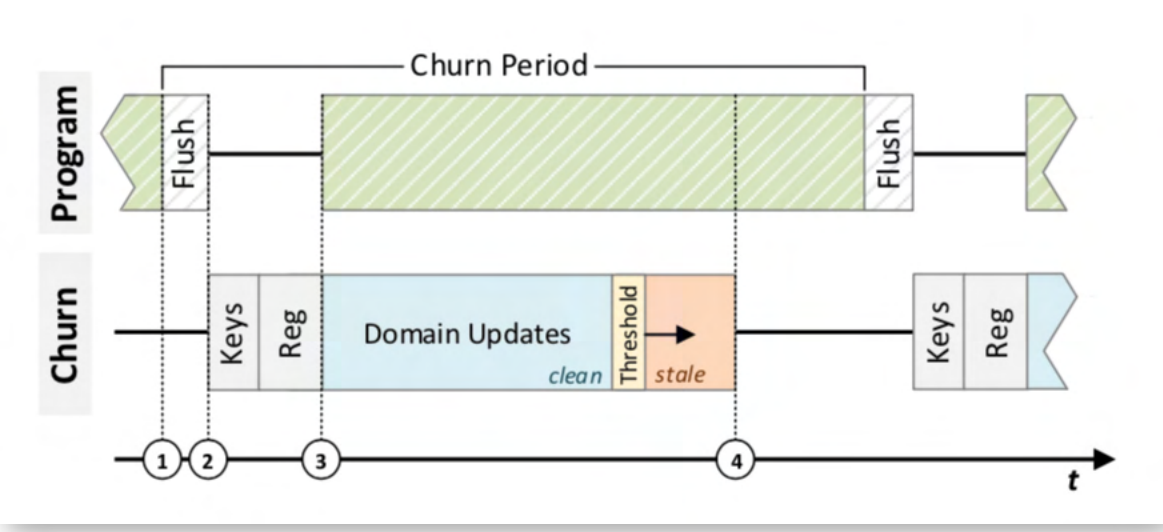


Domain Encryption Defense



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

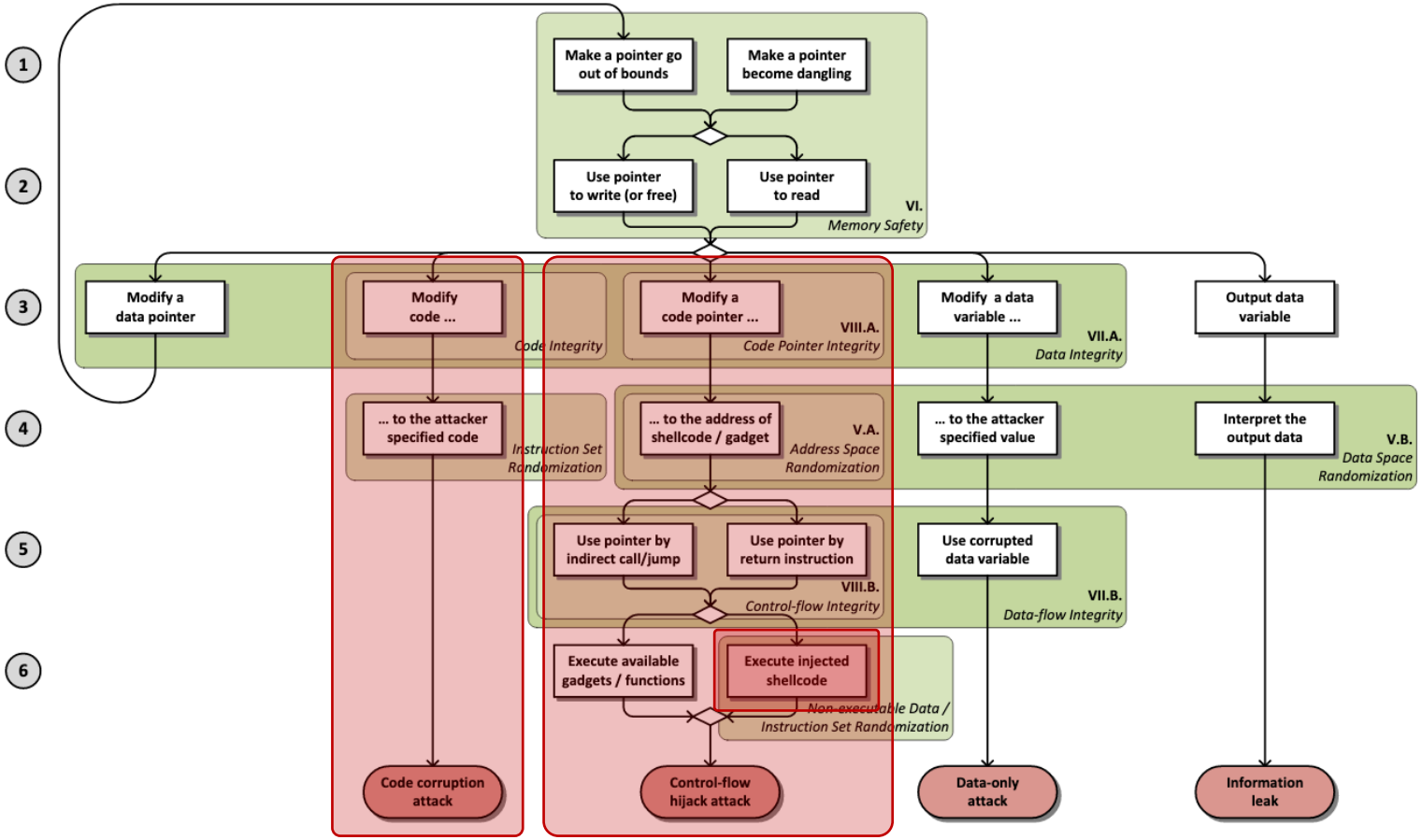


Attack Detector

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

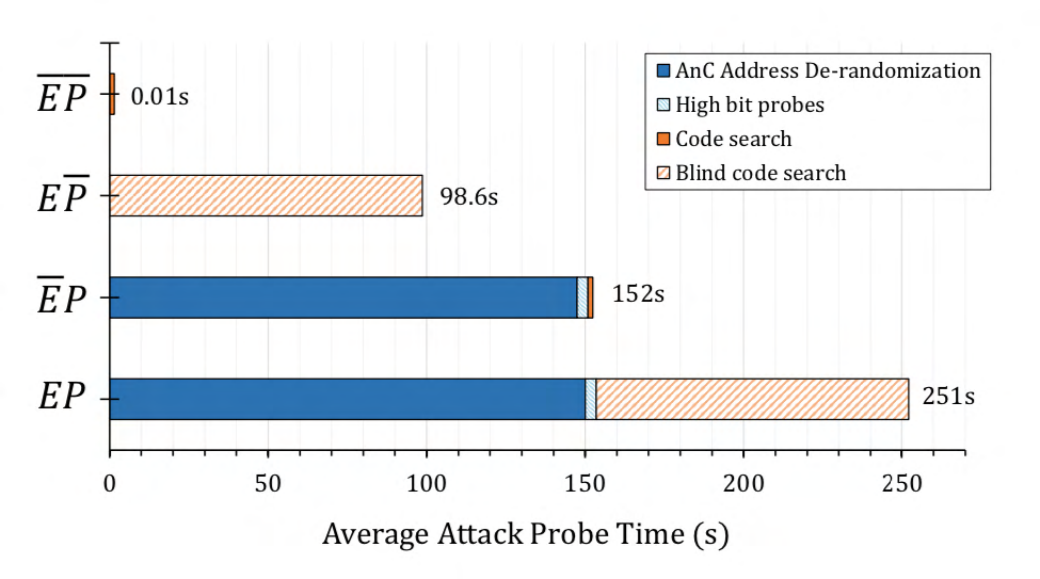
	<OP>	Check Condition	Rule
ABORT	Execute	Insn.tag != C	Only execute C
	ANY	R1/R2.tag == C	No C in the pipeline
	JAL(R)	R1.tag != CP	Jump target must be CP
	LD/ST	R1.tag != DP	Address must be a DP
CHURN	COMPARE	R1.tag != R2.tag	No inter-domain compares
	ANY (not JAL(R))	R1.tag == CP	CP arithmetic suspicious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

Attack Detector Defense



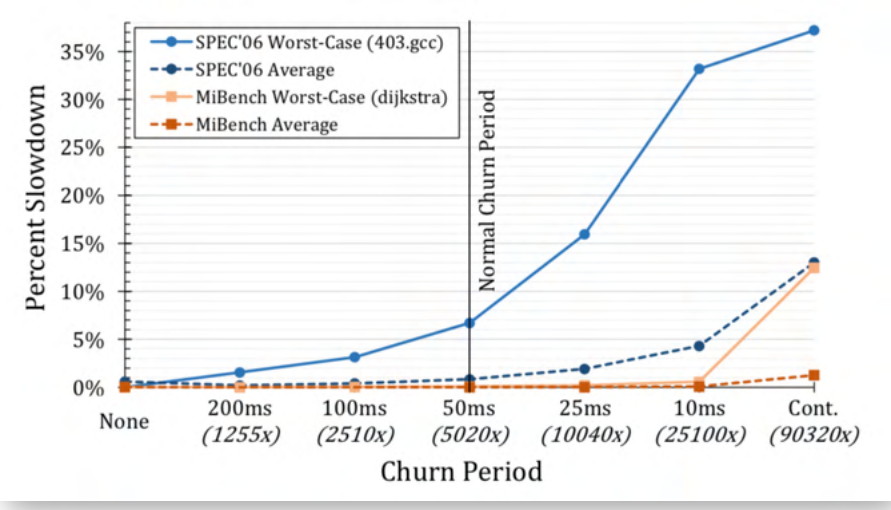
Evaluation – EMTD Effectiveness

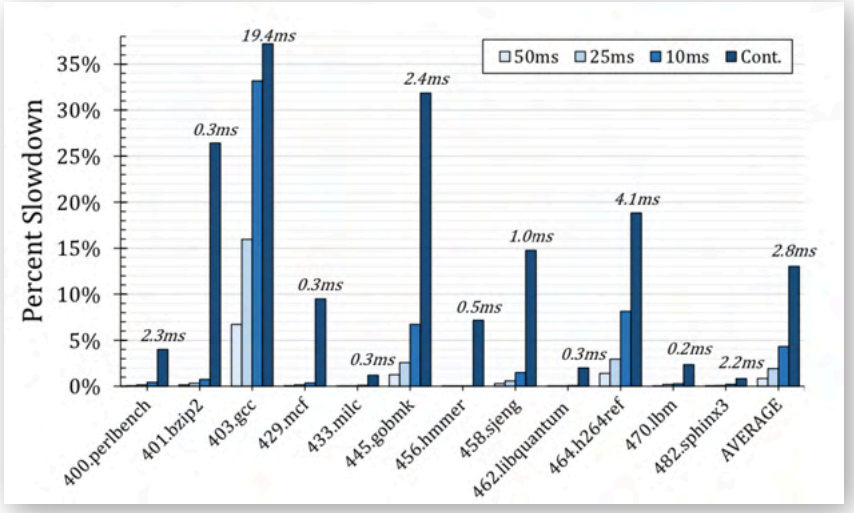
- Stacking defenses (ensemble) has clear benefits
- Attack probe time increases with more defenses applied
  - E = encryption, P = pointer displacement



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?