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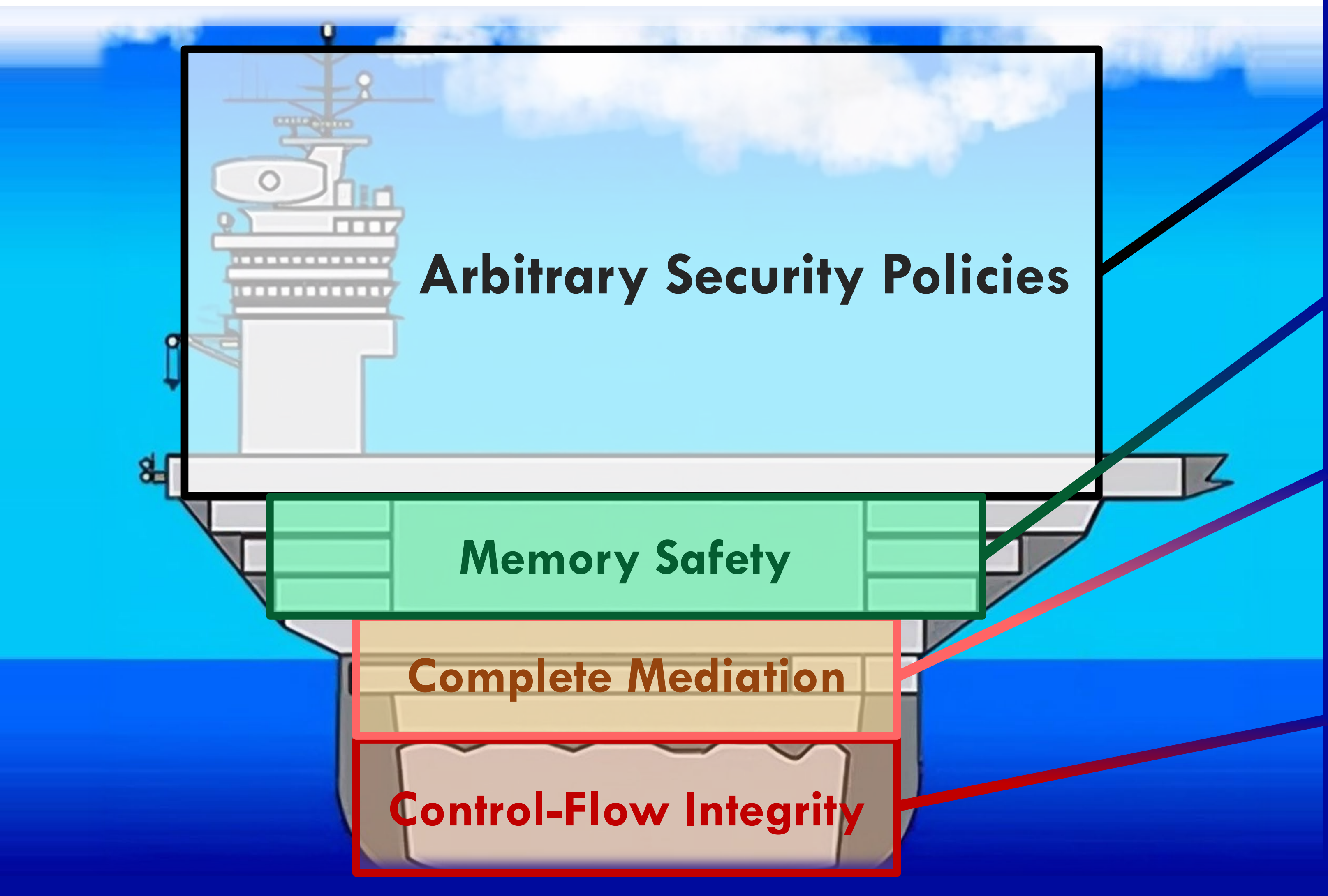
Software Attack Surface Reduction On The Fly

Dr. Kevin Hamlen

ONR Award N00014-21-1-2654

Foundations of Software Security



- Safety + Liveness = Everything
  - Safety: “bad events” prohibited
  - Liveness: “good events” guaranteed

- Memory Safety
  - Secure security state storage

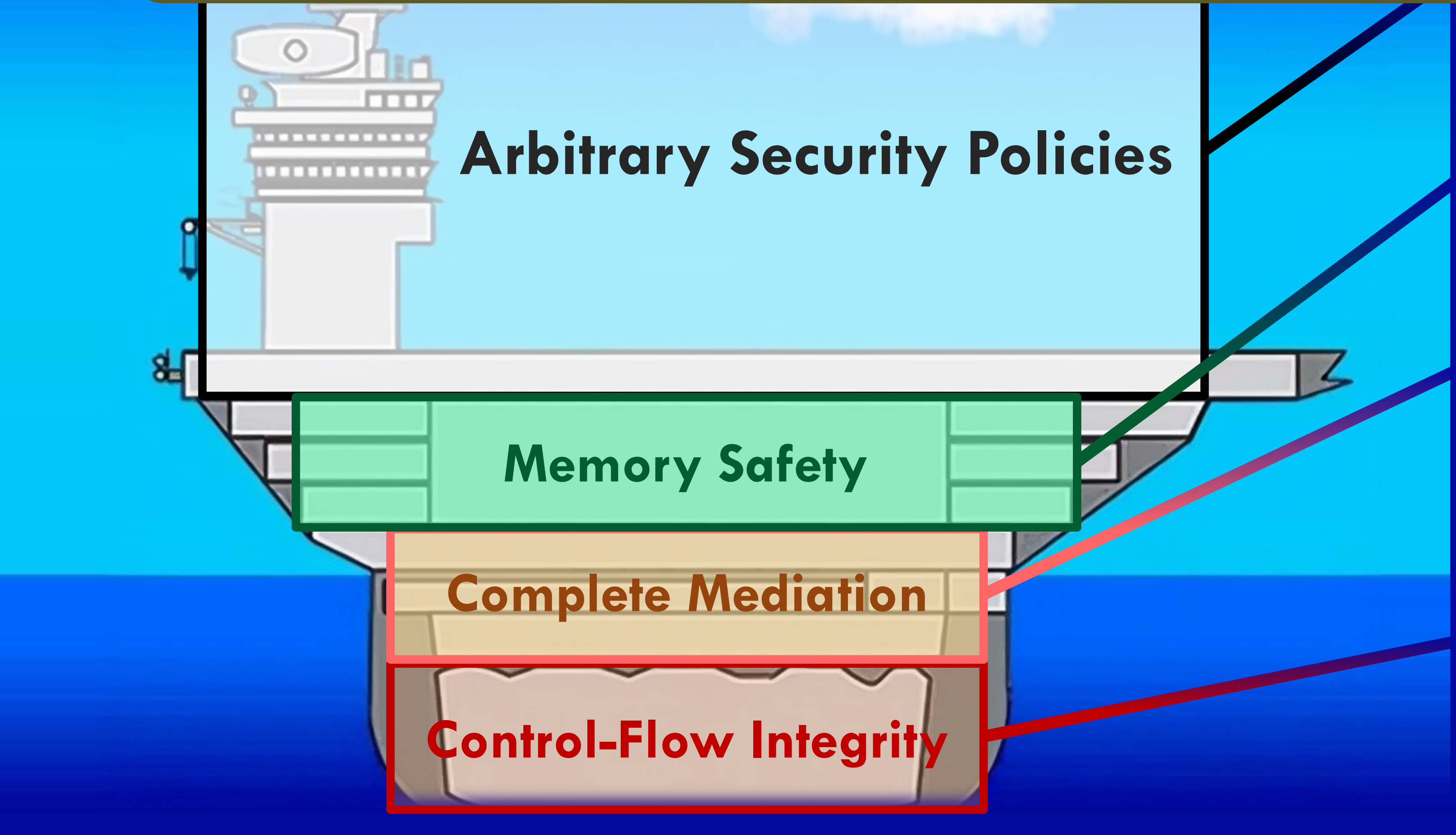
- Complete Mediation
  - Surround all security-relevant operations with uncircumventable guard code (security checks)

- Control-Flow Integrity (CFI)
  - Constrains execution order to a graph of allowed flows
  - Affords provably uncircumventable basic blocks of program instructions

Foundations of Software Security

Static Code Instrumentation

Dynamic Policy Enforcement

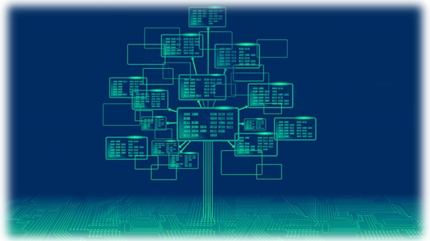



```
for (int i = 0; i < 32; ++i) {
  if (safe(&buf[i]))
    buf[i] = i;
  else
    abort(“memory corruption!”);
  if (++counter > max)
    abort(“deadlock alert”);
  if (check(&obj->method)
      && valid_args(buf, i)) {
    obj->method(buf, i);
  } else
    abort(“security alert!”);
}
```

Binary Code Debloating Architecture

1) Learn debloating policy from execution traces
   - consumer has no formal policy specification
   - consumer is not aware of all "undesired" program functionalities
2) Machine learning derives suitable policy from a whitelist of traces
3) Enforce learned policy with source-free, **context-sensitive** CFI
   - generalizes and subsumes non-contextual CFI and code byte erasure
4) Machine-validate binary hardening transforms for highest assurance
   - Picinæ: <u>P</u>latform <u>In</u> <u>C</u>oq for <u>IN</u>struction-level <u>A</u>nalysis of <u>E</u>xecutables

trace
whitelist

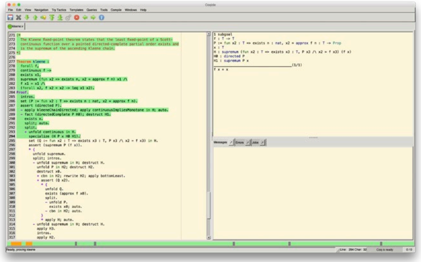


Machine Learning

policy

Binary, Context-sensitive CFI

debloated
binary



Formal Validation

Binary Code Debloating Architecture

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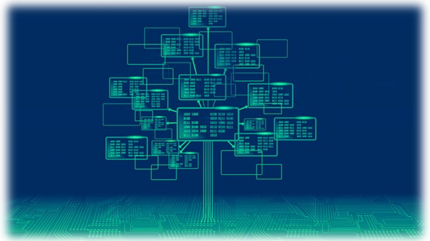
trace whitelist

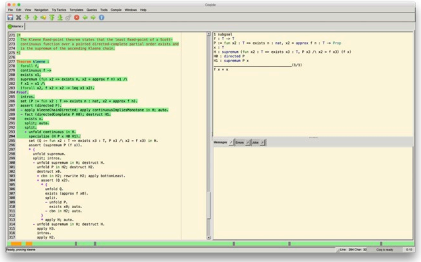


Machine Learning

policy

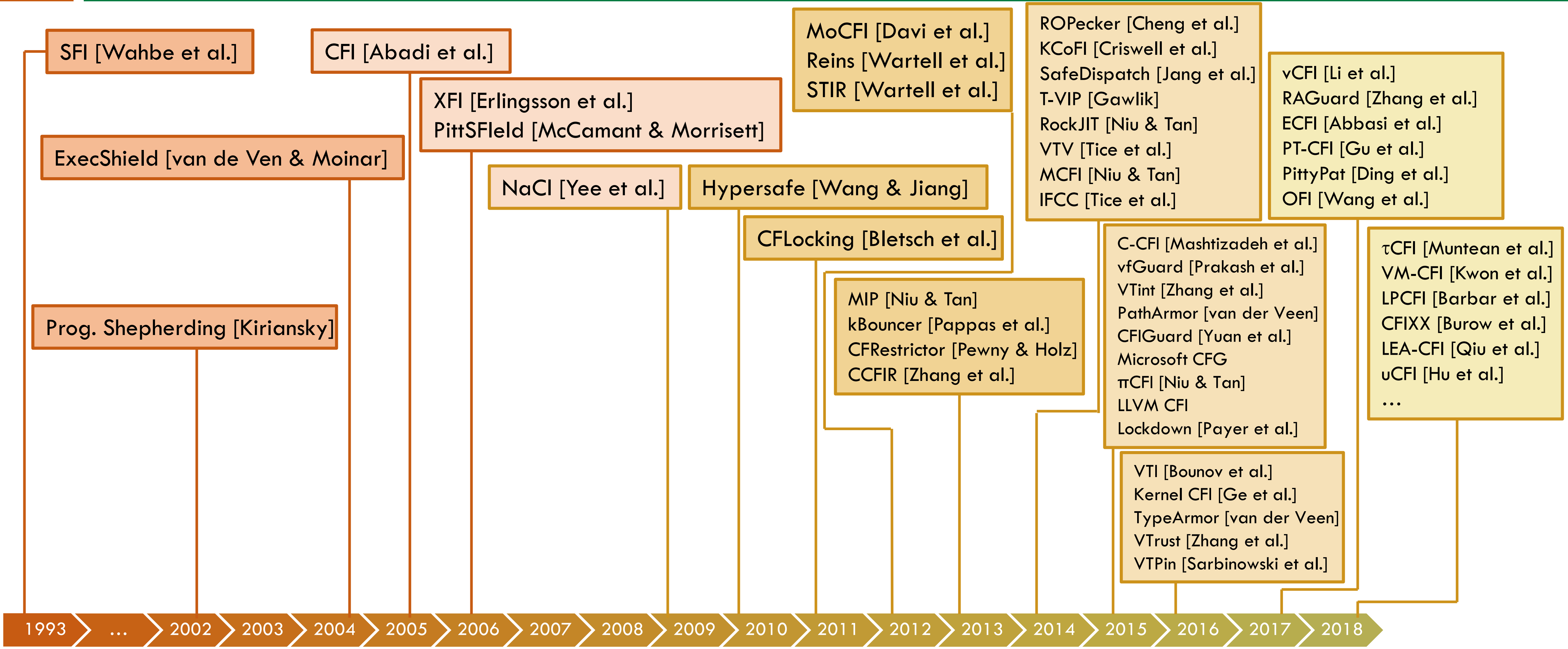
Binary, Context-sensitive CFI

debloated binary



Formal Validation

CFI Research Timeline



CFI Research Timeline

SFI [Wahbe et al.]

ExecShield [van de Ver

Prog. Shepherding [Kiri

1993 … 2002 200

SECURITY

- RIPE test suite

PERFORMANCE

- CPU SPEC benchmarks

COMPATIBILITY

-

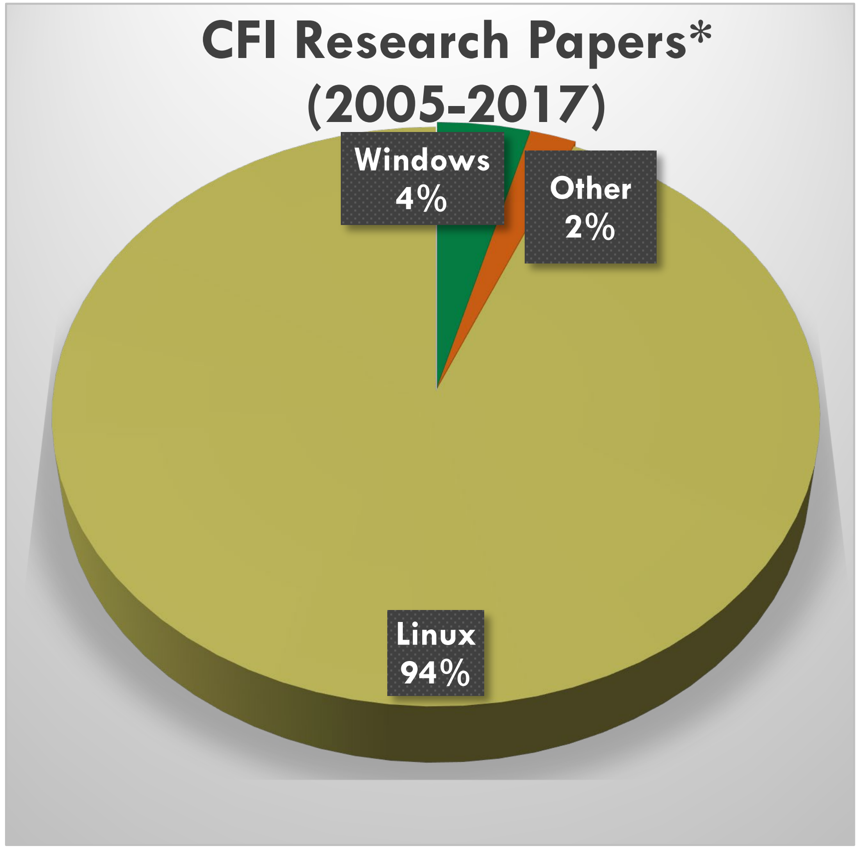
CFLocking [Bletsch et al.]

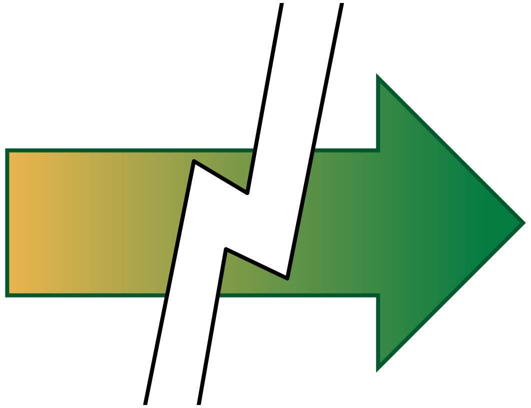
et al.]
rd [Zhang et al.]
bbasi et al.]
Gu et al.]
[Ding et al.]
ang et al.]

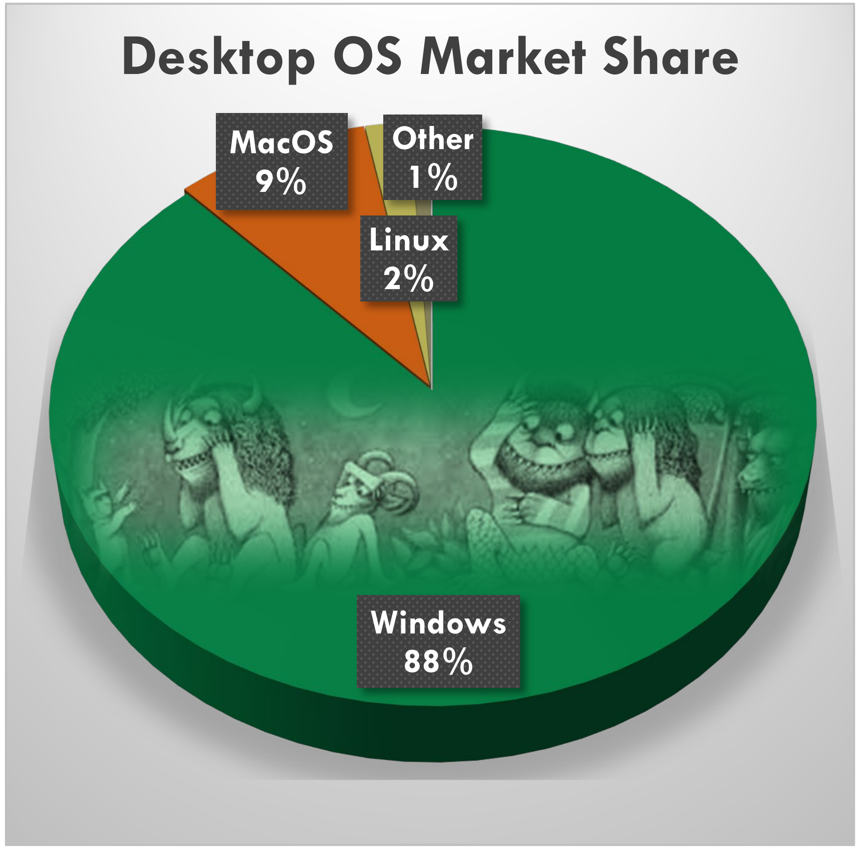
τCFI [Muntean et al.]
VM-CFI [Kwon et al.]
LPCFI [Barbar et al.]
CFIXX [Burow et al.]
LEA-CFI [Qiu et al.]
uCFI [Hu et al.]
…

18

Scalability Gap



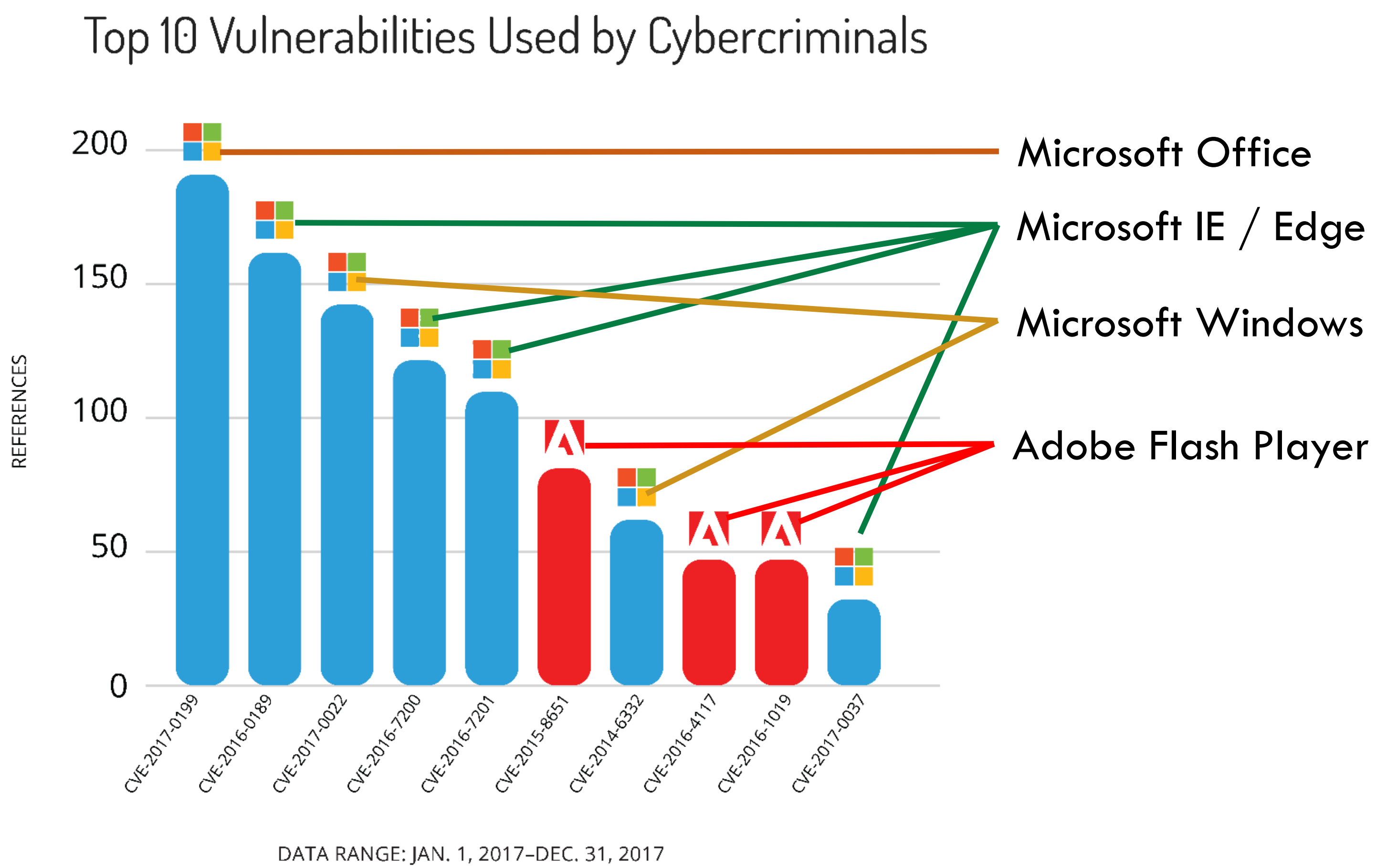


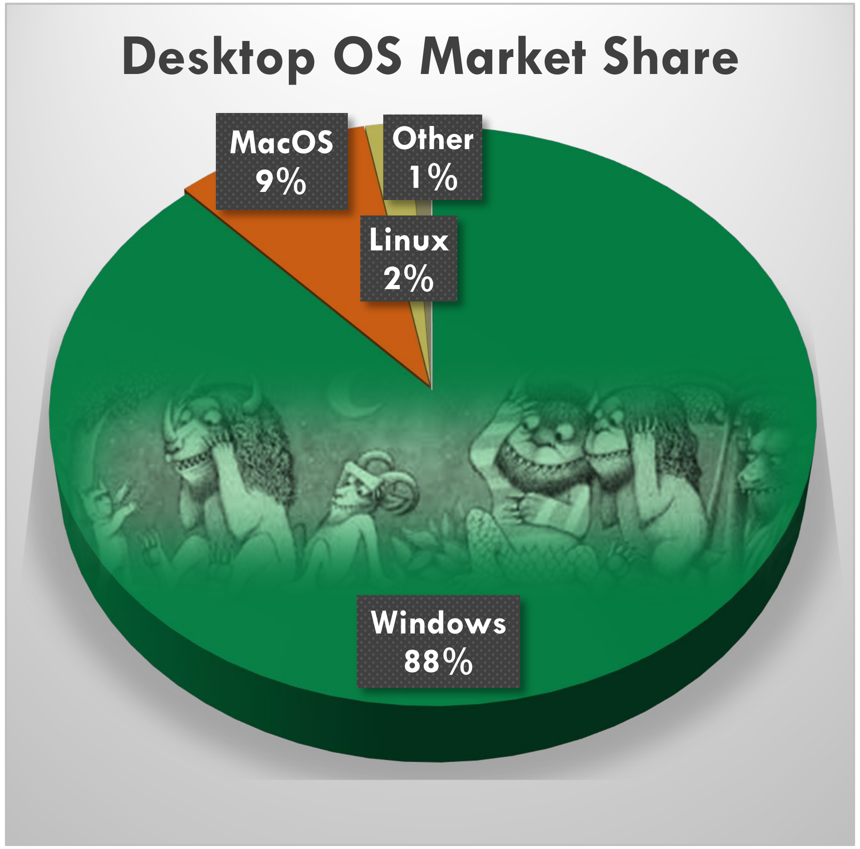


*Papers containing at least one experiment where at least <u>one</u> **<u>COMPLETE</u>** <u>non-benchmark</u> <u>application</u> for the indicated OS was rewritten & secured

Where the Wild Things Are

[RecordedFuture, CTA-2018-0327]





Soft(ware) Targets

- Windows/MacOS in mission-critical environments
  - "About 75% of control systems are on **Windows XP** or other **nonsupported** OSes." –Daryl Haegley, Office of Assistant Secretary of Defense for Energy, Installations and Environment
  - More than 25% of all government computers currently run an **outdated Windows** or **MacOS** operating system. [BitSight, 6/1/17]
  - DHS, Coast Guard, and Secret Service currently store top secret information on **outdated Windows 2003** servers. [OIG-18-56, 3/1/18]
  - Hundreds of *satellites* run **Windows 95** and/or are controlled by **Windows Mobile** devices.

20 Widespread Classes of CFI Compatibility Problems

Compatibility Metric	Real-world Software Examples
Function Pointers	7-Zip, Adobe Reader, Apache, Calculator, Chrome, Dropbox, Firefox, JVM, …
Callbacks	7-Zip, Adobe Reader, Apache, Calculator, Chrome, Dropbox, Firefox, JVM, …
Dynamic Linking	7-Zip, Adobe Reader, Apache, Calculator, Chrome, Dropbox, Firefox, JVM, …
Delay-Loading	Adobe Reader, Calculator, Chrome, Firefox, JVM, MS Paint, MS Powerpoint, …
Exporting/Importing Data Symbols	7-Zip, Apache, Calculator, Chrome, Dropbox, Firefox, MS Paint, MS Powerpoint, …
Virtual Functions	7-Zip, Adobe Reader, Calculator, Chrome, Dropbox, Firefox, JVM, Notepad, …
Writable Vtables	programs with UI's based on GTK+ (Linux) or COM (Windows)
Tail Calls	programs compiled with tail-call optimization (e.g., -O2 or /O2)
Switch-Case Statements	7-Zip, Adobe Reader, Apache, Calculator, Chrome, Dropbox, Firefox, JVM, …
Returns	almost every benign program
Unmatched Call/Return Pairs	Adobe Reader, Apache, Chrome, Firefox, JVM, MS PowerPoint, Visual Studio, …
Exceptions	7-Zip, Adobe Reader, Apache, Calculator, Chrome, Dropbox, Firefox, JVM, …
Calling Conventions	almost every program has functions
Multithreading	7-Zip, Adobe Reader, Apache, Calculator, Chrome, Dropbox, Firefox, JVM, …
TLS Callbacks	Adobe Reader, Chrome, Firefox, MS Paint, TeXstudio, UPX
Position-Independent Code	7-Zip, Adobe Reader, Apache, Calculator, Chrome, Dropbox, Firefox, JVM, …
Memory Management	7-Zip, Adobe Reader, Apache, Chrome, Dropbox, Firefox, MS PowerPoint, …
JIT Code	Adobe Flash, Chrome, Dropbox, Firefox, JVM, MS PowerPoint, PotPlayer, …
Self-Unpacking	programs decompressed by self-extractors (e.g., UPX, NSIS)
Runtime API Hooking	Microsoft Office, including MS Excel, MS PowerPoint, etc.

ConFIRM CFI Compatibility Benchmark Suite

Control-Flow Integrity Relevance Metrics (ConFIRM):

https://github.com/SoftwareLanguagesSecurityLab/Confirm

ConFIRM: Control-Flow Integrity Relevance Metrics

https://github.com/SoftwareLanguagesSecurityLab/Confirm

	LLVM (Windows)						LLVM (Linux)						
Test	CFI	ShadowStack	MCFG	OFI	Reins	GCC-VTV	CFI	ShadowStack	MCFI	πCFI	πCFI (nto)	PathArmor	Lockdown
fptr	6.35%	⚠	20.13%	4.35%	4.08%	⚠	6.97%	⚠	✗	-14.00%	-13.79%	⚠	174.92%
callback	⚠	⚠	⚠	128.39%	114.84%	⚠	⚠	⚠	✗	✗	✗	⚠	✗
load_time_dynlnk	2.74%	⚠	8.83%	3.36%	2.66%	⚠	1.33%	⚠	30.83%	31.52%	34.05%	74.54%	1.45%
run_time_dynlnk	⚠	⚠	17.63%	12.57%	11.48%	⚠	4.44%	⚠	✗	✗	✗	1,221.48%	✗
delay_load	N/A	N/A	8.16%	3.61%	✗	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
data_symbl	✓	⚠	✓	✓	✗	✓	✓	⚠	✓	✓	✓	✓	✓
vtbl_call	5.62%	⚠	27.71%	35.94%	31.17%	33.56%	5.94%	⚠	✗	-8.19%	-9.31%	⚠	227.82%
code_coop	⚠	⚠	⚠	✓	✗	⚠	⚠	⚠	⚠	⚠	⚠	⚠	⚠
tail_call	6.17%	⚠	9.51%	0.05%	0.05%	⚠	6.82%	⚠	✗	-17.69%	-17.37%	⚠	178.06%
switch	-5.80%	⚠	3.51%	22.82%	17.69%	⚠	-6.93%	⚠	-29.01%	-27.19%	-28.46%	⚠	85.85%
ret	⚠	18.04%	⚠	49.34%	48.49%	⚠	⚠	20.88%	70.72%	72.40%	71.52%	⚠	106.71%
unmatched_pair	⚠	⚠	⚠	✓	✓	⚠	⚠	⚠	✓	✓	✓	⚠	⚠
signal	✓	⚠	✓	✗	✗	✓	✓	⚠	✓	✓	✓	✗	✓
cppeh	✓	⚠	✓	✓	✗	✓	✓	⚠	✓	✓	✓	✗	✓
seh	✓	⚠	✓	✓	✗	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
veh	⚠	⚠	⚠	✓	✗	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
convention	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓
multithreading	⚠	⚠	⚠	⚠	⚠	⚠	⚠	⚠	⚠	⚠	⚠	⚠	⚠
tls_callback	N/A	N/A	N/A	✓	✗	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
pic	✓	✓	✓	⚠	⚠	✓	✓	✓	✓	✓	✓	✓	✓
mem	⚠	⚠	⚠	⚠	⚠	⚠	⚠	⚠	✗	✗	✗	✓	✗
jit	⚠	⚠	⚠	✗	✗	⚠	⚠	⚠	✗	✗	✗	⚠	✗
unpacking	N/A	N/A	N/A	✗	✗	N/A	N/A	N/A	N/A	N/A	N/A	✗	✗
api_hook	⚠	⚠	⚠	✗	✗	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Major Findings

- Multithreading + Unmatched call/return pairs = Trouble
  - unmatched call/returns arise from: exceptions, tail-call optimization
  - cross-thread stack smashing beats all CFI defenses we tested
  - seems hard to fix without huge performance overheads
- Runtime Code Generation
  - more prevalent than generally expected
    - rise of JIT-compiled languages, runtime hooking, self-extracting components
  - most RCG is beyond the reach of all CFI algorithms
- Questionable whether SPEC CPU adequately tests CFI performance
  - SPEC CPU benchmarks chosen/designed to test <u>CPU speeds</u>
  - Operation profiles prioritize opcodes that bottleneck <u>non-CFI software</u>
  - Mostly simple control-flow graphs

CFI Performance Measurement Problems

SPEC CPU Benchmark	CFI Solution									**Benchmark Correlation**
	MCFG	**Reins**	**GCC-VTV**	**LLVM-CFI**	**MCFI**	**πCFI**	**πCFI** (nto)	**PathArmor**	**Lockdown**	
perlbench				2.4	5.0	5.0	5.3	15.0	150.0	**0.09**
bzip2	−0.3	9.2		−0.7	1.0	1.0	0.8	0.0	8.0	**−0.12**
gcc					4.5	4.5	10.5	9.0	50.0	**0.02**
mcf	0.5	9.1		3.6	4.5	4.5	1.8	1.0	2.0	**−0.39**
gobmk	−0.2			0.2	7.0	7.5	11.8	0.0	43.0	**−0.09**
hmmer	0.7			0.1	0.0	0.0	−0.1	1.0	3.0	**0.33**
sjeng	3.4			1.6	5.0	5.0	11.9	0.0	80.0	**−0.03**
h264ref	5.4			5.3	6.0	6.0	8.3	1.0	43.0	**−0.09**
libquantum				−6.9	0.0	−0.3	−1.0	3.0	5.0	**0.51**
omnetpp	3.8		5.8		5.0	5.0	18.8			**−0.52**
astar	0.1		3.6	0.9	3.5	4.0	2.9		17.0	**0.92**
xalancbmk	5.5		24.0	7.2	7.0	7.0	17.6		118.0	**0.94**
milc	2.0			0.2	2.0	2.0	1.4	4.0	8.0	**0.40**
namd	0.1		−0.1	0.1	−0.5	−0.5	−0.5	3.0		**0.98**
dealII	−0.1		0.7	7.9	4.5	4.5	4.4			**−0.36**
soplex	2.3		0.5	−0.3	−4.0	−4.0	0.9	12.0		**0.89**
povray	10.8		−0.6	8.9	10.0	10.5	17.4		90.0	**0.88**
lbm	4.2			−0.2	1.0	1.0	−0.5	0.0	2.0	**−0.22**
sphinx3	−0.1			−0.8	1.5	1.5	2.4	3.0	8.0	**0.31**
ConFIRM median	9.51	4.59	33.56	5.19	30.83	−11.10	−11.60	648.01	140.82	**0.36**

CFI vs. Runtime Code Generation

- CFI Fundamental Assumptions (Abadi et al., 2005)
  - Non-Writable Code (NWC)
  - Non-Executable Data (NXD)
- Most Modern Software Violates Both
  - Rise of Just-In-Time (JIT) Languages since 2005
    - Lua, JavaScript, Python, Java, Ruby, PHP, Erlang, Wasm, Lisp, Etherium, …
    - Everything on .NET, all Microsoft COM software, …
  - All self-unpacking components (e.g., cloud), installers (e.g., UPX), …
  - Many forms of dynamic loading & hooking (example: Microsoft Office)

Existing Solutions

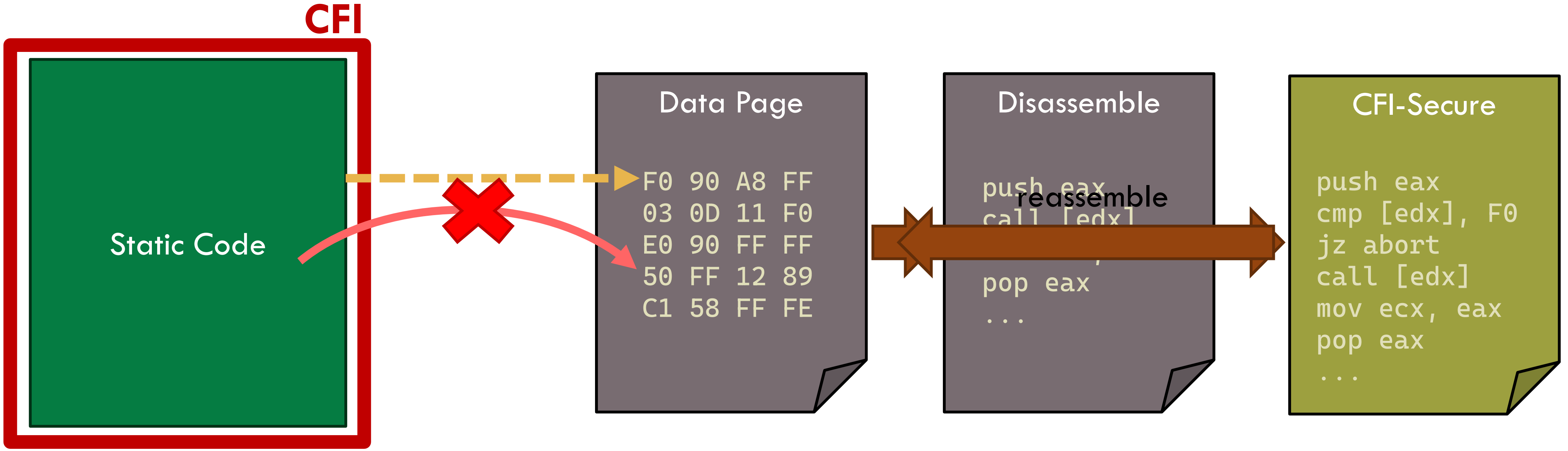
- Manually customize the code generator (RockJIT [Niu & Tan, CCS'14])
  - Extremely high maintenance burden
  - Only works for certain very specific code generation patterns (old JITs)
  - Incompatible with all modern software **(~9 years of 100% incompatibility)**
- Turn off all dynamic code generation
  - Massive performance hit **(e.g., 1600% overhead on JS Octane)**
  - Impossible for many products (.NET)
  - Introduces new compatibility & security problems

Real-world Example: Edge Browser

- Browser devs begin to realize that JIT is a huge security risk:
  - Over half of in-the-wild Chrome exploits from 2018-2021 abuse JIT vulnerabilities. [Mozilla Research, 2021]
  - More than 70% of the top programming languages are JIT-compiled, including JavaScript in almost all browsers.
- Microsoft turns off the JIT completely to enforce CFI in "secure mode"
  - *"As of Microsoft Edge 98, Control-flow Enforcement Technology (CET) and Arbitrary Code Guard (ACG) will be enabled in the renderer process when a site is in enhanced security mode. These additional mitigations* ***prevent dynamic code generation*** *in the renderer processes …"* [Microsoft Browser Vulnerability Research Lab, 2022]
- But JIT compilers are dynamic code generators (critical for performance)…

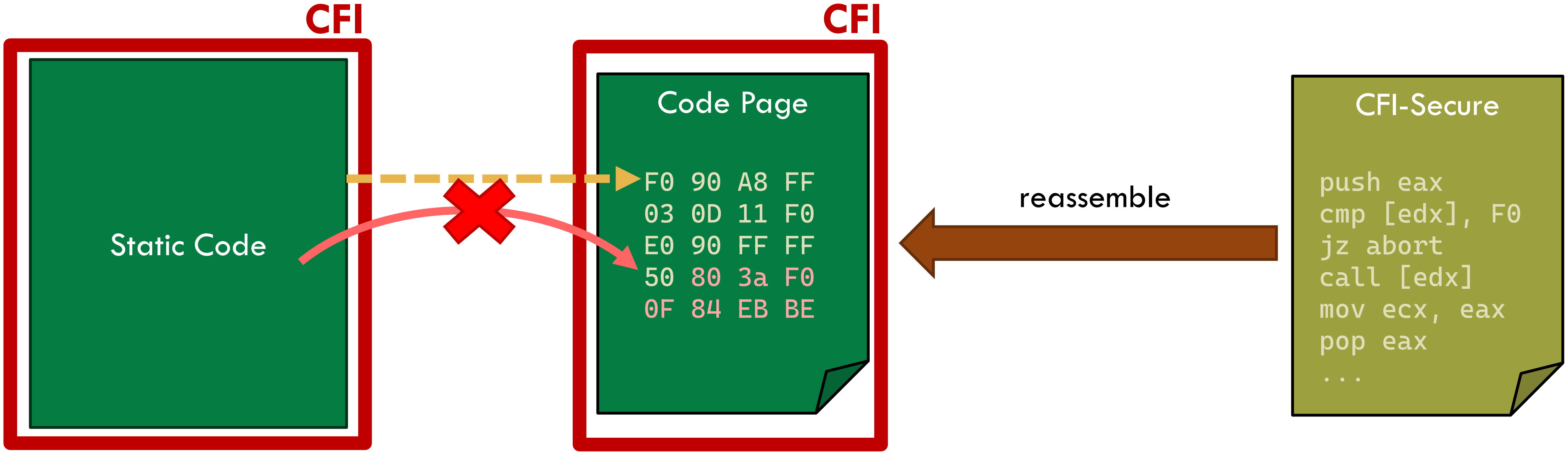
RENEW: Rewriting Newly Executable pages after Writes

E. Bauman, J. Duan, K.W. Hamlen, and Z. Lin, **"Renewable Just-In-Time Control-Flow Integrity,"** In *Proc. 26th Int. Sym. on Research in Attacks, Intrusions and Defenses (RAID)*, October 2023.



RENEW: Rewriting Newly Executable pages after Writes

Static+Dynamic Code Instrumentation
Dynamic Policy Enforcement



Challenges

- Disassembly + Reassembly must be *fast* and *secure*
  - Disassembly alone is provably undecidable in general!
- Must support *recursive (generational) dynamic code generation*
  - dynamic code may write new dynamic code
  - static code may edit dynamic code pages mid-execution
- Must support calls from dynamic code to static code
  - Static code pointer passed to dynamic code
  - Pointer might not target a CFI-sanctioned entry point!
- Real-world apps sometimes *read generated code as data* (ugh!)

Disassembly Undecidability


```
FF E0 5B 5D C3 0F
88 52 0F 84 EC 8B
```

- Disassemble this hex sequence
  - CISC disassembly is undecidable! [Fred Cohen, '86]

Valid Disassembly	
FF E0	jmp eax
5B	pop ebx
5D	pop ebp
C3	retn
0F 88 52 0F 84 EC	jcc
8B …	mov

Valid Disassembly	
FF E0	jmp eax
5B	pop ebx
5D	pop ebp
C3	retn
0F	db (1)
88 52 0F 84 EC	mov
8B …	mov

Valid Disassembly	
FF E0	jmp eax
5B	pop ebx
5D	pop ebp
C3	retn
0F 88	db (2)
52	push edx
0F 84 EC 8B …	jcc

Innovation: Superset Disassembly

Byte Sequence: FF E0 5B 5D C3 0F 88 B0 50 FF FF 8B

Disassembled **Invalid**

Hex
FF
E0
5B
5D
C3
0F
88
B0
50
FF
FF
8B

Included Disassembly
jmp eax
pop
L1: pop
retn
jcc
L2: mov
loopne
jmp L1
mov
jmp L2

Machine learning-based Disassembly Pruning

[Wartell, Zhou, Hamlen, Kantarcioglu, PAKDD'14]

- Insight: Distinguishing real code bytes from data bytes is a "noisy word segmentation problem".
  - Word segmentation: Given a stream of symbols, partition them into words that are contextually sensible. [Teahan, 2000]
  - Noisy word segmentation: Some symbols are noise (data).
- Machine Learning based disassembler
  - based on *k*th-order Markov model
  - Estimate the probability of the sequence B:

$$p(B|M_\alpha) = -\log \prod_{i=1}^{|B|} p(b_i|b_{i-k}^{i-1}, M_\alpha)$$

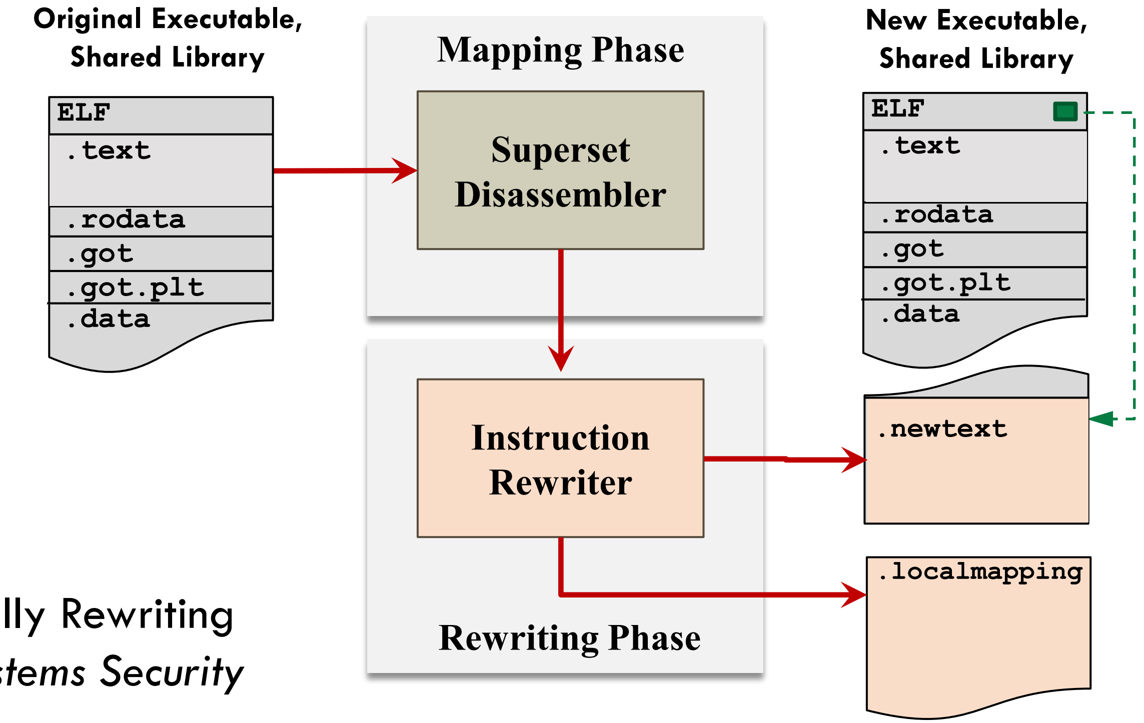
Wartell, Zhou, Hamlen, Kantarcioglu. "Shingled Graph Disassembly: Finding the Undecidable Path." PAKDD 2014.

Wartell, Zhou, Hamlen, Kantarcioglu, and Thuraisingham. "Differentiating code from data in x86 binaries." *ECML/PKDD* 2011.

Multiverse “Superset” Disassembler

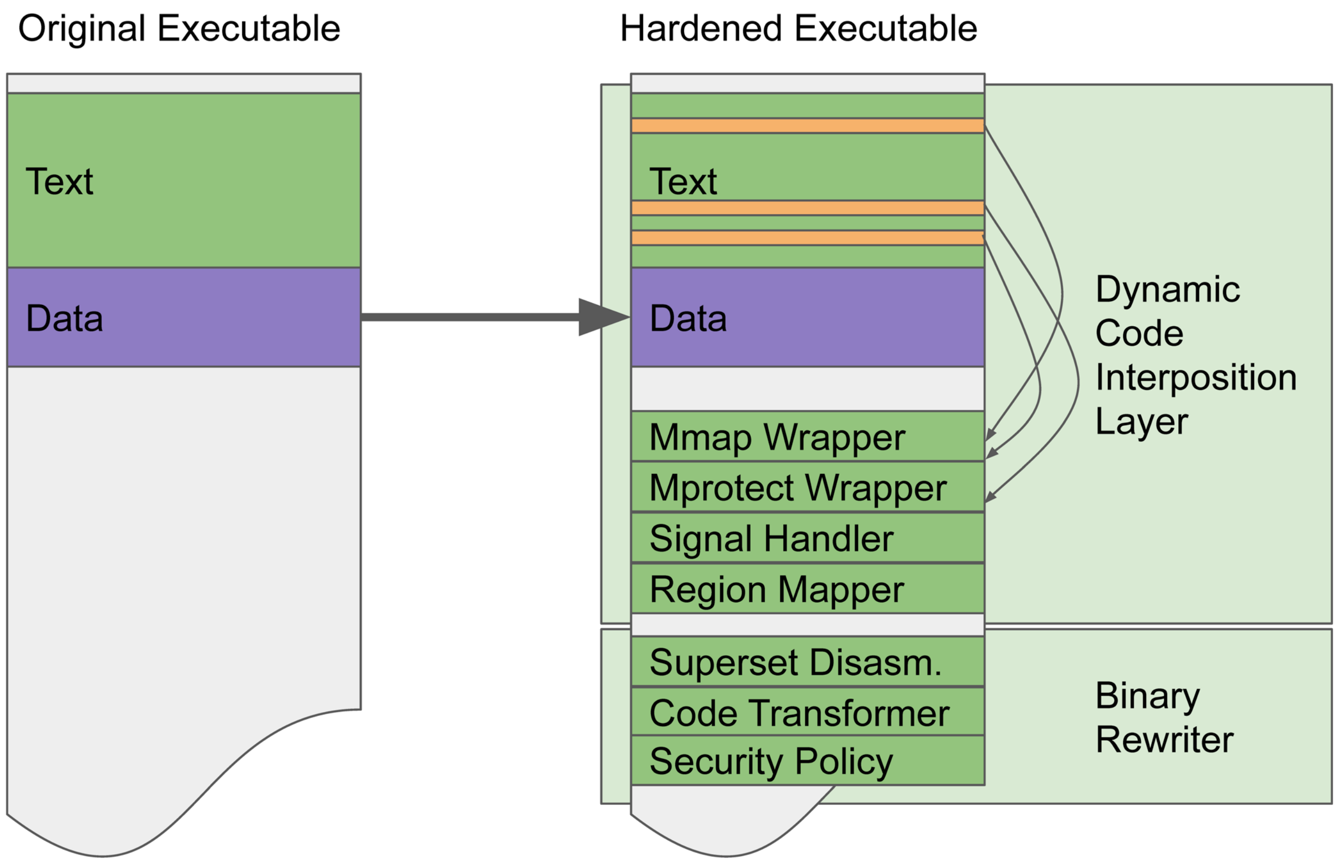
[Bauman, Lin & Hamlen, NDSS’18]

- Conservatively include *every possible* disassembly.
- Include and secure all of them.
- tested on 126 apps + 77 libs (all source-free)
- all application functionalities preserved
- 4-5x size increase of code segments (much smaller impact on overall file size)



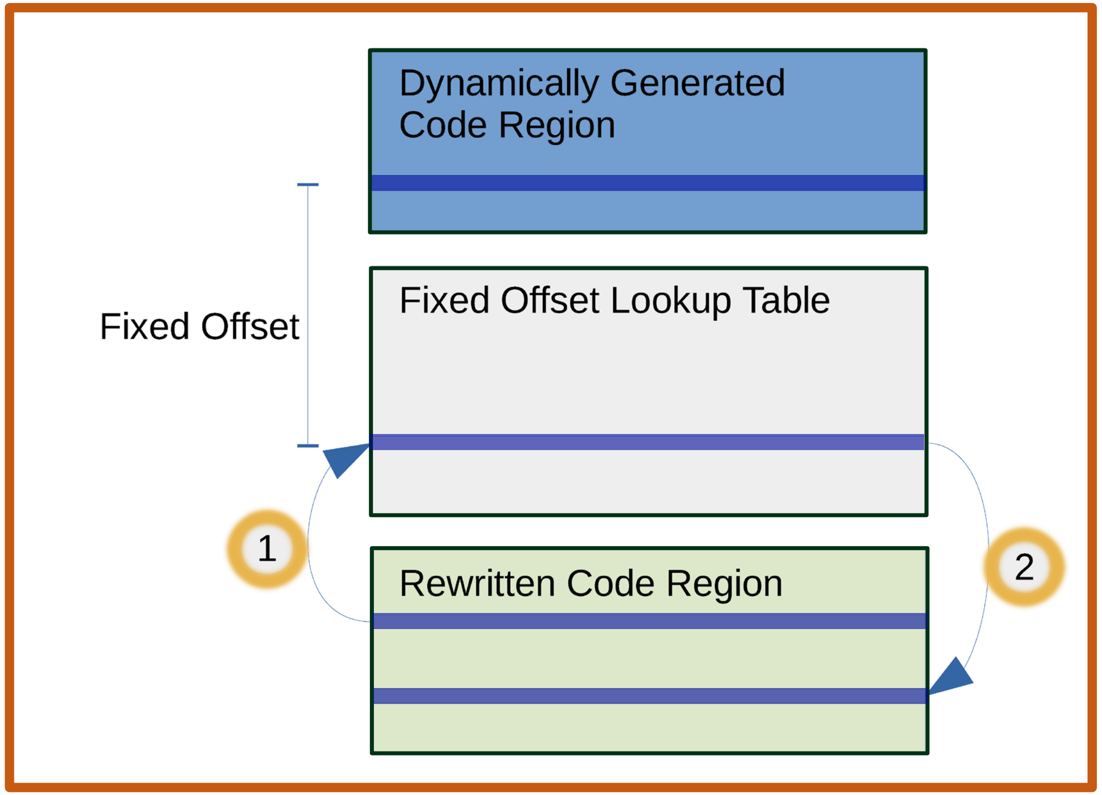
E. Bauman, Z. Lin, and K.W. Hamlen. “Superset Disassembly: Statically Rewriting x86 Binaries Without Heuristics”. In *Proc. Network & Distributed Systems Security (NDSS)*, 2018.

RENEW Overview

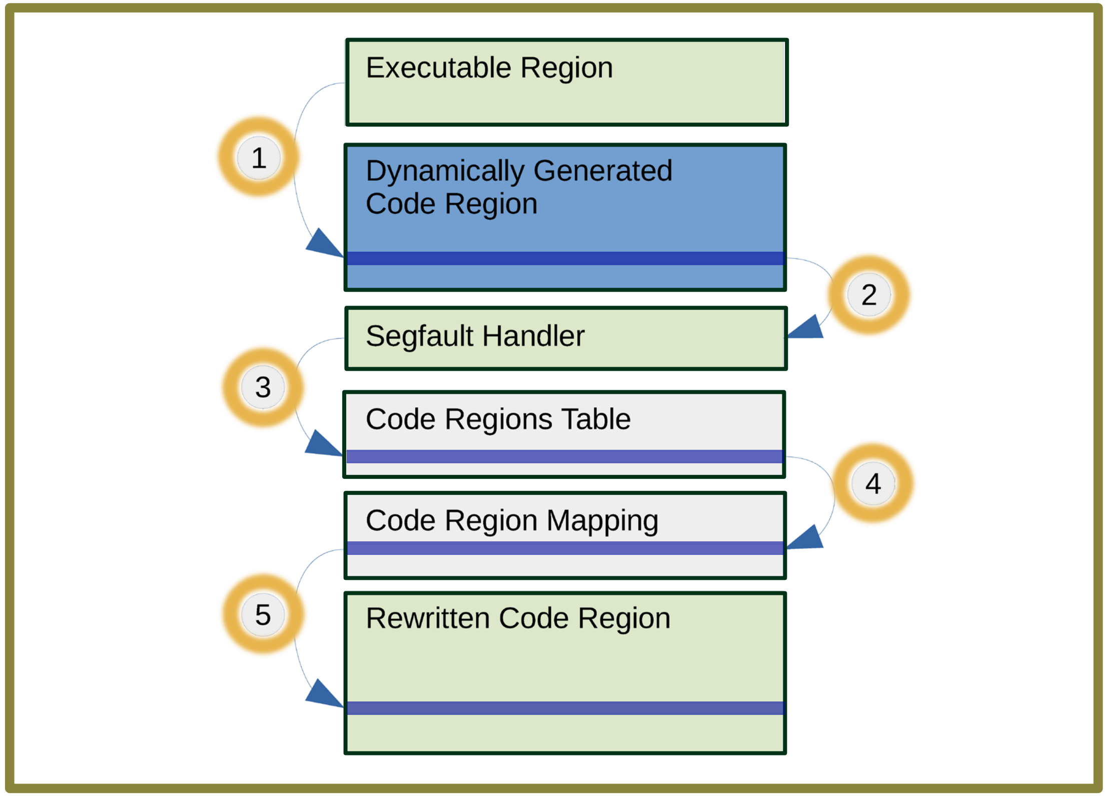


Optimization Strategy: Fast path + Slow path

Fast Path: Statically predictable flows



Slow path: Fall back to signal handlers



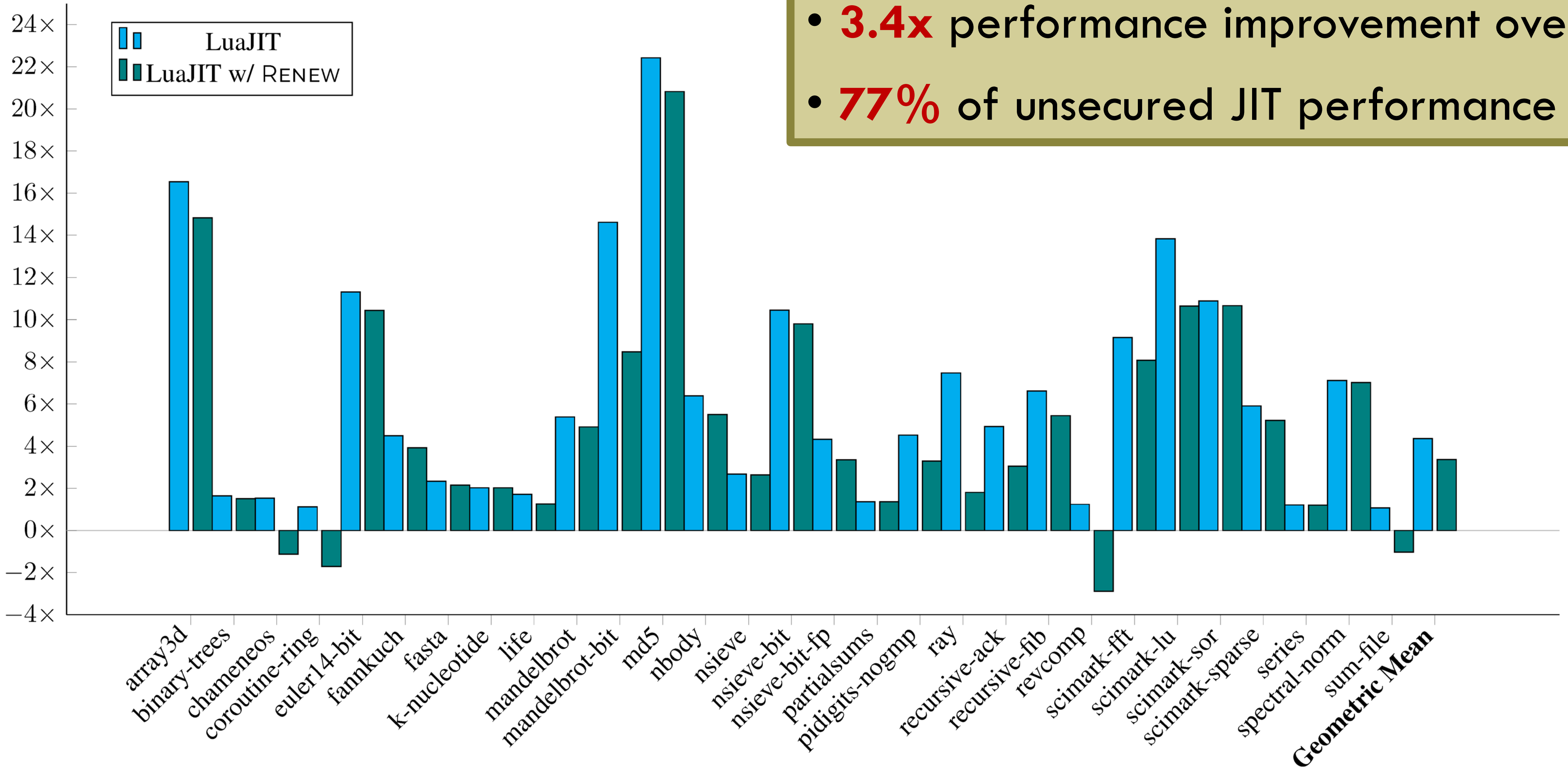
Proof-of-Concept Implementation

- Compact design and implementation
  - ~2000 lines of C code, plus in-lined assembly
  - includes entire disassembler, rewriter, interposition layer, etc.
  - included into target applications, so must be small
- Injected into target applications during compilation
  - shared library (`-Wl,-wrap=mmap -Wl,-wrap=mprotect`)
  - one-line change to application main function to call Renew initializer
- CFI static instrumentation of main app assumed
  - static CFI policy must permit Renew's static flows
  - Renew handles the dynamic flows
- Dramatically easier process than manual JIT redesign!

Evaluation

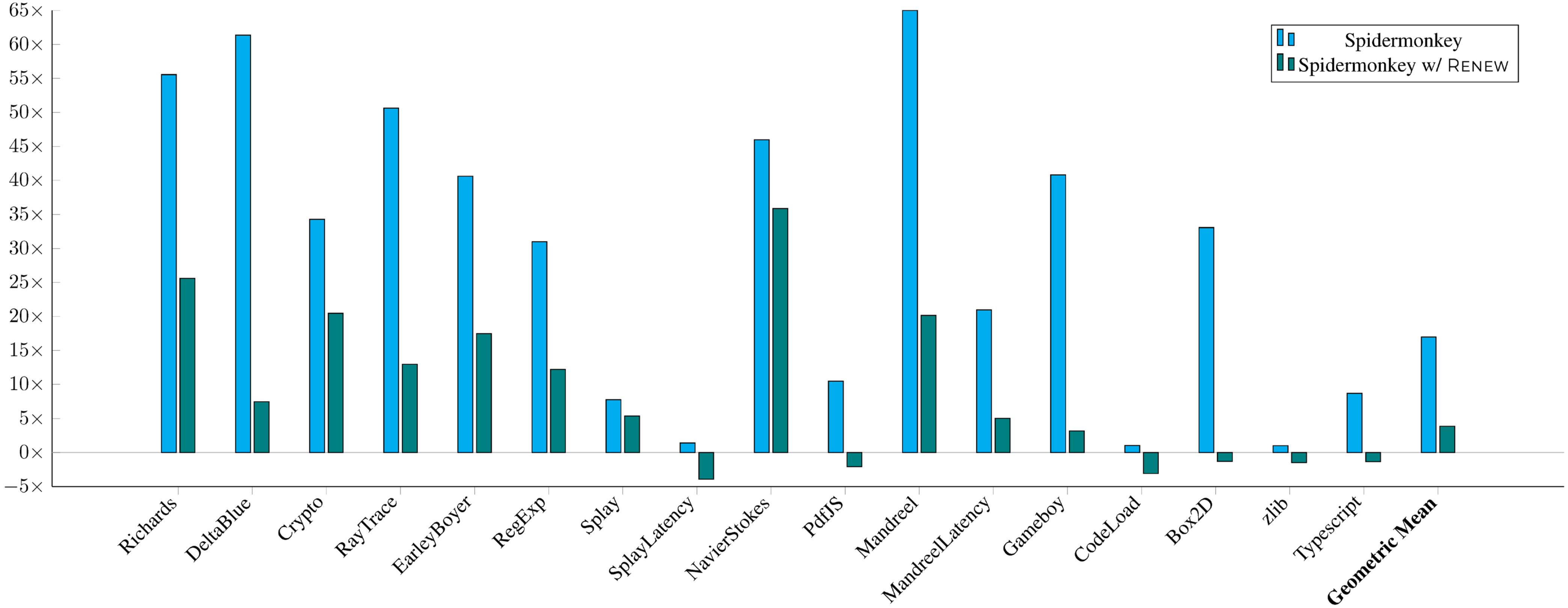
- Three main case-studies:
  - Lua (JIT compiler)
  - Firefox JavaScript (Spidermonkey JIT compiler)
  - UPX (installer / code unpacker)
- Completely different rewriting strategies
  - No common code generation patterns
  - Completely different control-flow patterns
  - Highly optimized, highly complex, high churn (most popular JITs and unpacker today, latest versions at time of implementation)
- No existing CFI solution works correctly on any of these target applications.

LuaJIT Evaluation Results



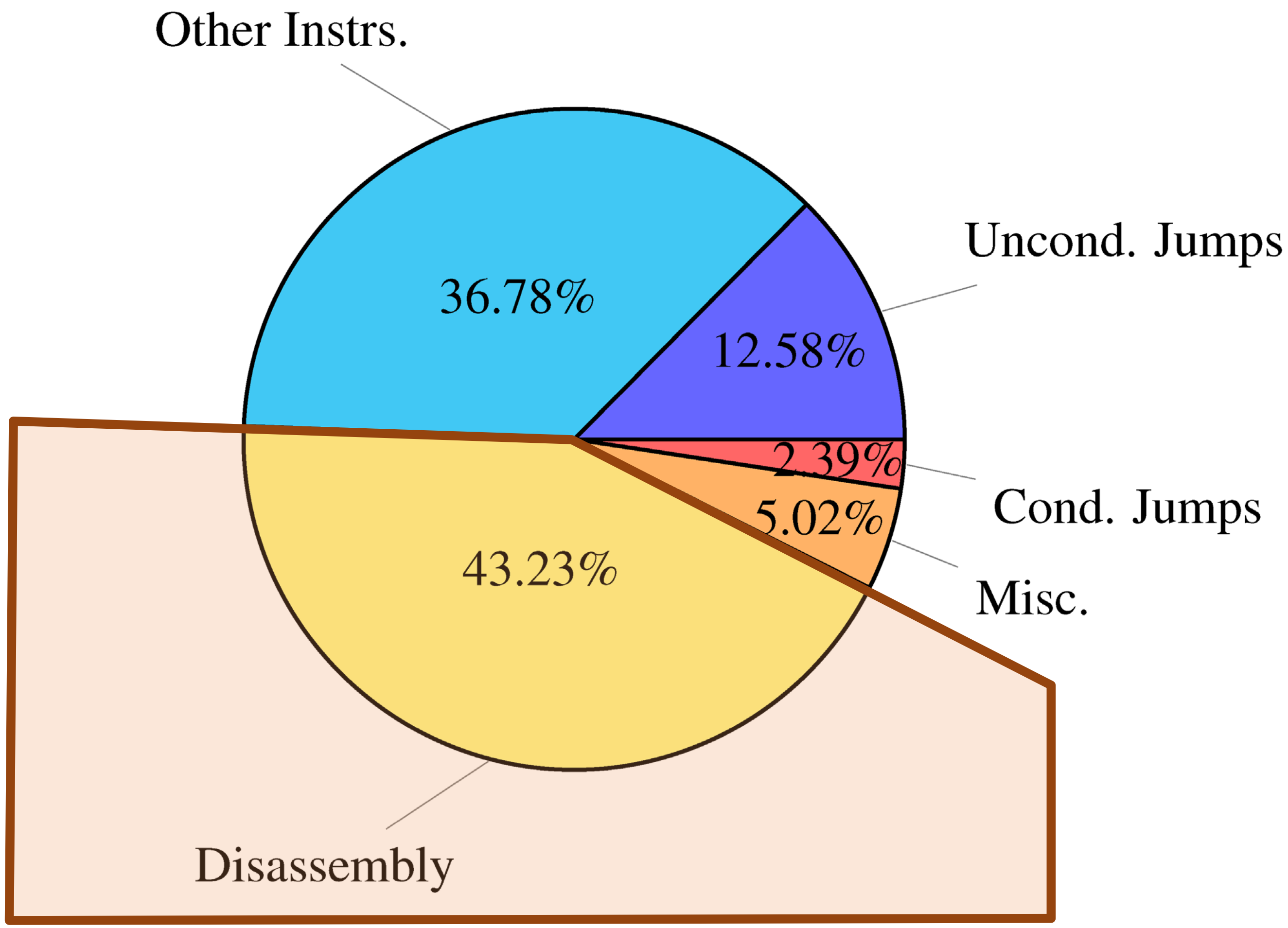
- **3.4x** performance improvement over JIT-off
- **77%** of unsecured JIT performance preserved

Firefox JS Evaluation



- **3.9x** performance improvement over JIT-off
- **23%** of unsecured JIT performance preserved

Overhead Breakdown



UPX Evaluation

- SPEC CPU benchmarks + GNU binutils apps packed using UPX
- Extremely difficult compatibility challenge
  - UPX uses a custom binary header format and IAT to save space
  - completely arbitrary code generation behavior (depends on packed code)
  - two highly compressed layers of unpacking
  - first layer defies conventional disassembly
- Results
  - **all tests worked out-of-the-box** (no changes to Renew required)
  - predictably high overhead (3.6x slowdown)
    - not really a fair performance test; we mainly wanted to test compatibility

Related Work Comparison

System	Year	SFI	CFI	Code-reuse Immunity	JIT	Packers	Source-agnostic
NaCl-JIT	2011	✓	✗	✓	✓	✗	✗
Librando	2013	✗	✗	⚠	✓	✗	✓
RockJIT	2014	✓	✓	✓	✓	✗	✗
SDCG	2015	✗	✗	✗	✓	✗	✗
JITScope	2015	✓	✓	✓	✓	✗	✗
JITGuard	2017	✗	✗	⚠	✓	✗	✗
RENEW	2022	✓	✓	✓	✓	✓	✓

⚠= Defense is diversity-based, so can be compromised by information disclosure.

THANK YOU!

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Software Attack Surface Reduction On The Fly

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