A few notes on hacker math

“Fundamental research challenges hidden in plain sight”

Sergey Bratus

CyberTruck Challenge 2025

Sergey’s disclaimers

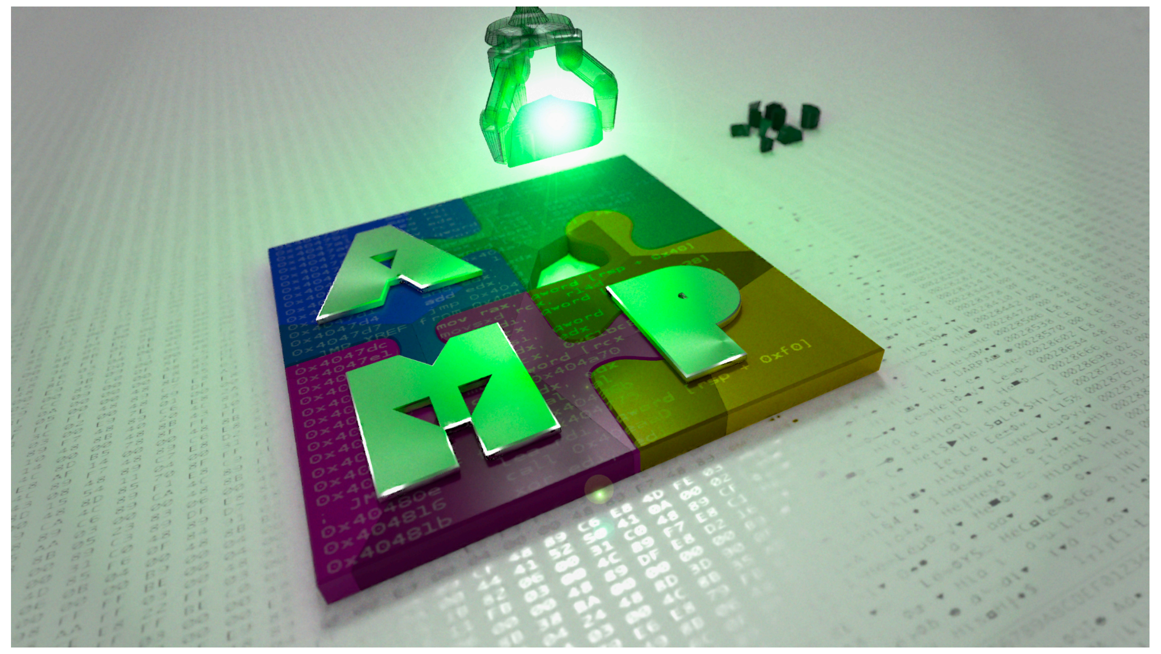
- Substantive: This is a personal perspective on other people’s amazing work. All credit goes to them, not me.
    - This is a tiny, biased sample of a great domain. Please tell me what I am missing!
- Trivial: I am a former mathematician. I tend to see math everywhere :)
- Obligatory: **The views, opinions and/or findings expressed are those of the author and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.**

Disclaimer for DARPA-funded research

This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA). The views, opinions and/or findings expressed are those of the author and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.

My DARPA programs

Safe Documents: Regain trust in electronic documents by creating tools to build **machine-readable unambiguous format definitions** and secure **verified parsers**



Assured Micropatching: Create tools for **rapid binary patching** of legacy mission-critical systems, even where the original source code or build process aren't available

Verified Security & Performance Enhancement of Large Legacy Software: Create practical tools for **incremental enhancement of software** systems with new verified code that is both correct-by-construction and safely composable with the rest of the system

My DARPA programs

HARDEN
Hardening Development Toolchains against Emergent Execution Engines

Hardening Development Toolchains Against Emergent Execution Engines:
Develop practical tools to anticipate, isolate, and mitigate **emergent behaviors** throughout the software lifecycle, to improve security outcomes in software for complex integrated systems

E-BOSS

Enhanced SBOM for Optimized Software Sustainment:
Develop Enhanced Software Bill of Material (eSBOM) advanced **metadata** technology to enable rapid triage-and-remediation of vulnerabilities in software at scale.

Hard hacking problems mean math

“Math pwns”

Hypothesis:

Biggest advances in hacking/cybersecurity come from nifty machine-readable mathematical representations of data & code—which are friendly to efficient algorithms.

Right representation => Math => Algorithm => Tool => Pwnage

Binary Diffing = Graph Isomorphism

Halvar Flake: BinDiff

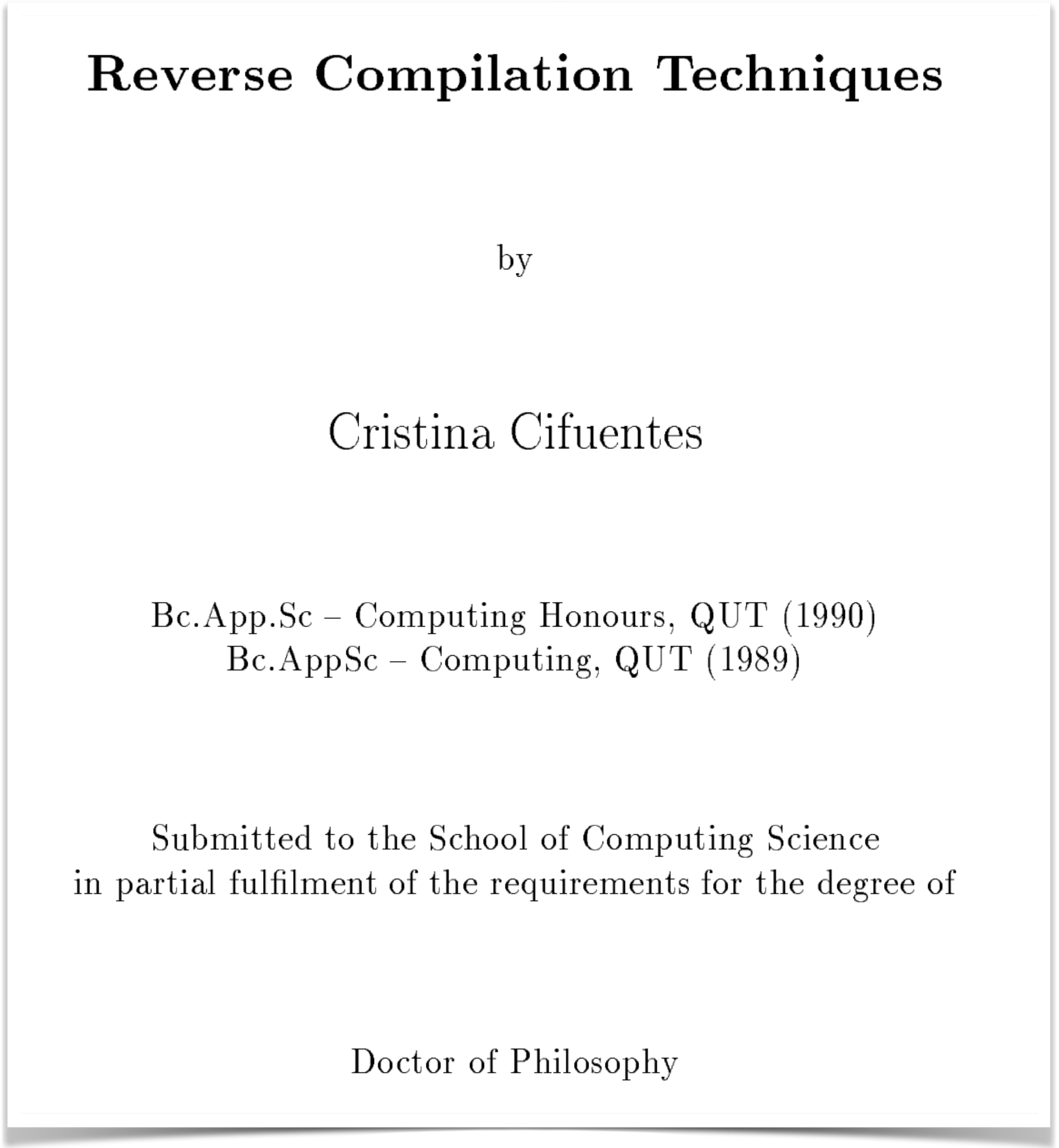
Representation => algorithms => pwnage

- Diffing binaries is useful (e.g., for patches) but hard.
    - Heuristics work, but only up to a point
- **Insight:** Graph isomorphism for basic block graphs!
    - Basic blocks make graphs, matching graphs ("graph isomorphism") is a hard algorithmic problem, but has efficient subcases
- Cf. Joxean Koret's *Diaphora* (https://github.com/joxeankoret/diaphora); QuarksLab's Diffing portal (https://diffing.quarkslab.com/)
- Also: Trail of Bits' *PolyFile* and *Graphtage* for diffing and merging arbitrary binary formats (https://blog.trailofbits.com/2020/08/28/graphtage/)

Decompilation: graph structuring

Cristina Cifuentes, Mother of decompilation

- Going back from compiled binary is hard, heuristics only get so far
- **Insight:**



Reverse Compilation Techniques

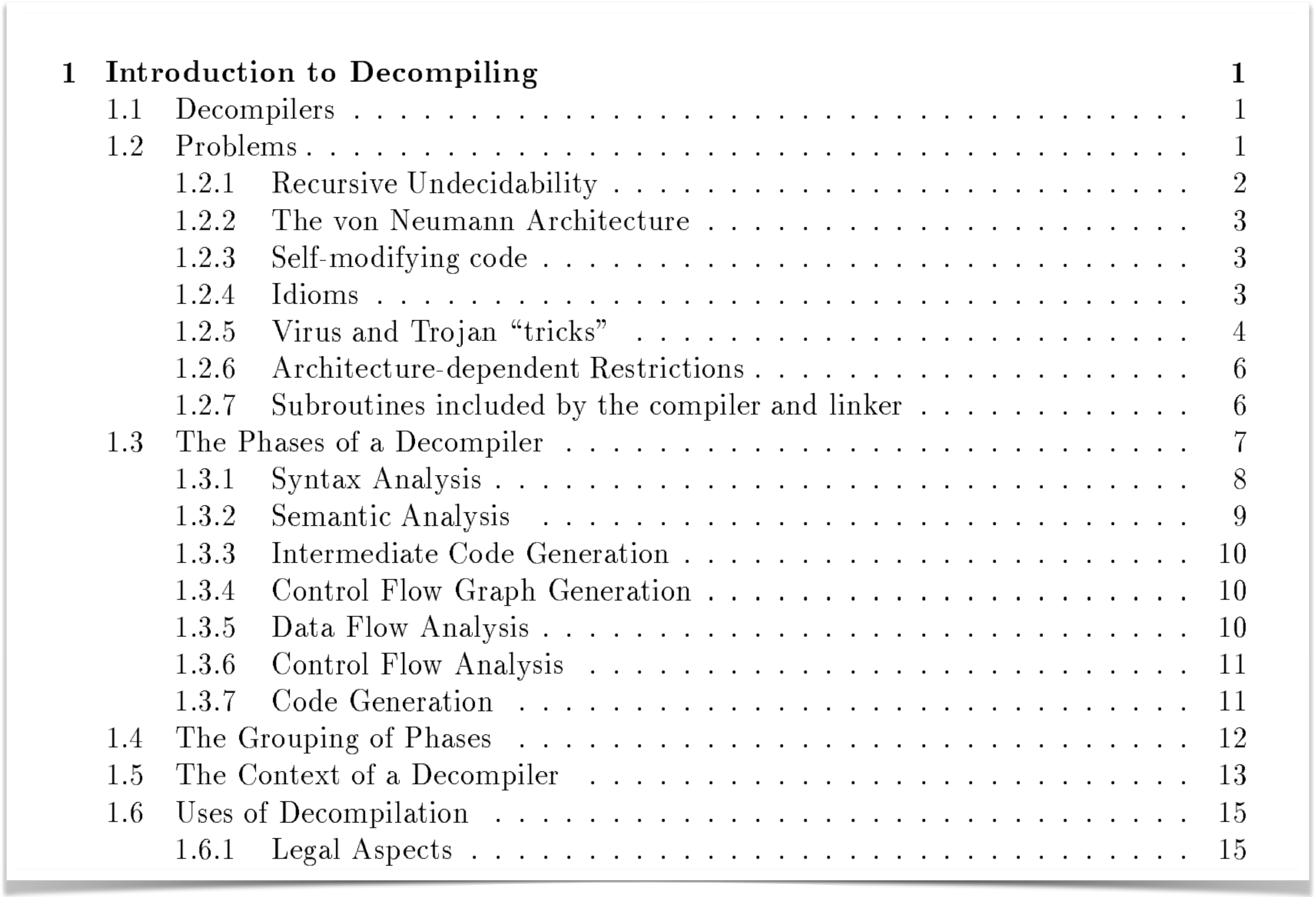
by

Cristina Cifuentes

Bc.App.Sc – Computing Honours, QUT (1990)
Bc.AppSc – Computing, QUT (1989)

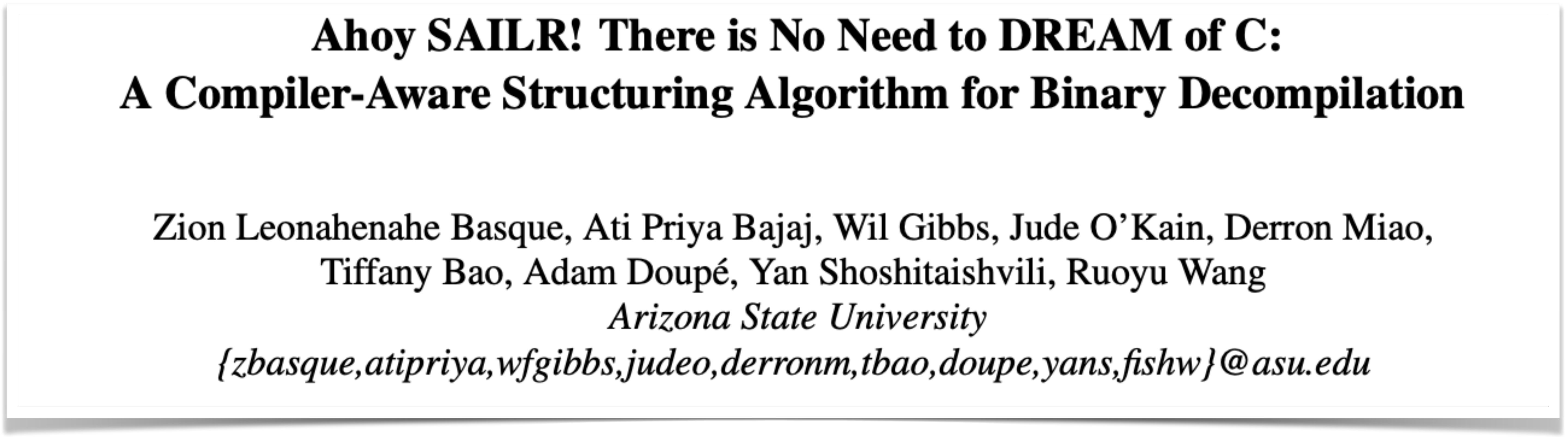
Submitted to the School of Computing Science
in partial fulfilment of the requirements for the degree of

Doctor of Philosophy



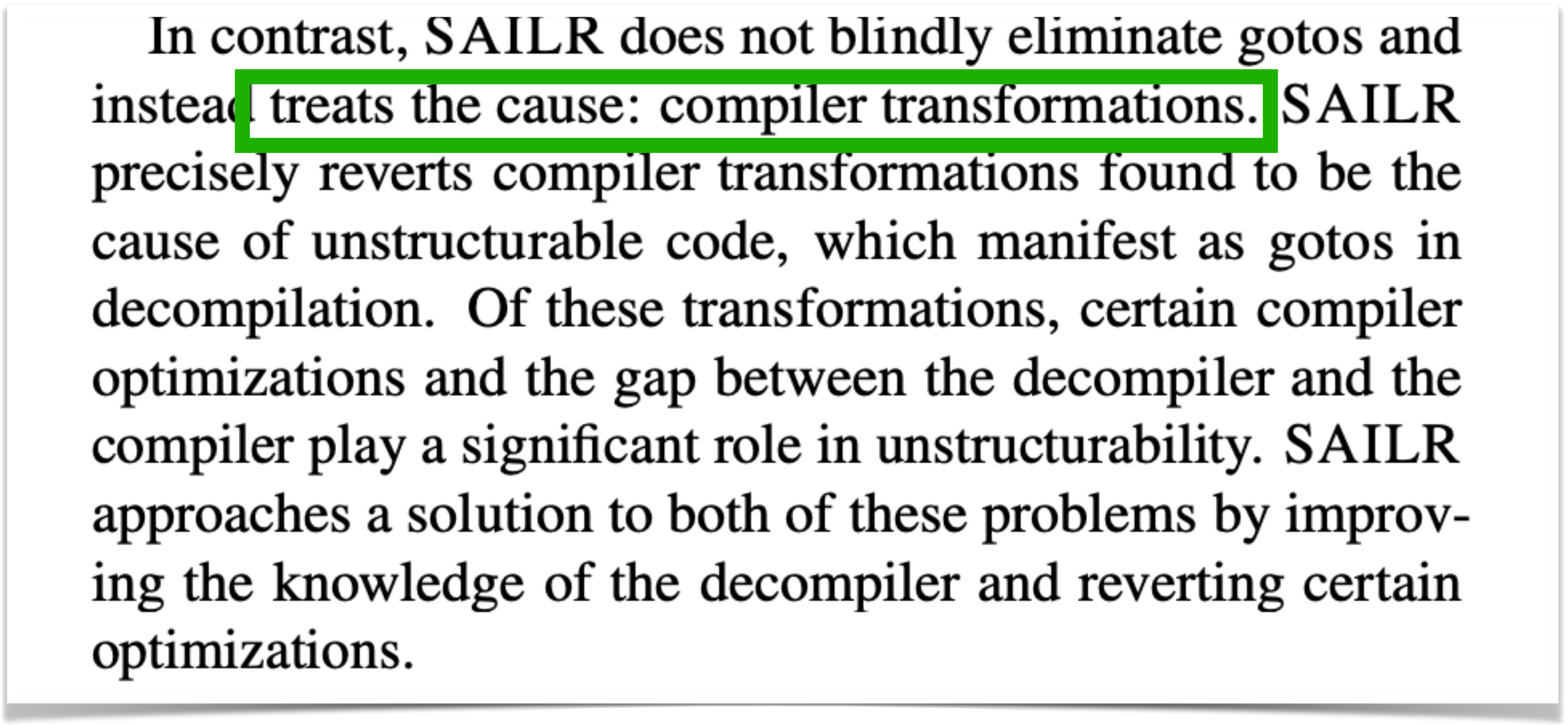
Decompilation, 30 years later

Still making progress: Hex-Rays, Binary Ninja, Ghidra, FoxDec, …



Ahoy SAILR! There is No Need to DREAM of C:
A Compiler-Aware Structuring Algorithm for Binary Decompilation

Zion Leonahenahe Basque, Ati Priya Bajaj, Wil Gibbs, Jude O'Kain, Derron Miao,
Tiffany Bao, Adam Doupé, Yan Shoshitaishvili, Ruoyu Wang
Arizona State University
{zbasque,atipriya,wfgibbs,judeo,derronm,tbao,doupe,yans,fishw}@asu.edu

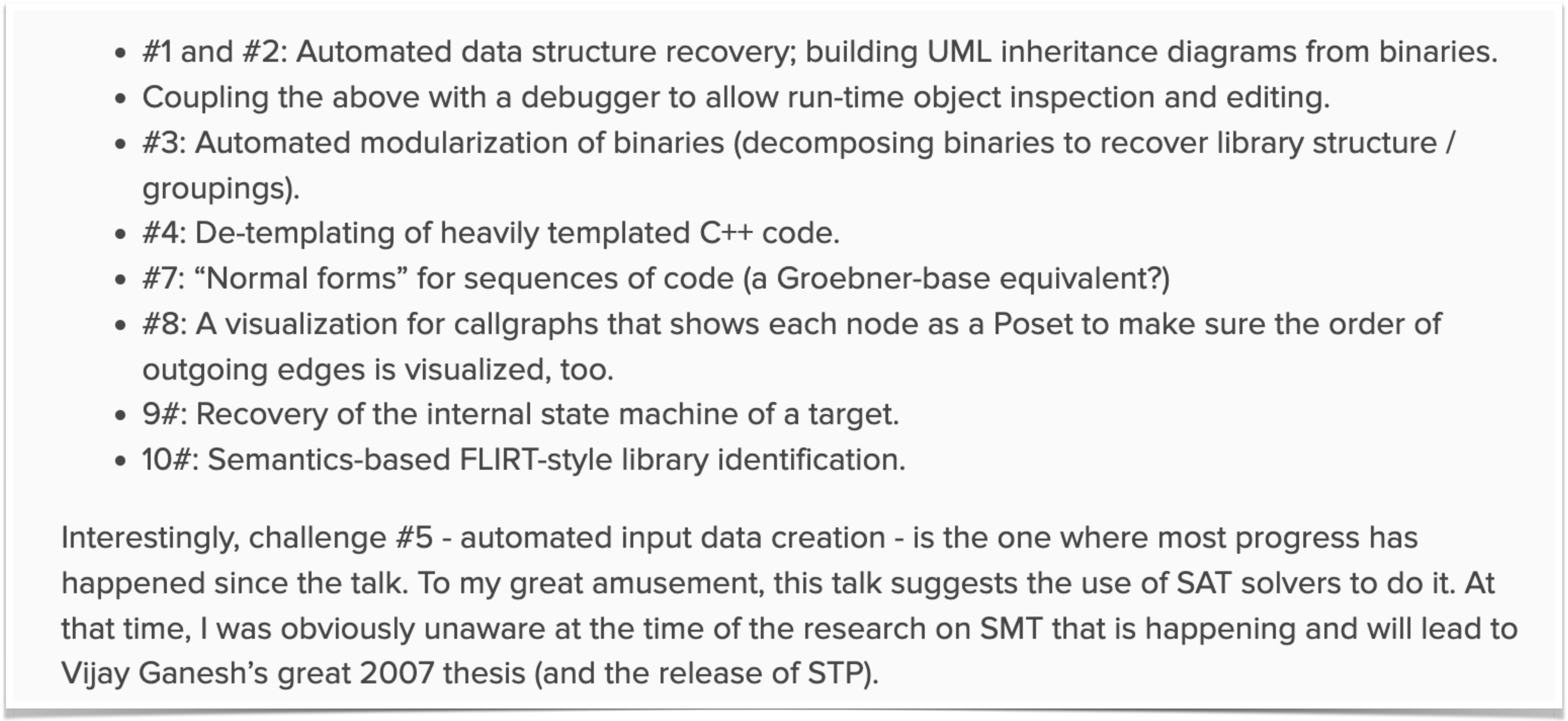


In contrast, SAILR does not blindly eliminate gotos and instead treats the cause: compiler transformations. SAILR precisely reverts compiler transformations found to be the cause of unstructurable code, which manifest as gotos in decompilation. Of these transformations, certain compiler optimizations and the gap between the decompiler and the compiler play a significant role in unstructurability. SAILR approaches a solution to both of these problems by improving the knowledge of the decompiler and reverting certain optimizations.

- More: https://mahaloz.re/dec-history-pt2

Reverse Engineering ~ Math

Halvar Flake's "RE 2006: New Challenges Need Changing Tools"



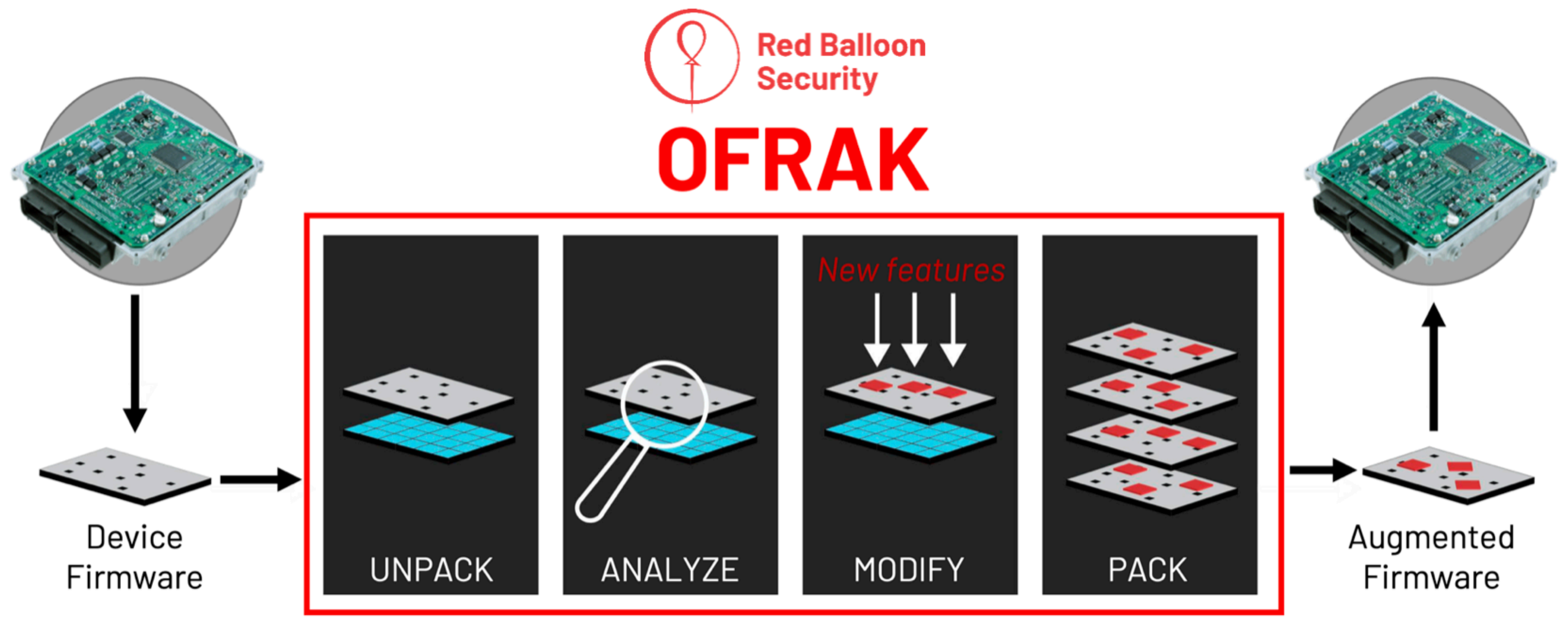
- #1 and #2: Automated data structure recovery; building UML inheritance diagrams from binaries.
- Coupling the above with a debugger to allow run-time object inspection and editing.
- #3: Automated modularization of binaries (decomposing binaries to recover library structure / groupings).
- #4: De-templating of heavily templated C++ code.
- #7: "Normal forms" for sequences of code (a Groebner-base equivalent?)
- #8: A visualization for callgraphs that shows each node as a Poset to make sure the order of outgoing edges is visualized, too.
- 9#: Recovery of the internal state machine of a target.
- 10#: Semantics-based FLIRT-style library identification.

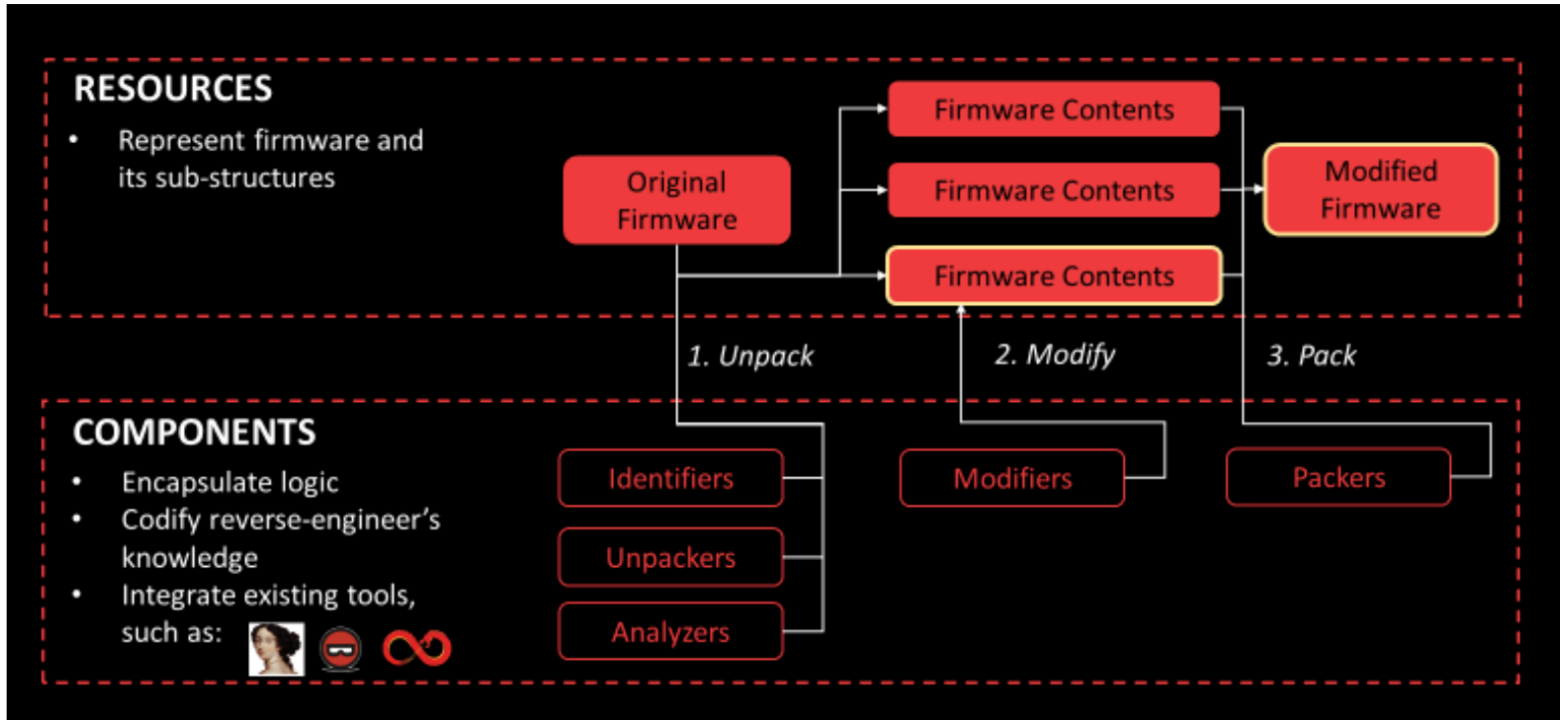
Interestingly, challenge #5 - automated input data creation - is the one where most progress has happened since the talk. To my great amusement, this talk suggests the use of SAT solvers to do it. At that time, I was obviously unaware at the time of the research on SMT that is happening and will lead to Vijay Ganesh's great 2007 thesis (and the release of STP).

https://thomasdullien.github.io/about/#2006

Modular framework for decompilation research

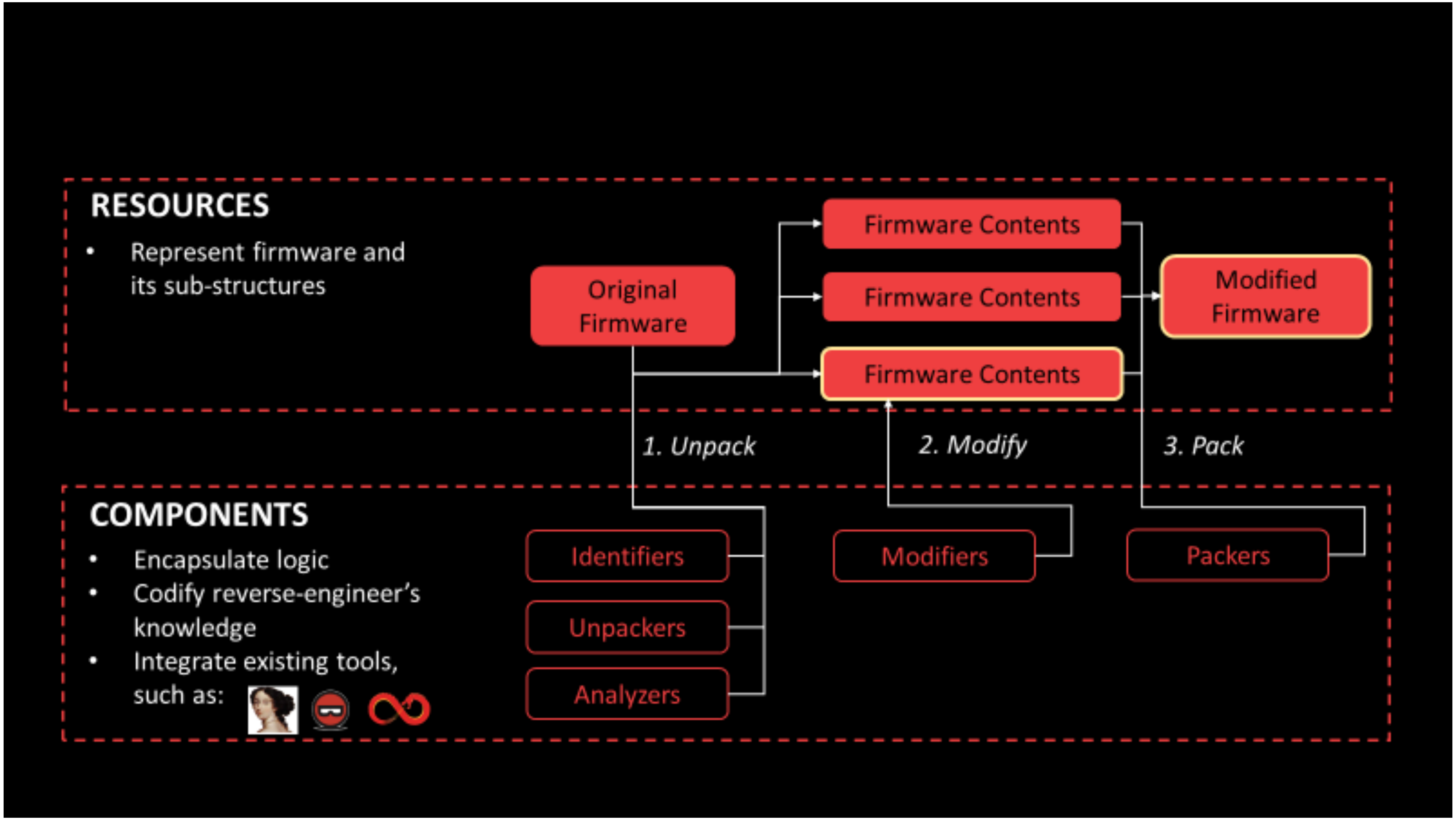
A new generation of tools for maintaining binaries



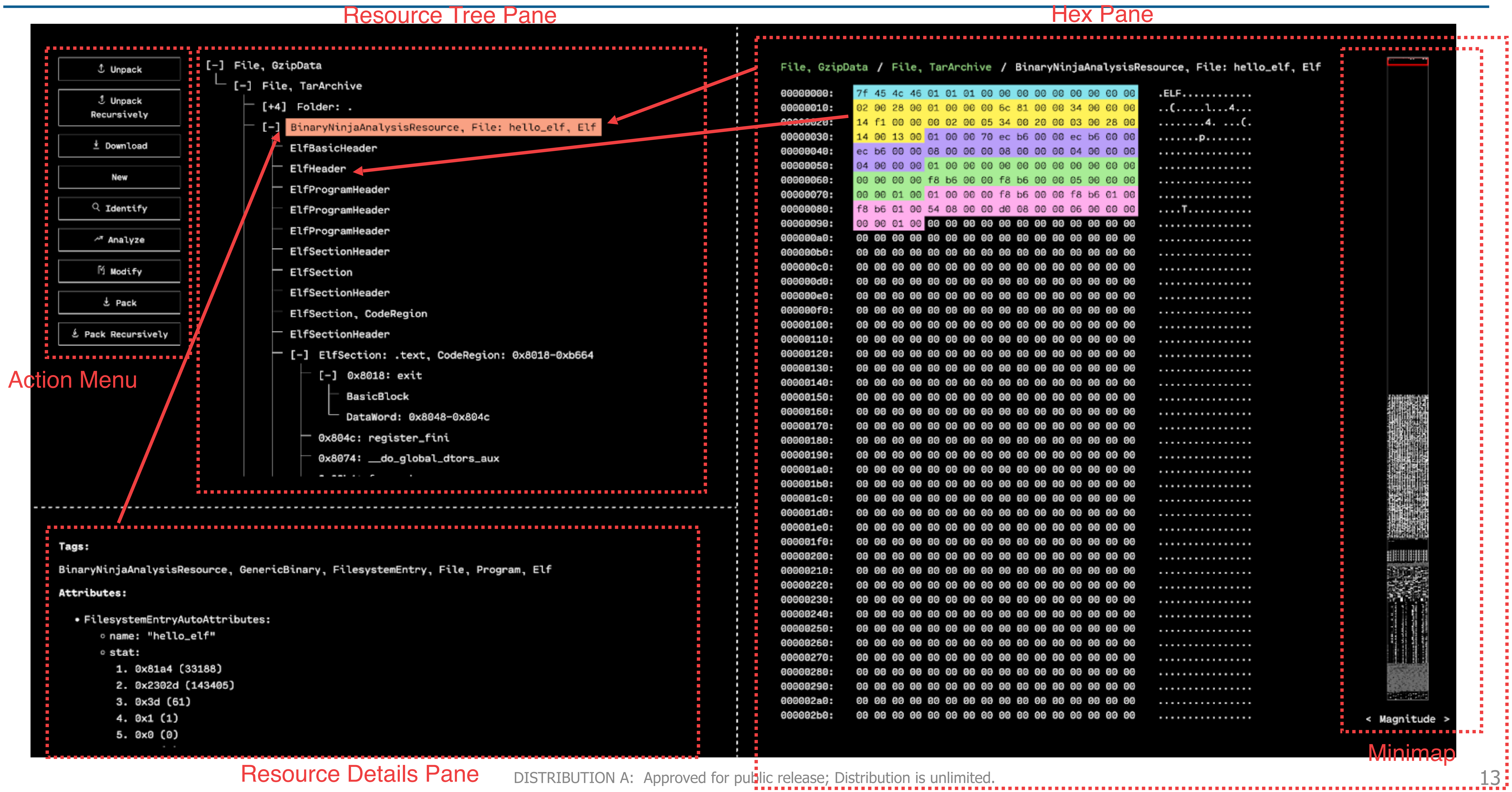


https://github.com/redballoonsecurity/ofrak

OFRAK cont.


RESOURCES
• Represent firmware and its sub-structures
Original Firmware
Firmware Contents
Firmware Contents
Firmware Contents
Modified Firmware
1. Unpack
2. Modify
3. Pack
COMPONENTS
• Encapsulate logic
• Codify reverse-engineer's knowledge
• Integrate existing tools, such as:
Identifiers
Unpackers
Analyzers
Modifiers
Packers

OFRAK cont.



```
[-] File, GzipData
 └ [-] File, TarArchive
     ├ [+4] Folder: .
     ├ [-] BinaryNinjaAnalysisResource, File: hello_elf, Elf
         ├ ElfBasicHeader
         ├ ElfHeader
         ├ ElfProgramHeader
         ├ ElfProgramHeader
         ├ ElfProgramHeader
         ├ ElfSectionHeader
         ├ ElfSection
         ├ ElfSectionHeader
         ├ ElfSection, CodeRegion
         ├ ElfSectionHeader
         ├ [-] ElfSection: .text, CodeRegion: 0x8018-0xb664
             ├ [-] 0x8018: exit
             │   ├ BasicBlock
             │   └ DataWord: 0x8048-0x804c
             ├ 0x804c: register_fini
             ├ 0x8074: __do_global_dtors_aux
```

```
File, GzipData / File, TarArchive / BinaryNinjaAnalysisResource, File: hello_elf, Elf

00000000:  7f 45 4c 46 01 01 01 00 00 00 00 00 00 00 00 00   .ELF............
00000010:  02 00 28 00 01 00 00 00 6c 81 00 00 34 00 00 00   ..(.....l...4...
00000020:  14 f1 00 00 00 02 00 05 34 00 20 00 03 00 28 00   ........4. ...(.
00000030:  14 00 13 00 01 00 00 70 ec b6 00 00 ec b6 00 00   .......p........
00000040:  ec b6 00 00 08 00 00 00 08 00 00 00 04 00 00 00   ................
00000050:  04 00 00 00 01 00 00 00 00 00 00 00 00 00 00 00   ................
00000060:  00 00 00 00 f8 b6 00 00 f8 b6 00 00 05 00 00 00   ................
00000070:  00 00 01 00 01 00 00 00 f8 b6 00 00 f8 b6 01 00   ................
00000080:  f8 b6 01 00 54 08 00 00 d0 08 00 00 06 00 00 00   ....T...........
00000090:  00 00 01 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
000000a0:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
000000b0:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
000000c0:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
000000d0:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
000000e0:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
000000f0:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
00000100:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
00000110:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
00000120:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
00000130:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
00000140:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
00000150:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
00000160:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
00000170:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
00000180:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
00000190:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
000001a0:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
000001b0:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
000001c0:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
000001d0:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
000001e0:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
000001f0:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
00000200:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
00000210:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
00000220:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
00000230:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
00000240:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
00000250:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
00000260:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
00000270:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
00000280:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
00000290:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
000002a0:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
000002b0:  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
```

Tags:

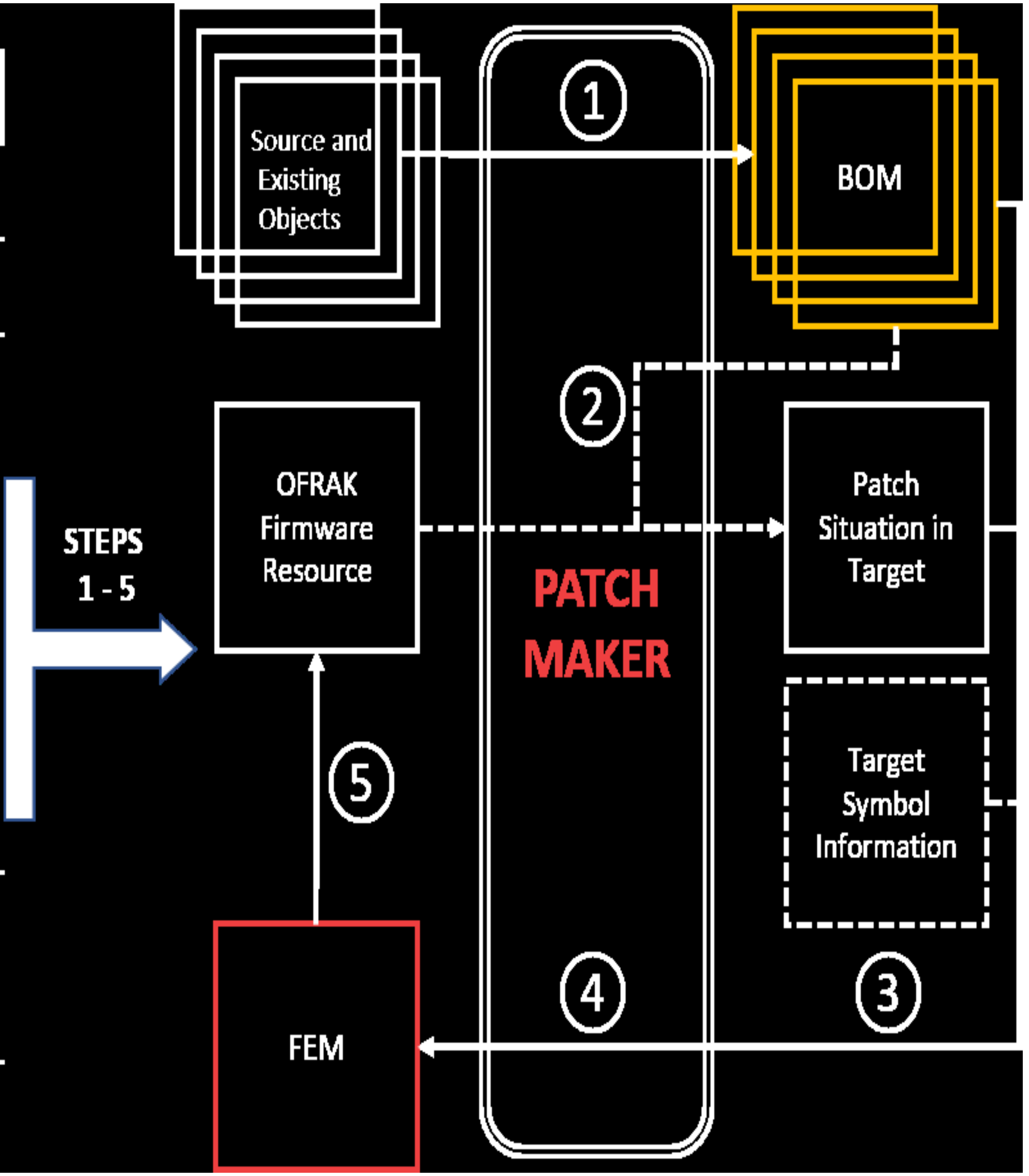
BinaryNinjaAnalysisResource, GenericBinary, FilesystemEntry, File, Program, Elf

Attributes:

- FilesystemEntryAutoAttributes:
  - name: "hello_elf"
  - stat:
    1. 0x81a4 (33188)
    2. 0x2302d (143405)
    3. 0x3d (61)
    4. 0x1 (1)
    5. 0x0 (0)

OFRAK Patch Maker

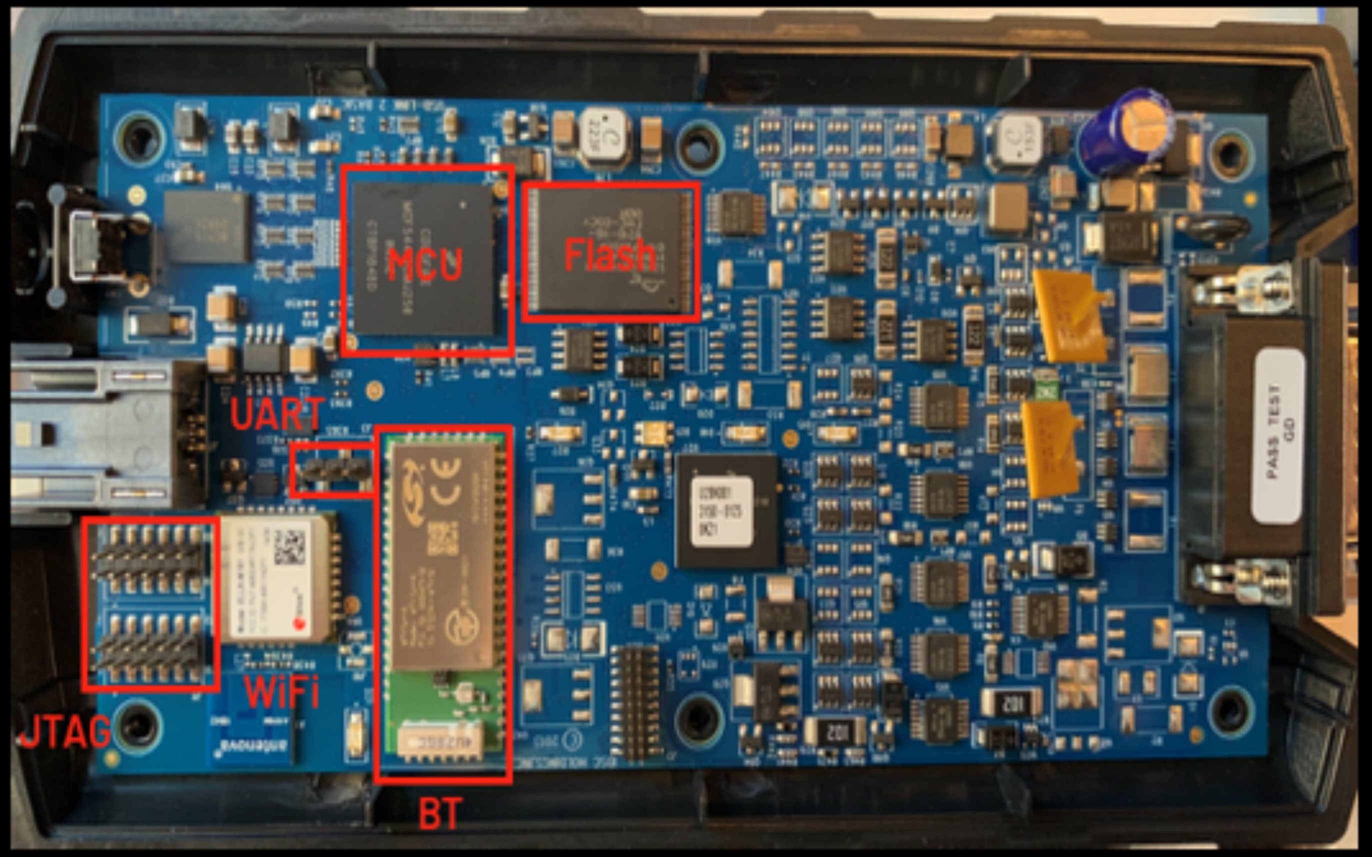
GOAL	Make patching compiled firmware as easy as patching source code
INPUTS	Code without Destination Information
OUTPUTS	Correctly Situated Binary Data
APPROACH	**Leverage & automate existing linker scripting functionality in a simple API** 1. Build BOM (Batch of Objects and Metadata) from source and existing objects 2. (Optional) Use OFRAK analysis and metadata in BOM to automatically generate mappings situating the patch in the target binary 3. (Optional) Provide additional symbol information derived from the target binary 4. Build FEM (Final Executable and Metadata) from BOM, patch mappings (generated in Step 2 or manually defined), and optional additional symbol information 5. Inject situated machine code in FEM into firmware
RESULTS	• 100x reduction in LoC for complex security feature build • 16x development time reduction for simple single-function vulnerability patch


STEPS 1 - 5
Source and Existing Objects
1
BOM
2
OFRAK Firmware Resource
PATCH MAKER
Patch Situation in Target
Target Symbol Information
5
FEM
4
3

Diagnostics adapter autotomy

```
[autotomy_modifier.py:  137] Autotomy applied to 574 functions and 0 data ranges from 24 entry points (0x23fbc bytes code, 0x0 data)
```

PROBLEM	Ground vehicle diagnostics adapter used by DoD customer(s) comes packaged with Bluetooth and WiFi connectivity
CHALLENGE	Can we remove unwanted features from firmware with no source code access?
APPROACH	Use OFRAK, a modular firmware reverse engineering and analysis framework built by Red Balloon Security (RBS) under DARPA AMP, to apply RBS's proprietary Autotomy algorithm to remove unused and unwanted features.
RESULTS	• Permanently disabled Bluetooth and WiFi in firmware by removing all associated code • Removed 144KB of code / added free space • Modifying device firmware was extremely easy – no manufacturer signature to bypass



WEIRD MACHINES

Top Right: *Hardware teardown results of the ground vehicle diagnostics adapter*

Bottom Right: *Example outcome of a payload taking advantage of free space with ASCII animation playing instead of normal ping function*

Modular framework for binary research

A new generation of tools for maintaining binaries

- CodeCut: https://github.com/JHUAPL/CodeCut
- Codehawk (*): https://github.com/static-analysis-engineering/codehawk
- VIBES: https://github.com/draperlaboratory/VIBES
- Remill, Anvil, Relic LLVM lifters: https://github.com/lifting-bits/remill, https://github.com/lifting-bits/anvill, https://github.com/lifting-bits/rellic
- PATE binary patch verifier: https://github.com/GaloisInc/pate
- MCTrace code release: https://github.com/GaloisInc/mctrace
- Binary analysis and rewriting tools used by PATE and MCTrace: https://github.com/GaloisInc/macaw, reopt, what4, crucible, elf-edit, renovate, etc.

(*) See https://www.aarno-labs.com/blog/post/high-assurance-remediation-of-cve-2024-12248/

“Weaponizing the Chomsky syntax hierarchy

Kaminsky/Sassaman/Patterson: Breaking X.509 => LangSec (*)

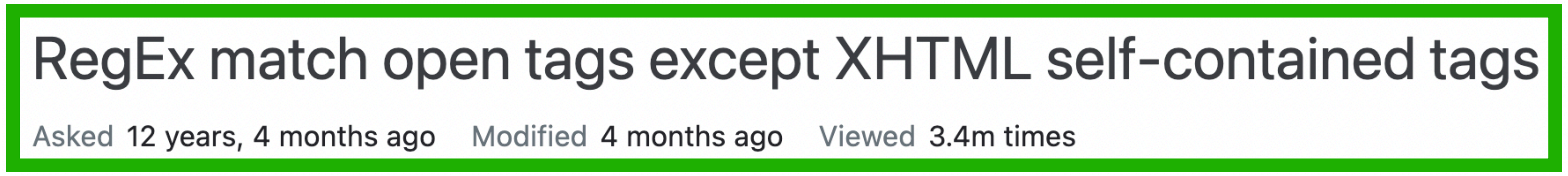
- Why so many “input validation/sanitization” bugs in everything?
    - What are programmers doing that they can’t ever get right?
- **Insight**: Inputs have grammars. Complex grammars are hard to parse. Ambiguous grammars are impossible to validate. Sanitization is an anti-pattern.
    - Many bugs uncovered, hardened/correct parsers built

SafeDocs

Safe Documents: Safely intake electronic data by creating tools to build <u>machine-readable</u> <u>unambiguous</u> format definitions and secure <u>verified</u> parsers

(*) https://langsec.org/

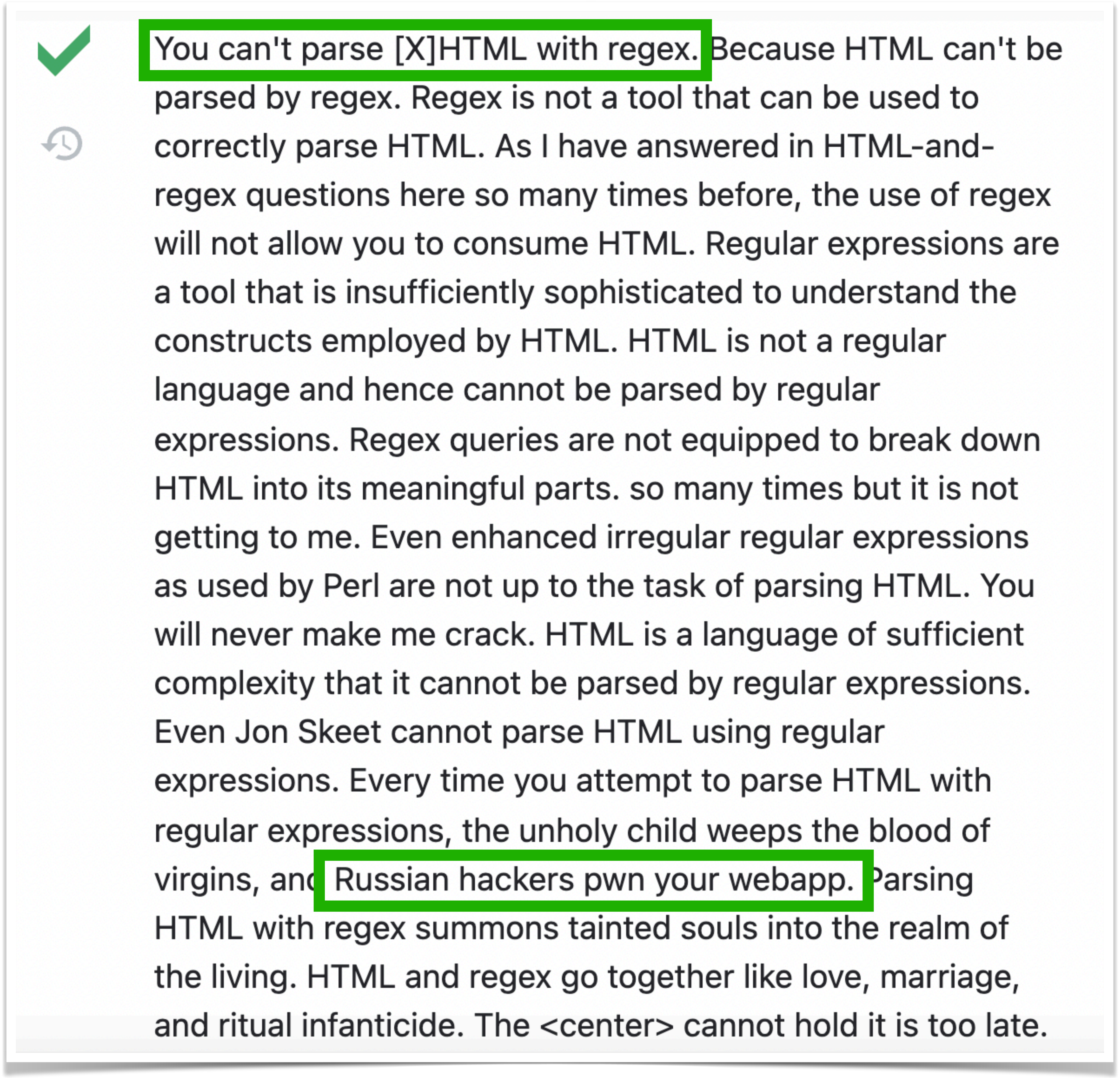
“Recognizer doesn’t match the input language”



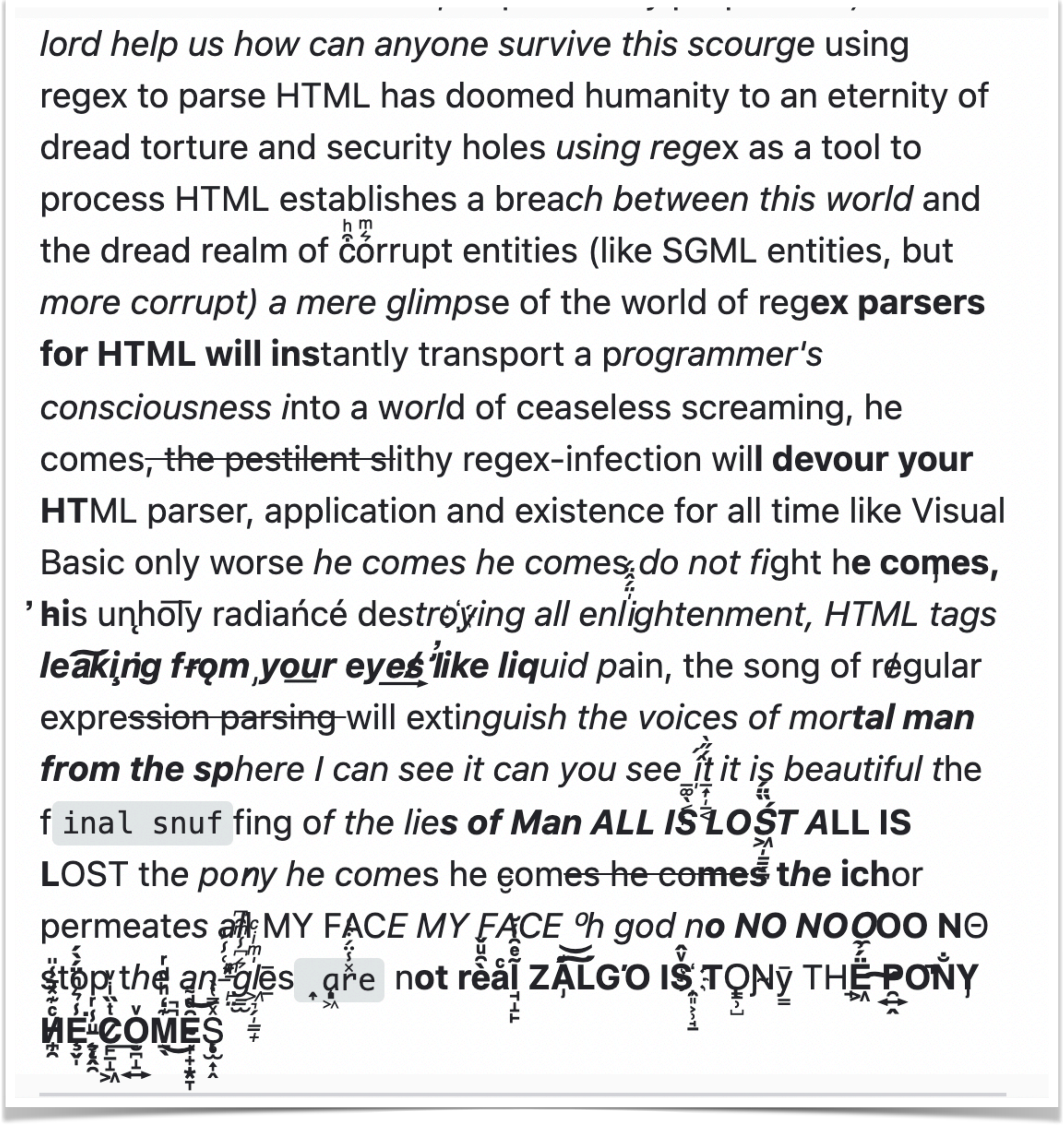
RegEx match open tags except XHTML self-contained tags

Asked 12 years, 4 months ago Modified 4 months ago Viewed 3.4m times

https://stackoverflow.com/questions/1732348/regex-match-open-tags-except-xhtml-self-contained-tags



You can't parse [X]HTML with regex. Because HTML can't be parsed by regex. Regex is not a tool that can be used to correctly parse HTML. As I have answered in HTML-and-regex questions here so many times before, the use of regex will not allow you to consume HTML. Regular expressions are a tool that is insufficiently sophisticated to understand the constructs employed by HTML. HTML is not a regular language and hence cannot be parsed by regular expressions. Regex queries are not equipped to break down HTML into its meaningful parts. so many times but it is not getting to me. Even enhanced irregular regular expressions as used by Perl are not up to the task of parsing HTML. You will never make me crack. HTML is a language of sufficient complexity that it cannot be parsed by regular expressions. Even Jon Skeet cannot parse HTML using regular expressions. Every time you attempt to parse HTML with regular expressions, the unholy child weeps the blood of virgins, and Russian hackers pwn your webapp. Parsing HTML with regex summons tainted souls into the realm of the living. HTML and regex go together like love, marriage, and ritual infanticide. The <center> cannot hold it is too late.



lord help us how can anyone survive this scourge using regex to parse HTML has doomed humanity to an eternity of dread torture and security holes *using regex* as a tool to process HTML establishes a brea*ch between this world* and the dread realm of c̶orrupt entities (like SGML entities, but *more corrupt) a mere glimp*se of the world of rege**x parsers for HTML will ins**tantly transport a *programmer's consciousness* into a wor*ld* of ceaseless screaming, he comes~~, the pestilent sl~~ithy regex-infection wil**l devour your HT**ML parser, application and existence for all time like Visual Basic only worse *he comes he comes do not fi*ght h**e comes, hi**s unholy radiancé destroying *all enlightenment, HTML tags* ***leaking from your eyes like liq****uid* pain, the song of re̸gular expre~~ssion parsing~~ will extin*guish the voices of mor**tal man*** ***from the sp****here I can see it can you see it it is beautiful* the f`inal snuf`fing *of the lie****s of Man ALL IS LOST ALL IS*** **LOST** the pon*y he comes* he c̶omes ~~he comes~~ ***the ich***or permeates all MY FACE *MY FACE ᵒh god no* ***NO NOOOO NO*** *stop the an*gles `are` **not real ZALGO IS TONY THE PONY HE COMES**

A LangSec view of data languages

Complexity class	Examples	Model needed to correctly parse/accept	Complexity to <u>verify</u> implementation	Security
Recursively enumerable	Javascript, Flash, “benign programs”*	Turing machine	In general, impossible	Gift to attackers
Recursive	Some limited programs	Always-stopping Turing machines	In general, impossible	
Context-sensitive	Document & image formats, PDF, MPEG, DNS, SMB, ASN.1, X.509, actual XML	Linear-bounded automata (random-access memory)	Likely not safe or securable in general	🟥
Mildly context-sensitive	Subsets of document & protocol formats	Embedded pushdown automata “stack of stacks”	“Research needed”	🟧
Context-free	HTML*, JSON*, XML*	Pushdown automata ”stacks”	“Feasible, with challenges”	🟨
CALC-regular “regular+length fields”	Many TCP/IP* protocols	Finite state machines with accumulators	Feasible	Safe if done right
Regular	IPv4	Finite state machines	Known & efficient	

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Context-free	HTML*, JSON*, XML*	Pushdown automata ”stacks”	“Feasible, with challenges”	🟨
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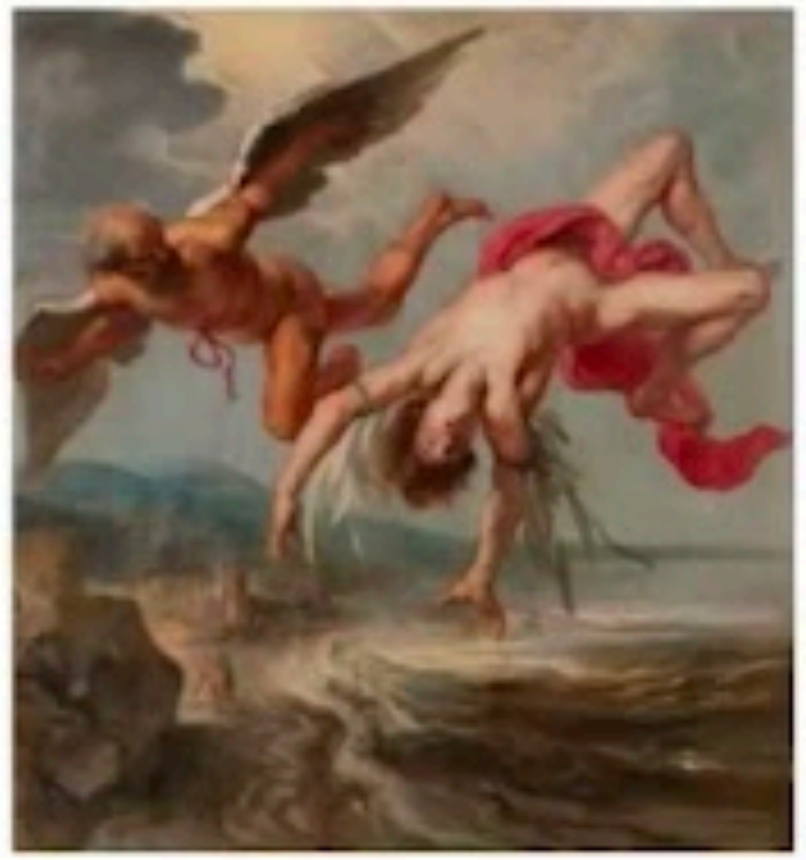
Good news: this work has started!

Data Definition Languages (DDLs):



(1)

DaeDaLus (Galois, Inc.)

(2)

Parsley

Parsley DDL (SRI)

(3)

Parser combinators for binary formats, in C. Yes, in C. What? Don't look at me like that.

Hammer/VALARIN
(Special Circumstances, LLC/BAE)

(4)

Arlington PDF Model
(PDF Association)

Image credits:
[1] https://en.wikipedia.org/wiki/Icarus#/media/File:Gowy-icaro-prado.jpg
[2] Natarajan Shankar, SRI
[3] Meredith L. Patterson, Special Circumstances LLC
[4] PDF Association

Microsoft Research Summit 2021

pdf-association/
safedocs

PDF association

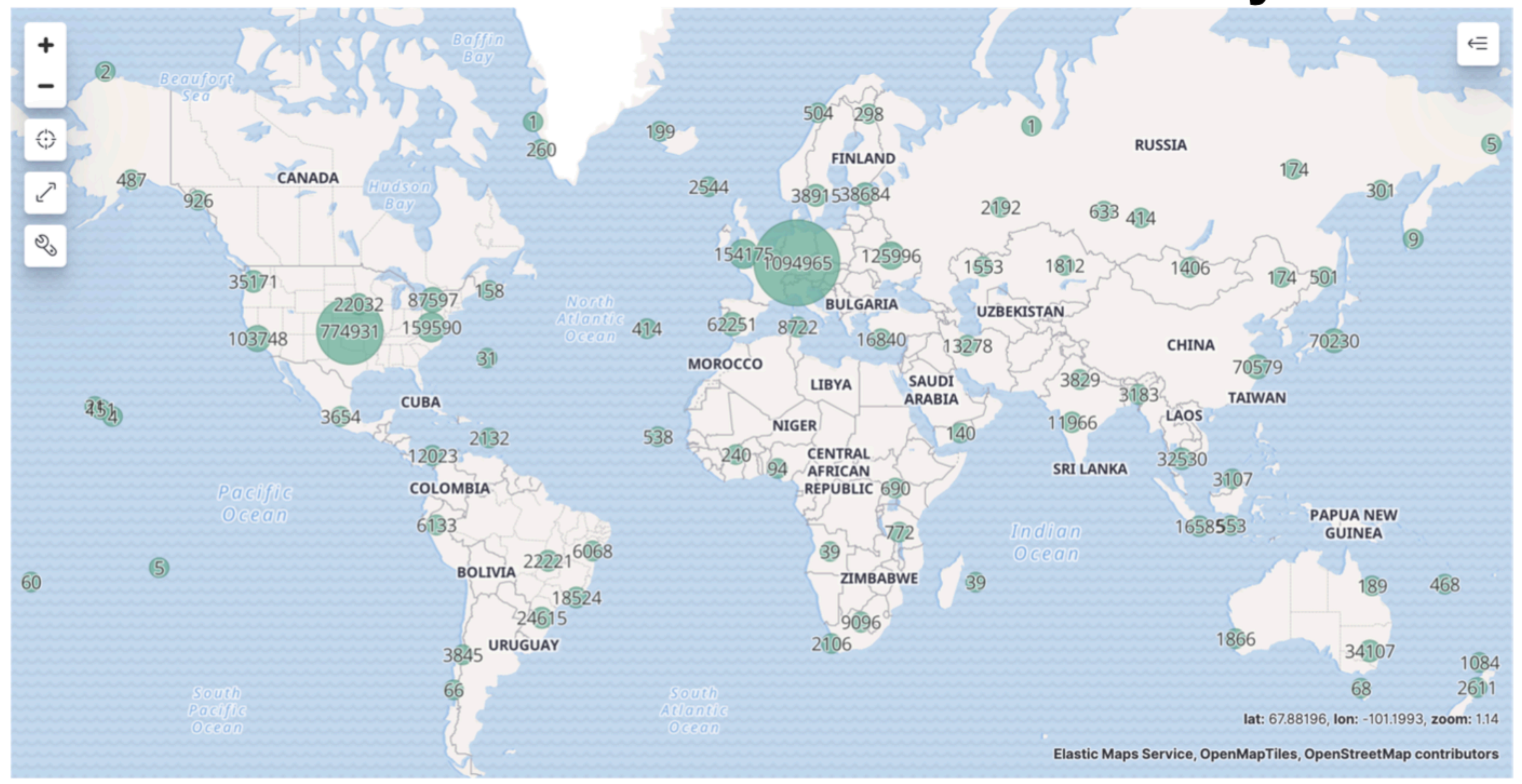
Artifacts from the DARPA-funded SafeDocs research program

“***Demystifying PDF through a machine-readable definition,***” Peter Wyatt, CTO of PDF Association
“*Building a File Observatory for Secure Parser Development,*” Tim Allison et al., NASA Jet Propulsion Lab
"*Accessible Formal Methods for Verified Parser Development,*” Letitia Li et al., BAE Systems
“*RL-GRIT: Reinforcement Learning for Grammar Inference*," Walt Woods et al., Galois Inc.

A few resources by SafeDocs

- First ever **machine-readable object model for PDF** 1.6 through 2.0
  500+ objects, 3,500+ keys, 5000 rules, 40 relationship predicate types
- Exposed multiple bugs in existing validators and parsers, 600+ deviations
- 100+ disambiguating candidate edits proposed and adopted into ISO PDF 2.0 standard (32000-2:2020, 1000 pages, 79 normative references)

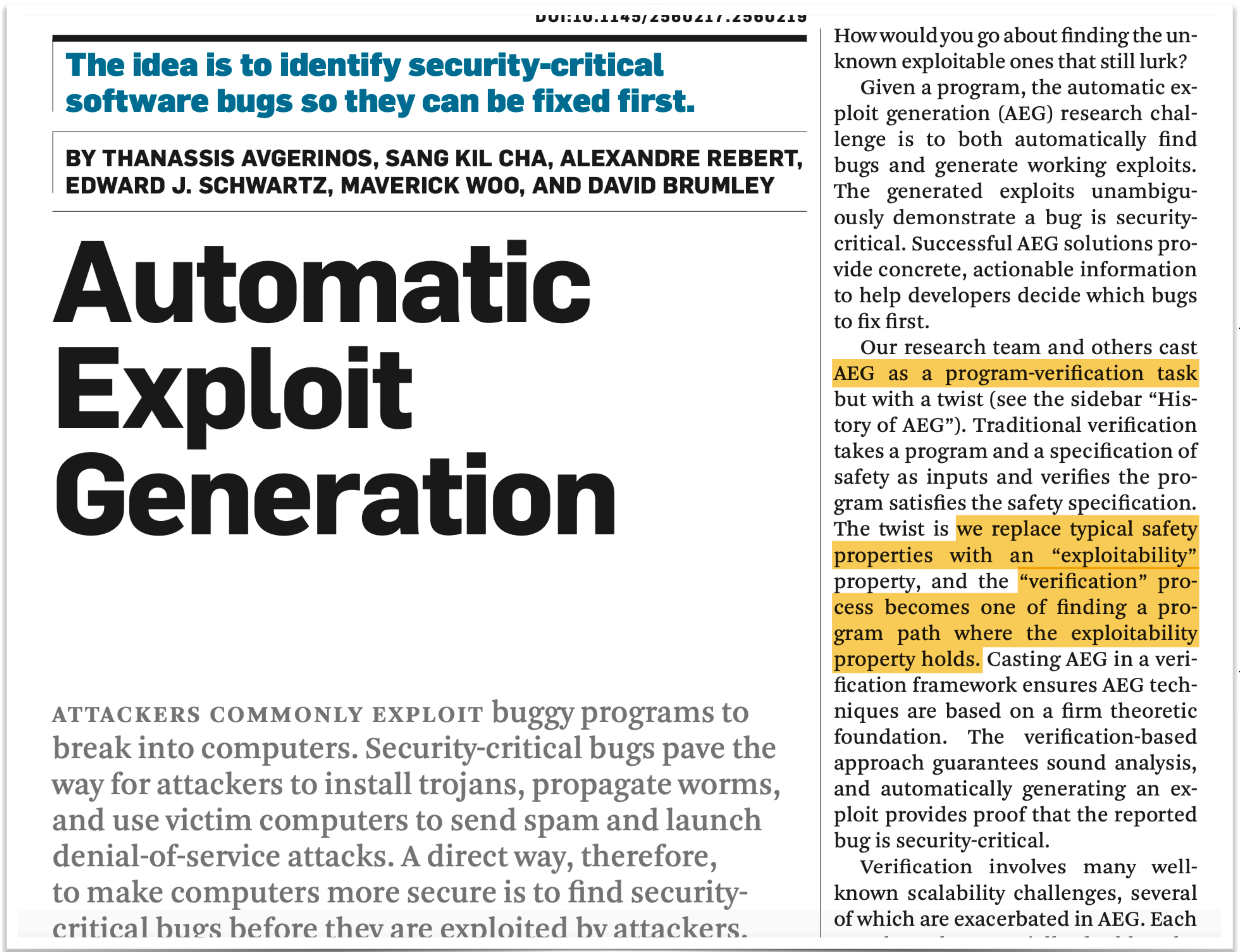
Map of PDFs in the July 2020 Common Crawl Data -- GeoLocation of URL/IPs via MaxMind's GeoIP City Database



- First ever Internet-scale observatory for a major document format, global coverage
- Based on Apache CommonCrawl, AWS
- Automatic identification of malformations, with attribution and estimated impact
- https://digitalcorpora.org/corpora/file-corpora/cc-main-2021-31-pdf-untruncated/ (sponsored by AWS)

Exploitation = proofs + programming

Exploits are proofs, exploitation is verification


DOI:10.1145/2560217.2560219

The idea is to identify security-critical software bugs so they can be fixed first.

BY THANASSIS AVGERINOS, SANG KIL CHA, ALEXANDRE REBERT, EDWARD J. SCHWARTZ, MAVERICK WOO, AND DAVID BRUMLEY

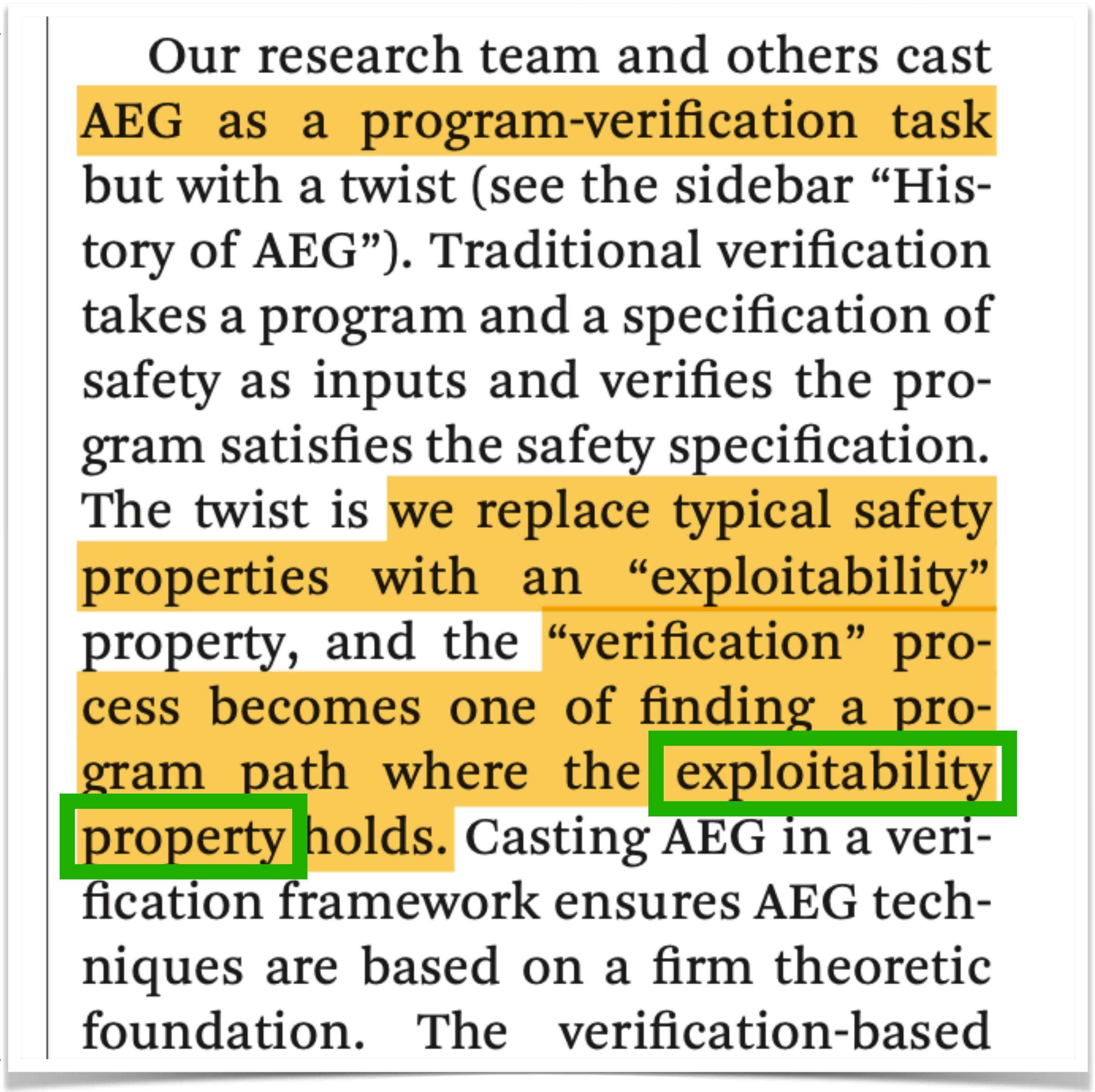
Automatic Exploit Generation

ATTACKERS COMMONLY EXPLOIT buggy programs to break into computers. Security-critical bugs pave the way for attackers to install trojans, propagate worms, and use victim computers to send spam and launch denial-of-service attacks. A direct way, therefore, to make computers more secure is to find security-critical bugs before they are exploited by attackers. How would you go about finding the unknown exploitable ones that still lurk?

Given a program, the automatic exploit generation (AEG) research challenge is to both automatically find bugs and generate working exploits. The generated exploits unambiguously demonstrate a bug is security-critical. Successful AEG solutions provide concrete, actionable information to help developers decide which bugs to fix first.

Our research team and others cast AEG as a program-verification task but with a twist (see the sidebar "History of AEG"). Traditional verification takes a program and a specification of safety as inputs and verifies the program satisfies the safety specification. The twist is we replace typical safety properties with an "exploitability" property, and the "verification" process becomes one of finding a program path where the exploitability property holds. Casting AEG in a verification framework ensures AEG techniques are based on a firm theoretic foundation. The verification-based approach guarantees sound analysis, and automatically generating an exploit provides proof that the reported bug is security-critical.

Verification involves many well-known scalability challenges, several of which are exacerbated in AEG. Each


Our research team and others cast AEG as a program-verification task but with a twist (see the sidebar "History of AEG"). Traditional verification takes a program and a specification of safety as inputs and verifies the program satisfies the safety specification. The twist is we replace typical safety properties with an "exploitability" property, and the "verification" process becomes one of finding a program path where the exploitability property holds. Casting AEG in a verification framework ensures AEG techniques are based on a firm theoretic foundation. The verification-based

"Verification .. becomes finding a program path [with] the **exploitability property**"

Automated Exploitation Grand Challenge

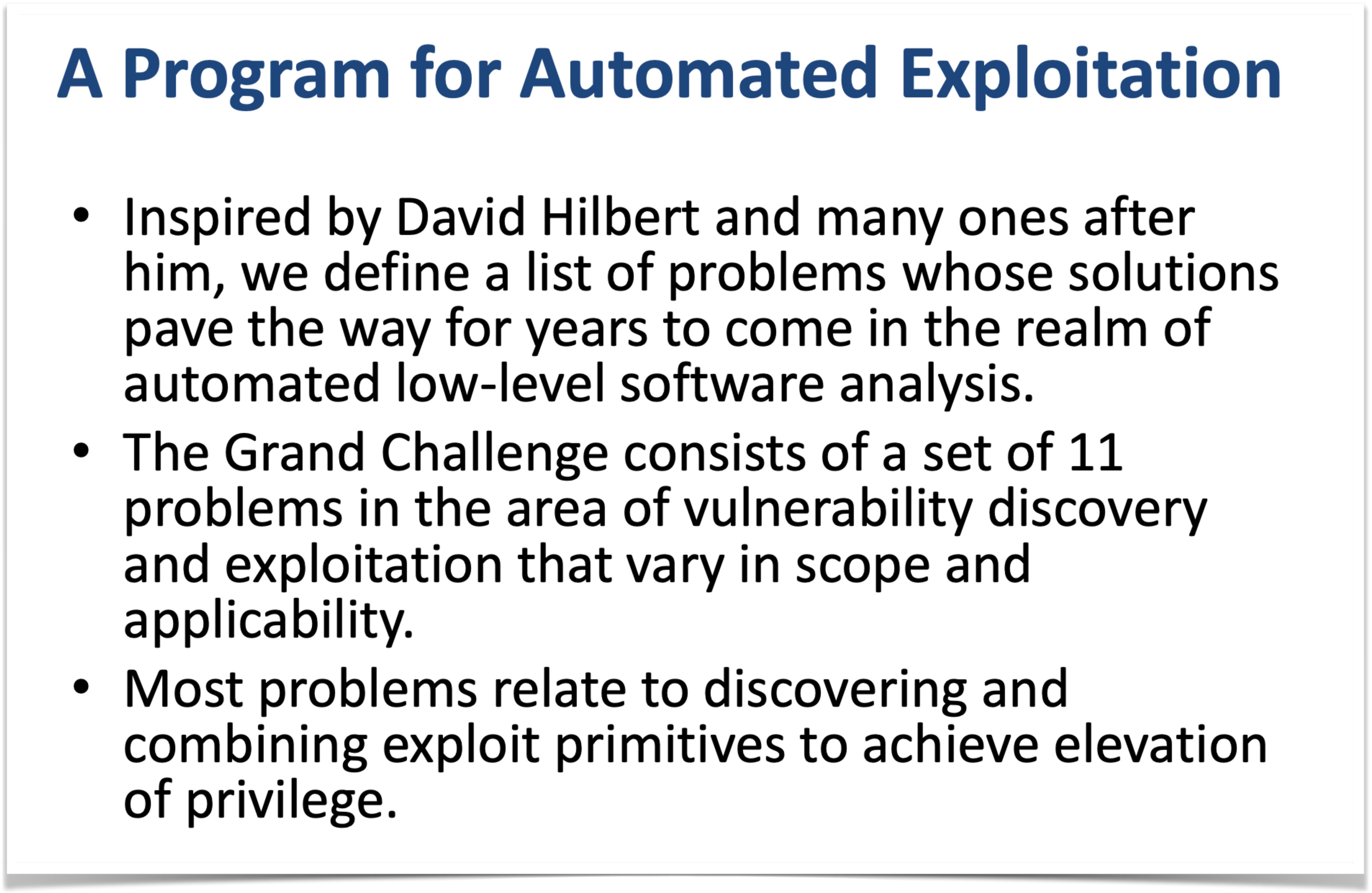
Julien Vanegue's Challenge Problems

The Automated Exploitation Grand Challenge

Tales of Weird Machines

Julien Vanegue
julien.vanegue@gmail.com

H2HC conference, Sao Paulo, Brazil
October 2013



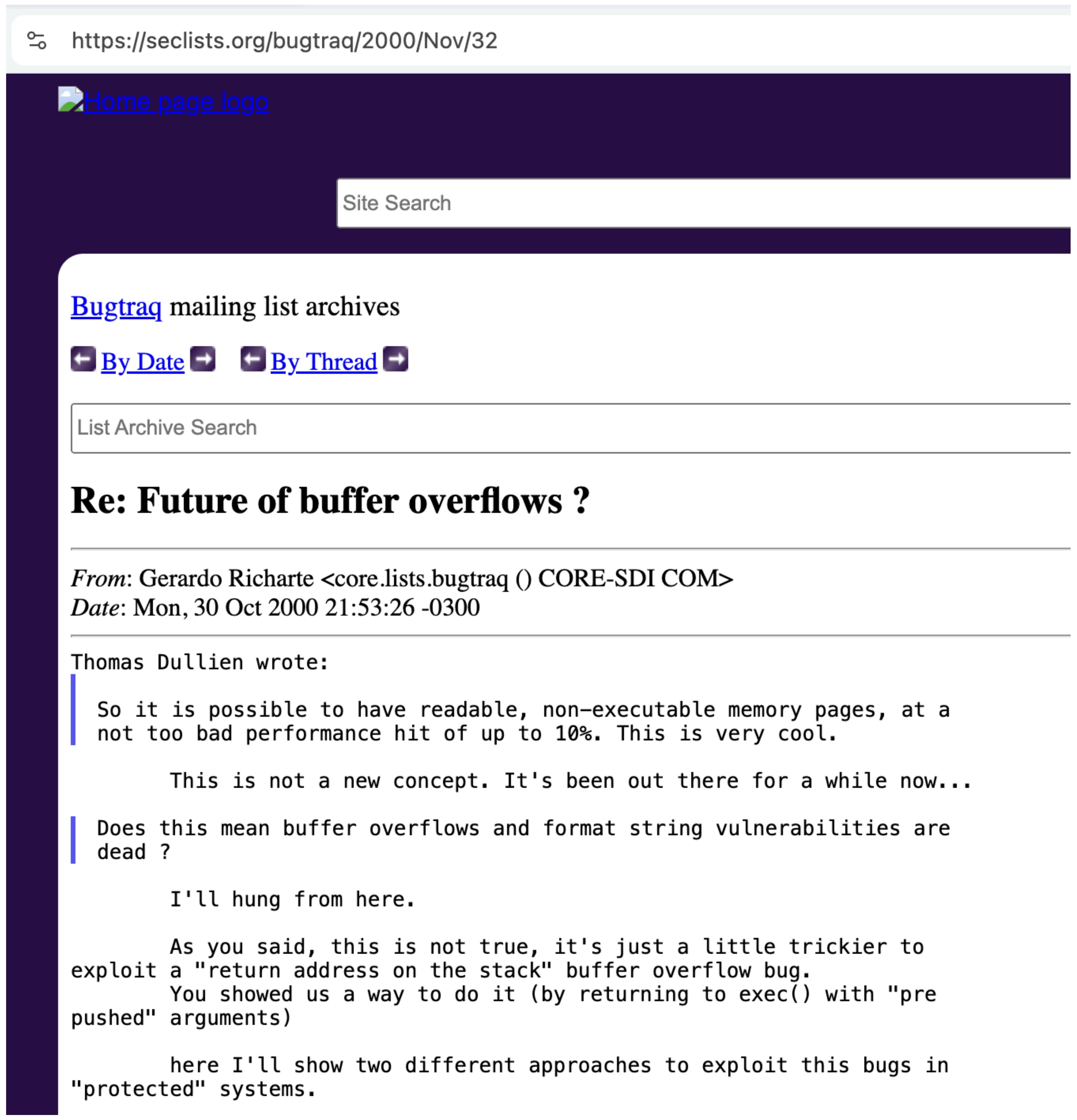
A Program for Automated Exploitation

- Inspired by David Hilbert and many ones after him, we define a list of problems whose solutions pave the way for years to come in the realm of automated low-level software analysis.
- The Grand Challenge consists of a set of 11 problems in the area of vulnerability discovery and exploitation that vary in scope and applicability.
- Most problems relate to discovering and combining exploit primitives to achieve elevation of privilege.

https://openwall.info/wiki/_media/people/jvanegue/files/aegc_vanegue.pdf

What are ‘exploitability properties’?

Hypothesis: primitives add up to generic programmability


https://seclists.org/bugtraq/2000/Nov/32

Home page logo

Site Search

Bugtraq mailing list archives

By Date By Thread

List Archive Search

Re: Future of buffer overflows ?

From: Gerardo Richarte <core.lists.bugtraq () CORE-SDI COM>
Date: Mon, 30 Oct 2000 21:53:26 -0300

```
Thomas Dullien wrote:

  So it is possible to have readable, non-executable memory pages, at a
  not too bad performance hit of up to 10%. This is very cool.

        This is not a new concept. It's been out there for a while now...

  Does this mean buffer overflows and format string vulnerabilities are
  dead ?

        I'll hung from here.

        As you said, this is not true, it's just a little trickier to
exploit a "return address on the stack" buffer overflow bug.
        You showed us a way to do it (by returning to exec() with "pre
pushed" arguments)

        here I'll show two different approaches to exploit this bugs in
"protected" systems.
```

```
        Here I present a way to code any program, or almost any program,
in a way such that it can be fetched into a buffer overflow in a platform
where the stack (and any other place in memory, but libc) is executable:
```

Gerardo Richarte (gera),
https://seclists.org/bugtraq/2000/Nov/32

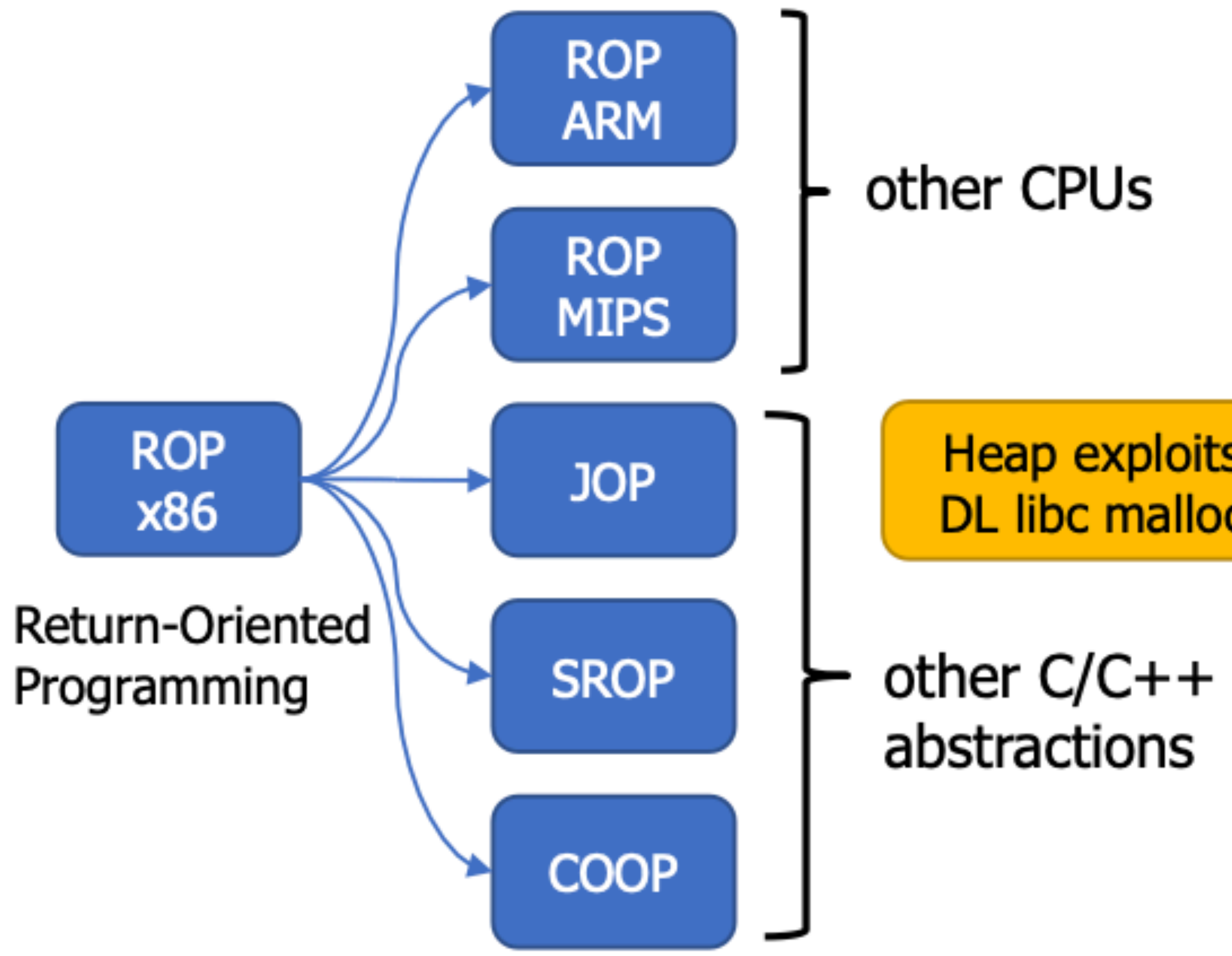
In 7-8 more years, we will know this as Return Oriented Programming (ROP), Jump Oriented Programming (JOP), and many other kinds of *OP

Exploitation = programming + proofs

General-purpose programmability via exploit primitives is a recurring pattern

Stack

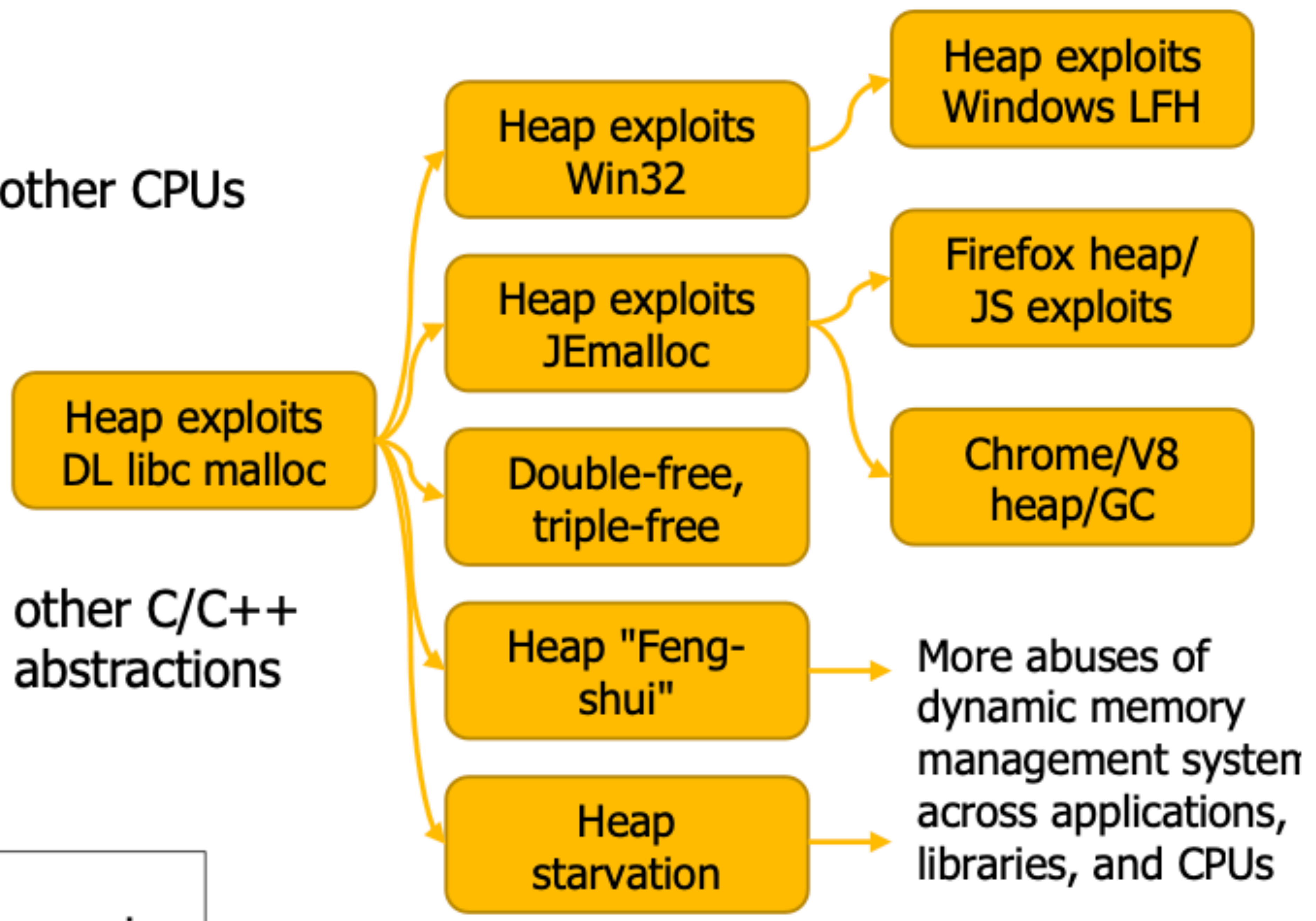
(late 1990s – mid 2000s)
Adversarial reuse of C/C++ control flow implementation patterns



JOP Jump
SROP = Signal Oriented Programming
COOP Counterfeit Object

Heap

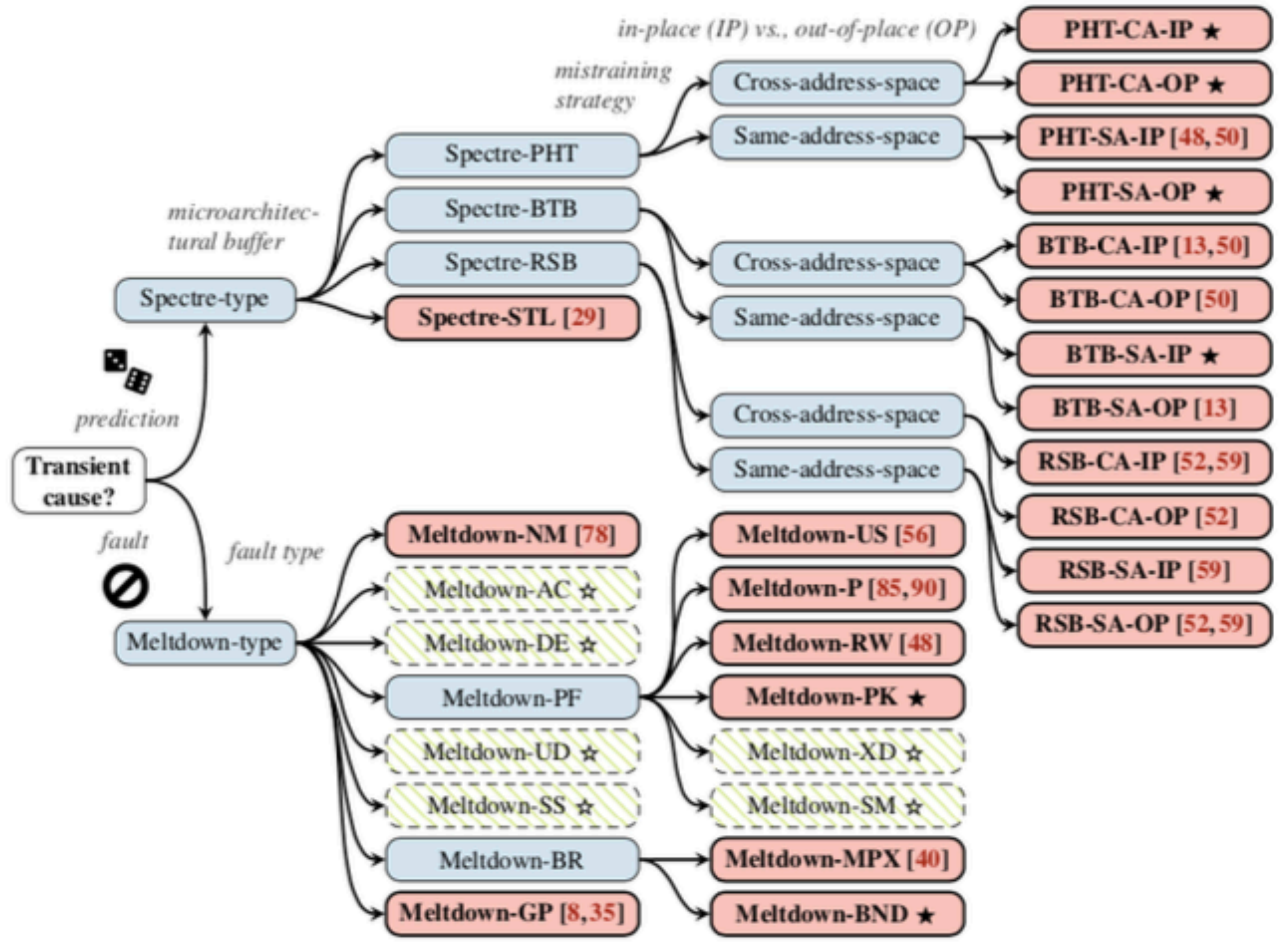
(early 2000s – mid 2010s)
Adversarial reuse of memory management patterns



Heap exploits DL libc malloc
Heap exploits Win32
Heap exploits JEmalloc
Double-free, triple-free
Heap "Feng-shui"
Heap starvation
Heap exploits Windows LFH
Firefox heap/ JS exploits
Chrome/V8 heap/GC
More abuses of dynamic memory management systen across applications, libraries, and CPUs

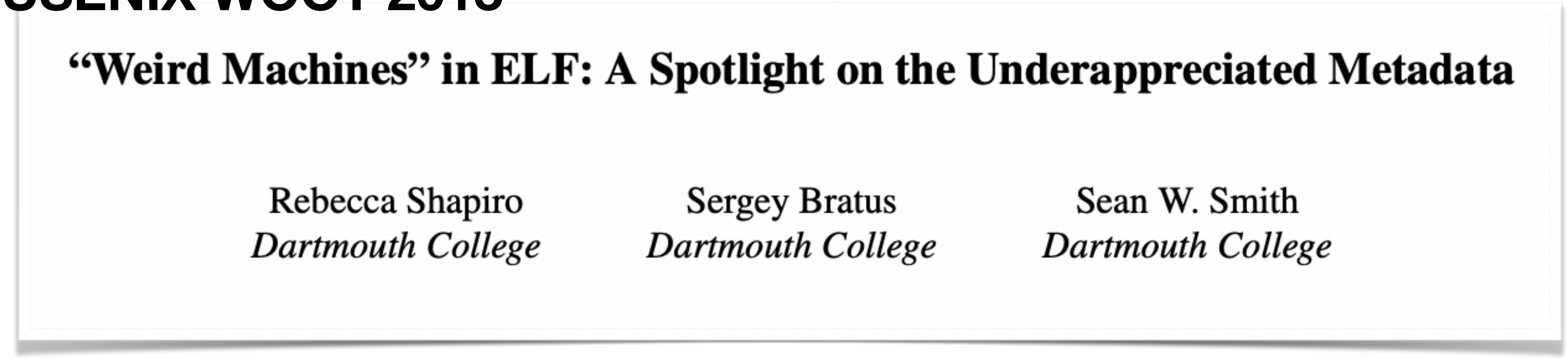
CPU

(late 2010s – now)
Meltdown and Spectre types of vulnerabilities (currently 40+ and counting)



Weird machines: mostly harmless?

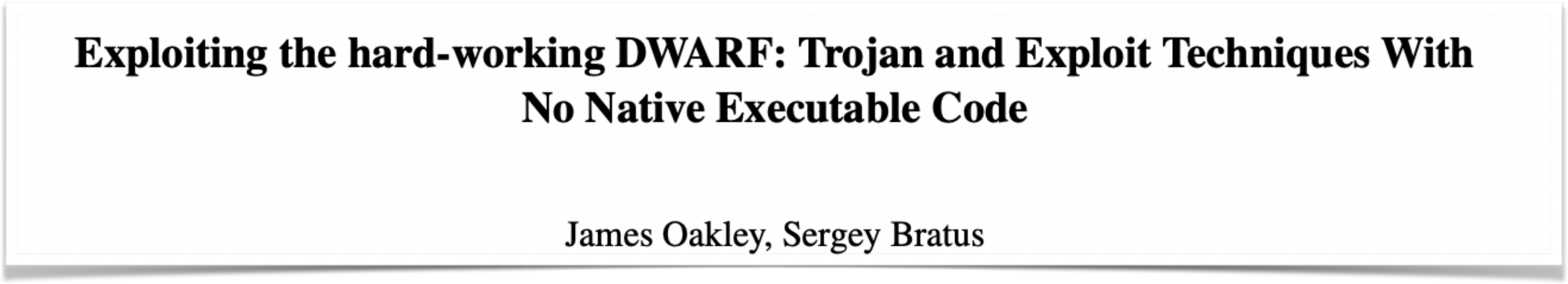
USENIX WOOT 2013



“Weird Machines” in ELF: A Spotlight on the Underappreciated Metadata

Rebecca Shapiro, *Dartmouth College*; Sergey Bratus, *Dartmouth College*; Sean W. Smith, *Dartmouth College*

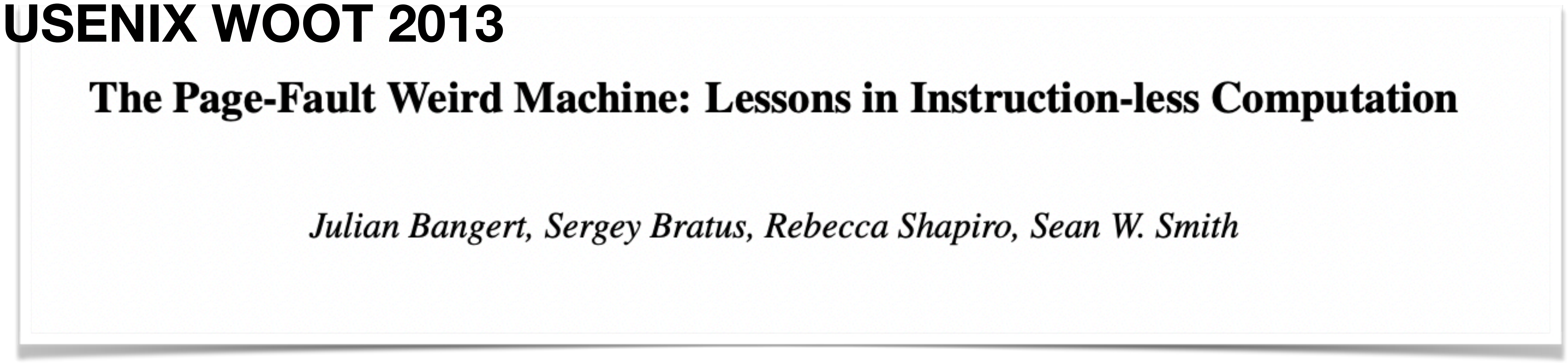
USENIX WOOT 2011



Exploiting the hard-working DWARF: Trojan and Exploit Techniques With No Native Executable Code

James Oakley, Sergey Bratus

USENIX WOOT 2013



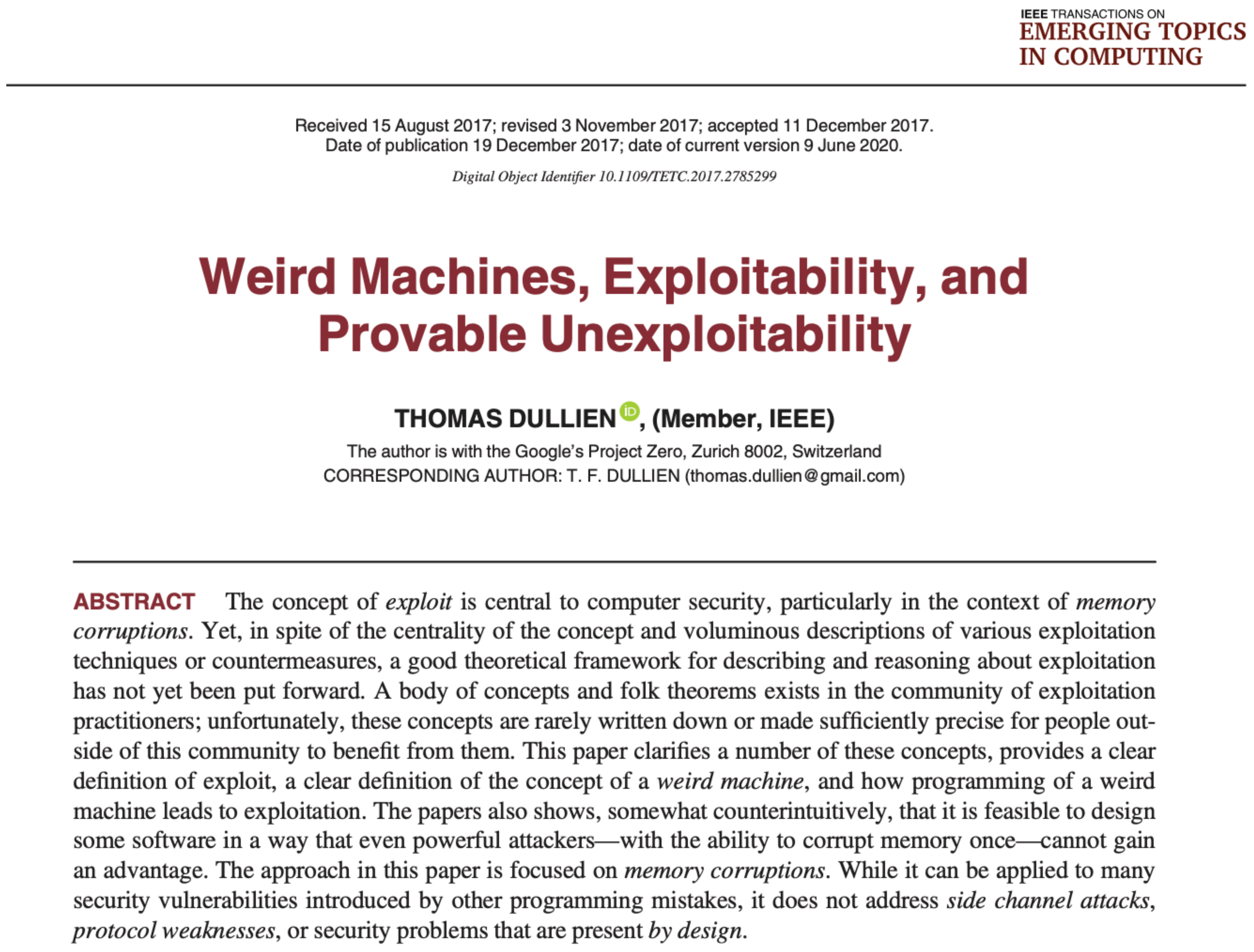
The Page-Fault Weird Machine: Lessons in Instruction-less Computation

Julian Bangert, Sergey Bratus, Rebecca Shapiro, Sean W. Smith

Core OS mechanisms are unexpectedly Turing-complete as attacker’s input-driven agents

- ELF loader/relocator is T.-c.
  - PE and Mach-O are too (cf. LOCREATE, *Uninformed 6:3*)
- So is the DWARF exception handler VM, helpfully linked into C/C++ programs
- So is the **x86 MMU** on its configs (GDT + IDT + TSS + PTEs)

Defining the common exploitability pattern



IEEE TRANSACTIONS ON
EMERGING TOPICS
IN COMPUTING

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Digital Object Identifier 10.1109/TETC.2017.2785299

Weird Machines, Exploitability, and Provable Unexploitability

THOMAS DULLIEN, (Member, IEEE)
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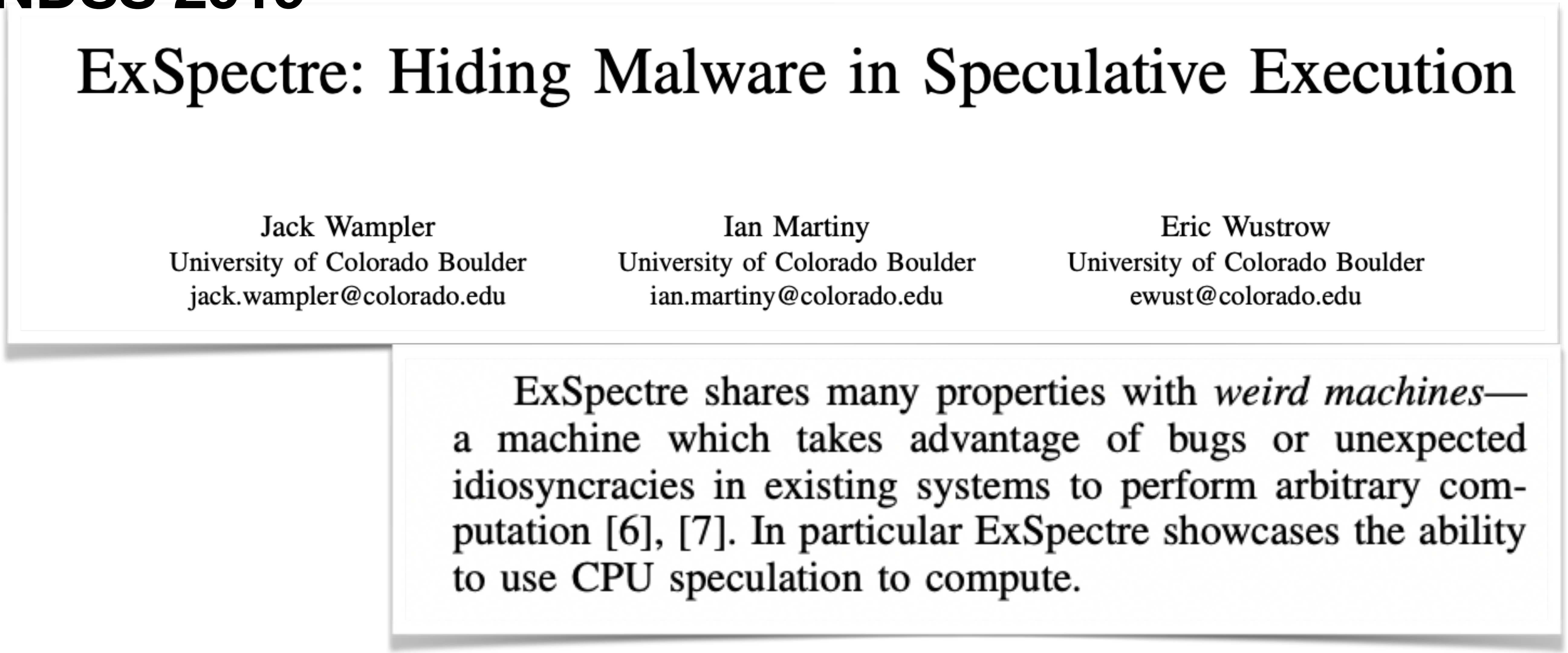
ABSTRACT The concept of *exploit* is central to computer security, particularly in the context of *memory corruptions*. Yet, in spite of the centrality of the concept and voluminous descriptions of various exploitation techniques or countermeasures, a good theoretical framework for describing and reasoning about exploitation has not yet been put forward. A body of concepts and folk theorems exists in the community of exploitation practitioners; unfortunately, these concepts are rarely written down or made sufficiently precise for people outside of this community to benefit from them. This paper clarifies a number of these concepts, provides a clear definition of exploit, a clear definition of the concept of a *weird machine*, and how programming of a weird machine leads to exploitation. The papers also shows, somewhat counterintuitively, that it is feasible to design some software in a way that even powerful attackers—with the ability to corrupt memory once—cannot gain an advantage. The approach in this paper is focused on *memory corruptions*. While it can be applied to many security vulnerabilities introduced by other programming mistakes, it does not address *side channel attacks*, *protocol weaknesses*, or security problems that are present *by design*.

A brief history:

https://weirdmachines.gitlab.io/

Not so harmless: Spectre is more than a side-channel

NDSS 2019



ExSpectre: Hiding Malware in Speculative Execution

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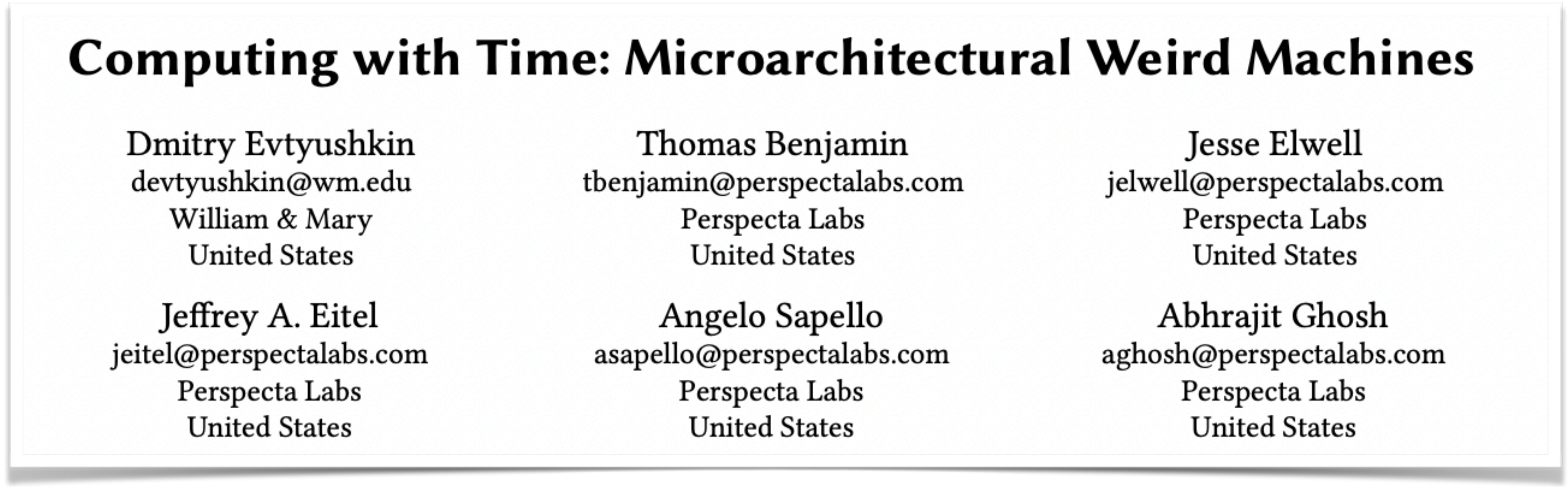
ExSpectre shares many properties with *weird machines*—a machine which takes advantage of bugs or unexpected idiosyncracies in existing systems to perform arbitrary computation [6], [7]. In particular ExSpectre showcases the ability to use CPU speculation to compute.

ASPLOS 2021, Distinguished paper



Computing with Time: Microarchitectural Weird Machines

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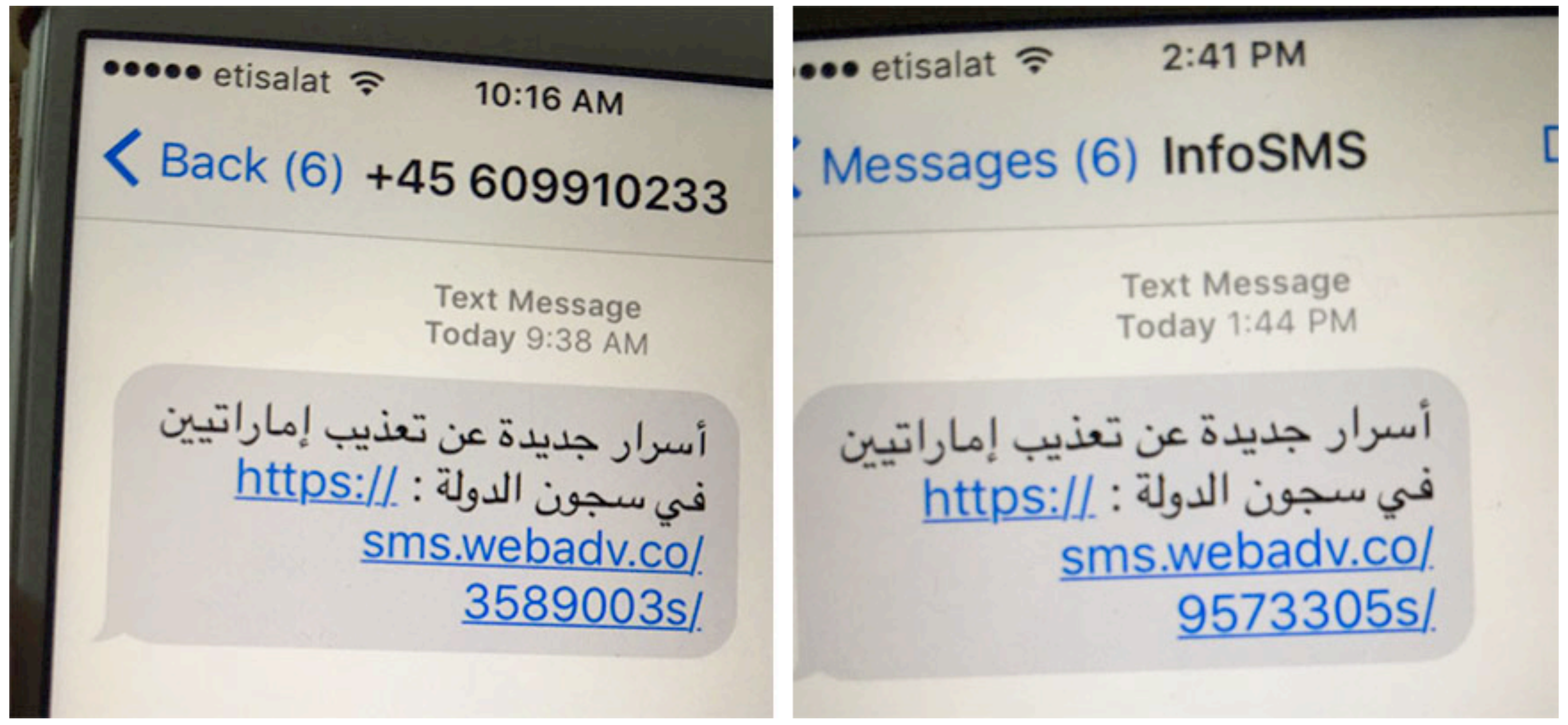
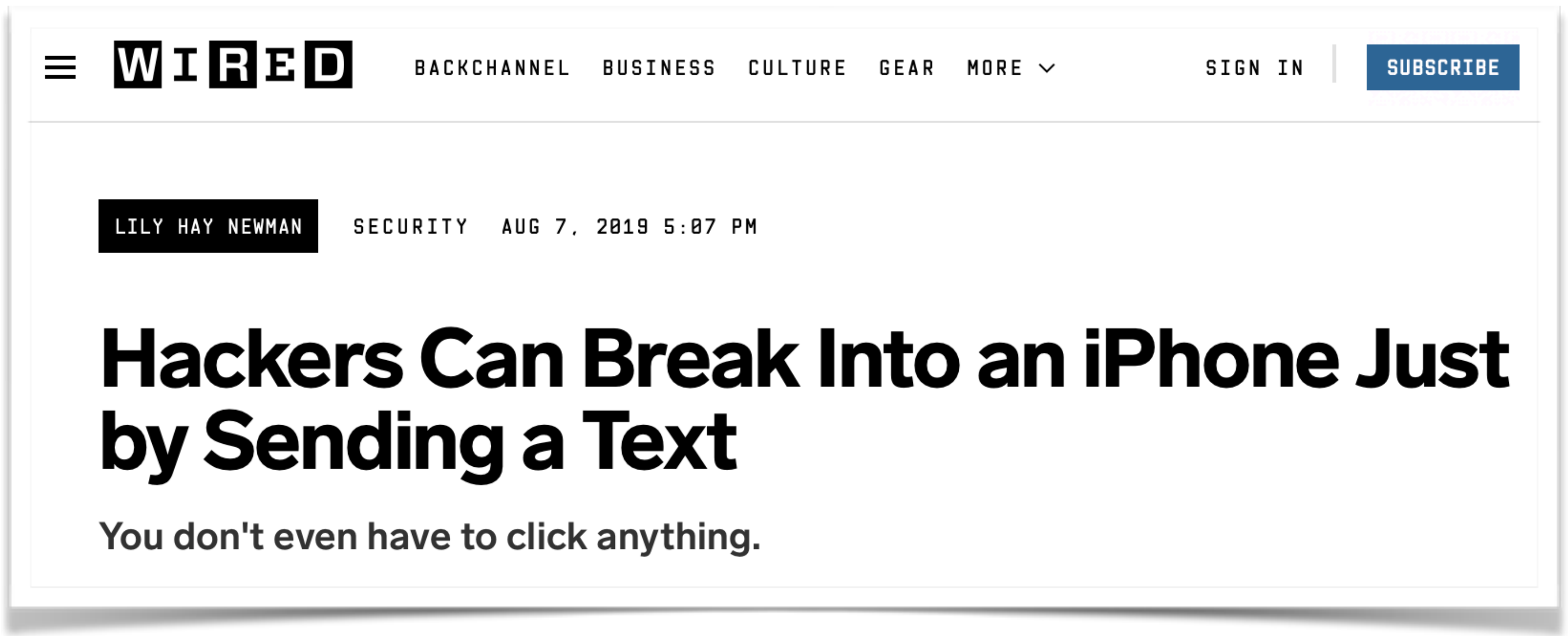
- Modern CPU optimization layers contain **enough shared state and logic** to form a transient, mostly unobservable emergent computing/ execution environment
- **Interactions** between different CPU optimizations' internal states can serve as logical **gates and circuits** adding up to a virtual CPU
  - Programmed by seemingly meaningless series of memory reads and writes
  - Results are read off as timings of races

No longer just theory: iMessage exploitation

From single click to zero-click



etisalat 10:16 AM
Back (6) +45 609910233
Text Message Today 9:38 AM
أسرار جديدة عن تعذيب إماراتيين في سجون الدولة : https://sms.webadv.co/3589003s/
etisalat 2:41 PM
Messages (6) InfoSMS
Text Message Today 1:44 PM
أسرار جديدة عن تعذيب إماراتيين في سجون الدولة : https://sms.webadv.co/9573305s/

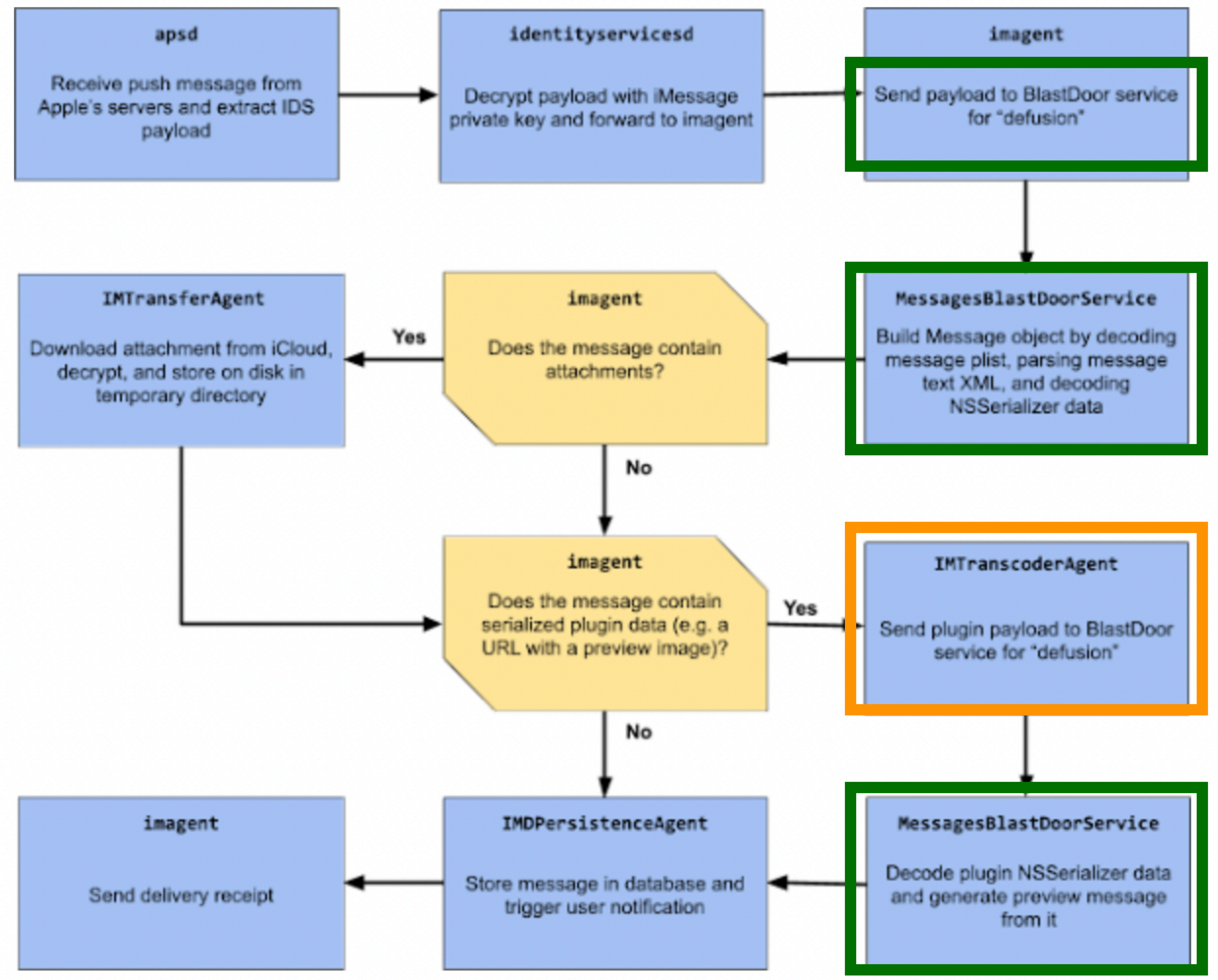


LILY HAY NEWMAN SECURITY AUG 7, 2019 5:07 PM

Hackers Can Break Into an iPhone Just by Sending a Text

You don't even have to click anything.

Enter the BlastDoor sandbox

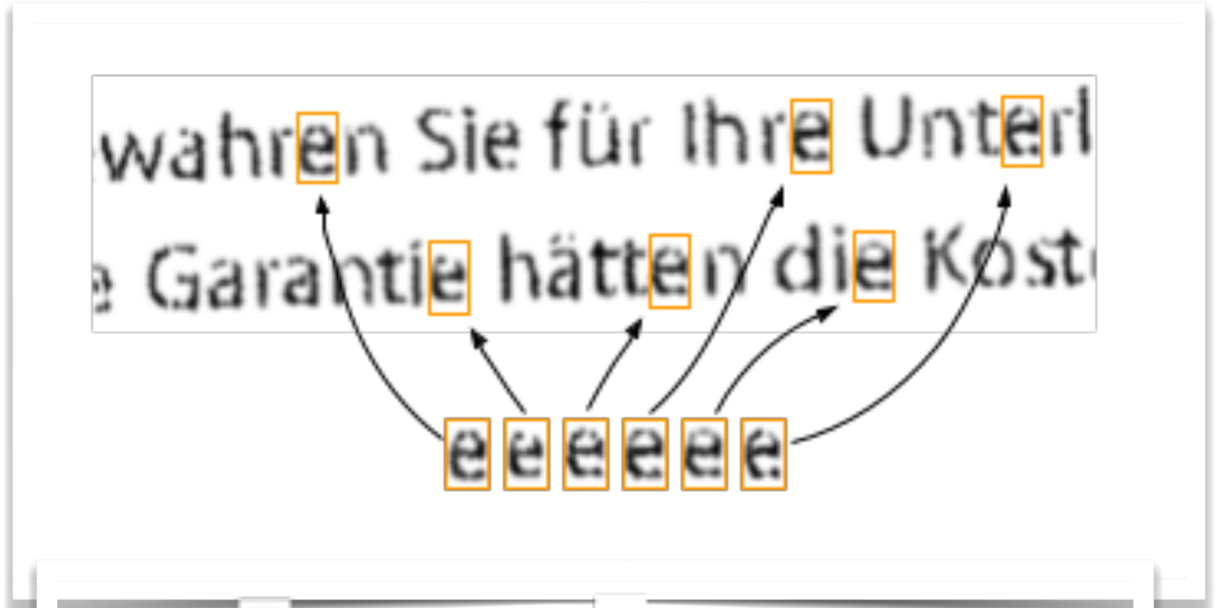


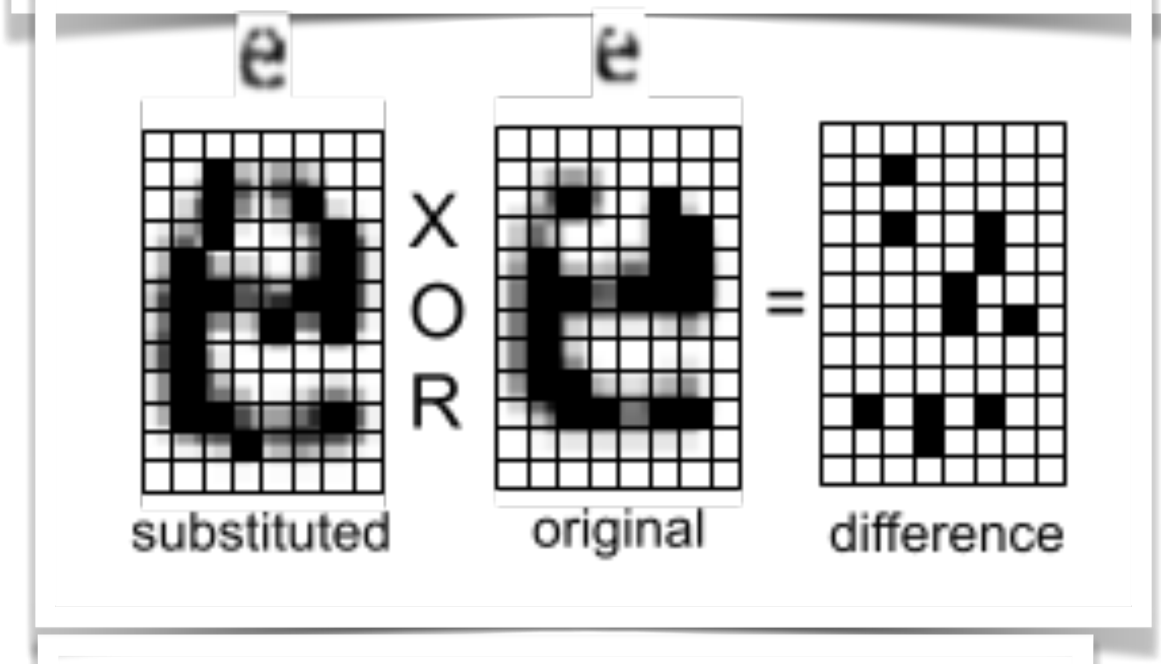
apsd
Receive push message from Apple's servers and extract IDS payload
identityservicesd
Decrypt payload with iMessage private key and forward to imagent
imagent
Send payload to BlastDoor service for "defusion"
MessagesBlastDoorService
Build Message object by decoding message plist, parsing message text XML, and decoding NSSerializer data
imagent
Does the message contain attachments?
Yes
IMTransferAgent
Download attachment from iCloud, decrypt, and store on disk in temporary directory
No
imagent
Does the message contain serialized plugin data (e.g. a URL with a preview image)?
Yes
IMTranscoderAgent
Send plugin payload to BlastDoor service for "defusion"
MessagesBlastDoorService
Decode plugin NSSerializer data and generate preview message from it
No
IMDPersistenceAgent
Store message in database and trigger user notification
imagent
Send delivery receipt

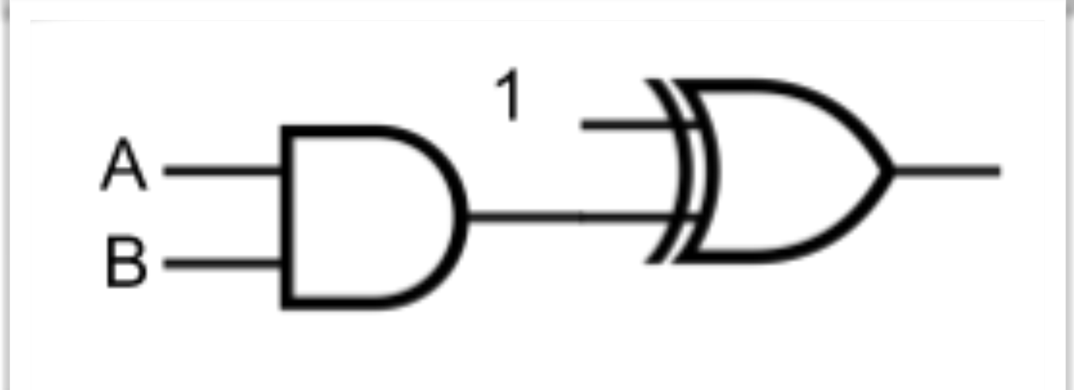
WM in iMessage’s looping GIFs

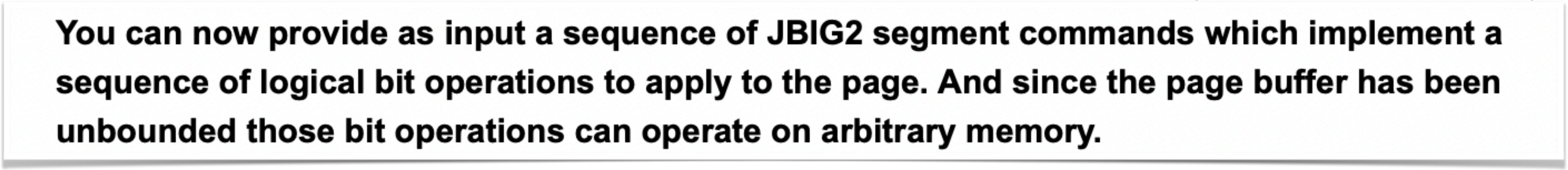
https://googleprojectzero.blogspot.com/2021/12/a-deep-dive-into-nso-zero-click.html

- Pass received files with **.gif** extension to **ImageIO** library
- ImageIO ignores extension and guesses file type [exploit passes a PDF file]
- **CoreGraphics PDF** parser has an integer overflow, but no JavaScript to exploit it [are we just going to safely crash? No.]
- …but it has **JBIG2** decompression of glyphs, with **XOR** logic over memory areas
    - …which will apply **out of buffer’s bounds**, thanks to the overflow;
    - this makes **logical gates**. Logical gates make a **virtual machine** as fast and reliable as JavaScript!








You can now provide as input a sequence of JBIG2 segment commands which implement a sequence of logical bit operations to apply to the page. And since the page buffer has been unbounded those bit operations can operate on arbitrary memory.

Fully automated exploitation & patching?

DARPA and ARPA-H’s Artificial Intelligence Cyber Challenge (AIxCC) brings together the foremost experts in AI and cybersecurity to safeguard the software critical to all Americans.

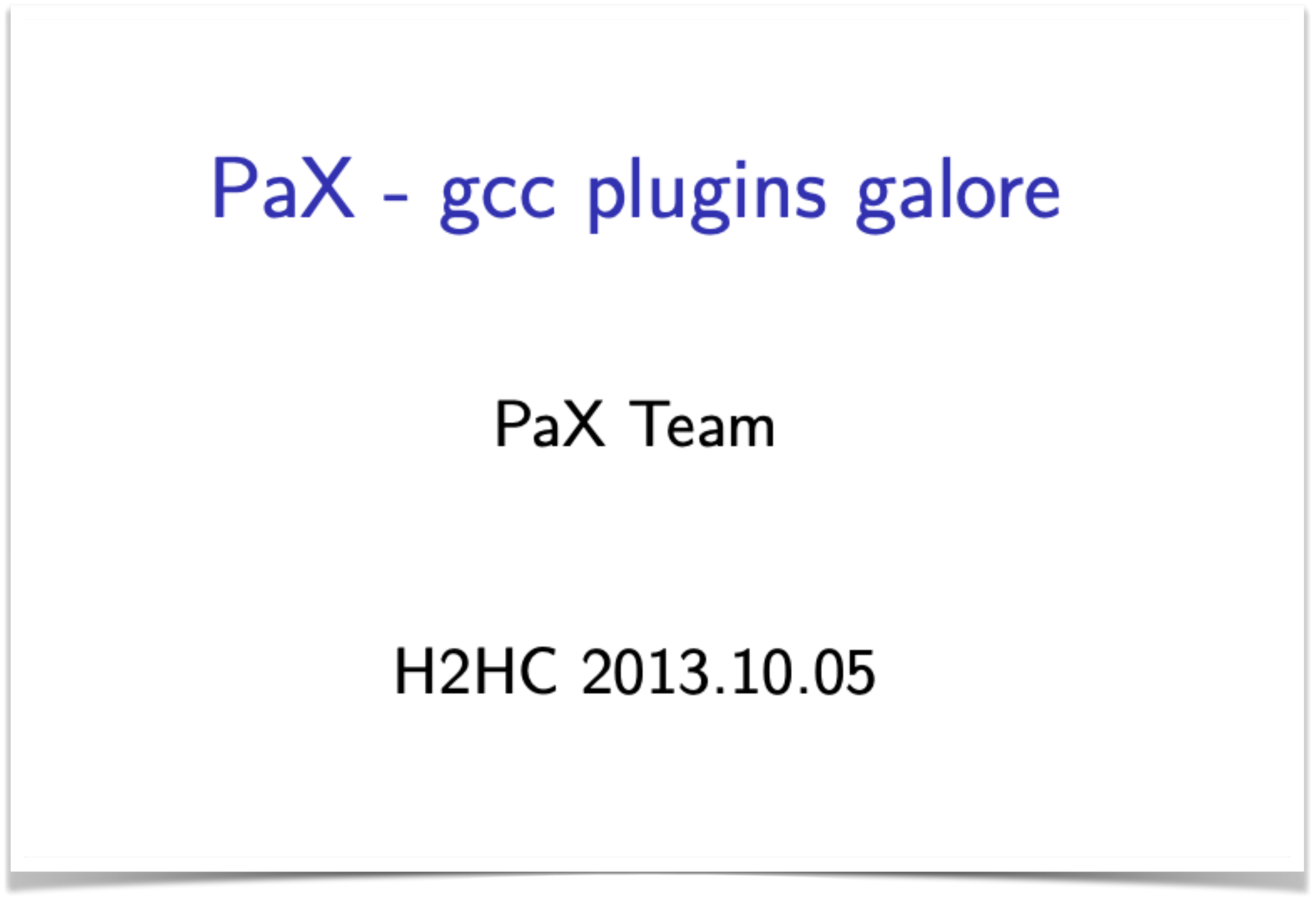
AIxCC is excited to have Anthropic, Google, Microsoft, OpenAI, the Linux Foundation, the Open Source Security Foundation, Black Hat USA, and DEF CON as collaborators in this effort.

https://aicyberchallenge.com/

Where else is hacker math hiding?

“IRs are magic”

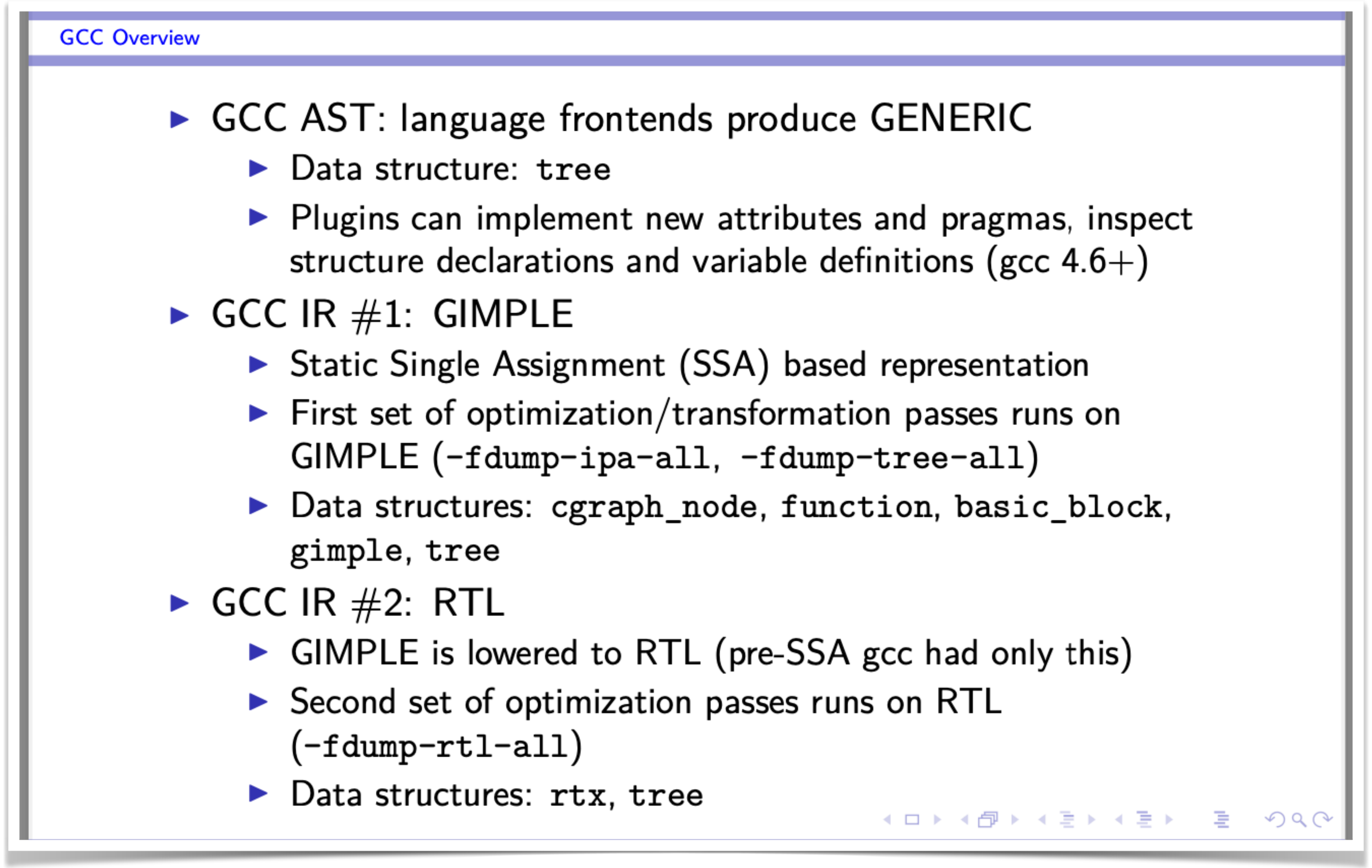
Intermediate Representations make analysis go



PaX - gcc plugins galore

PaX Team

H2HC 2013.10.05



GCC Overview

- GCC AST: language frontends produce GENERIC
  - Data structure: `tree`
  - Plugins can implement new attributes and pragmas, inspect structure declarations and variable definitions (gcc 4.6+)
- GCC IR #1: GIMPLE
  - Static Single Assignment (SSA) based representation
  - First set of optimization/transformation passes runs on GIMPLE (`-fdump-ipa-all`, `-fdump-tree-all`)
  - Data structures: `cgraph_node`, `function`, `basic_block`, `gimple`, `tree`
- GCC IR #2: RTL
  - GIMPLE is lowered to RTL (pre-SSA gcc had only this)
  - Second set of optimization passes runs on RTL (`-fdump-rtl-all`)
  - Data structures: `rtx`, `tree`

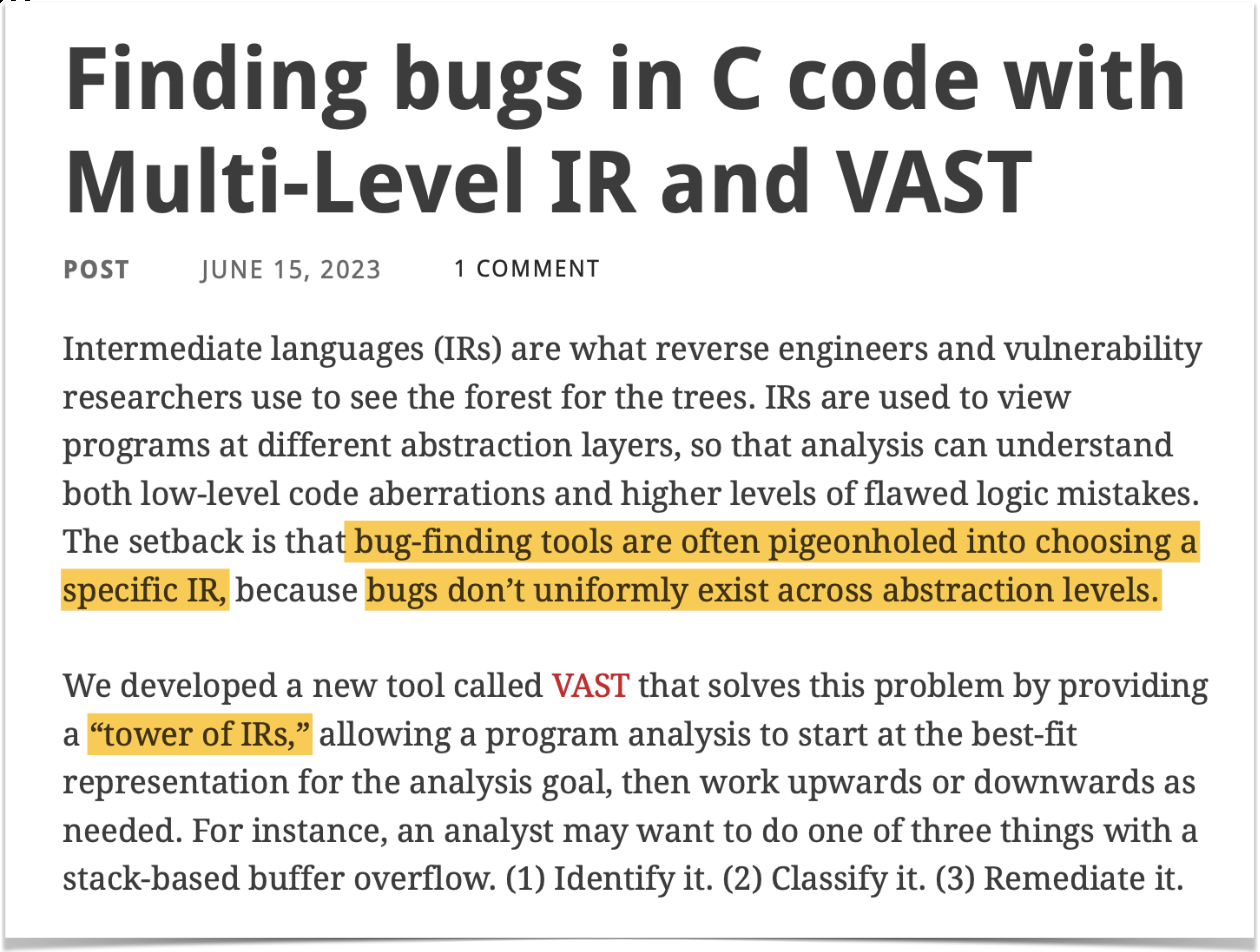
- GrSecurity/PaX made revolutionary Linux kernel hardening with compiler plugins — operating over **GCC IRs**

https://grsecurity.net/papers

Towers of Intermediate Representations

“IRs are useful. What’s an IR?”

- IRs are everywhere
  - LLVM passes ~ IRs, MLIR
  - Ghidra uses P-code
  - Angr uses VEX
  - Binary Ninja has 3 public IRs
- But what is an IR?
  - Trail of Bits: ***Why use only one IR at a time?***



Finding bugs in C code with Multi-Level IR and VAST

POST JUNE 15, 2023 1 COMMENT

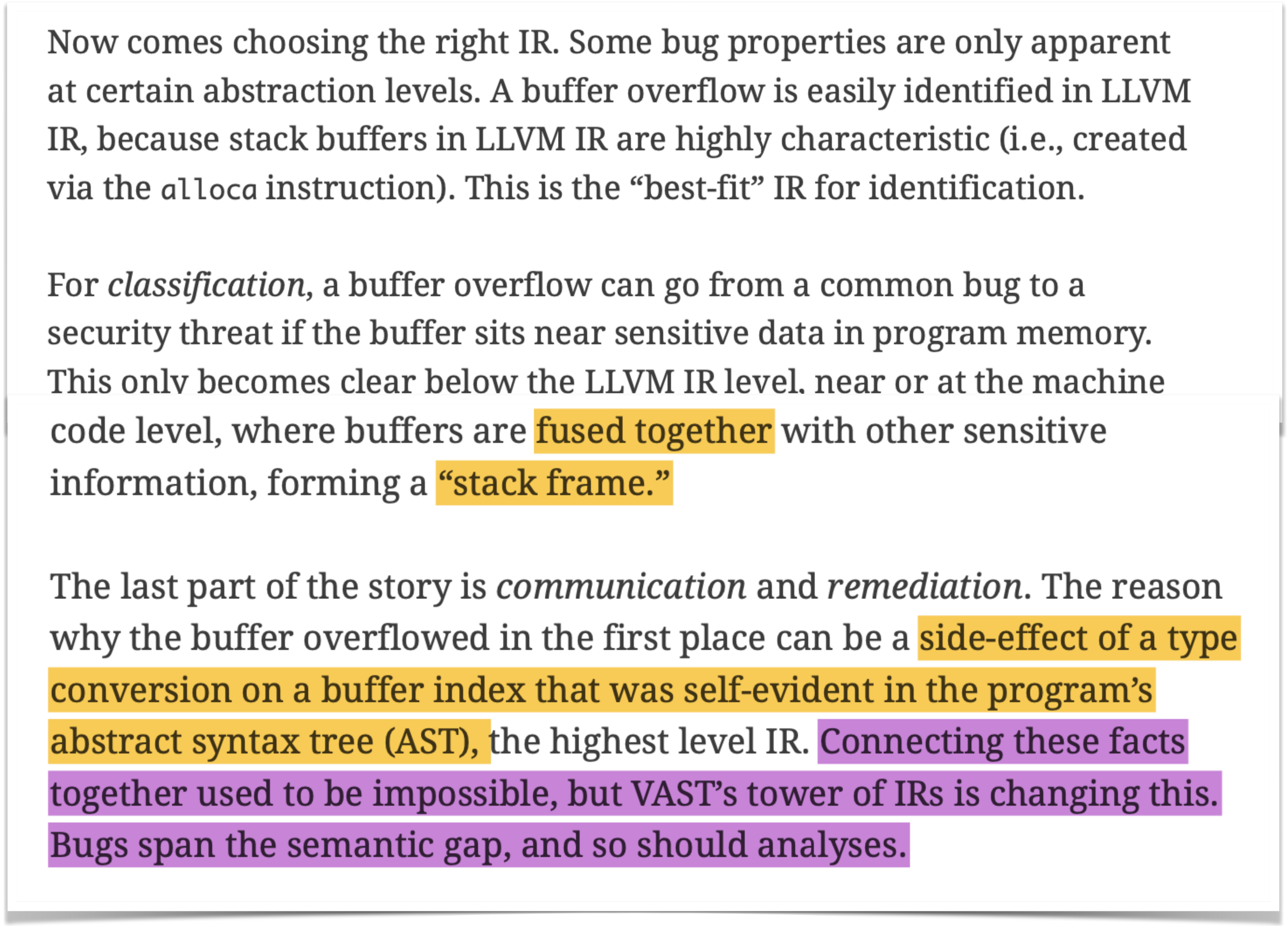
Intermediate languages (IRs) are what reverse engineers and vulnerability researchers use to see the forest for the trees. IRs are used to view programs at different abstraction layers, so that analysis can understand both low-level code aberrations and higher levels of flawed logic mistakes. The setback is that bug-finding tools are often pigeonholed into choosing a specific IR, because bugs don’t uniformly exist across abstraction levels.

We developed a new tool called VAST that solves this problem by providing a “tower of IRs,” allowing a program analysis to start at the best-fit representation for the analysis goal, then work upwards or downwards as needed. For instance, an analyst may want to do one of three things with a stack-based buffer overflow. (1) Identify it. (2) Classify it. (3) Remediate it.

https://blog.trailofbits.com/2023/06/15/finding-bugs-with-mlir-and-vast/

Bugs span the semantic gap, and so should analyses!

Move up and down the tower of IRs as needed



Now comes choosing the right IR. Some bug properties are only apparent at certain abstraction levels. A buffer overflow is easily identified in LLVM IR, because stack buffers in LLVM IR are highly characteristic (i.e., created via the `alloca` instruction). This is the "best-fit" IR for identification.

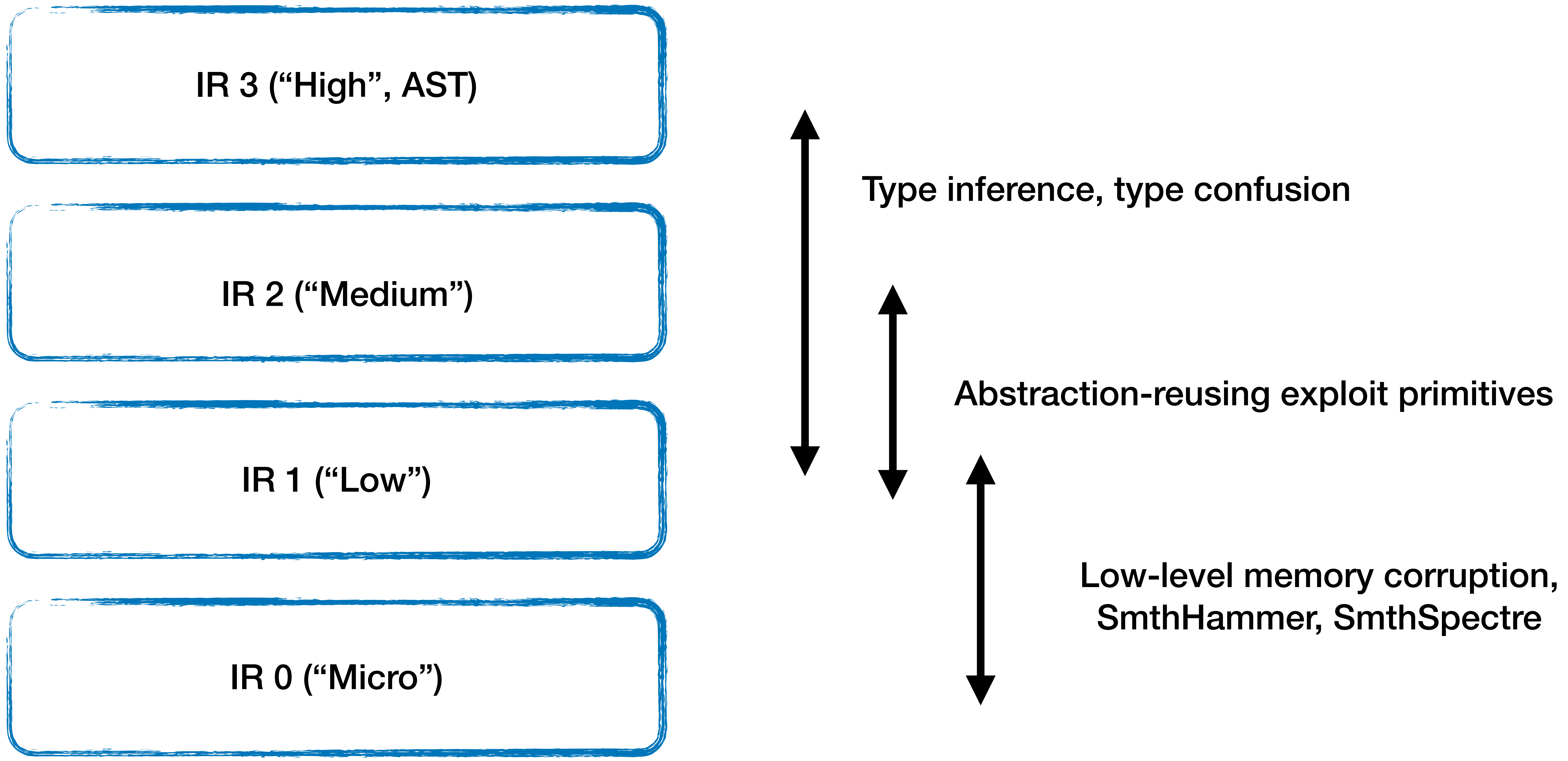
For *classification*, a buffer overflow can go from a common bug to a security threat if the buffer sits near sensitive data in program memory. This only becomes clear below the LLVM IR level, near or at the machine code level, where buffers are fused together with other sensitive information, forming a "stack frame."

The last part of the story is *communication* and *remediation*. The reason why the buffer overflowed in the first place can be a side-effect of a type conversion on a buffer index that was self-evident in the program's abstract syntax tree (AST), the highest level IR. Connecting these facts together used to be impossible, but VAST's tower of IRs is changing this. Bugs span the semantic gap, and so should analyses.

- Buffer overflows: at LLVM IR
- Adjacency: below LLVM IR
- Out-of-type references: AST
- ToB solution: **VAST/Multiplier**
  - Get all the IRs (as dialects of MLIR)
  - ***"Move up or down as needed"***

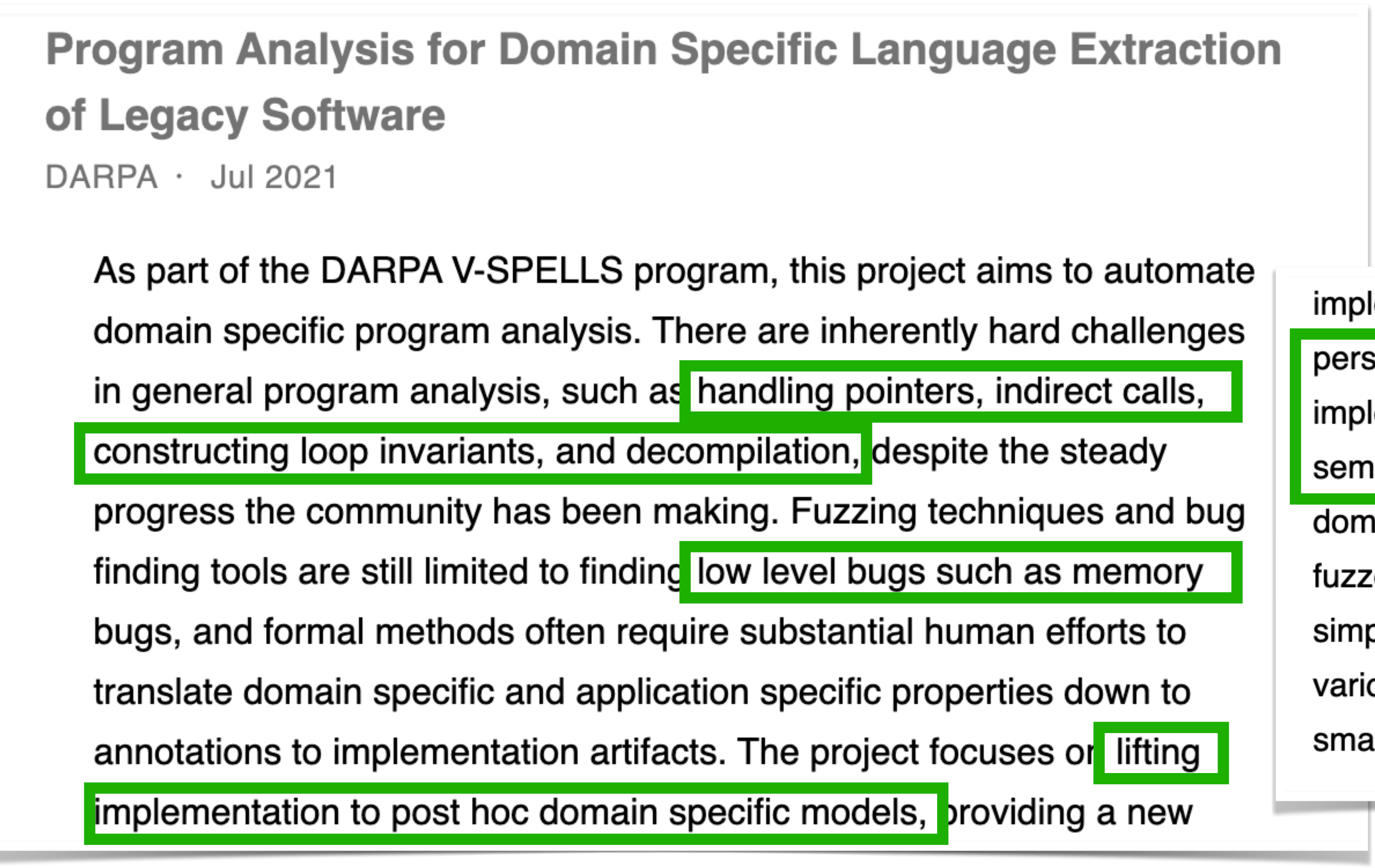
A tower of IRs

A sequence of compatible, interoperating IRs


IR 3 (“High”, AST)
IR 2 (“Medium”)
IR 1 (“Low”)
IR 0 (“Micro”)
Type inference, type confusion
Abstraction-reusing exploit primitives
Low-level memory corruption, SmthHammer, SmthSpectre

“For my analyses, I’d rather use DSLs”

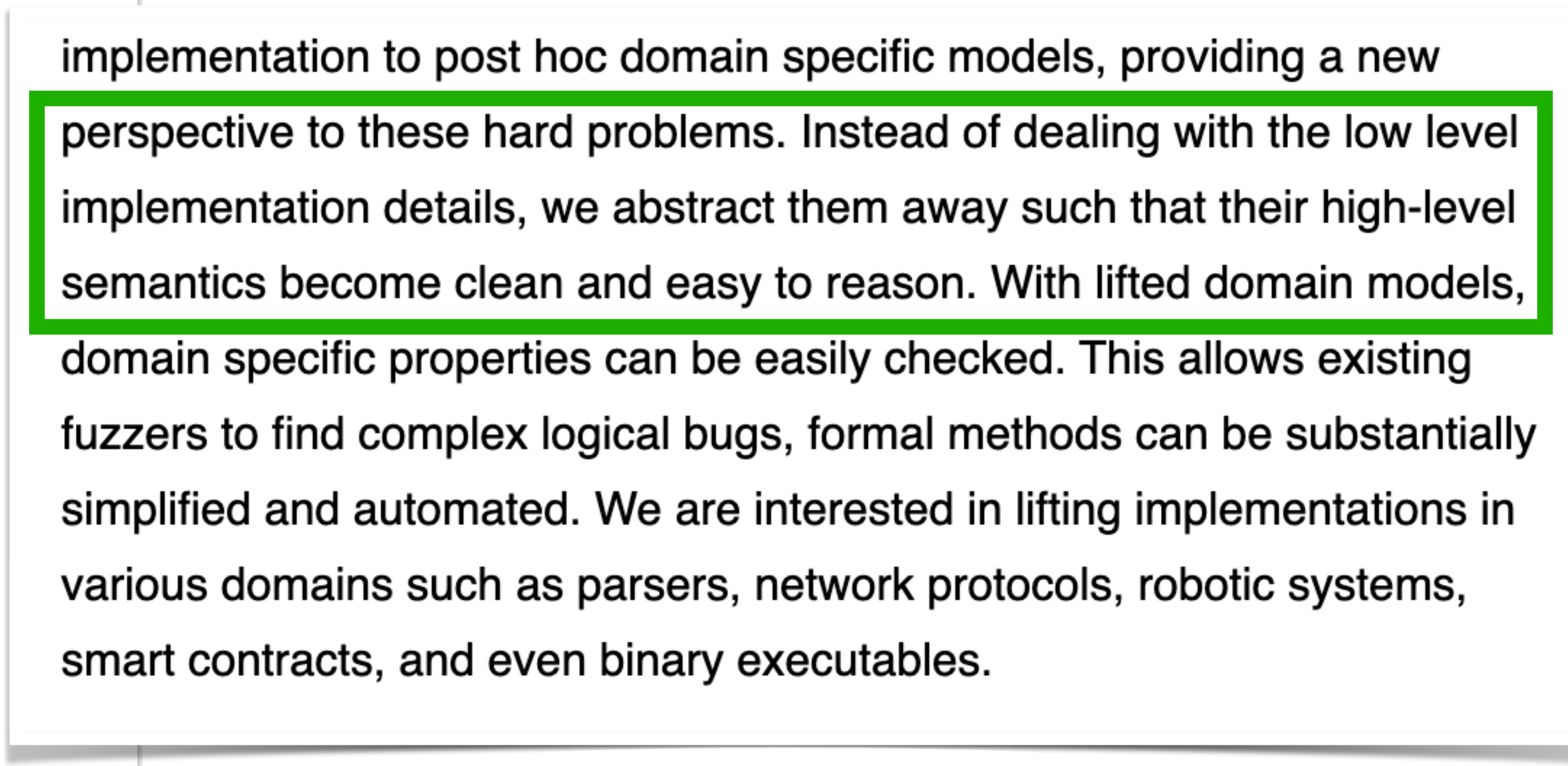
Hard problems remain hard, but scalability increases



Program Analysis for Domain Specific Language Extraction of Legacy Software

DARPA · Jul 2021

As part of the DARPA V-SPELLS program, this project aims to automate domain specific program analysis. There are inherently hard challenges in general program analysis, such as handling pointers, indirect calls, constructing loop invariants, and decompilation, despite the steady progress the community has been making. Fuzzing techniques and bug finding tools are still limited to finding low level bugs such as memory bugs, and formal methods often require substantial human efforts to translate domain specific and application specific properties down to annotations to implementation artifacts. The project focuses on lifting implementation to post hoc domain specific models, providing a new



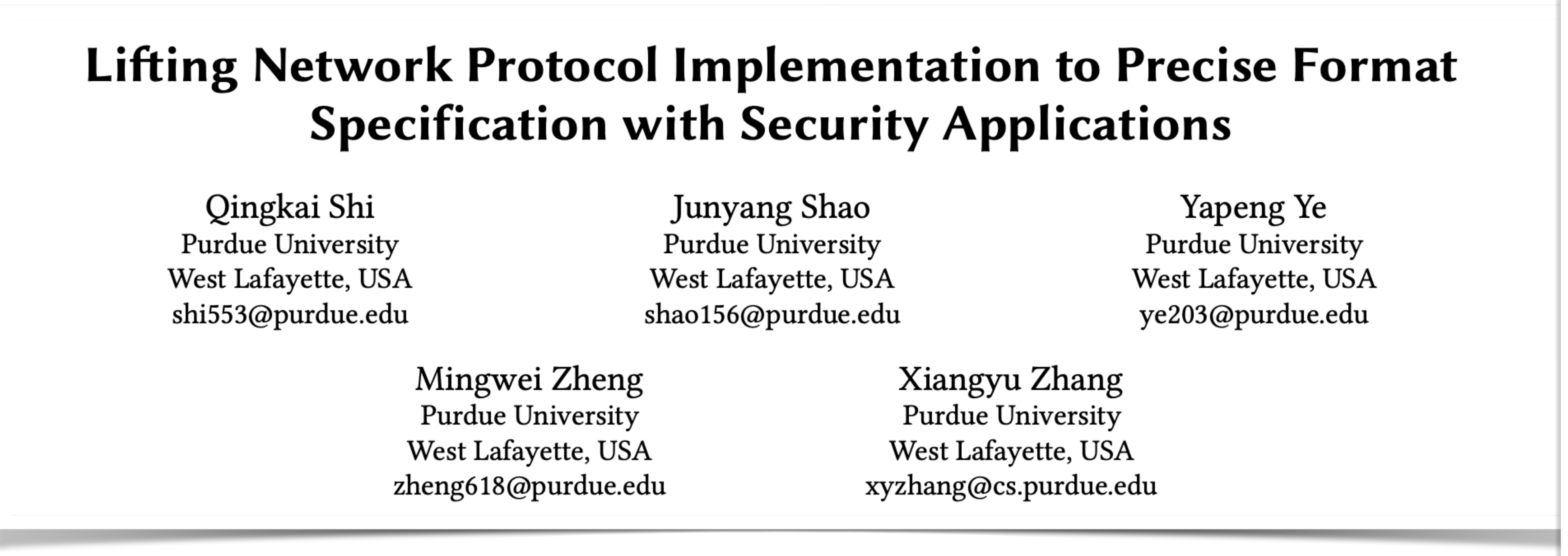
implementation to post hoc domain specific models, providing a new perspective to these hard problems. Instead of dealing with the low level implementation details, we abstract them away such that their high-level semantics become clean and easy to reason. With lifted domain models, domain specific properties can be easily checked. This allows existing fuzzers to find complex logical bugs, formal methods can be substantially simplified and automated. We are interested in lifting implementations in various domains such as parsers, network protocols, robotic systems, smart contracts, and even binary executables.

Prof. Xiangyu Zhang, Purdue U.

https://www.cs.purdue.edu/homes/xyzhang/

Lifting gets CVEs that fuzzing misses

50+ new CVEs in network protocols


Lifting Network Protocol Implementation to Precise Format Specification with Security Applications

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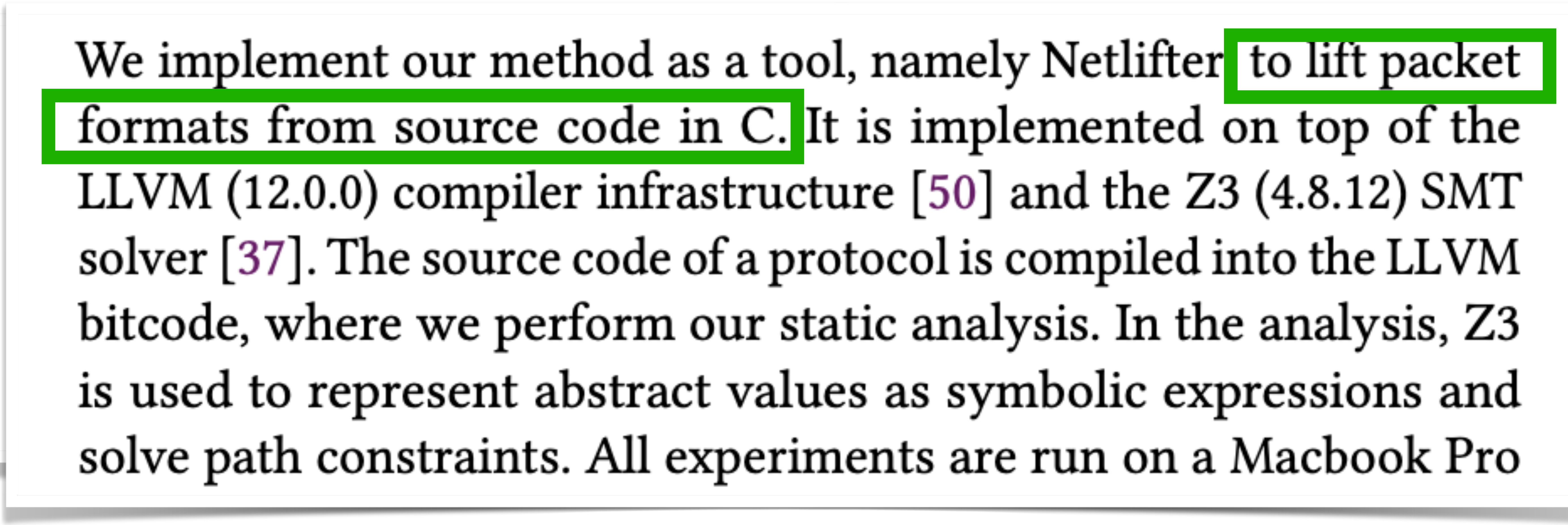
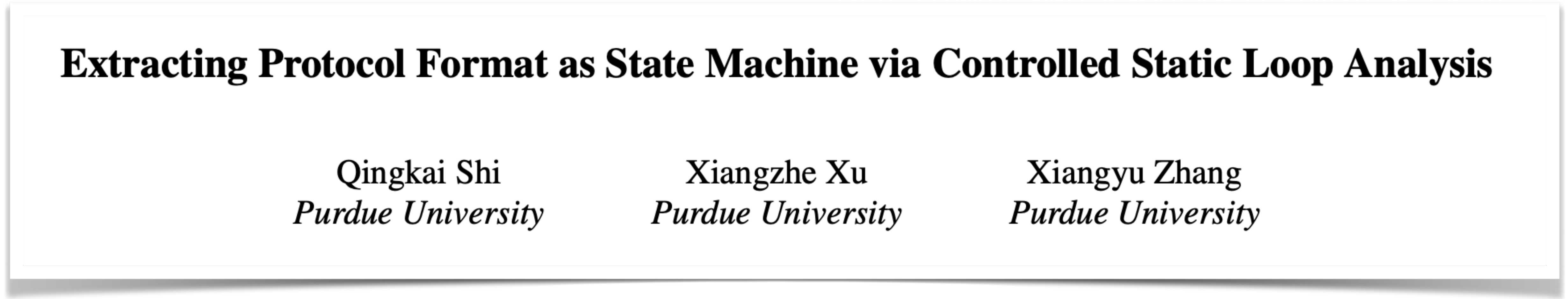
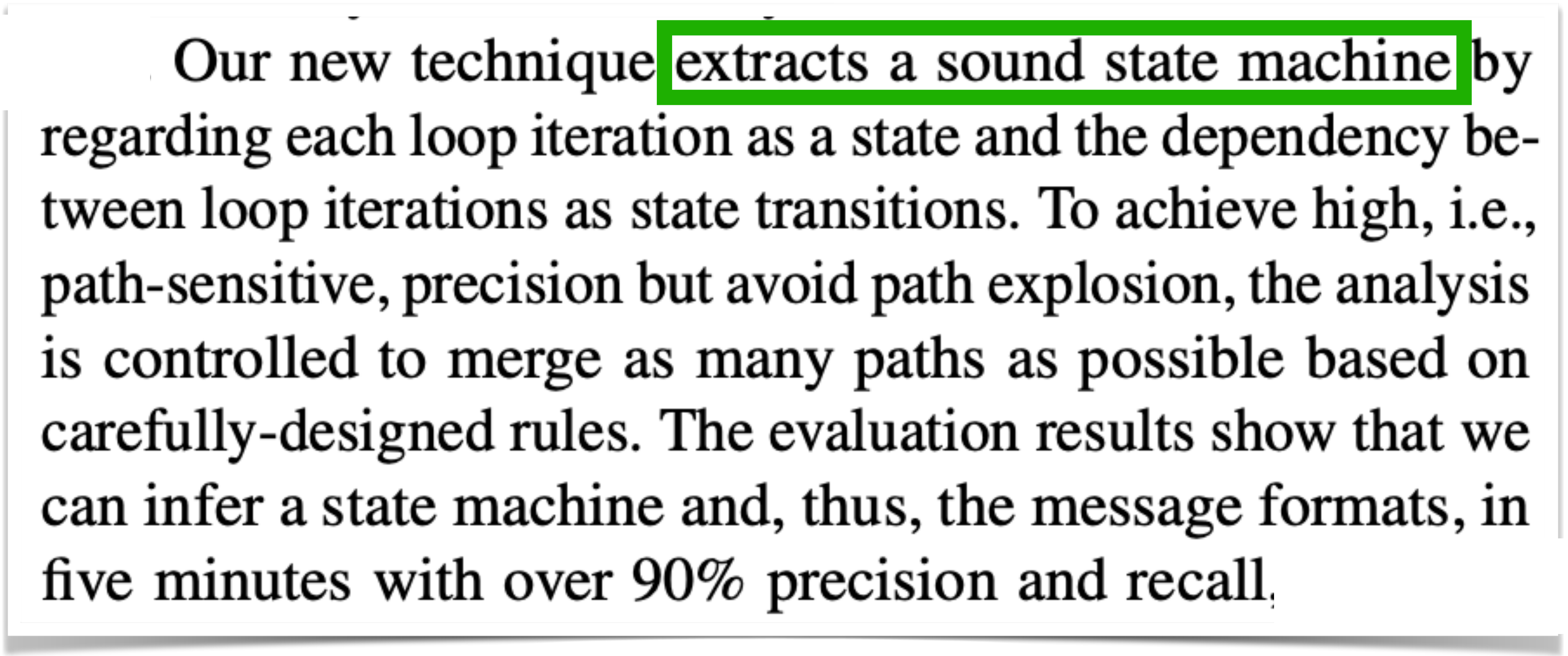

We implement our method as a tool, namely Netlifter to lift packet formats from source code in C. It is implemented on top of the LLVM (12.0.0) compiler infrastructure [50] and the Z3 (4.8.12) SMT solver [37]. The source code of a protocol is compiled into the LLVM bitcode, where we perform our static analysis. In the analysis, Z3 is used to represent abstract values as symbolic expressions and solve path constraints. All experiments are run on a Macbook Pro


Extracting Protocol Format as State Machine via Controlled Static Loop Analysis

Qingkai Shi
Purdue University

Xiangzhe Xu
Purdue University

Xiangyu Zhang
Purdue University


Our new technique extracts a sound state machine by regarding each loop iteration as a state and the dependency between loop iterations as state transitions. To achieve high, i.e., path-sensitive, precision but avoid path explosion, the analysis is controlled to merge as many paths as possible based on carefully-designed rules. The evaluation results show that we can infer a state machine and, thus, the message formats, in five minutes with over 90% precision and recall.

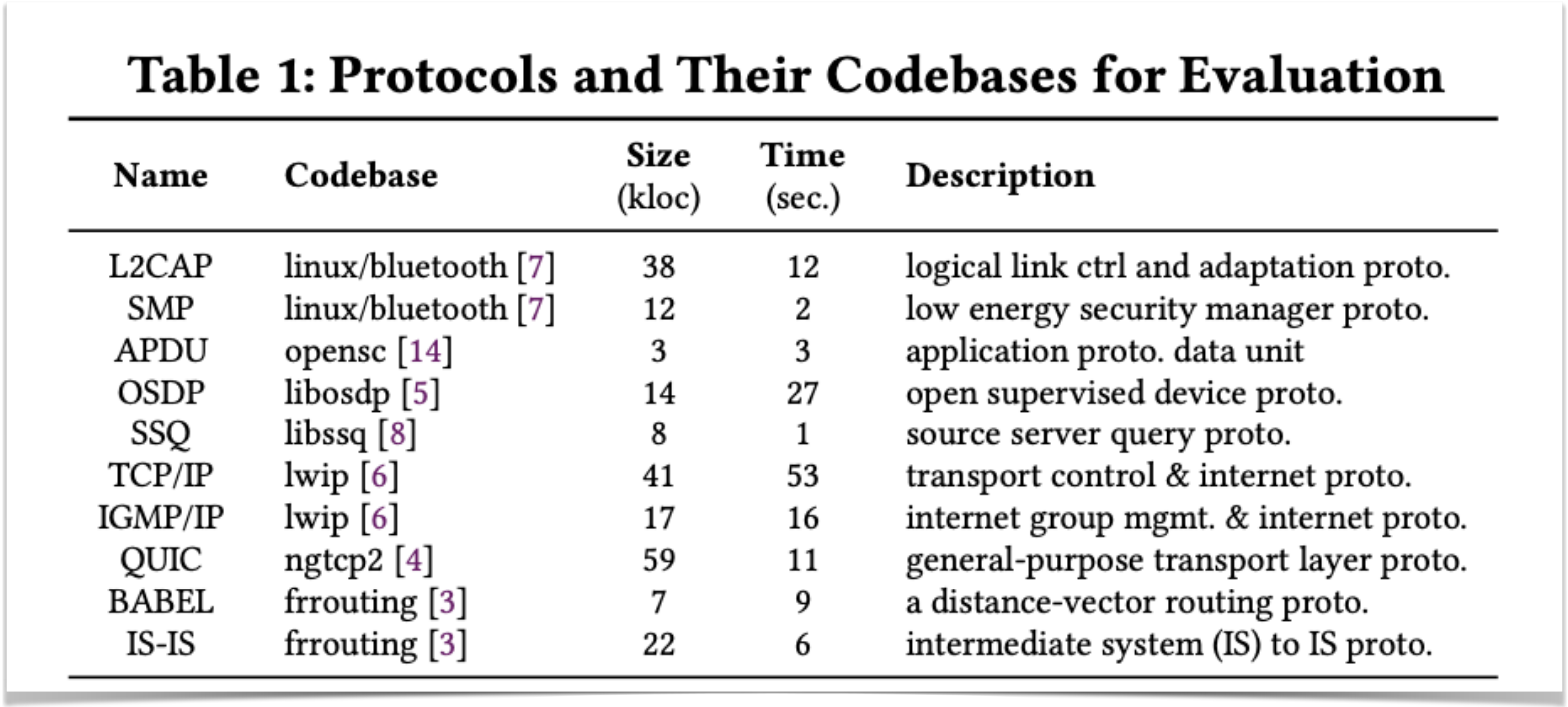


Table 1: Protocols and Their Codebases for Evaluation

Name	Codebase	Size (kloc)	Time (sec.)	Description
L2CAP	linux/bluetooth [7]	38	12	logical link ctrl and adaptation proto.
SMP	linux/bluetooth [7]	12	2	low energy security manager proto.
APDU	opensc [14]	3	3	application proto. data unit
OSDP	libosdp [5]	14	27	open supervised device proto.
SSQ	libssq [8]	8	1	source server query proto.
TCP/IP	lwip [6]	41	53	transport control & internet proto.
IGMP/IP	lwip [6]	17	16	internet group mgmt. & internet proto.
QUIC	ngtcp2 [4]	59	11	general-purpose transport layer proto.
BABEL	frrouting [3]	7	9	a distance-vector routing proto.
IS-IS	frrouting [3]	22	6	intermediate system (IS) to IS proto.

Codebases chosen by recent activity, presence of fuzzing harness

50+ new CVEs claimed

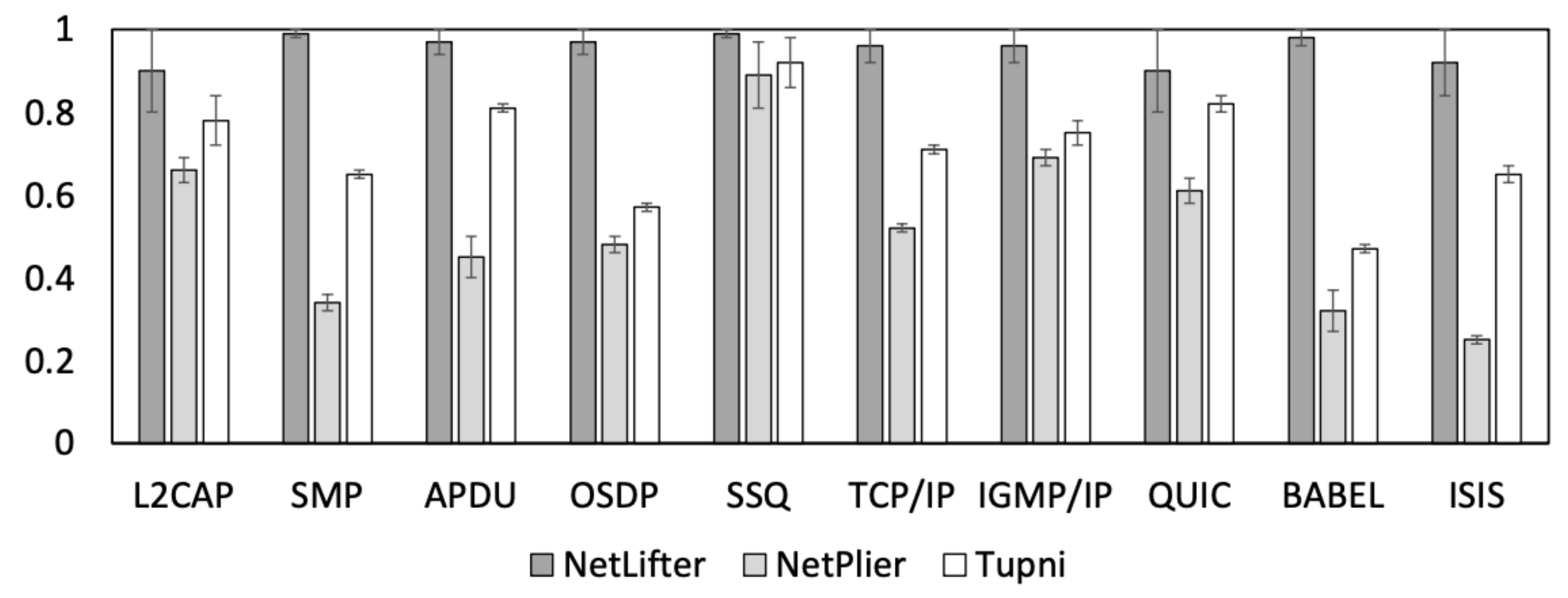
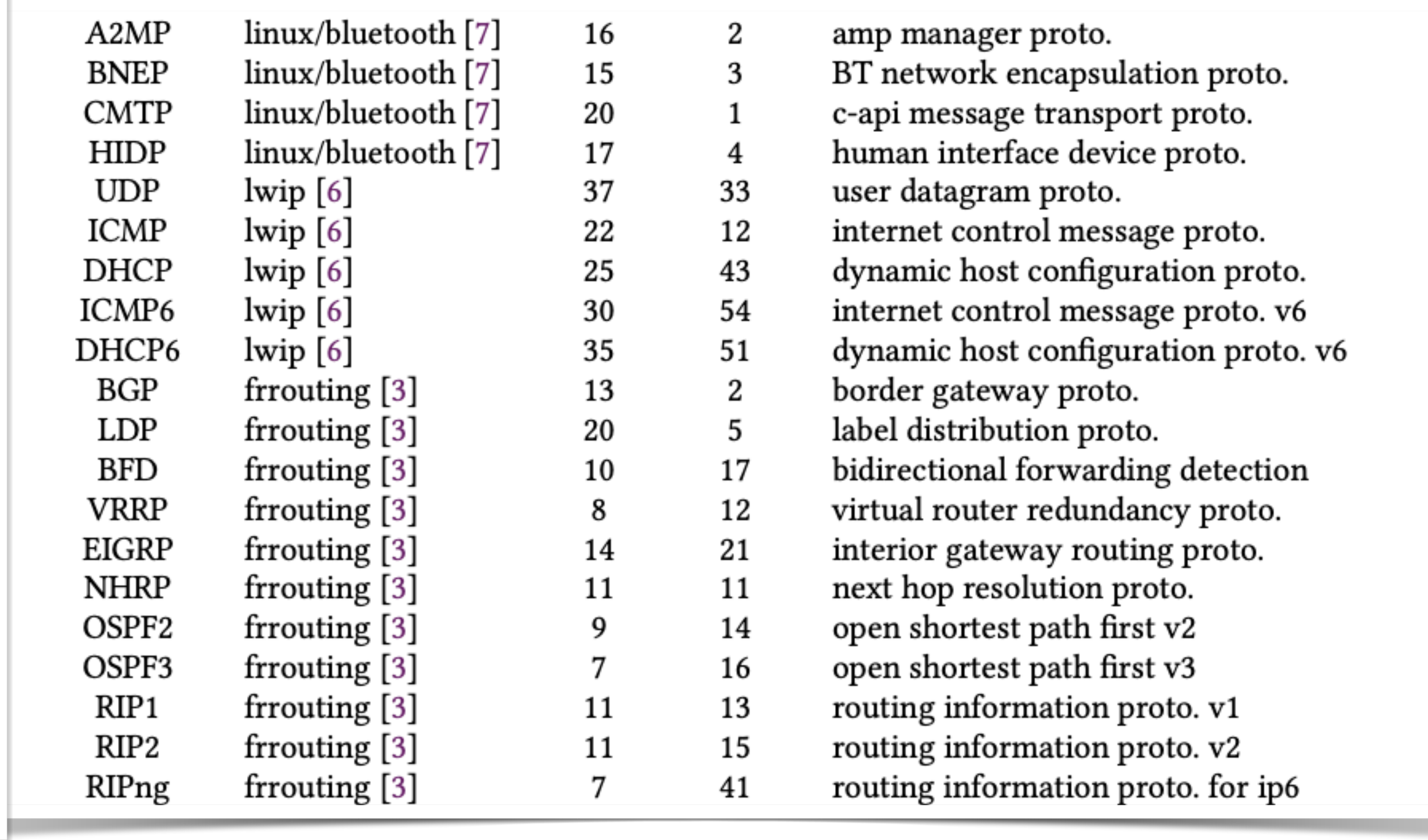


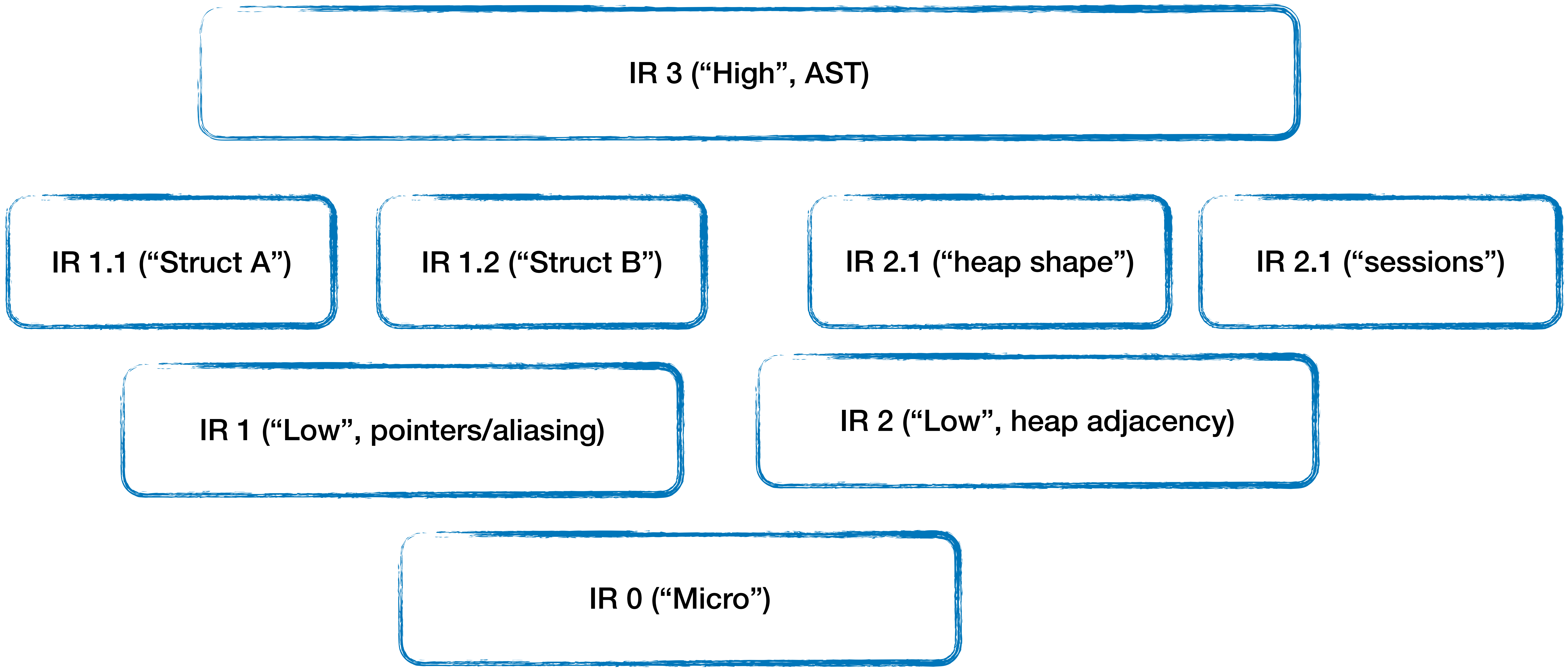
Figure 13: The y-axis is the number of covered branches normalized to one. It shows the branch coverage averaged over twenty runs with a 95% confidence interval.



A2MP	linux/bluetooth [7]	16	2	amp manager proto.
BNEP	linux/bluetooth [7]	15	3	BT network encapsulation proto.
CMTP	linux/bluetooth [7]	20	1	c-api message transport proto.
HIDP	linux/bluetooth [7]	17	4	human interface device proto.
UDP	lwip [6]	37	33	user datagram proto.
ICMP	lwip [6]	22	12	internet control message proto.
DHCP	lwip [6]	25	43	dynamic host configuration proto.
ICMP6	lwip [6]	30	54	internet control message proto. v6
DHCP6	lwip [6]	35	51	dynamic host configuration proto. v6
BGP	frrouting [3]	13	2	border gateway proto.
LDP	frrouting [3]	20	5	label distribution proto.
BFD	frrouting [3]	10	17	bidirectional forwarding detection
VRRP	frrouting [3]	8	12	virtual router redundancy proto.
EIGRP	frrouting [3]	14	21	interior gateway routing proto.
NHRP	frrouting [3]	11	11	next hop resolution proto.
OSPF2	frrouting [3]	9	14	open shortest path first v2
OSPF3	frrouting [3]	7	16	open shortest path first v3
RIP1	frrouting [3]	11	13	routing information proto. v1
RIP2	frrouting [3]	11	15	routing information proto. v2
RIPng	frrouting [3]	7	41	routing information proto. for ip6

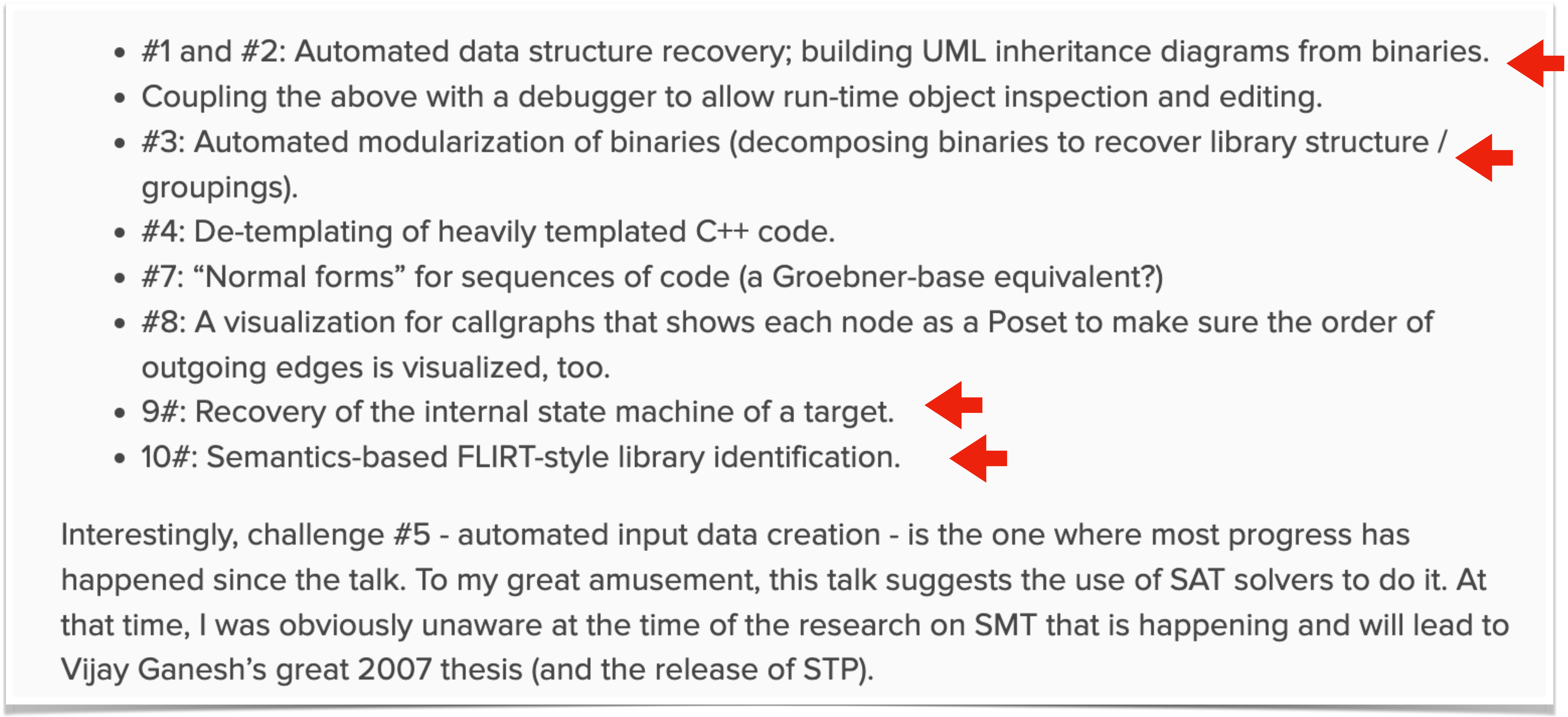
A tree of IRs? A lattice of IRs?

“A sufficiently lifted IR is indistinguishable from a DSL”



Reverse Engineering ~ IR tower/tree lifting?

Halvar's "RE 2006: New Challenges Need Changing Tools" talk



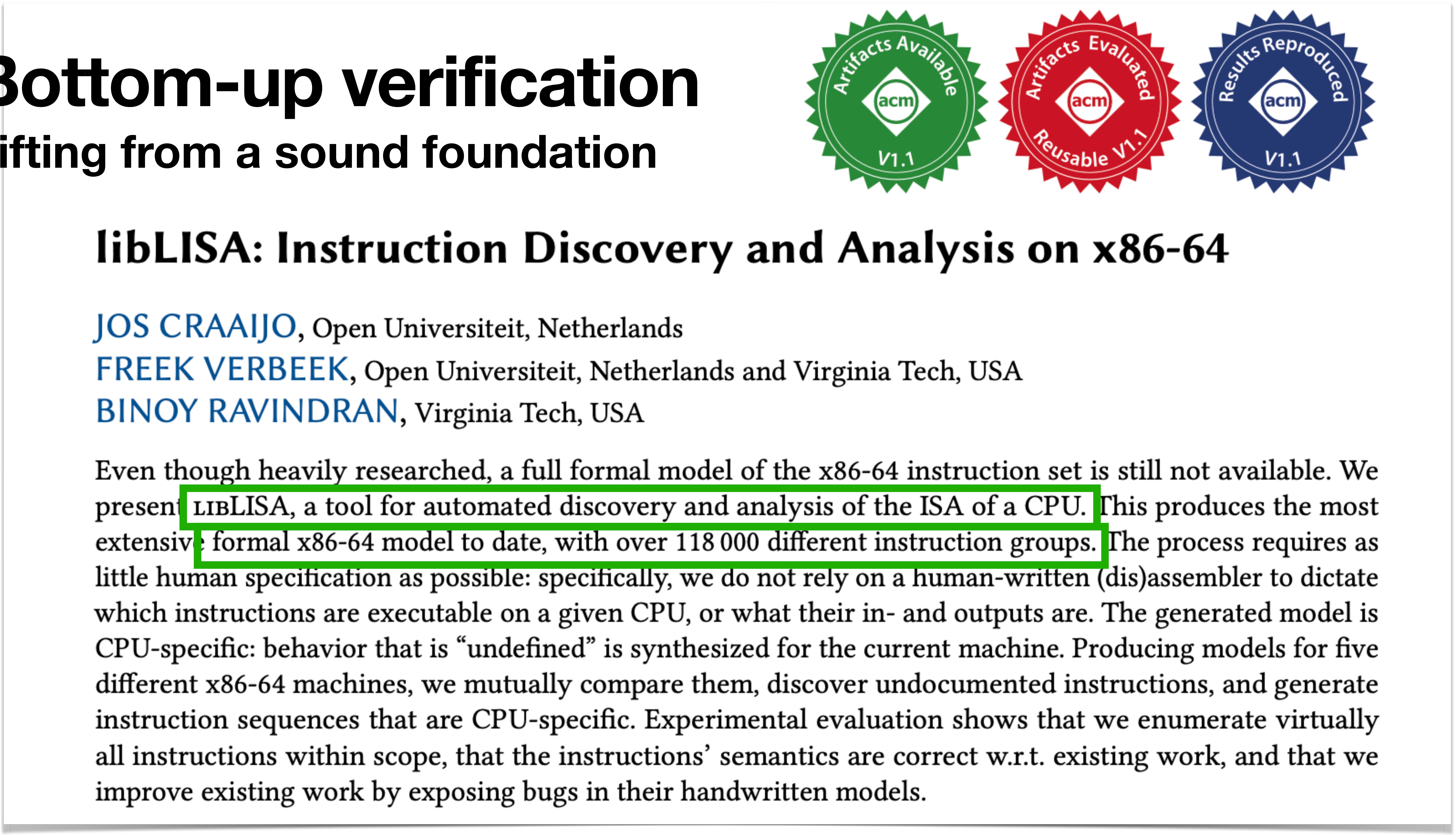
- #1 and #2: Automated data structure recovery; building UML inheritance diagrams from binaries.
- Coupling the above with a debugger to allow run-time object inspection and editing.
- #3: Automated modularization of binaries (decomposing binaries to recover library structure / groupings).
- #4: De-templating of heavily templated C++ code.
- #7: "Normal forms" for sequences of code (a Groebner-base equivalent?)
- #8: A visualization for callgraphs that shows each node as a Poset to make sure the order of outgoing edges is visualized, too.
- 9#: Recovery of the internal state machine of a target.
- 10#: Semantics-based FLIRT-style library identification.

Interestingly, challenge #5 - automated input data creation - is the one where most progress has happened since the talk. To my great amusement, this talk suggests the use of SAT solvers to do it. At that time, I was obviously unaware at the time of the research on SMT that is happening and will lead to Vijay Ganesh's great 2007 thesis (and the release of STP).

https://thomasdullien.github.io/about/#2006

Bottom-up verification

Lifting from a sound foundation



libLISA: Instruction Discovery and Analysis on x86-64

JOS CRAAIJO, Open Universiteit, Netherlands
FREEK VERBEEK, Open Universiteit, Netherlands and Virginia Tech, USA
BINOY RAVINDRAN, Virginia Tech, USA

Even though heavily researched, a full formal model of the x86-64 instruction set is still not available. We present LIBLISA, a tool for automated discovery and analysis of the ISA of a CPU. This produces the most extensive formal x86-64 model to date, with over 118 000 different instruction groups. The process requires as little human specification as possible: specifically, we do not rely on a human-written (dis)assembler to dictate which instructions are executable on a given CPU, or what their in- and outputs are. The generated model is CPU-specific: behavior that is "undefined" is synthesized for the current machine. Producing models for five different x86-64 machines, we mutually compare them, discover undocumented instructions, and generate instruction sequences that are CPU-specific. Experimental evaluation shows that we enumerate virtually all instructions within scope, that the instructions' semantics are correct w.r.t. existing work, and that we improve existing work by exposing bugs in their handwritten models.

Recompilable/patchable/verifiable IRs

Recompilable disassembly with proofs

Verifiably Correct Lifting of Position-Independent x86-64 Binaries to Symbolized Assembly

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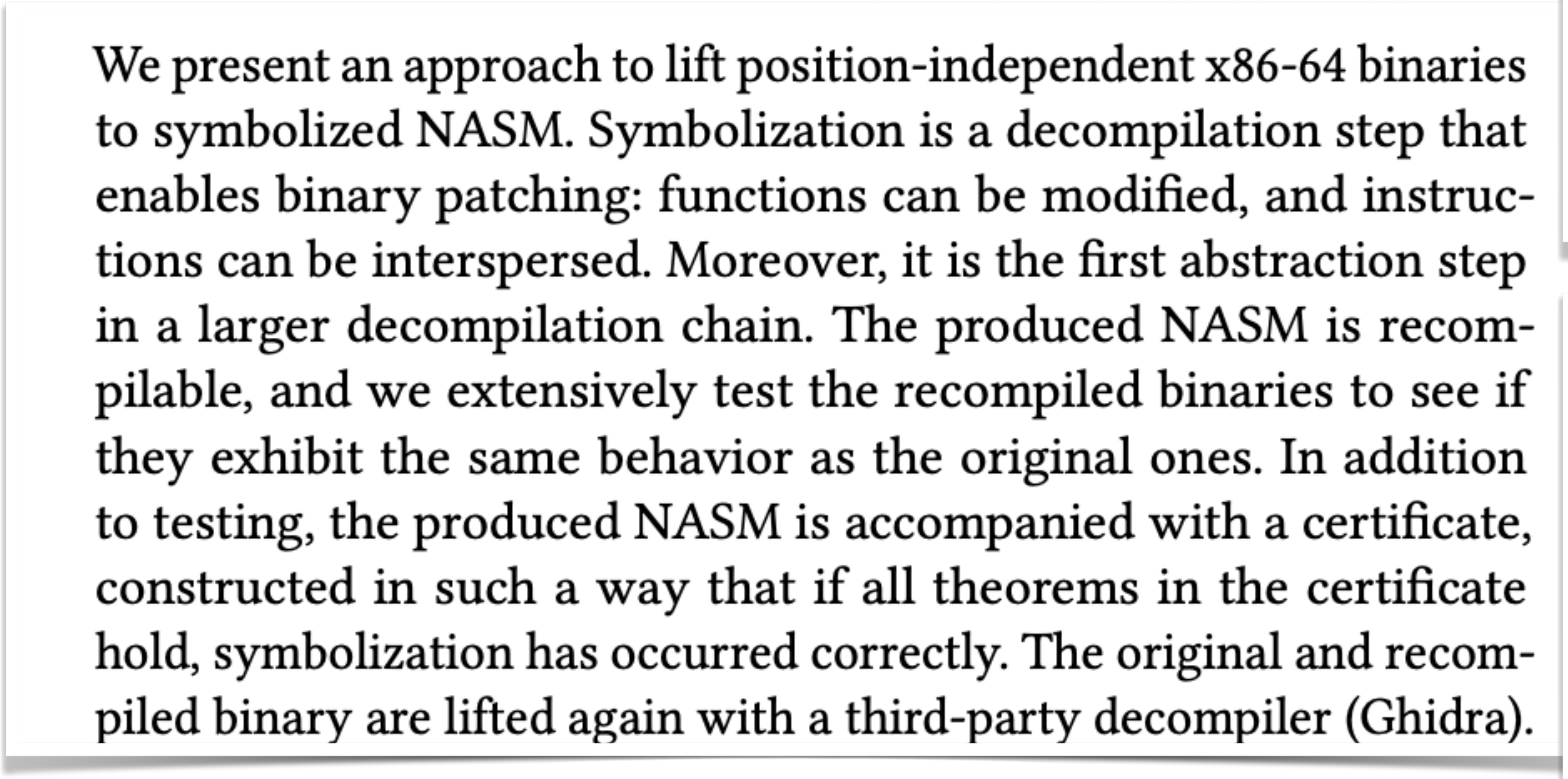
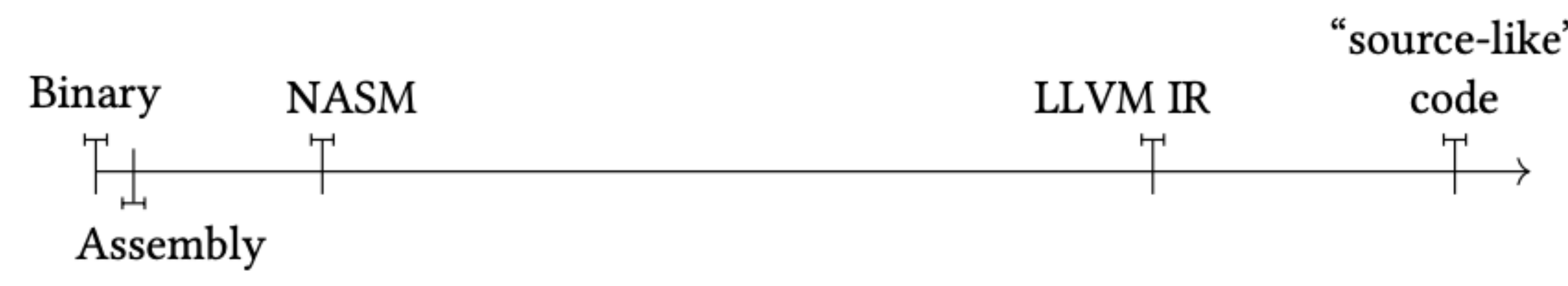
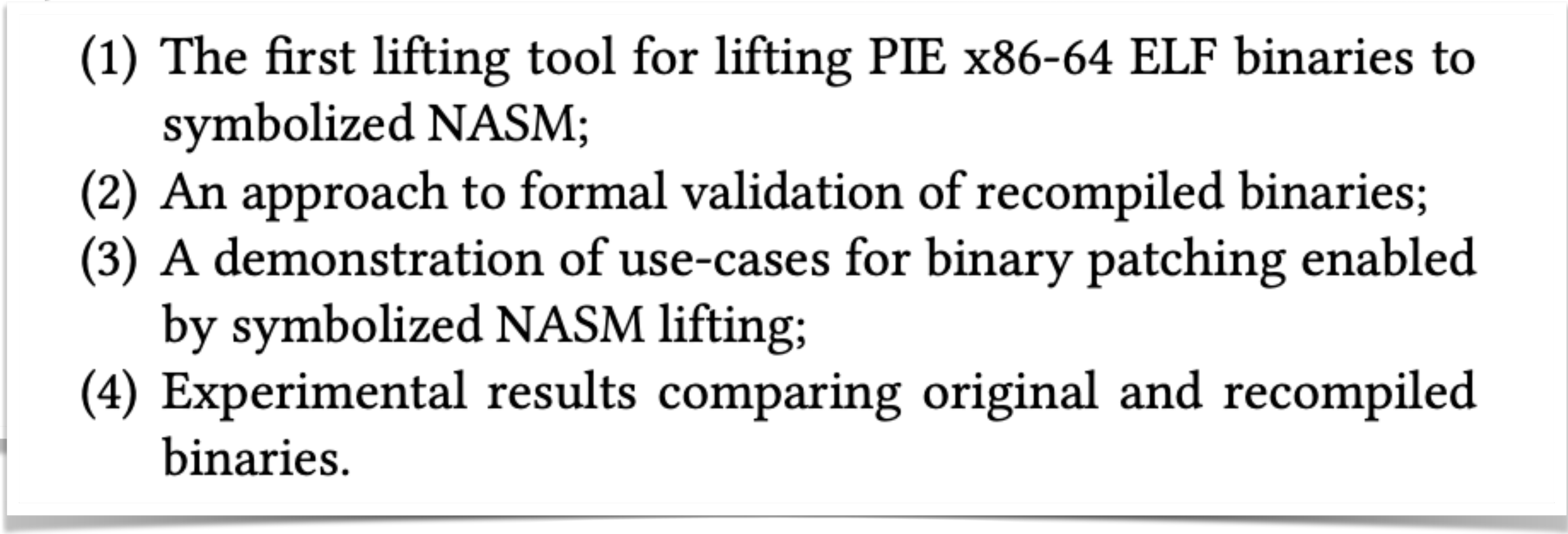


We present an approach to lift position-independent x86-64 binaries to symbolized NASM. Symbolization is a decompilation step that enables binary patching: functions can be modified, and instructions can be interspersed. Moreover, it is the first abstraction step in a larger decompilation chain. The produced NASM is recompilable, and we extensively test the recompiled binaries to see if they exhibit the same behavior as the original ones. In addition to testing, the produced NASM is accompanied with a certificate, constructed in such a way that if all theorems in the certificate hold, symbolization has occurred correctly. The original and recompiled binary are lifted again with a third-party decompiler (Ghidra).





(1) The first lifting tool for lifting PIE x86-64 ELF binaries to symbolized NASM;
(2) An approach to formal validation of recompiled binaries;
(3) A demonstration of use-cases for binary patching enabled by symbolized NASM lifting;
(4) Experimental results comparing original and recompiled binaries.

Is this the year of the first-class* IRs?

(*) Machine-readably defined as mathematical objects friendly to efficient algorithms

Right representation => Math => Algorithm => Tool => Pwnage

Memorizer

Object-granular instrumentation of the Linux 6.6 kernels

- Original by *Nathan Dautenhahn at Rice U.*, currently developed at *UIUC*
- Stable, available with build instructions, manuals, and usage examples
    - https://github.com/ITI/memorizer/
    - Docs: https://github.com/ITI/memorizer/tree/linux-6.6.y-memorizer-dev/Documentation
    - Builds for Qemu, x86-64, InitRAM

How can we use it to improve software development, maintenance and sustainment?

We are still living out the 1960s software development revolution

Awesome:

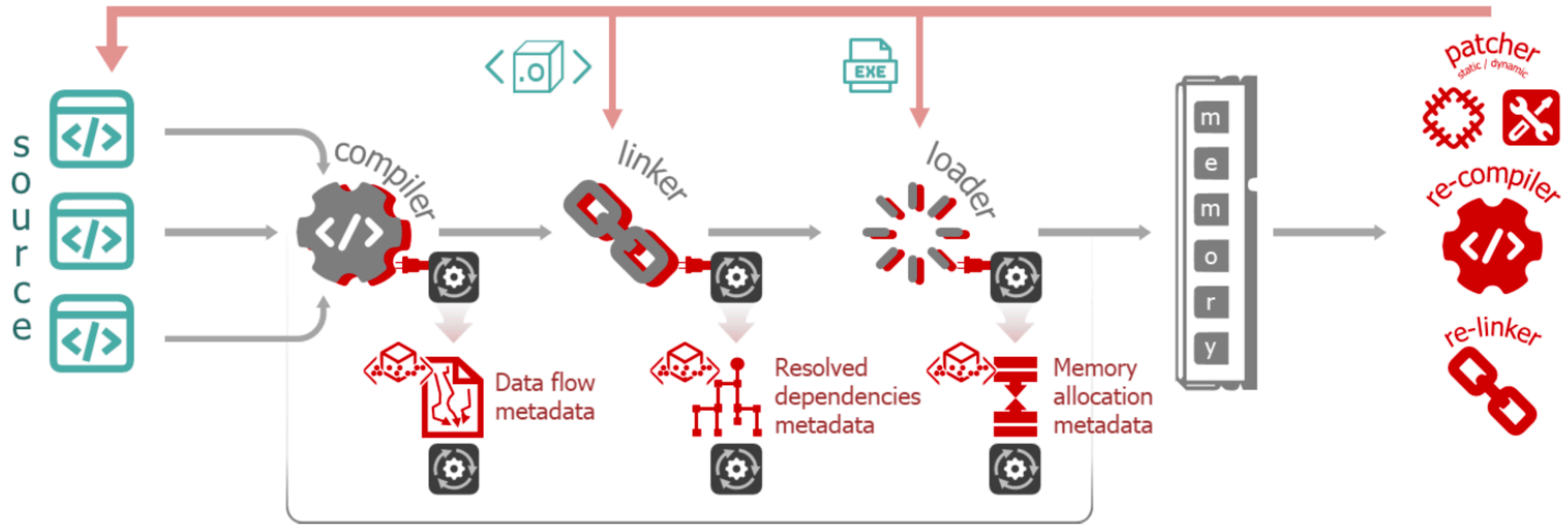
- High-level programming languages
- Automating software composition (linkers)
- Large reusable code libraries

And yet:

- Source -> compiler -> linker -> **unmaintainable** binary
- Binaries aren’t meant to be incrementally updated
  - “Tear down & rebuild the house to remodel a room”

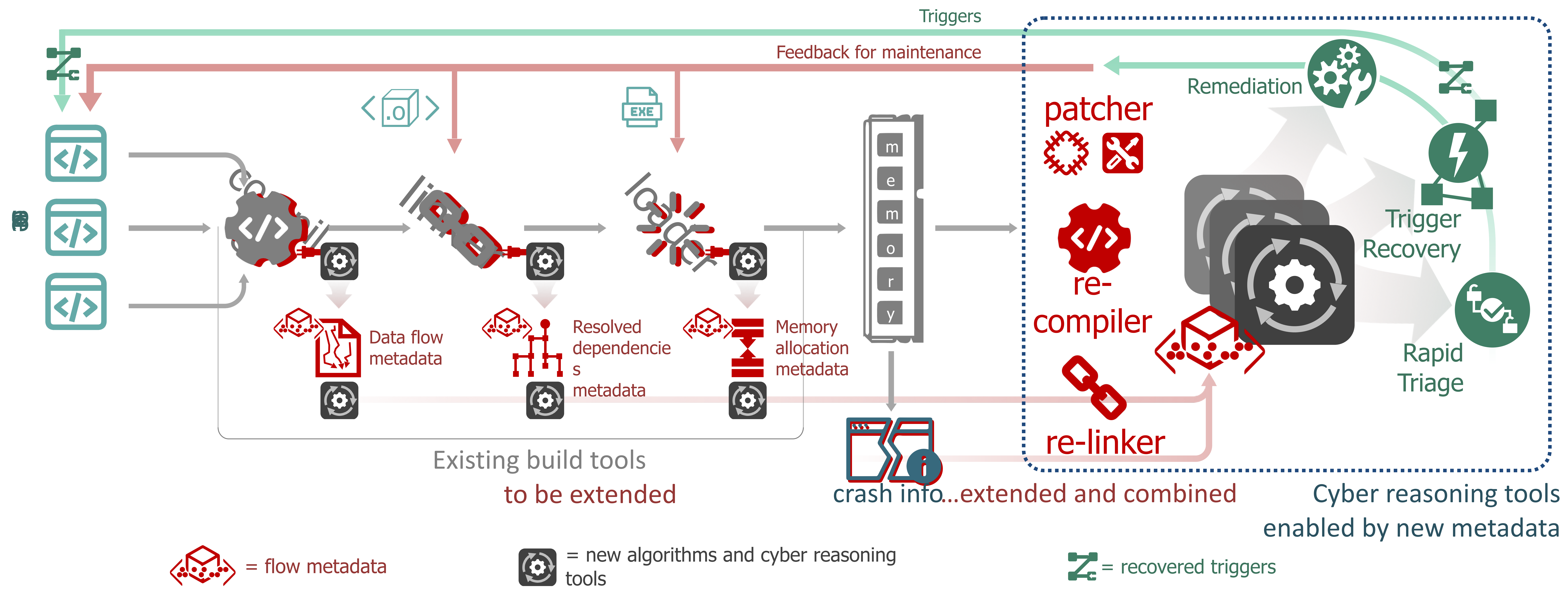
https://en.wikipedia.org/wiki/Grace_Hopper

New tools to maintain software post-compilation & post-linking



Advanced metadata is generated at each stage of the build process, enables maintenance of binaries

E-BOSS: enhance SBOMs with flow metadata to trace flaws to triggers



- Keep advanced metadata in addition to symbols to effectively trace back flaw evidence to triggers
- Enhance SBOMs with new types of rich metadata, enabling cyber reasoning for triage and remediation
- Remediate with eSBOMs: Recover paths and triggers to crash site from crash snapshots (“crash dumps”), remediate by blocking triggers once recovered
  - Block triggers and flows leading to quick remediation

Thank you!

DARPA
June 17, 2025
Hyatt Regency Crystal City, Arlington, VA
Save the Date
Resilient Software Systems
COLLOQUIUM
Forging a New Era of Cyber Resiliency

Thank you