Semi-automated Feature-Debloating of Binary Software*

Dr. Kevin W. Hamlen
Louis A. Beecherl, Jr. Distinguished Professor
Computer Science Department
The University of Texas at Dallas

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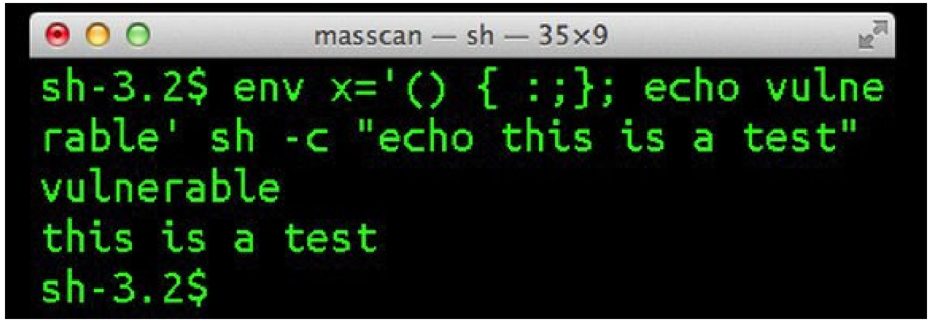
Binary Control-flow Trimming

- **Objective:** Erase (“debloat”) unwanted/unneeded features in binary software without the aid of source code
- **Motivating Example:** Linux Bash + Shellshock



- Discovered September 2014
- Bash shells execute certain environment variable texts as code(!!)
- Allows attackers to remote-compromise most Linux systems
- Window of vulnerability: 25 years(!!)
- Probably NOT originally a bug!
  - introduced in 1989 to facilitate function-import into child shells
  - never clearly documented, eventually forgotten

Research Challenges

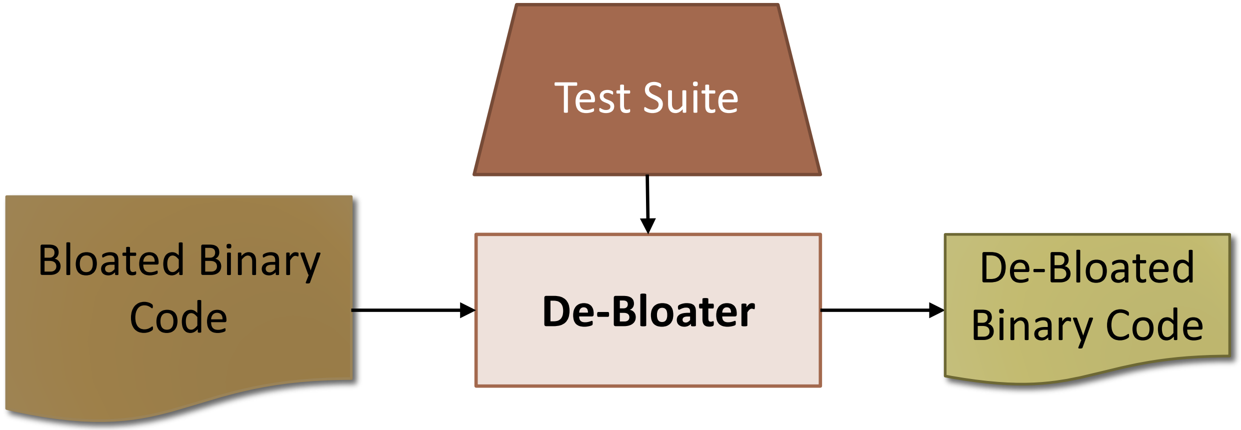
- Can we automatically erase unneeded (risky) functionalities from binary software?
  - Admins might not even know that the undesired functionality exists, and therefore *cannot necessarily demonstrate bugs/vulnerabilities.*
  - Demonstration of desired functionalities will usually be incomplete.
    - large input spaces (e.g., unbounded streams of network packets)
  - No assumptions about code design/provenance
    - arbitrary source languages
    - arbitrary compilation toolchains
    - simplifying assumption: not obfuscated (we can at least disassemble it)
- Can we do so without introducing significant inefficiencies?
  - no virtualization layers introduced
  - "debloated" code should be runnable on bare hardware

Basic Workflow

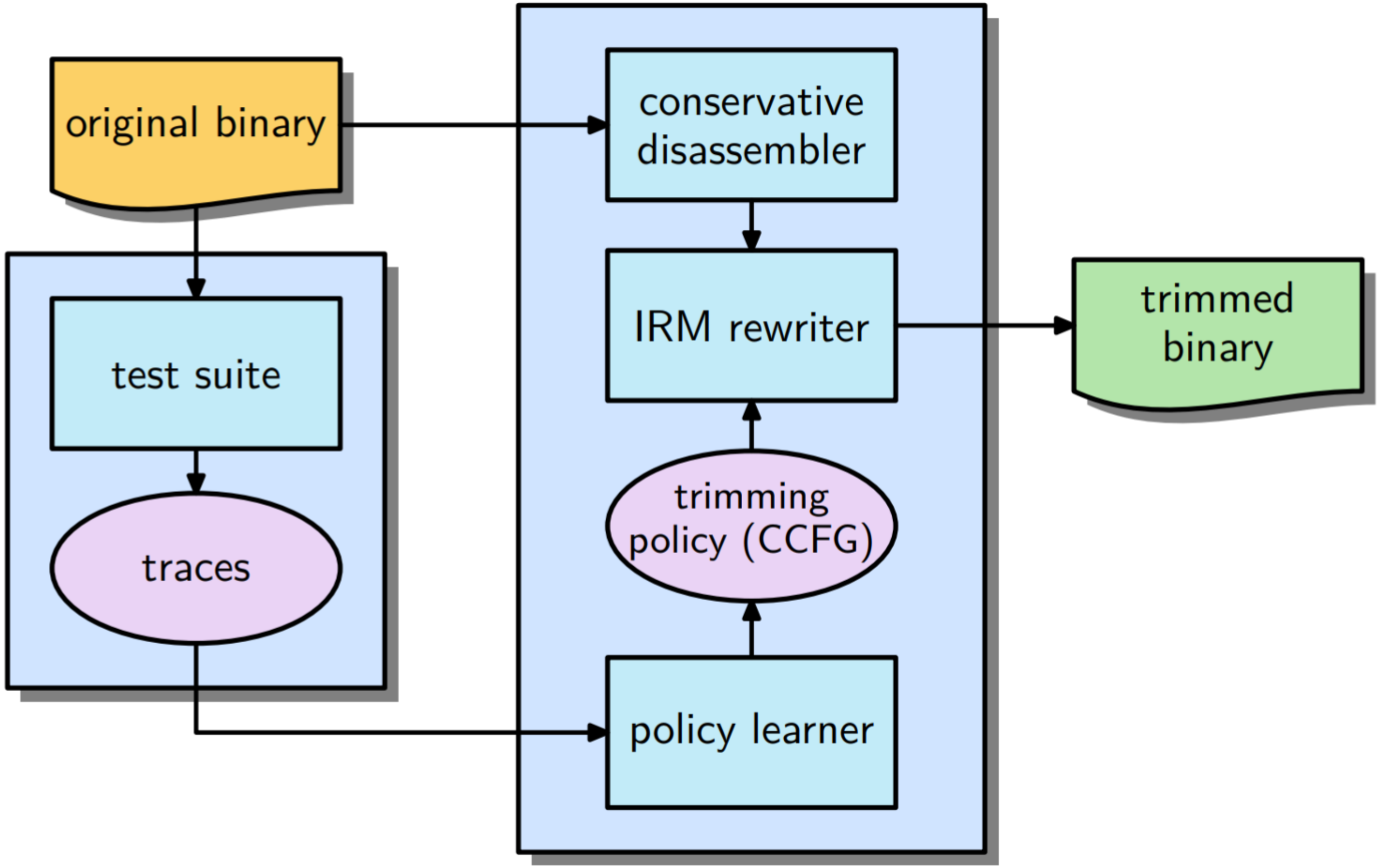
(1) Demonstrate representative desired functionalities by running the target software on various inputs in an emulator/VM.

(2) Submit resulting logs along with original binary code to de-bloater.

(3) If resulting de-bloated binary is unsatisfactory (e.g., needed functionalities missing), then repeat with more/better tests.



Binary Control-flow Trimming Architecture



Stepwise Usage

1. CCFI-protect binary with a permit-all policy
   - `rewriter-makeout.py --learn --target $BCFT_TARGET_BINARY …`

2. run new binary in emulator (PIN) on training inputs
   - `pin -i … -o … -- $PROGRAM $ARGS`

3. learn a CCFI policy from the traces logged by the emulator
   - `learner.py $PROGRAM_TRACES_DIR`

4. replace the permit-all policy with the learned policy
   - `rewriter-makeout.py --policy $POLICY_FILE --target $BCFT_BINARY`

Experiments and Evaluations

- Performance:
  - SPEC CPU Benchmark.
  - Lighttpd, Nginx web-servers.
  - Proftpd, pureftpd, vsftpd ftp-servers.
- Test-suite for accuracy and security:

Program	Test Suite	Debloated Functionalities
GCC	Its own source code.	-m32 (accuracy)
Ftp-servers	Random files mixed with commands (e.g. rm).	SITE, DELETE (security, accuracy)
Browsers	Quantcast top 475K URLs.	Incognito, cookies add/delete(accuracy)
ImageMagic convert	Converting random jpgs to png.	resizing(accuracy)
Exim	Random emails to a specific address.	-ps (security), -oMs(accuracy)
Node.js	Java scrip code not using `serialize()`.	`serialize()`(security)

Vulnerabilities Removed

Successfully removed Shellshock vulnerability using only the pre-Shellshock test-suite shipped with bash.

Program	CVE numbers
Bash	CVE-2014-6271, -6277, -6278, -7169
ImageMagic	CVE-2016-3714, -3715, -3716, -3717, -3718
Proftpd	CVE-2015-3306
Node.js	CVE-2017-5941
Exim	CVE-2016-1531

Limitations and Scope

- **DON'T** use this if…
  - … you have full source code and can recompile all system components.
  - … you want to shrink the software's memory image.
  - … it is difficult/impossible to demonstrate all critical functionalities.
    - (In future research we want to relax this restriction.)
- **DO** use this if…
  - … you don't have or don't trust some/all of the source code for the software.
  - … the software has *no formal specification* of correctness/security.
  - … you have no developer cooperation for finding/fixing bugs/features.
  - … you want to run the code natively (no VM).

Obvious Approach: Code Byte Erasure

```
0749eb90  f0 32 7d 60 95 48 d0 62  08 80 4b 67 b4 4a 21 dc  |.2}`.H.b..Kg.J!.|
0749eba0  80 3f 6c dd 4a f5 a3 d4  ce 32 8d e4 21 d7 a5 5a  |.?l.J....2..!..Z|
0749ebb0  92 93 4b f1 ca 0a ce 3c  b9 14 20 a5 00 a4 4a 3e  |..K....<.. ...J>|
0749ebc0  bd 4b 8c b4 d1 90 2b 25  a9 c8 f4 c8 10 85 fb d6  |.K....+%........|
0749ebd0  fc 2a 1f c6 8a 7f 25 e7  47 f4 95 01 e2 d7 82 fe  |.*....%.G.......|
0749ebe0  22 95 fa 8e 49 e4 50 98  d3 84 95 a7 97 1d 97 92  |"...I.P.........|
0749ebf0  25 32 9f 90 0c a9 07 73  c2 2b 49 06 4c 1a 26 69  |%2.....s.+I.L.&i|
0749ec00  b2 75 3e 20 db 65 bf 22  68 cf 29 1b 8a 65 8d 54  |.u> .e."h.)..e.T|
0749ec10  91 ba 33 f3 05 59 07 39  cd 43 96 6f 5d 88 bb 7a  |..3..Y.9.C.o]..z|
0749ec20  aa ae d2 04 b1 c6 33 25  8c 68 f7 c7 79 23 ef 66  |......3%.h..y#.f|
0749ec30  7a aa 41 e7 99 55 1d 46  79 64 2a 6c 1f a9 64 63  |z.A..U.Fyd*l..dc|
0749ec40  ef f9 87 72 3f d9 5a 9f  48 0d 92 96 72 0d 1b a4  |...r?.Z.H...r...|
0749ec50  a6 2e 08 b0 96 cc e6 37  88 f0 57 32 3b 21 6d d9  |.......7..W2;!m.|
0749ec60  e4 6b f1 ef 14 25 65 e3  3c b3 ee 60 bc a4 ea 44  |.k...%e.<..`...D|
0749ec70  64 49 0d 59 0b 45 3f f0  75 a4 24 be 41 f5 52 ad  |dI.Y.E?.u.$.A.R.|
0749ec80  32 65 33 4d 9c 83 8e 97  69 57 f2 5d 72 93 dd b1  |2e3M....iW.]r...|
0749ec90  d0 c6 dc c8 43 89 6e 1e  8b d9 2e 67 52 3e 26 3f  |....C.n....gR>&?|
0749eca0  46 cc 92 a7 e1 f3 af 9c  c8 b3 17 fe ff 8a bb 7a  |F..............z|
0749ecb0  f6 e9 99 6d 8b 24 dc 84  97 67 b6 d5 5b 73 a6 fc  |...m.$...g..[s..|
0749ecc0  50 a6 cf fe 92 7d c3 2f  2e 7e e8 b7 8f 9b 71 5f  |P....}./.~....q_|
0749ecd0  b0 43 79 5c f1 63 9d b7  2f 7e b1 f3 f6 87 5f b0  |.Cy\.c../~...._.|
0749ece0  64 84 86 98 59 f7 d2 96  42 28 5a 96 8e d1 17 4f  |d...Y...B(Z....O|
0749ecf0  f4 2d a6 94 06 0f fb 57  83 fe 60 59 8e 32 70 23  |.-.....W..`Y.2p#|
0749ed00  c1 8a 98 43 0b 90 26 24  03 ce 3d 21 79 0b 75 f9  |...C..&$..=!y.u.|
```

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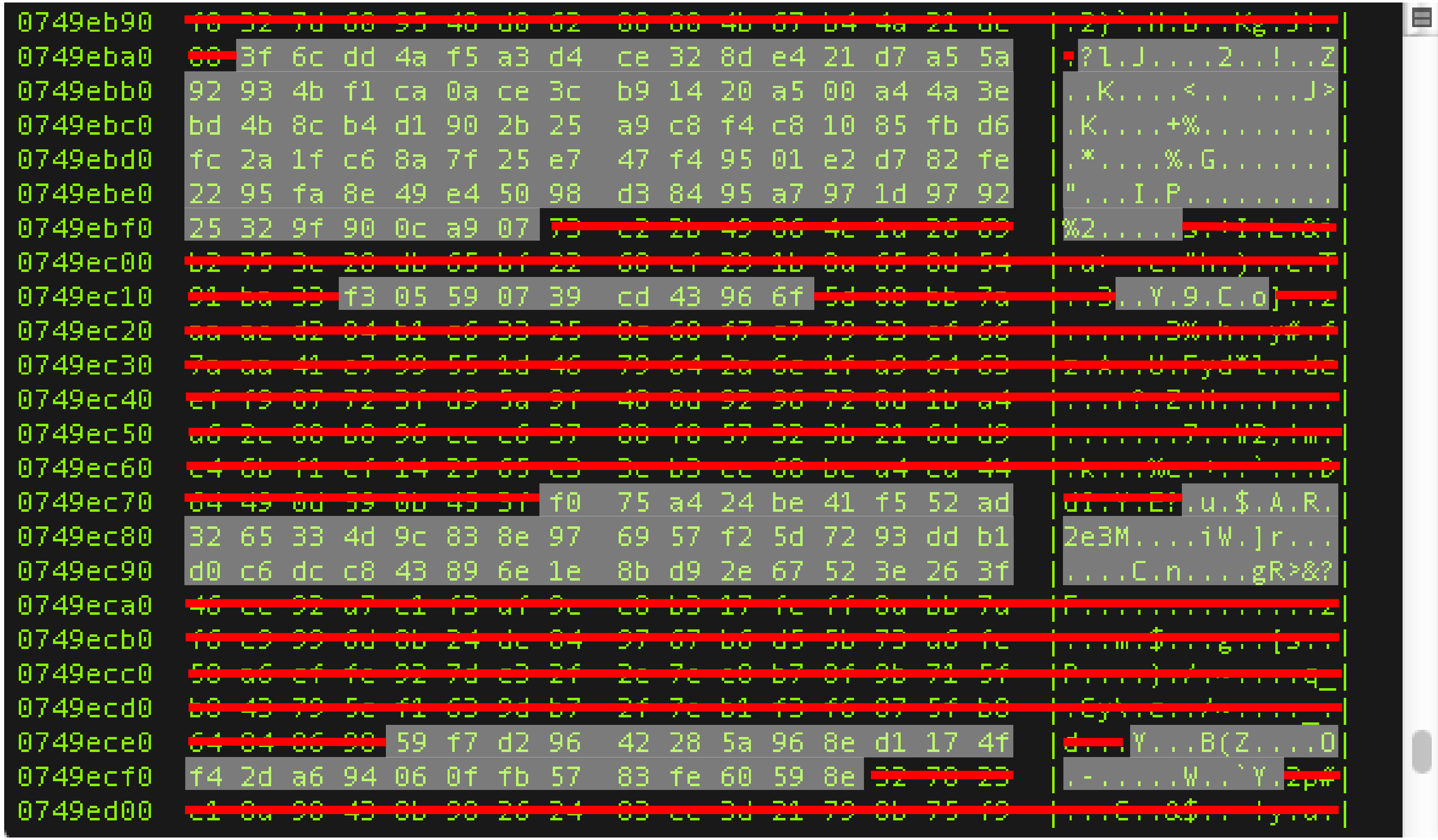
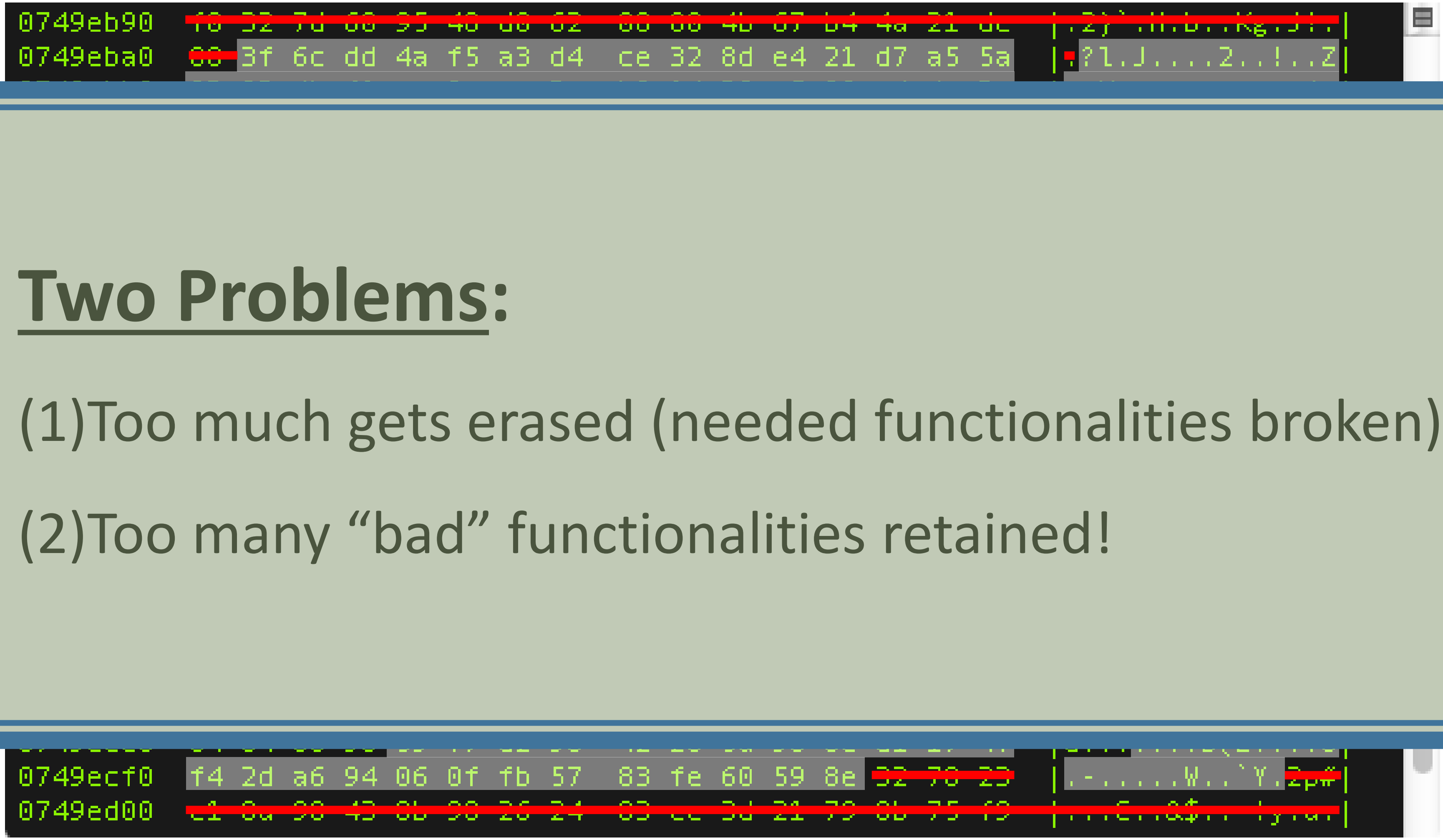
```
0749eb90  f0 32 7d 60 95 48 d0 62  08 80 4b 67 b4 4a 21 dc  |.2}`.H.b..Kg.J!.|
0749eba0  80 3f 6c dd 4a f5 a3 d4  ce 32 8d e4 21 d7 a5 5a  |.?l.J....2..!..Z|
0749ebb0  92 93 4b f1 ca 0a ce 3c  b9 14 20 a5 00 a4 4a 3e  |..K....<.. ...J>|
0749ebc0  bd 4b 8c b4 d1 90 2b 25  a9 c8 f4 c8 10 85 fb d6  |.K....+%........|
0749ebd0  fc 2a 1f c6 8a 7f 25 e7  47 f4 95 01 e2 d7 82 fe  |.*....%.G.......|
0749ebe0  22 95 fa 8e 49 e4 50 98  d3 84 95 a7 97 1d 97 92  |"...I.P.........|
0749ebf0  25 32 9f 90 0c a9 07 73  c2 2b 49 06 4c 1a 26 69  |%2.....s.+I.L.&i|
0749ec00  b2 75 3e 20 db 65 bf 22  68 cf 29 1b 8a 65 8d 54  |.u> .e."h.)..e.T|
0749ec10  91 ba 33 f3 05 59 07 39  cd 43 96 6f 5d 88 bb 7a  |..3..Y.9.C.o]..z|
0749ec20  aa ae d2 04 b1 c6 33 25  8c 68 f7 c7 79 23 ef 66  |......3%.h..y#.f|
0749ec30  7a aa 41 e7 99 55 1d 46  79 64 2a 6c 1f a9 64 63  |z.A..U.Fyd*l..dc|
0749ec40  ef f9 87 72 3f d9 5a 9f  48 0d 92 96 72 0d 1b a4  |...r?.Z.H...r...|
0749ec50  a6 2e 08 b0 96 cc e6 37  88 f0 57 32 3b 21 6d d9  |.......7..W2;!m.|
0749ec60  e4 6b f1 ef 14 25 65 e3  3c b3 ee 60 bc a4 ea 44  |.k...%e.<..`...D|
0749ec70  64 49 0d 59 0b 45 3f f0  75 a4 24 be 41 f5 52 ad  |dI.Y.E?.u.$.A.R.|
0749ec80  32 65 33 4d 9c 83 8e 97  69 57 f2 5d 72 93 dd b1  |2e3M....iW.]r...|
0749ec90  d0 c6 dc c8 43 89 6e 1e  8b d9 2e 67 52 3e 26 3f  |....C.n....gR>&?|
0749eca0  46 cc 92 a7 e1 f3 af 9c  c8 b3 17 fe ff 8a bb 7a  |F..............z|
0749ecb0  f6 e9 99 6d 8b 24 dc 84  97 67 b6 d5 5b 73 a6 fc  |...m.$...g..[s..|
0749ecc0  50 a6 cf fe 92 7d c3 2f  2e 7e e8 b7 8f 9b 71 5f  |P....}./.~....q_|
0749ecd0  b0 43 79 5c f1 63 9d b7  2f 7e b1 f3 f6 87 5f b0  |.Cy\.c../~...._.|
0749ece0  64 84 86 98 59 f7 d2 96  42 28 5a 96 8e d1 17 4f  |d...Y...B(Z....O|
0749ecf0  f4 2d a6 94 06 0f fb 57  83 fe 60 59 8e 32 70 23  |.-.....W..`Y.2p#|
0749ed00  c1 8a 98 43 0b 90 26 24  03 ce 3d 21 79 0b 75 f9  |...C..&$..=!y.u.|
```

Obvious Approach: Code Byte Erasure



Obvious Approach: Code Byte Erasure



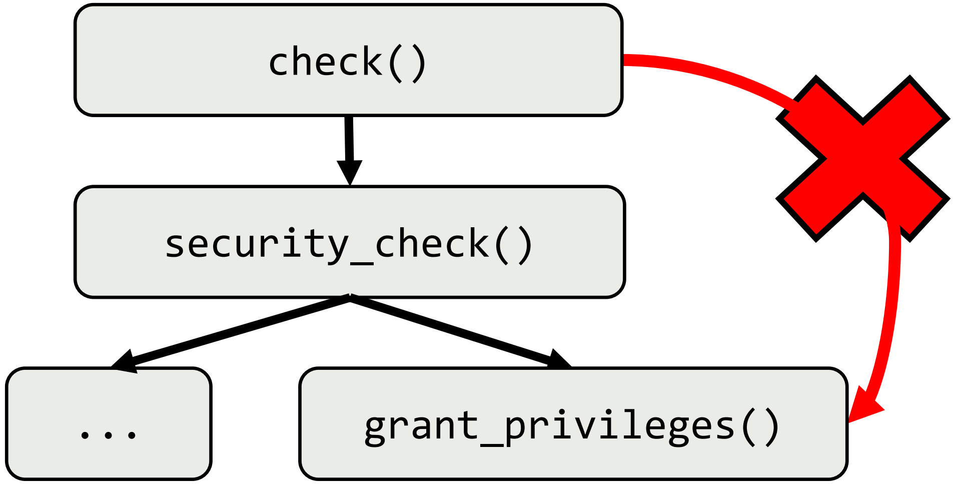
<u>Two Problems</u>:

(1)Too much gets erased (needed functionalities broken)

(2)Too many “bad” functionalities retained!

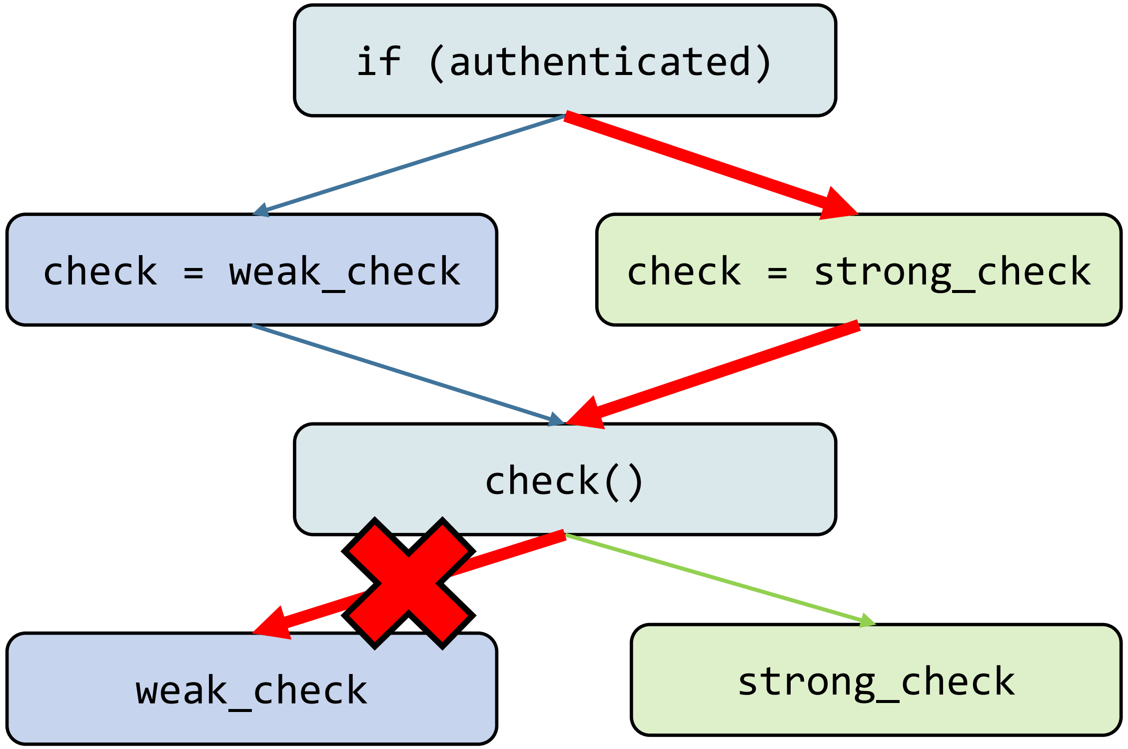
Code Erasure vs. Edge Erasure

```
void access_database() {

    bool (*check)(void);
    char vul_buf[N];

    check = &security_check;

    ...


    scanf("%s", vul_buf);

    if (check()) {
        grant_privileges();
    }
}
```



Edge Erasure vs. Flow Erasure

```
void access_database() {

    bool (*check)(void);
    char vul_buf[N];

    if (authenticated)
        check = weak_check;
    else
        check = strong_check;

    scanf("%s", vul_buf);

    if (check()) {
        grant_privileges();
    }
}
```

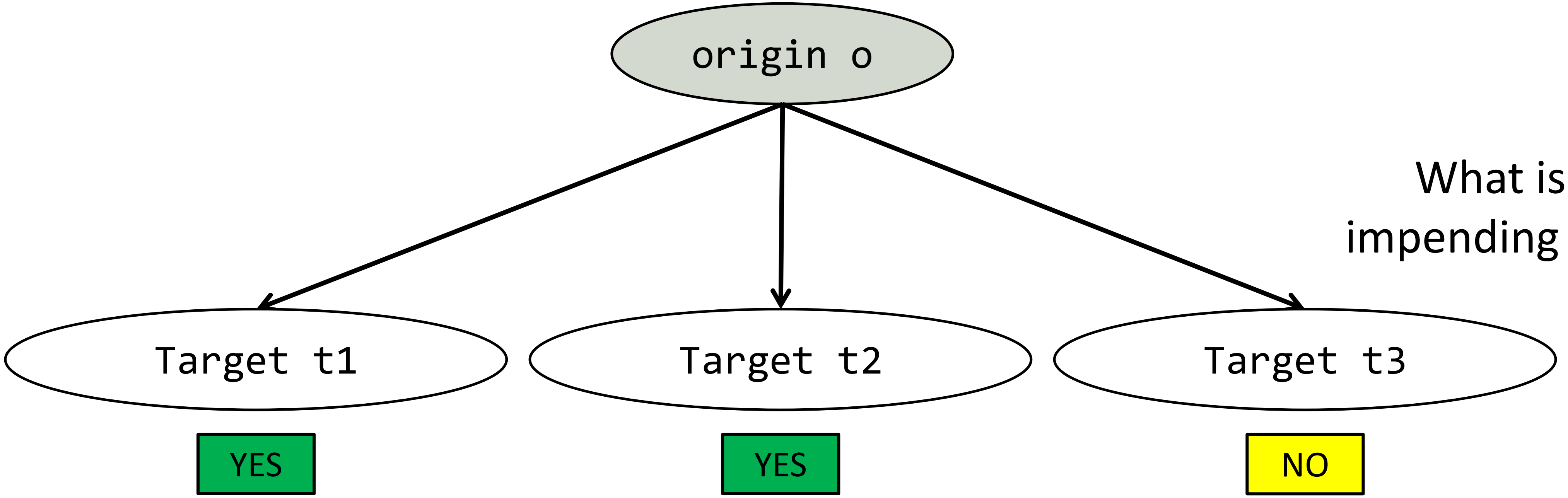


Contextual Control-flow Integrity (CCFI)

- Basic implementation strategy
  - Replace each jump/branch/call instruction in the original code with a *check-then-jump* sequence
  - The "check" code updates and consults a saved *context history* of previous jumps.
- Requirements
  - ALL jump/branch/calls must be replaced
  - saved context history must be protected from attacker modification
- Prior work
  - non-contextual CFI enforcement is well-established
  - contextual CFI is very hard to implement efficiently
    - PathArmor [Van Der Veen et al.; USENIX Sec '15]: only checks system API calls, has high overhead
- Main challenge #1: How to learn a CCFI policy without a spec?
- Main challenge #2: How to enforce such fine-grained CCFI efficiently?

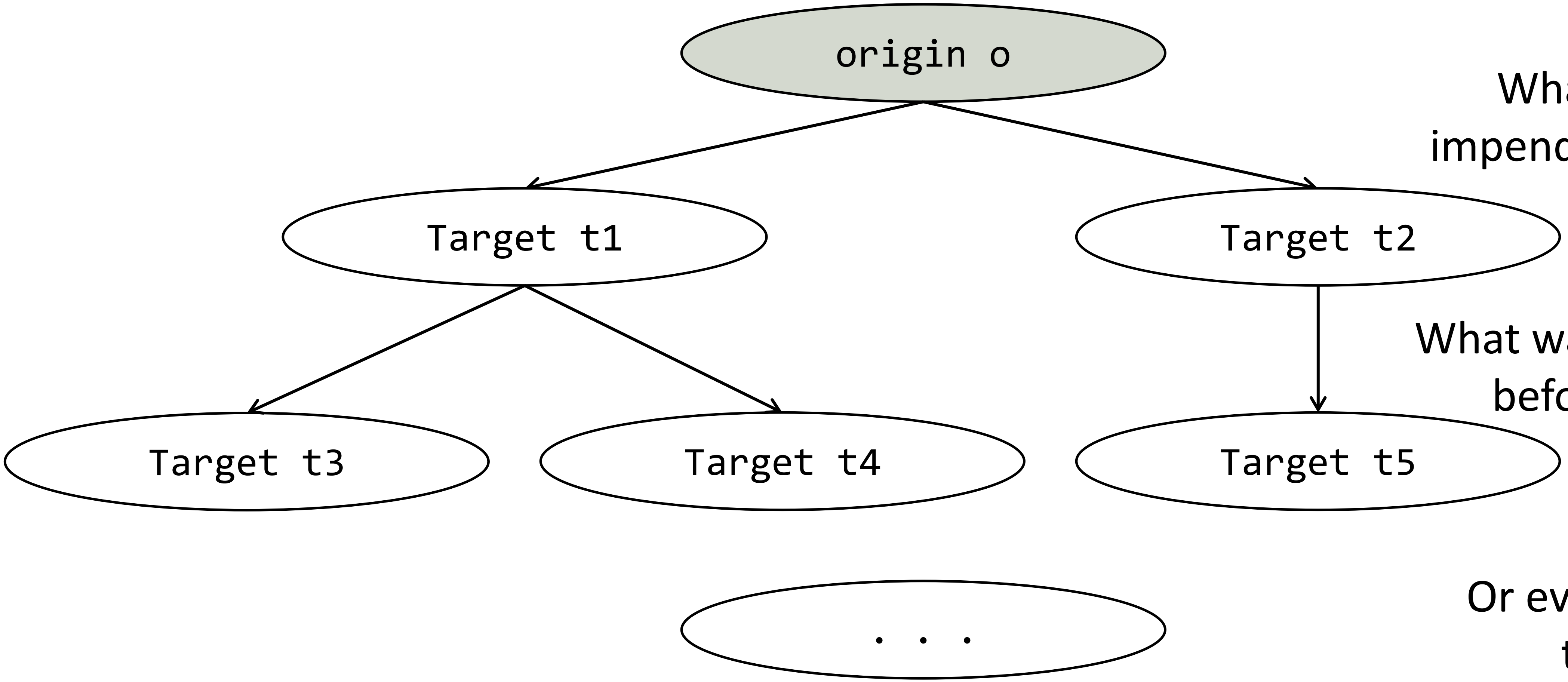
Learning CFG Policy

- Decision Trees at every branch site.



What is the impending target?

Learning Contextual CFG Policy



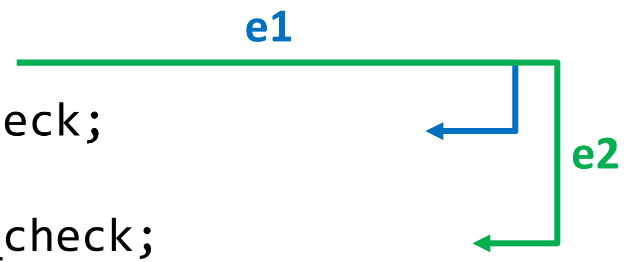
What is the impending target?

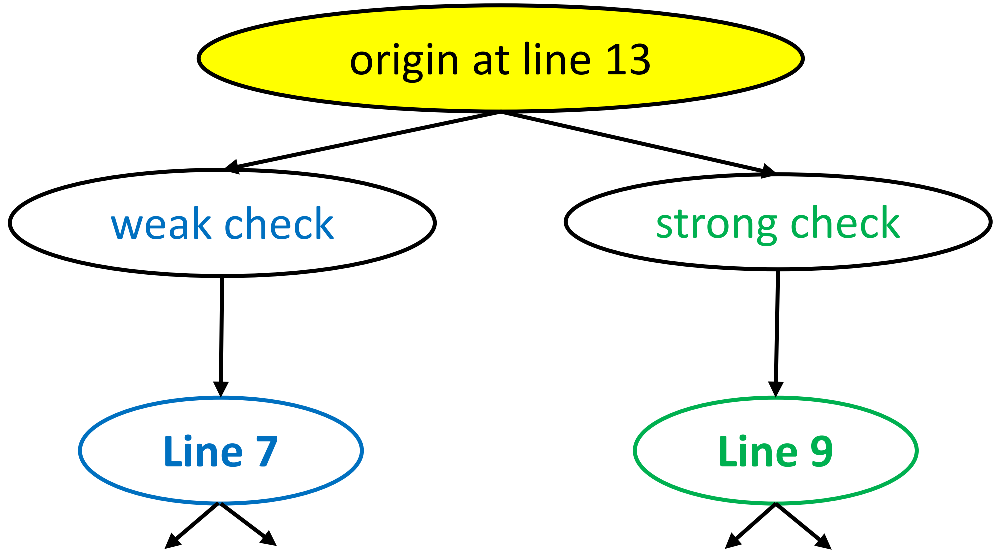
What was the target before that?

Or even before that?

Contextual CFG Trees

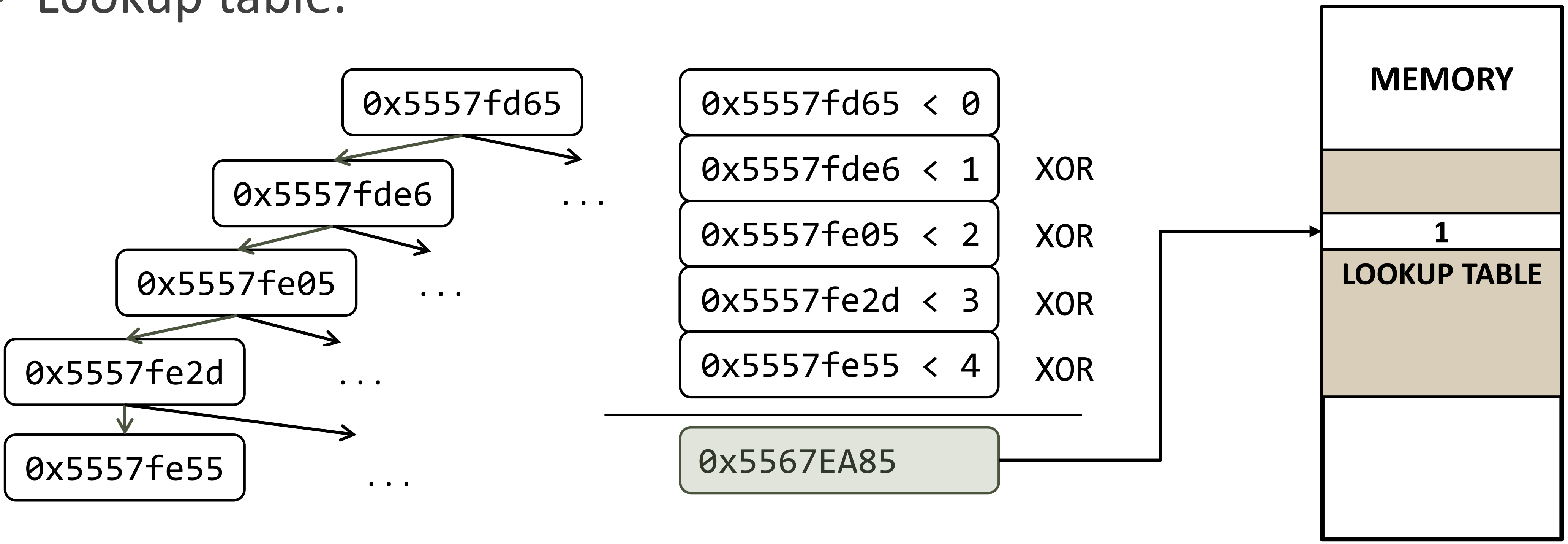
```
1   void access_database() {
2
3       bool (*check)(void);
4       char vul_buf[N];
5
6       if (authenticated)
7           check = weak_check;
8       else
9           check = strong_check;
10
11      scanf("%s", vul_buf);
12
13      if (check()) {
14          grant_privileges();
15      }
16  }
```





Policy Representation

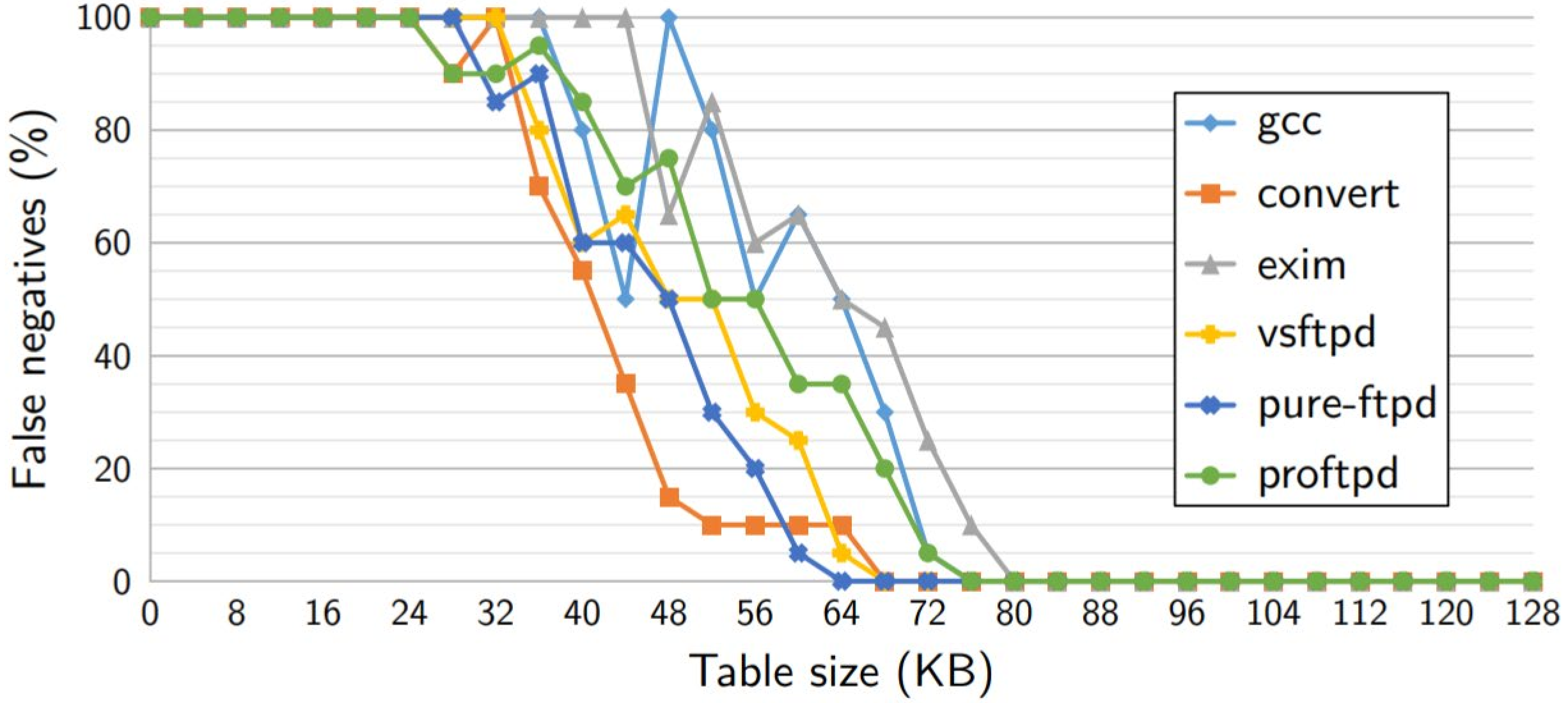
- Lookup table.



$$hash(\chi) = \bigoplus_{i=1}^{|\chi|}((\pi_2 \chi_i) \ll (|\chi| - i)s) \qquad hash(\chi e) = (hash(\chi) \ll s) \oplus (\pi_2 e)$$

Hash Table Sizes

A table of size n B can whitelist $8n$ contexts.



Guard Checks

Description	Original code	Rewritten Code
Conditional Jumps	*jcc l*	call *jcc*_fall .quad *l*
Indirect calls	call *r*/[*m*]	mov *r*/[*m*], %rax call indirect_call

Indirect Jumps	jmp *r*/[*m*]	mov %rax, -16(%rsp)
		mov *r*/[*m*], %rax
		call indirect_jump

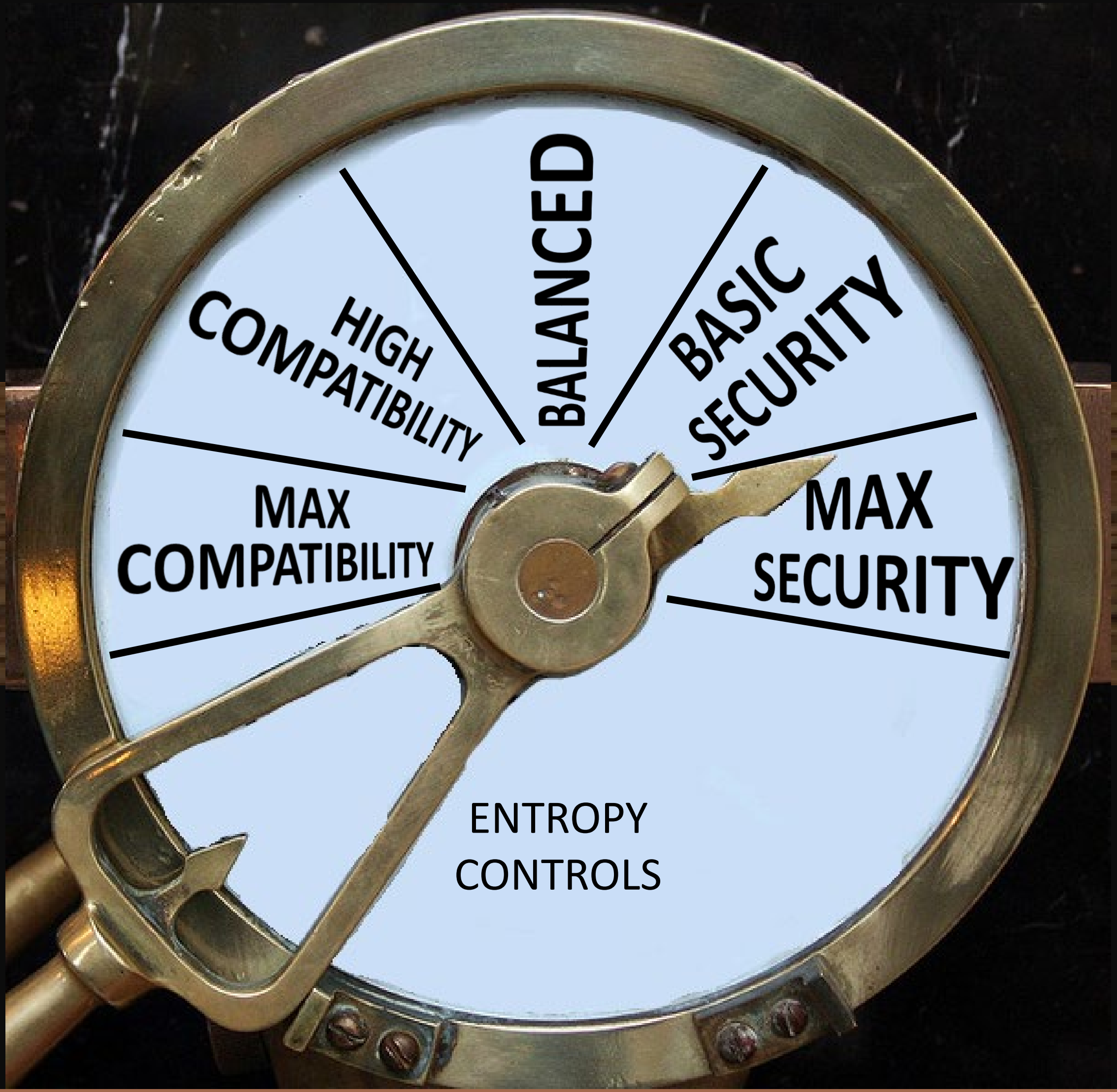
Variable Returns	ret *n*	pop %rdx lea *n*(%rsp), %rsp push %rdx jmp return
Returns	ret	mov (%rsp), %rdx jmp return

Label	Assembly Code
indirect_jump:	push %rax common-guard mov -8(%rsp), %rax ret
indirect_call:	push %rax common-guard ret
return:	common-guard ret
*jcc*_fall:	*jcc* jump_l jmp fall_l
*jcc*_back:	*jcc* jump_l jmp back_l
jump_l:	xchg (%rsp), %rax mov (%rax), %rax jmp condition_jump
fall_l:	xchg (%rsp), %rax lea 8(%rax), %rax jmp condition_jump
back_l:	xchg (%rsp), %rax lea 8(%rax), %rax xchg (%rsp), %rax ret
condition_jump:	push %rax common-guard pop %rax xchg (%rsp), %rax ret

Context Protection with Wide Registers

Guard Name	Guard Code			
	Legacy-mode		**SHA-extension**	
before-check	1:movd	*r*, %xmm11	1:movd	*r*, %xmm11
	2:psubd	%xmm12, %xmm11	2:psubd	%xmm12, %xmm11
			3:sha1msg1	%xmm14, %xmm13
			4:sha1msg2	%xmm13, %xmm13
			5:pslrdq	$4, %xmm13
	3:pxor	%xmm11, %xmm13	6:pxor	%xmm11, %xmm13
check	4:movd	%xmm13, *r*	7:movd	%xmm13, *r*
	5:and	$(max\_hash - 1)$, *r*	8:and	$(max\_hash - 1)$, *r*
	6:bt	*r*, (HASH_TABLE)	9:bt	*r*, (HASH_TABLE)
	7:jnb	TRAP	10:jnb	TRAP
after-check	8:pextrd	$3, %xmm14, *r*	11:pslldq	$4, %xmm14
	9:pslldq	$4, %xmm14	12:psllw	$1, %xmm14
	10:pxor	%xmm11, %xmm14	13:pxor	%xmm11, %xmm14
	11:movd	*r*, %xmm11		
	12:pxor	%xmm11, %xmm13		
	13:pslld	$1, %xmm13		
	14:pslld	$1, %xmm14		

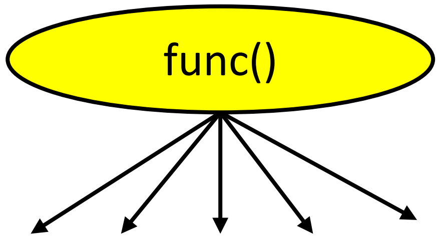
Tuning Policy Strictness



Decision Trees and Entropy

- High entropy node = high uncertainty = incomplete testing

```
void dispatch(void (*func)()) {
    func();
    LOG();
}
```

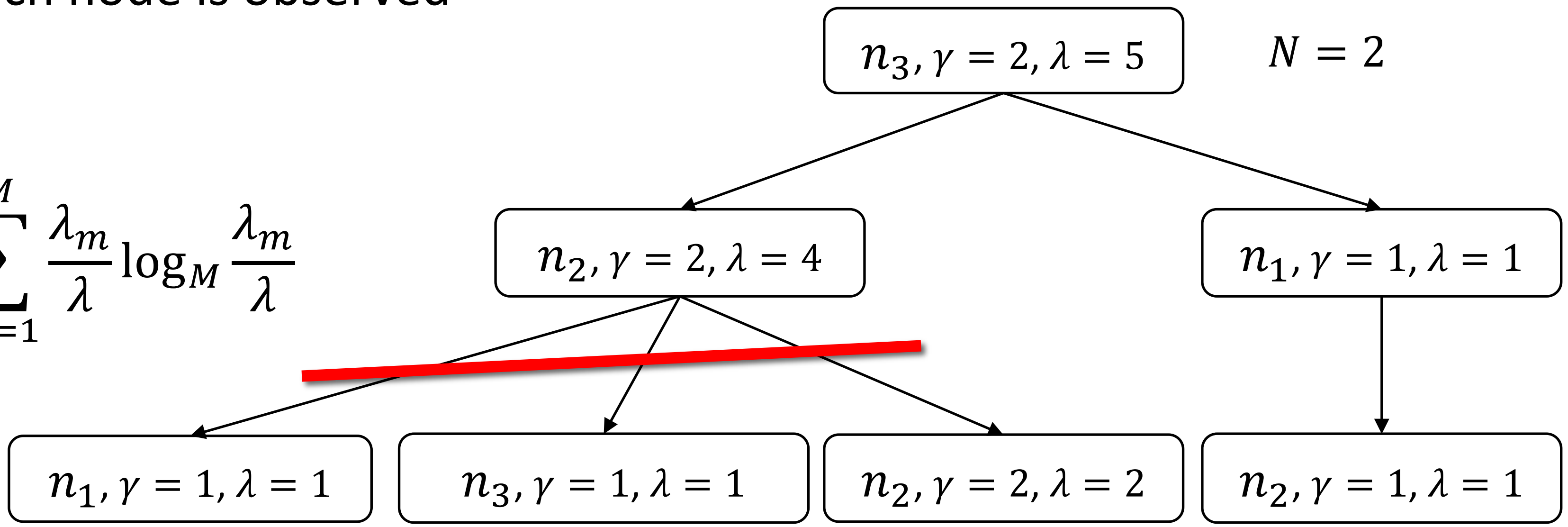


Relaxing the policy

- **Relaxation philosophy:**
  - Relaxed policy is always as strict as non-contextual CFI.
  - Relaxations merely identify some context as irrelevant to the enforcement decision.

- **Parameters**
  - λ = # times the node observed in all traces
  - γ = # traces in which node is observed
  - N = total traces
  - M = # children

$$score(n) = \frac{\gamma}{N} \times -\frac{1}{\mathrm{M}^2} \sum_{m=1}^{M} \frac{\lambda_m}{\lambda} \log_M \frac{\lambda_m}{\lambda}$$

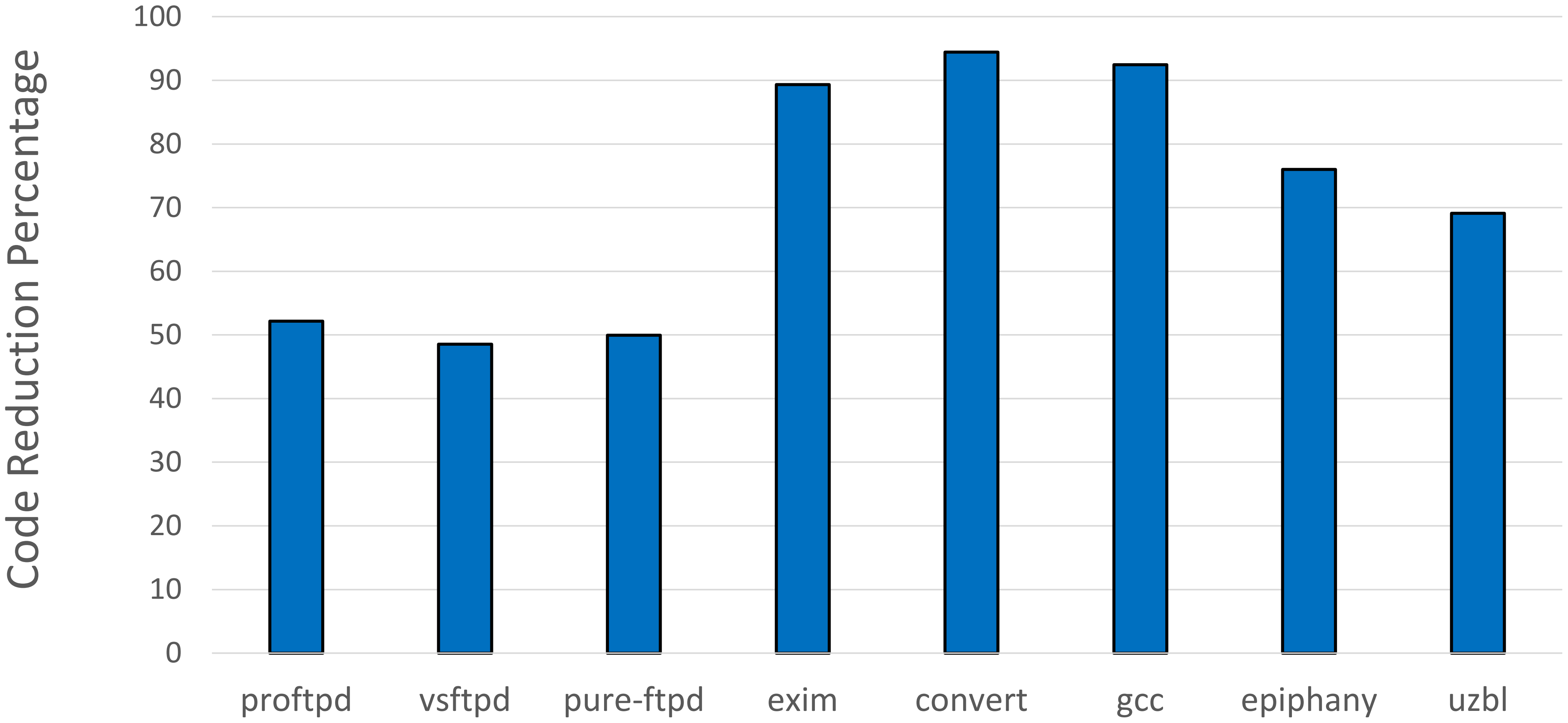


Accuracy

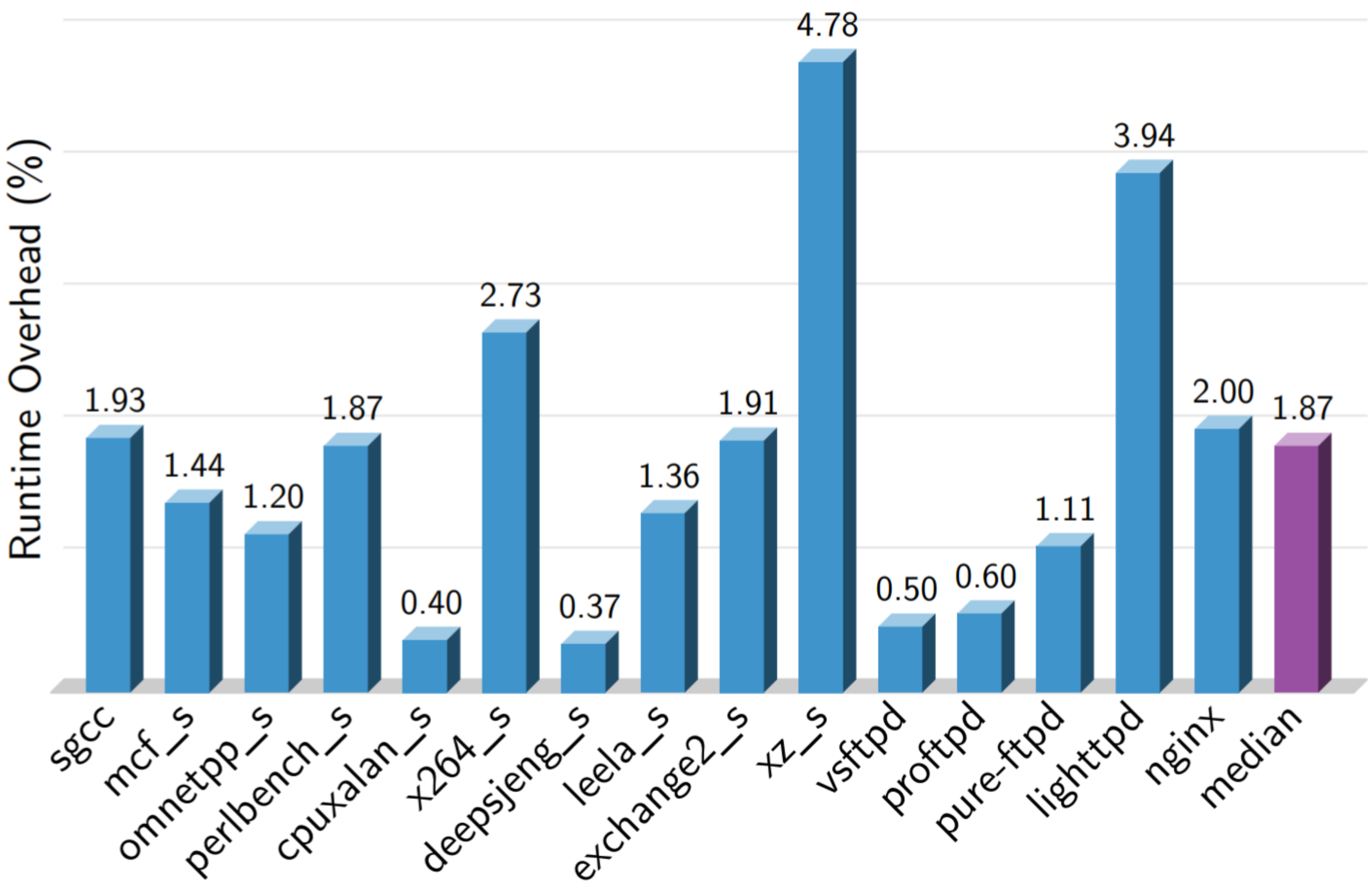
		Program											
		proftpd			vsftpd			pure-ftpd			exim		
	Sample Size	10	100	500	10	100	500	10	100	500	10	100	200
	t^*	0.48	0.37	0.00	0.38	0.23	0.00	0.41	0.28	0.00	0.25	0.53	0.00
FP	**t=0.00**	45.00	3.00	0.00	35.00	2.00	0.00	25.00	2.50	0.00	35.00	7.50	0.00
	t=0.25	30.00	1.50	0.00	25.00	1.50	0.00	25.00	1.50	0.00	15.00	1.00	0.00
	$t=t^*$	25.00	1.00	0.00	25.00	1.50	0.00	10.00	1.50	0.00	20.00	0.00	0.00
FN		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

		Program											
		epiphany				uzbl				convert			gcc
	Sample Size	10	100	500	1000	10	100	500	1000	10	100	200	10
	t^*	0.93	0.81	0.33	0.00	0.92	0.83	0.65	0.45	0.64	0.54	0.00	0.00
FP	**t=0.00**	85.00	40.00	8.70	0.00	90.00	50.50	10.70	4.30	20.00	2.50	0.00	0.00
	t=0.25	40.00	10.00	0.40	0.00	40.00	3.50	0.90	0.85	15.00	1.00	0.00	0.00
	$t=t^*$	0.00	6.50	0.30	0.00	30.00	2.50	0.60	0.35	10.00	0.00	0.00	0.00
FN		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Reachable Code Reduction



Run-time Overhead



CFI ≠ Debloating

- Policies enforced by prior CFI works:
  - Source-aware CFI solutions: CFG derived from source code semantics
  - Binary-only CFI solutions: Approximate the source CFG from binary semantics
  - Both approaches preserve developer-intended, consumer-unwanted edges.

- Prior contextual CFI solution:
  - PathArmor [Van Der Veen et al.; USENIX Security 2015]
    - Contextual checks only performed at system call sites
    - Insufficient granularity to debloat fine-grained code blocks from software
    - Performance overhead too high if applied to every branch instruction

Comparison with RAZOR [Qian et al. (USENIX'19)]

	RAZOR	Control-flow Trimming
Strategy	Heuristics applied to code structure and traces	Machine learning (decision trees)
Policy Expressiveness	Static CFI	Contextual CFI
Debloating rate	~71%	~71%
Performance Overhead	1.7%	1.9%

Conclusion

- Main achievements
  - Binary software debloating using <u>incomplete</u> test-suite and no source code
  - First fine-grained contextual CFI enforcement at every branch site with high performance (1.8% overhead)
- Challenges for Future Research / Transition
  - Highly interactive software (diverse traces) can create high training burden. Could couple with directed fuzzers to improve training effectiveness.
  - Training process automatically detects uncertainties and ambiguities. Feed this information back to (non-expert) users to help them refine the training?

THANK YOU

QUESTIONS?