LAVA: Large-scale Automated Vulnerability Addition

Tim Leek, Patrick Hulin, Ryan Whelan (MIT/LL),

Brendan Dolan-Gavitt (NYU),

Fredrick Ulrich, Andrea Mambretti, Wil Robertson, and Engin Kirda (Northeastern)

May 22, 2016

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The problem: vulnerability discovery

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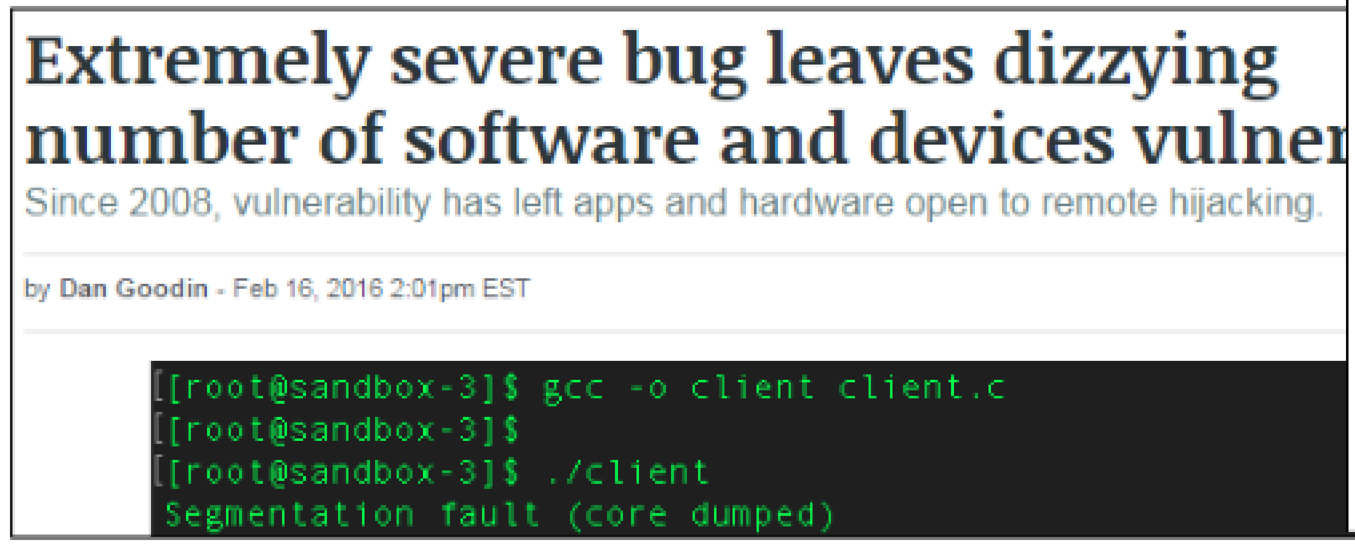

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by Dan Goodin - Feb 16, 2016 2:01pm EST

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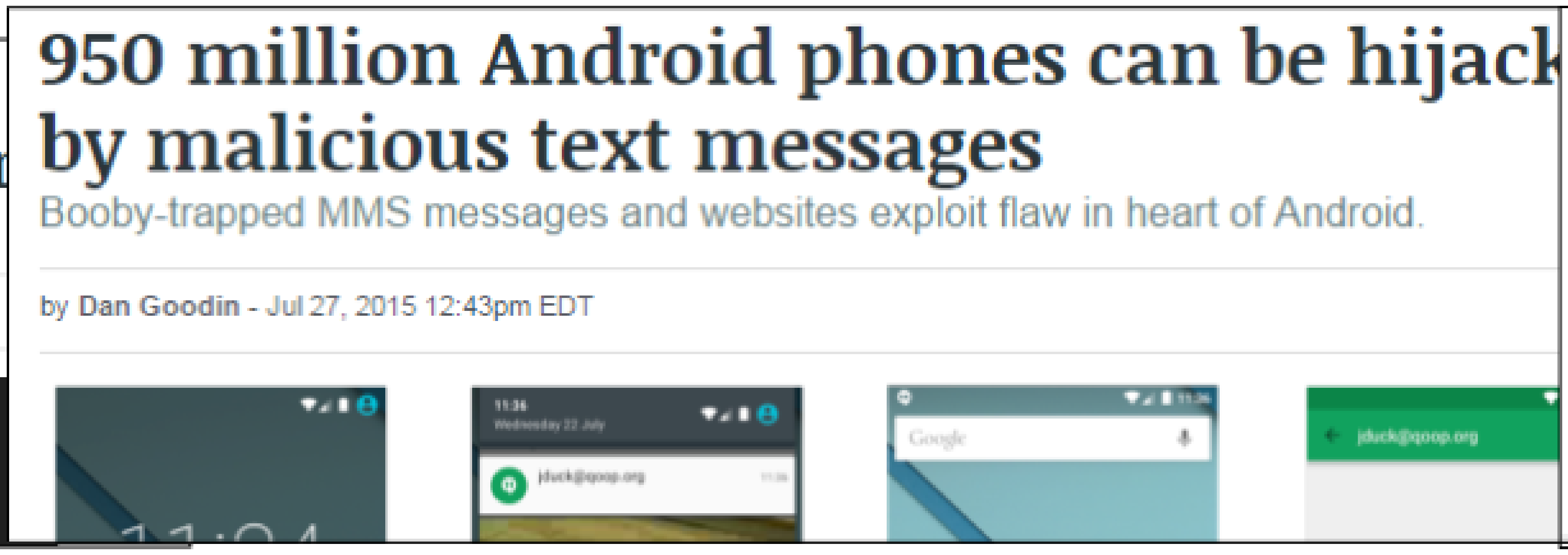

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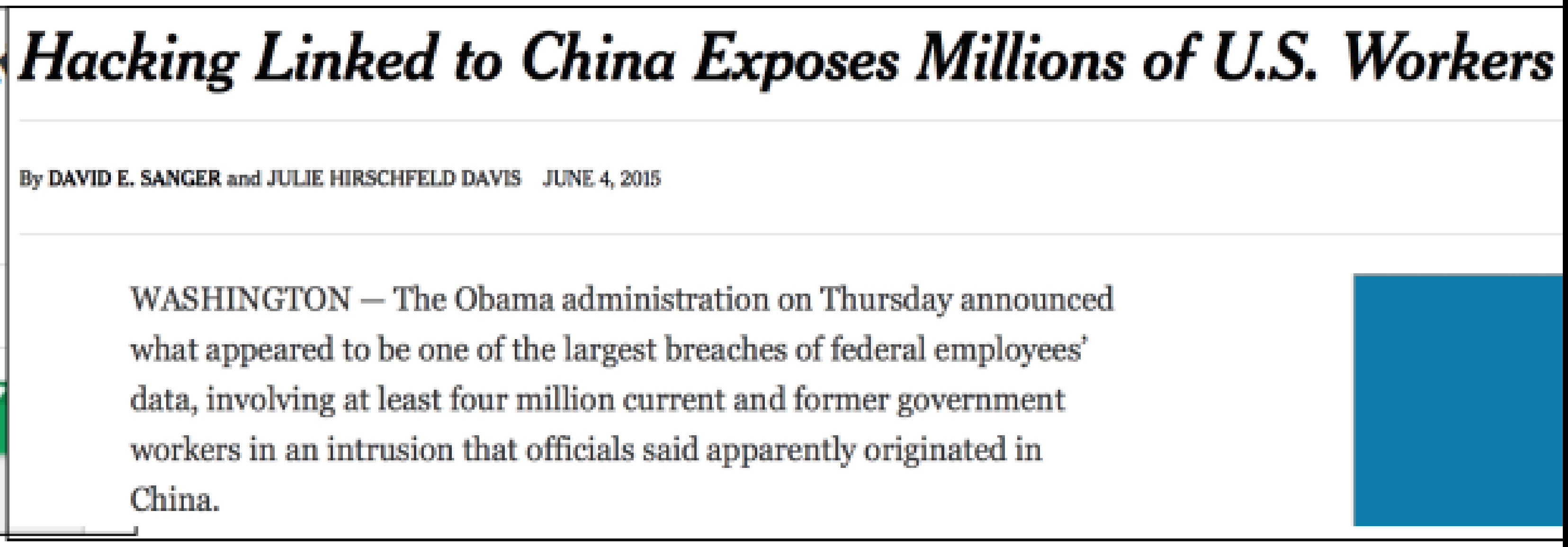

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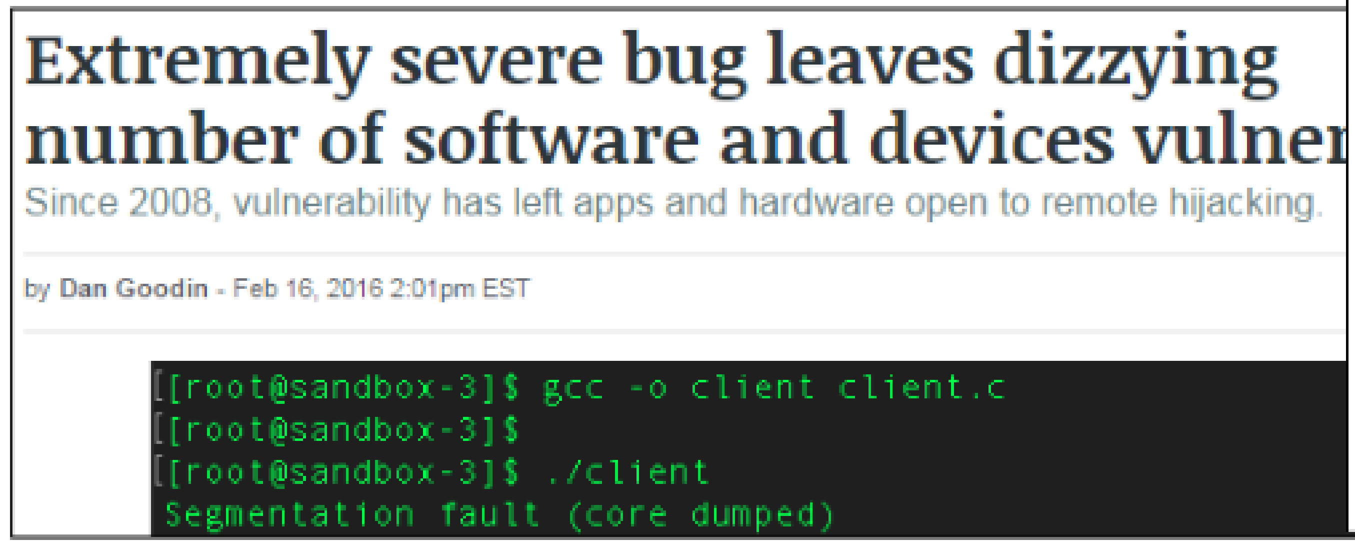

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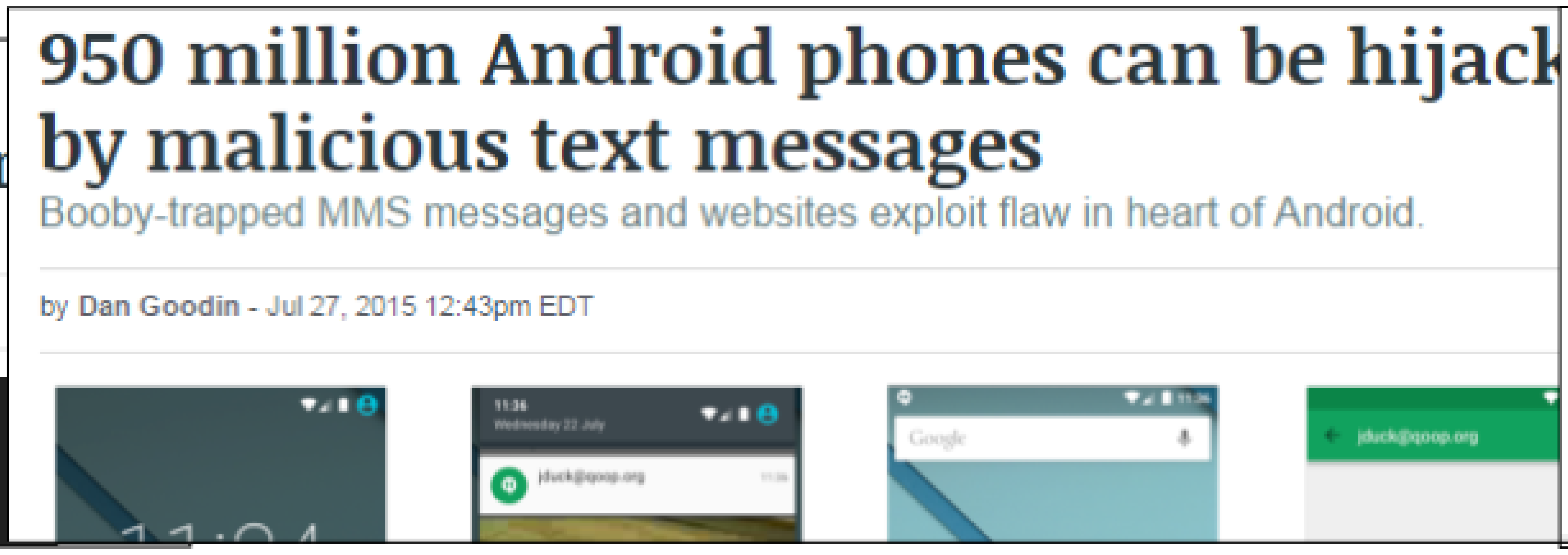

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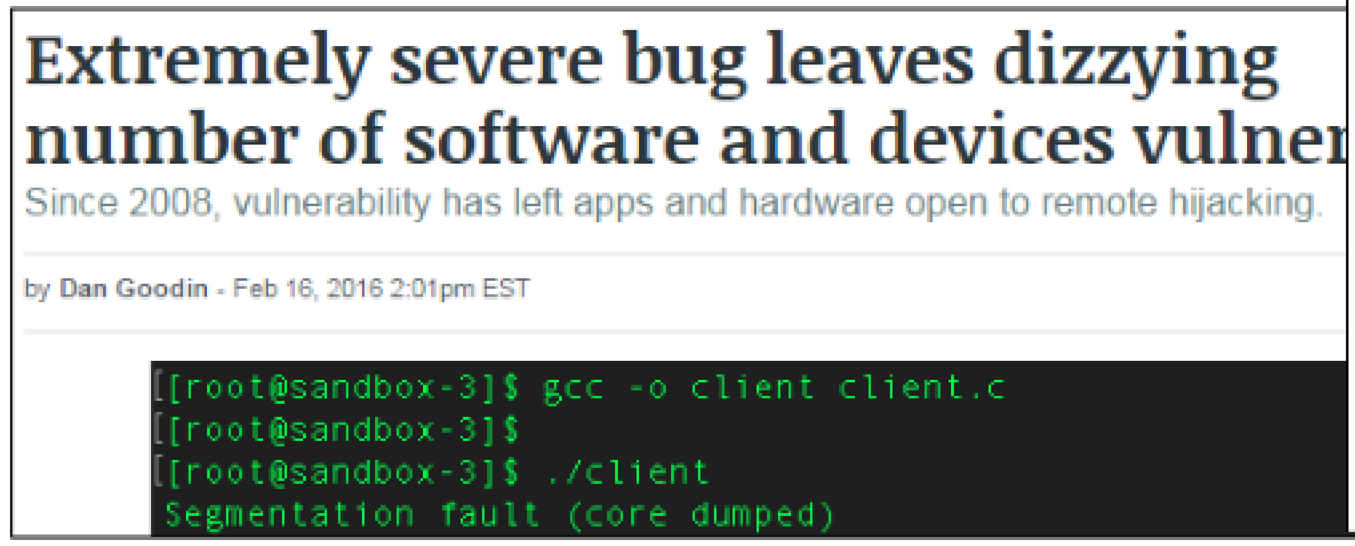

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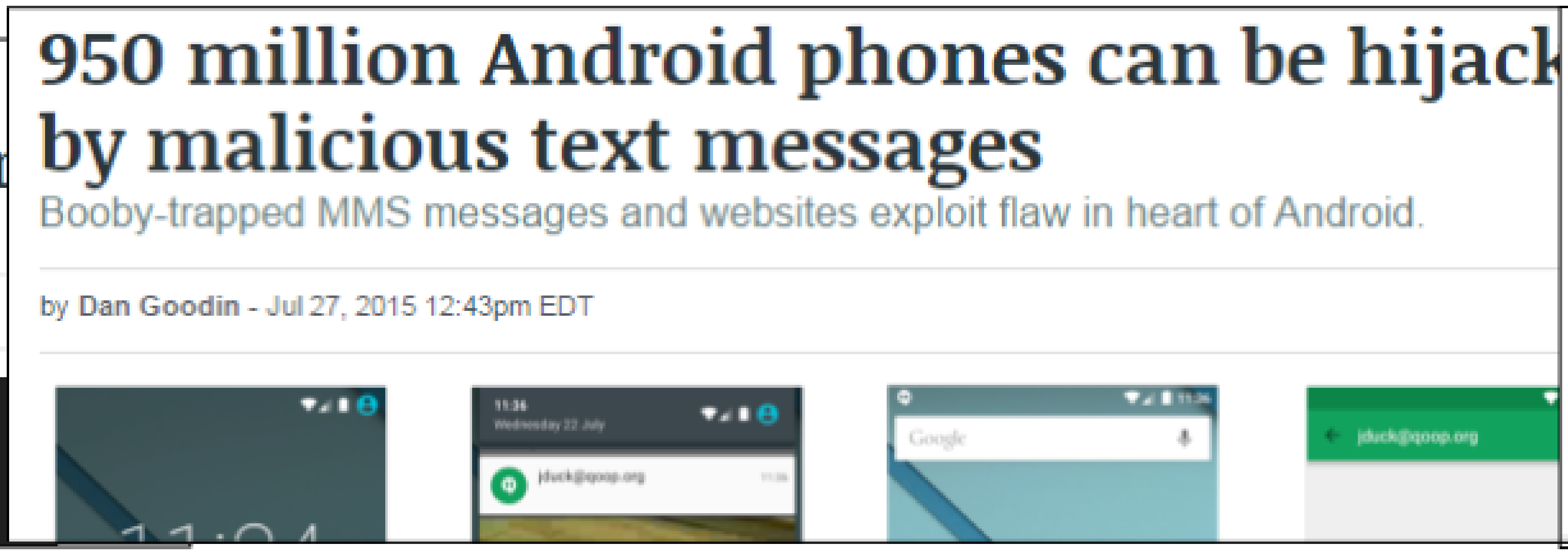

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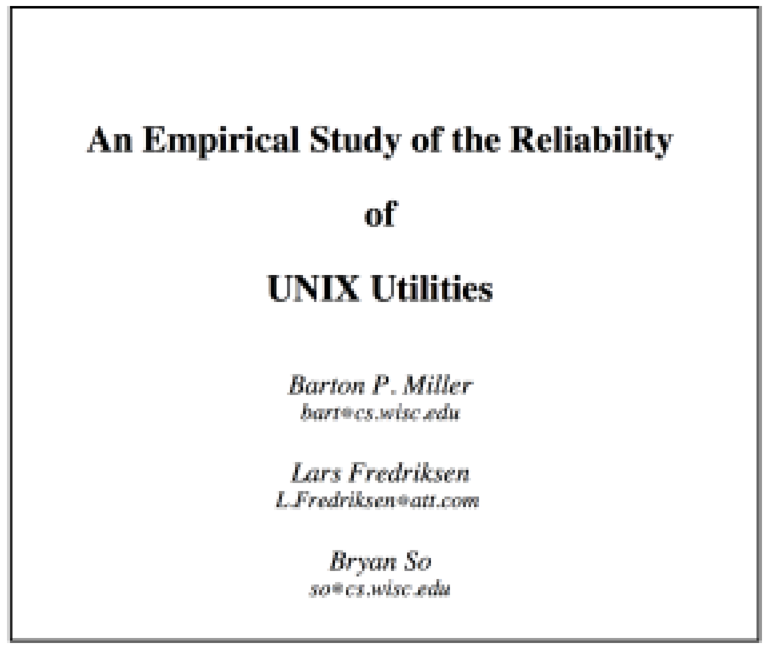

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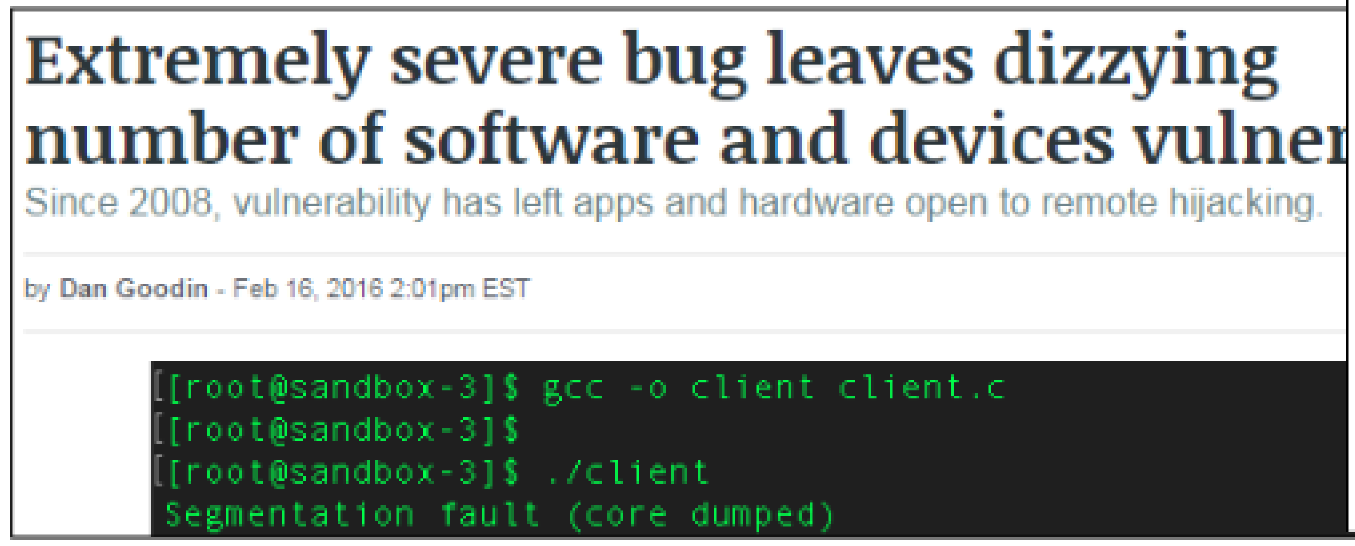

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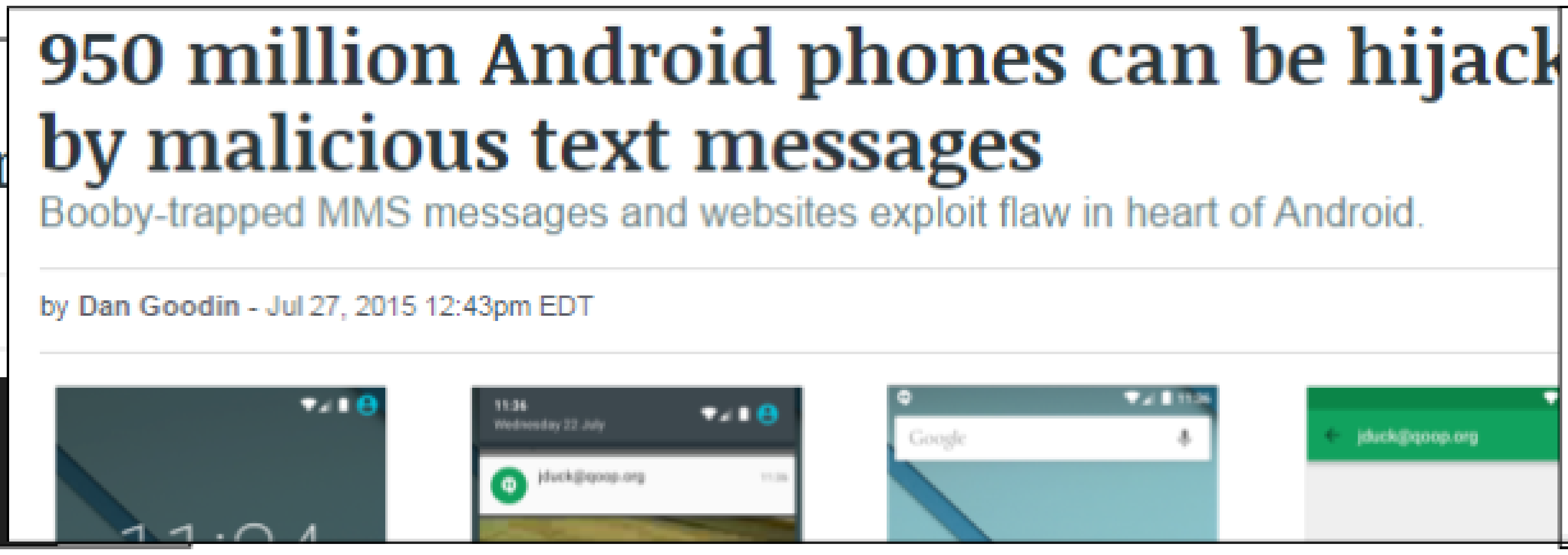

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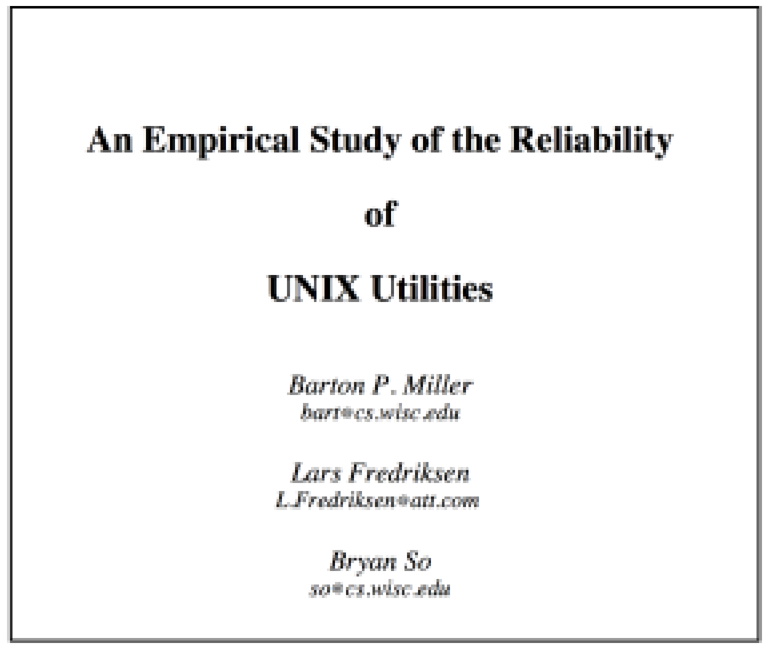

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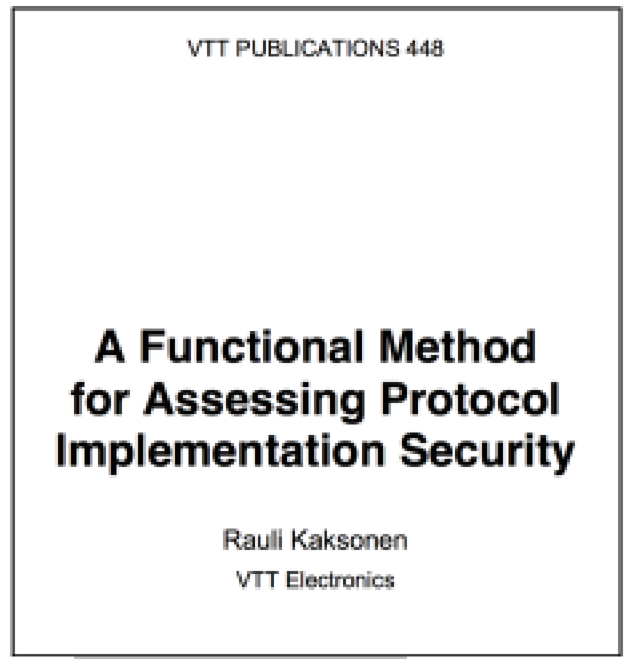

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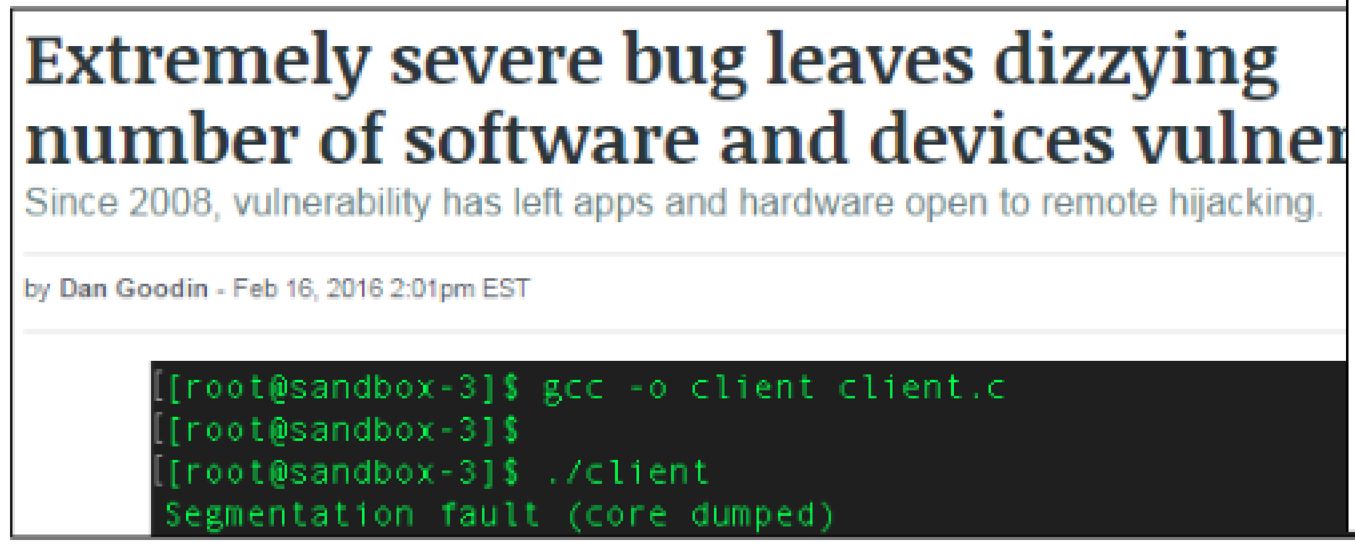

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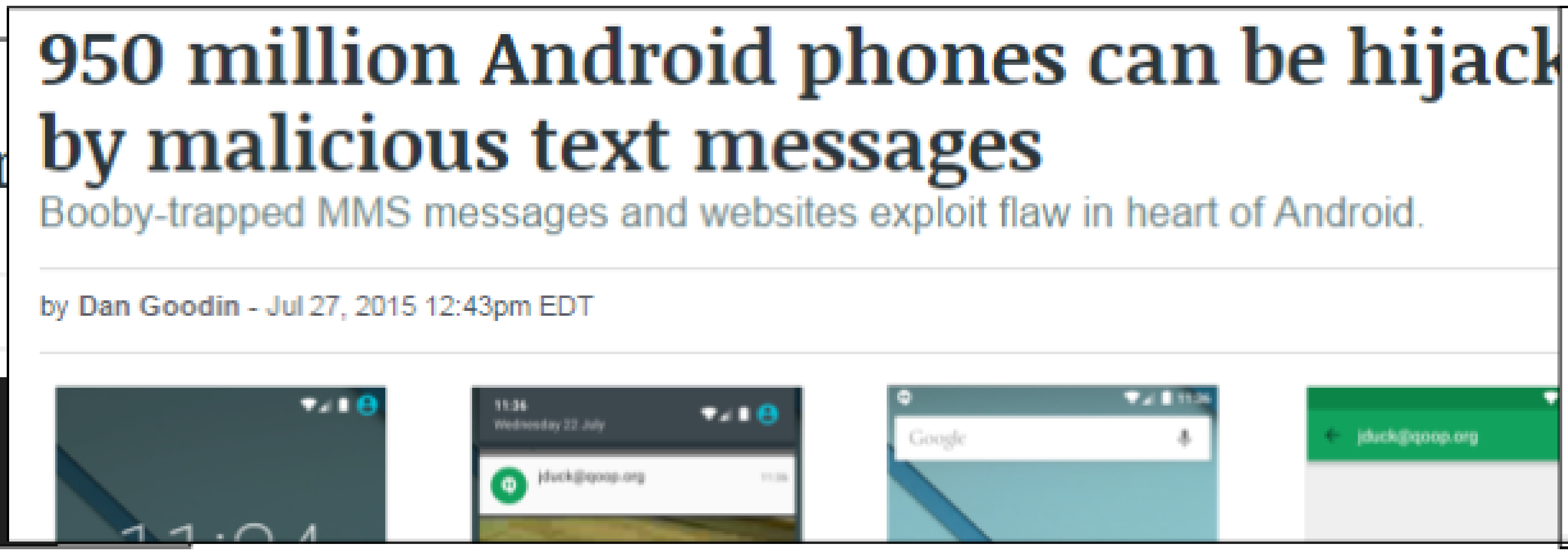

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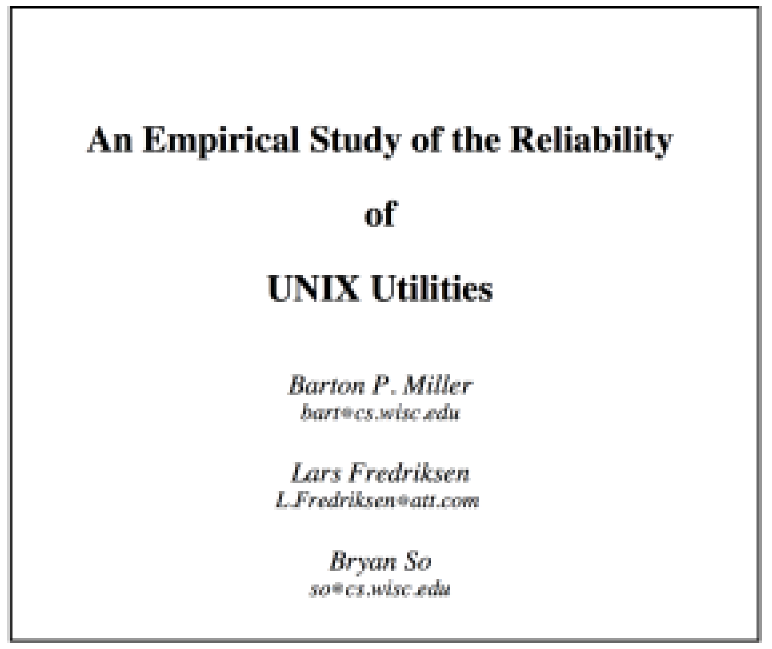

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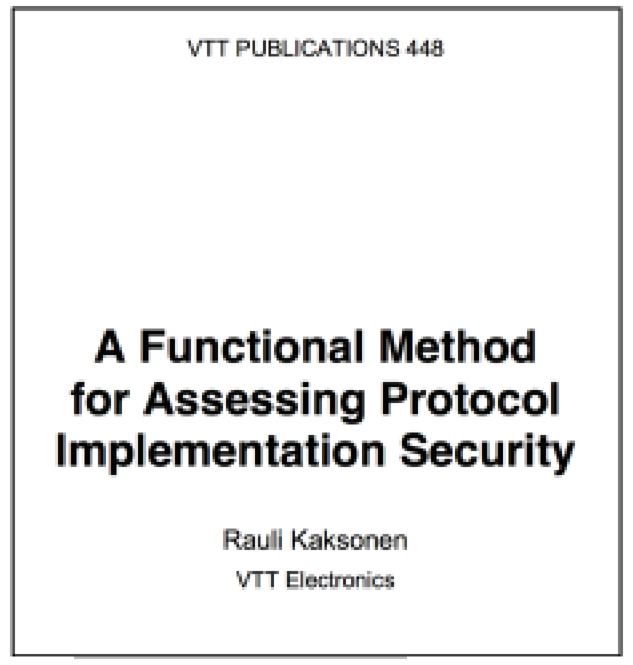

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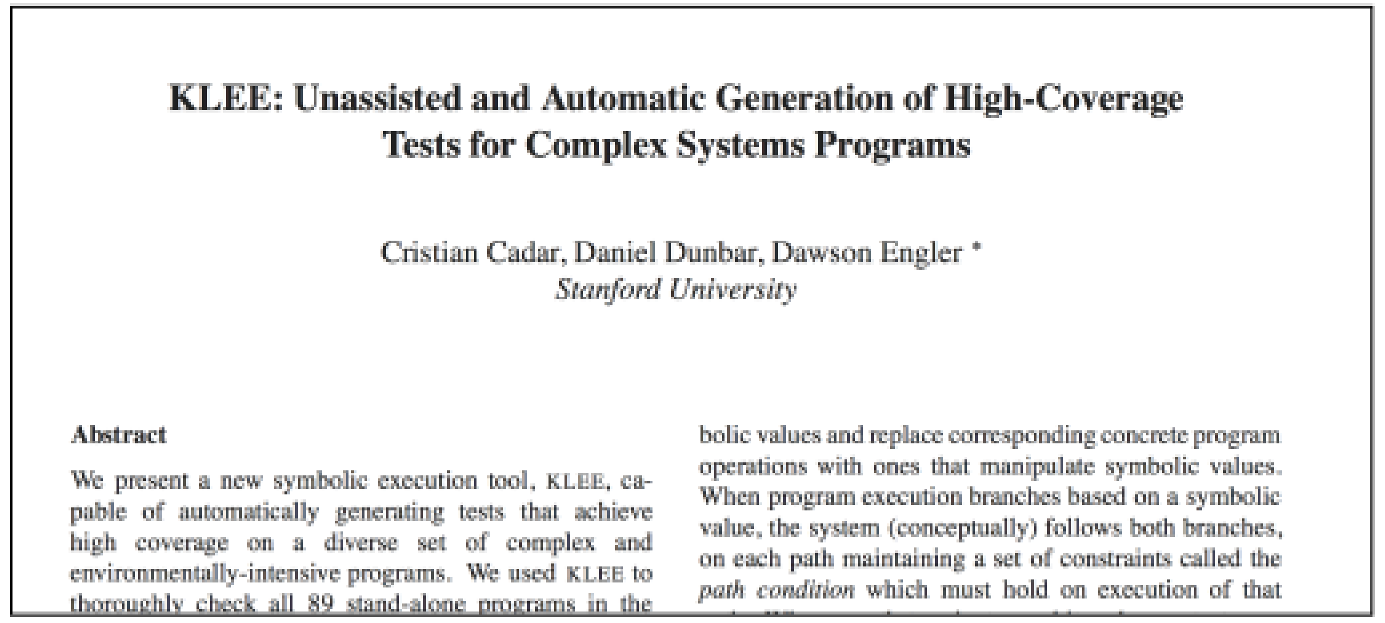

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Cristian Cadar, Daniel Dunbar, Dawson Engler *
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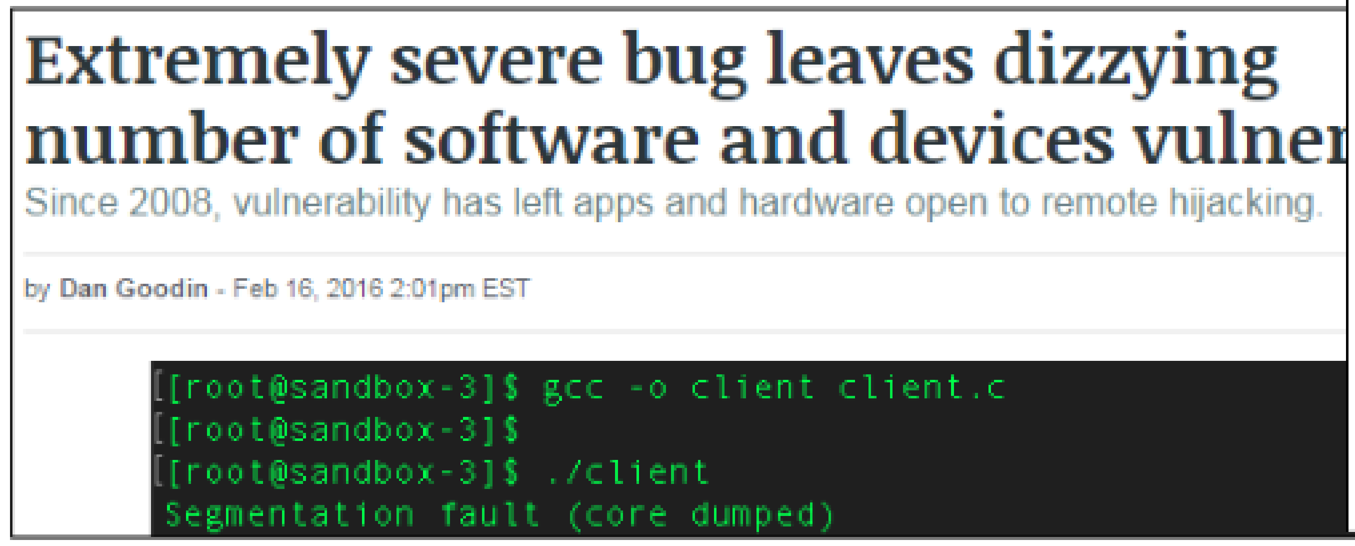

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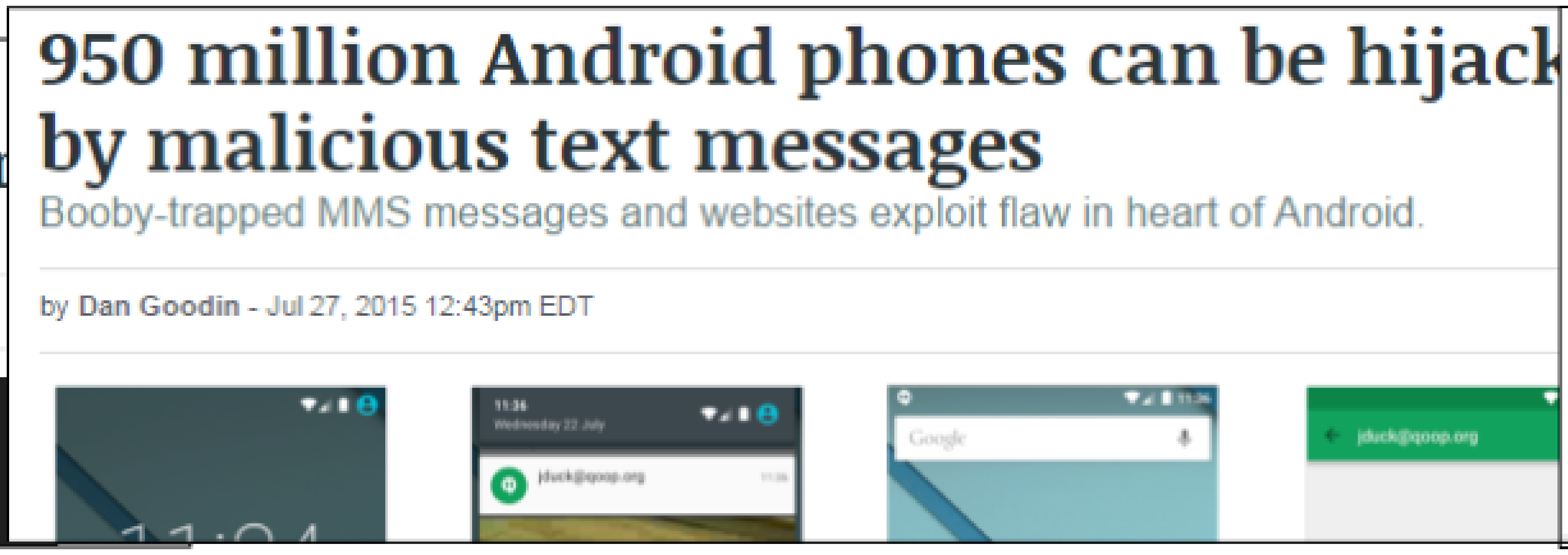

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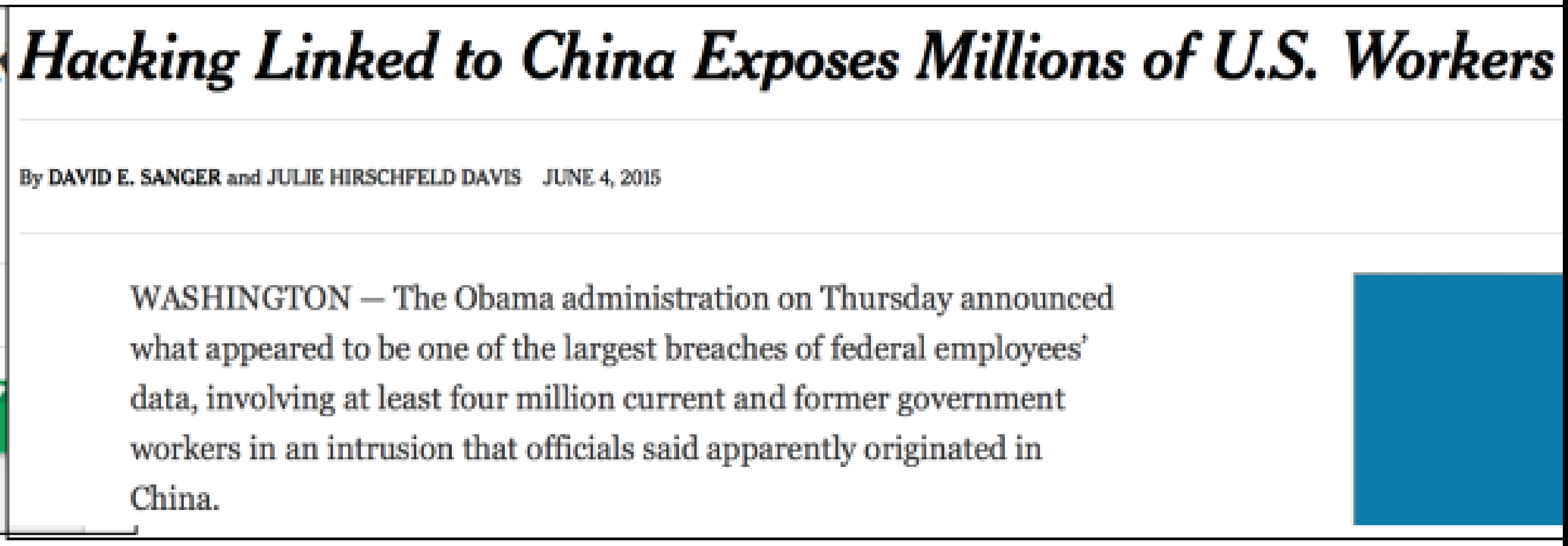

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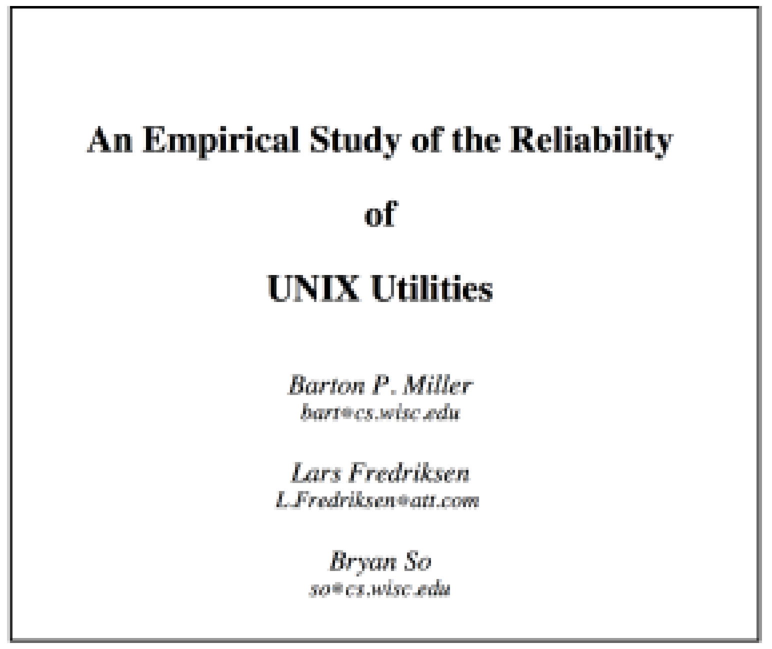

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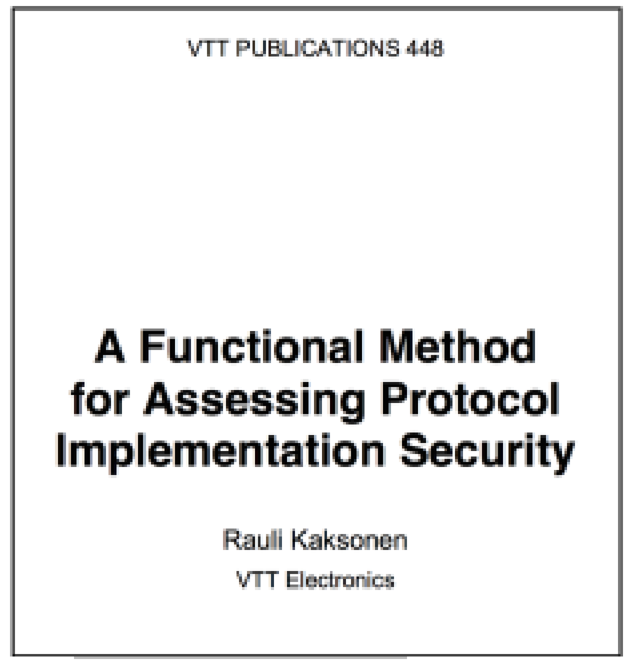

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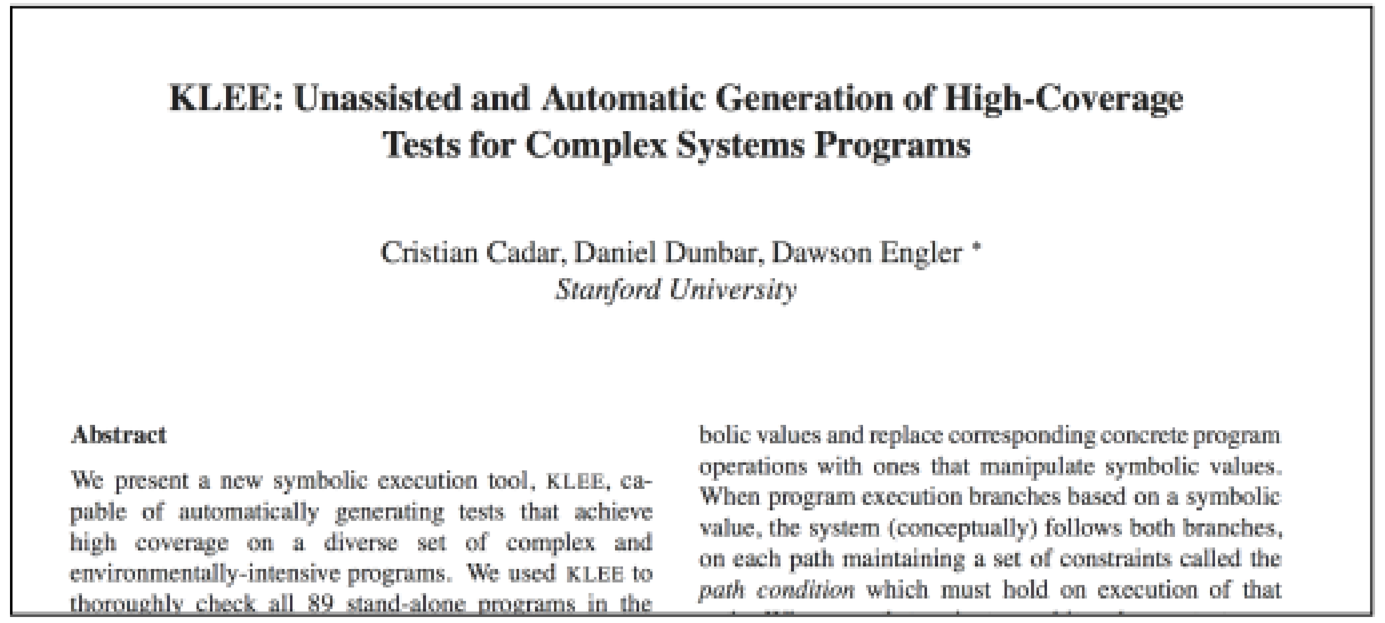

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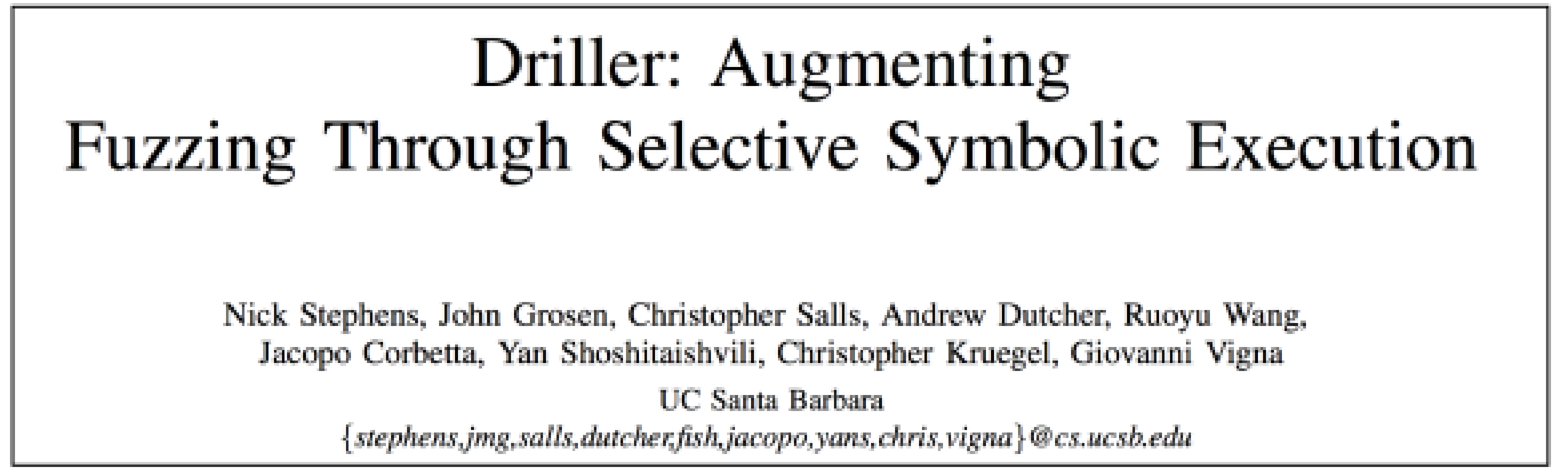

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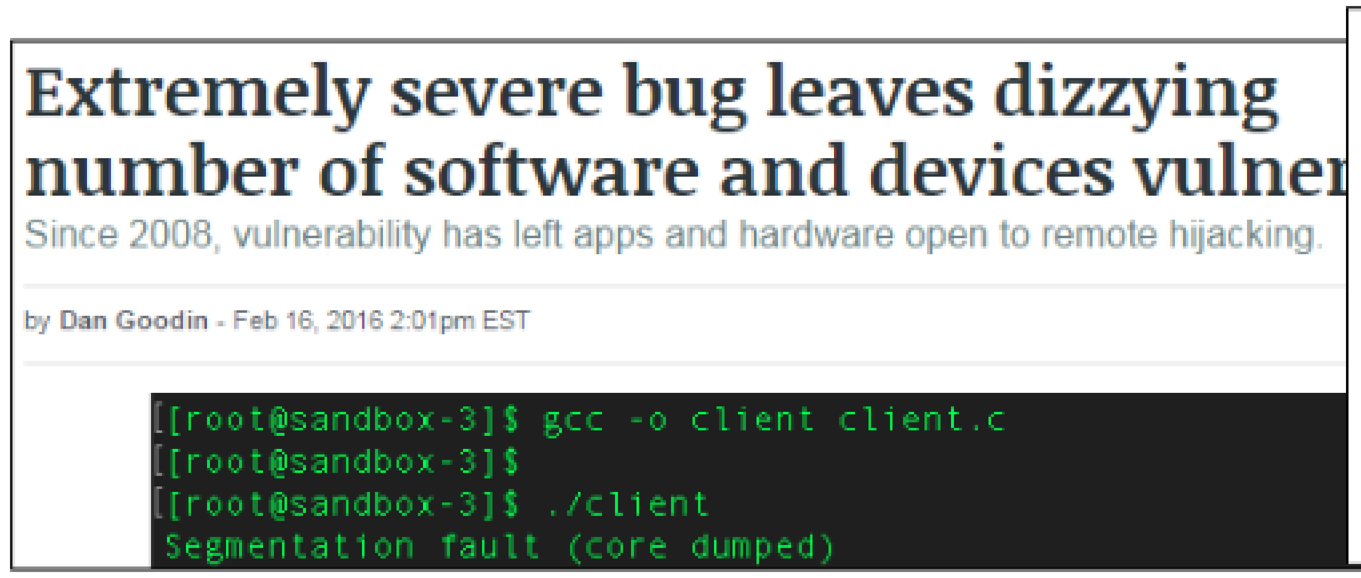

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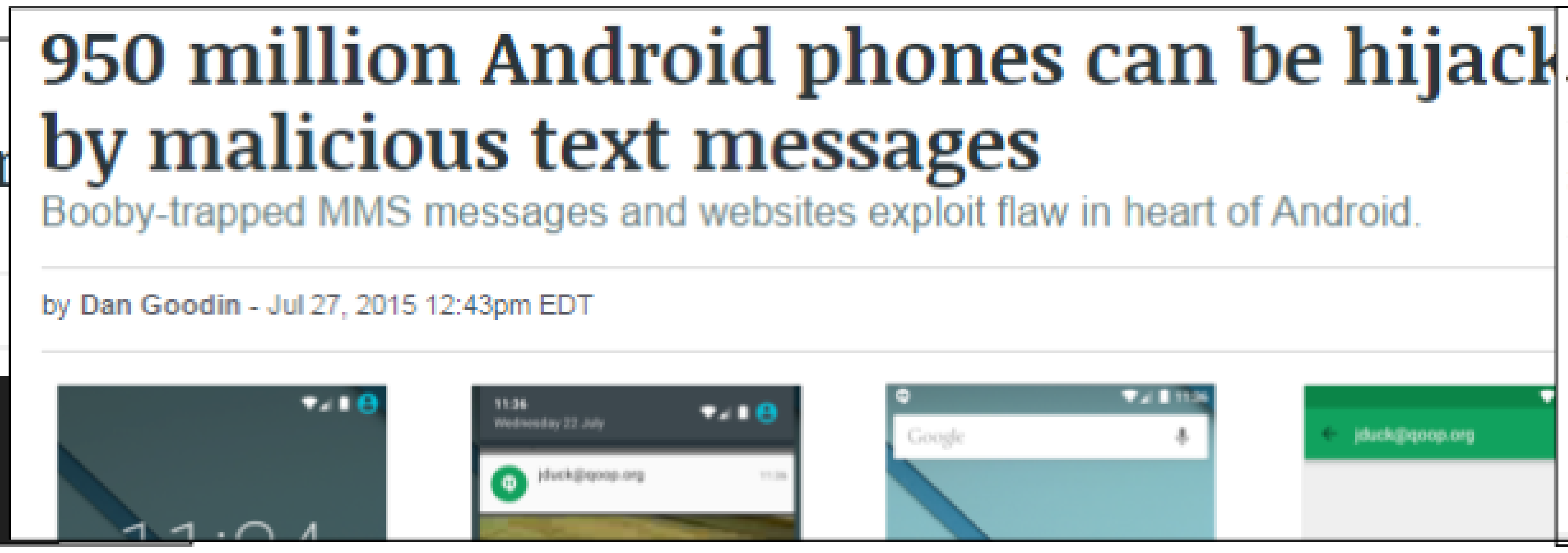

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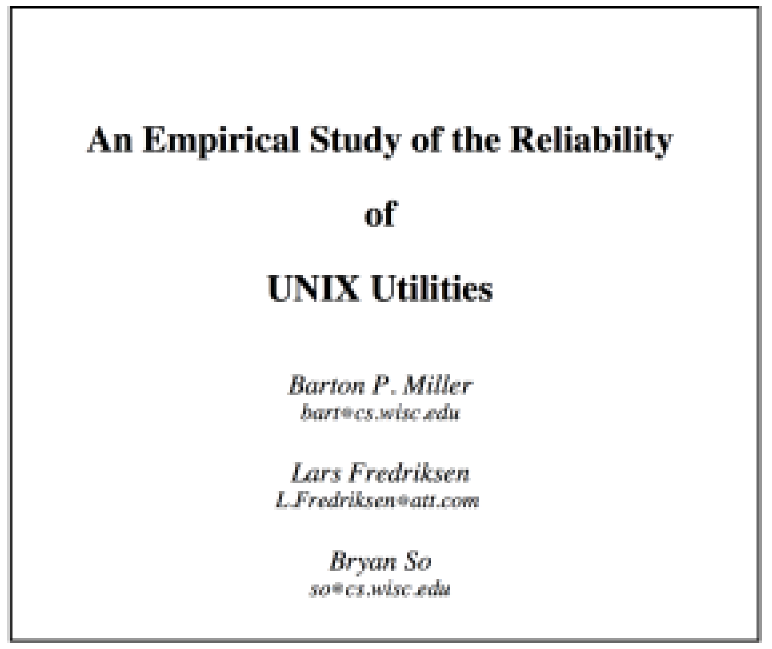

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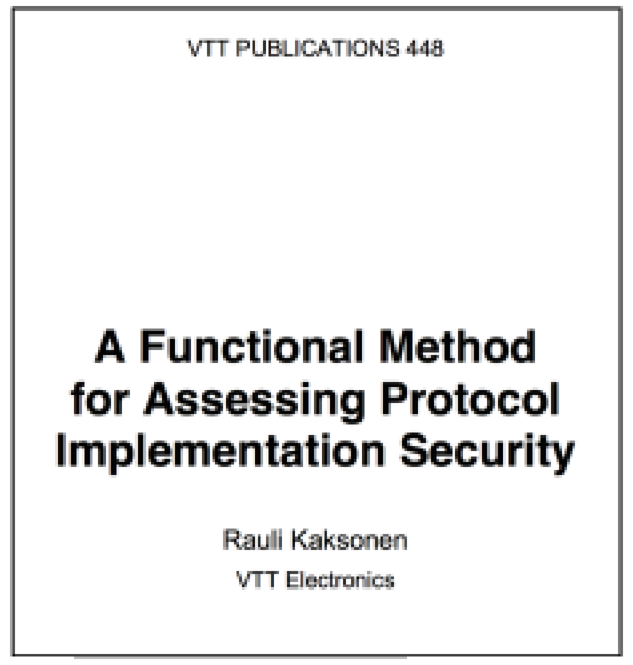

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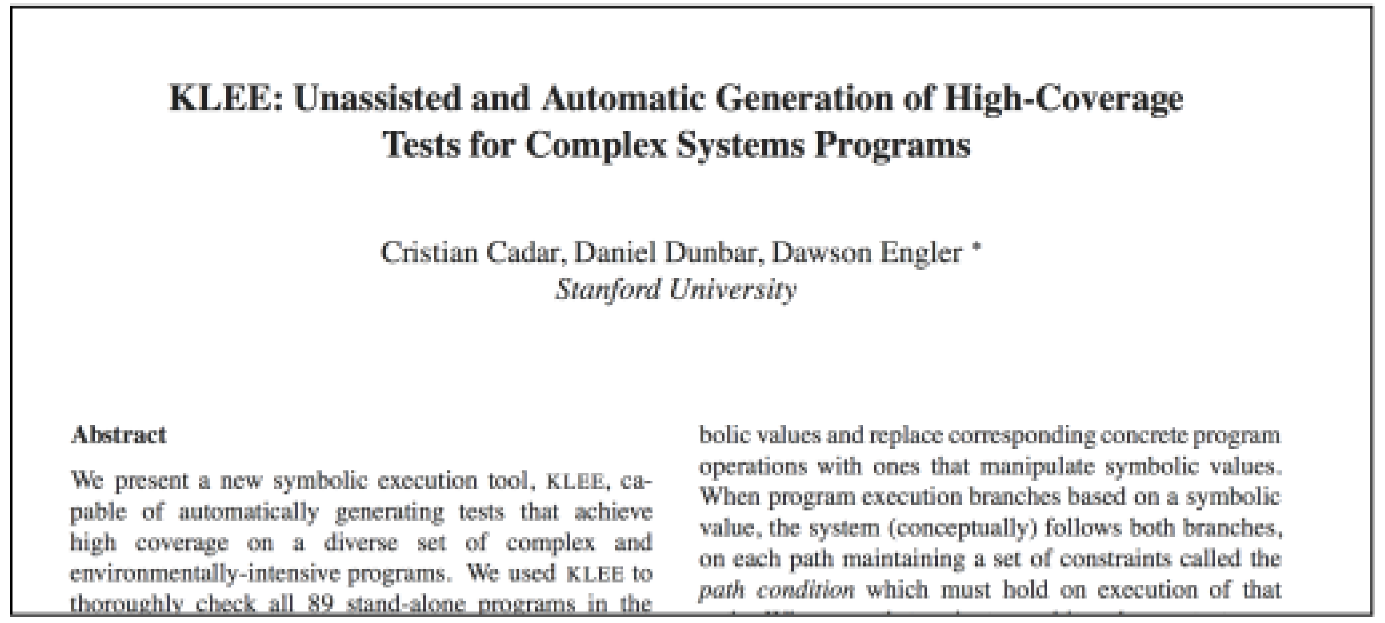

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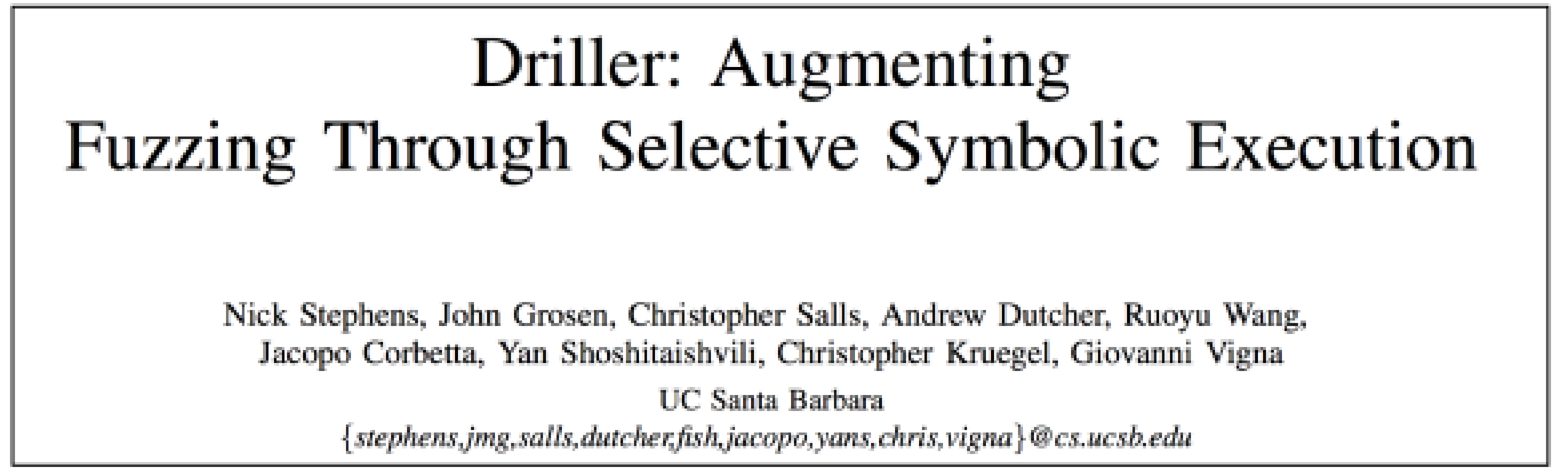

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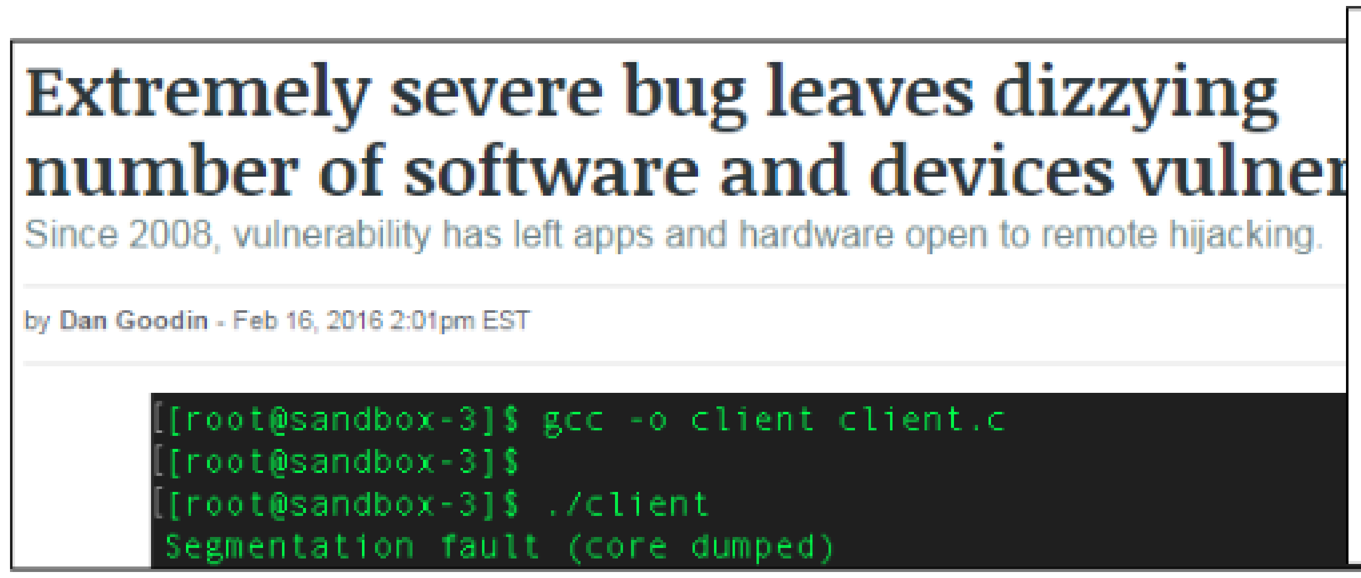

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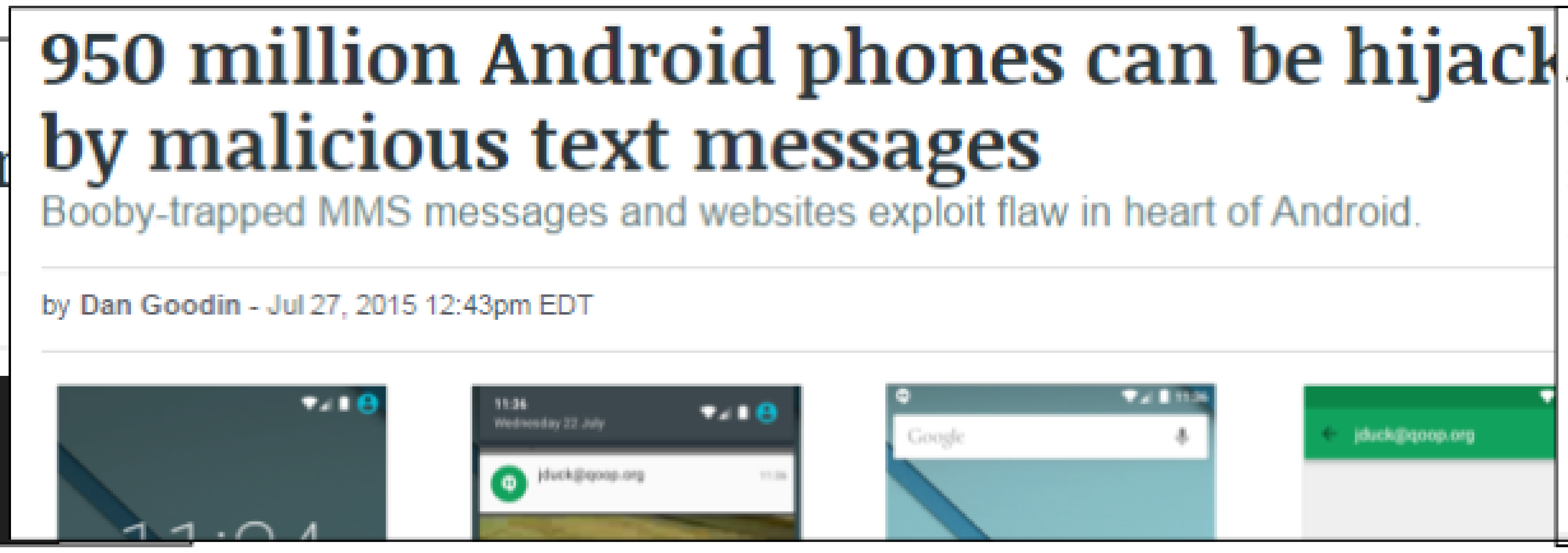

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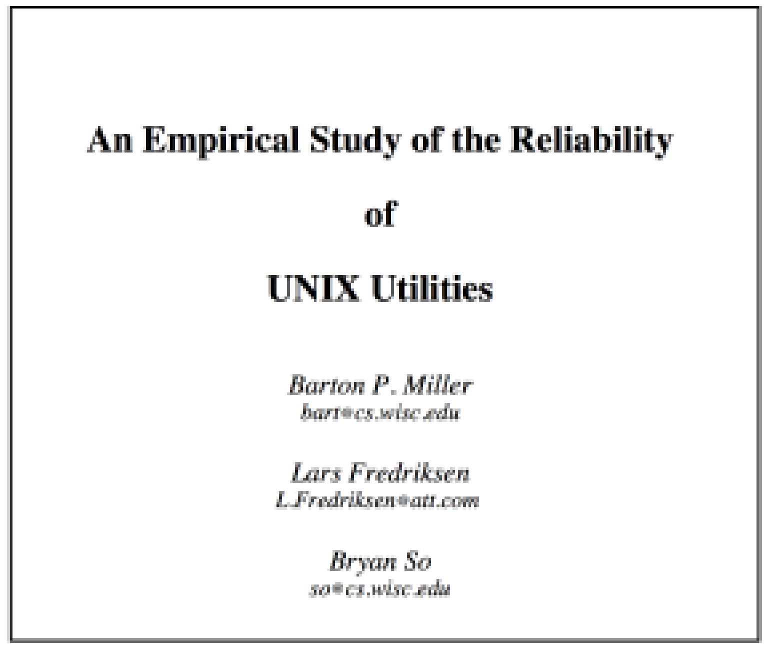

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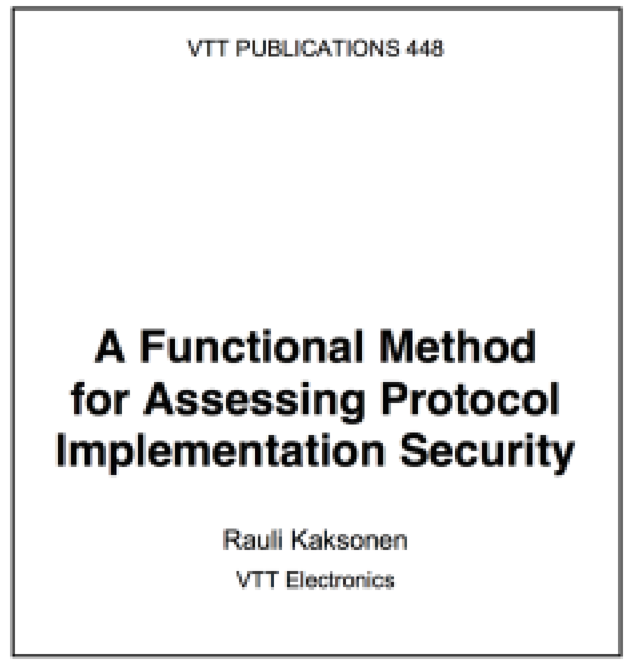

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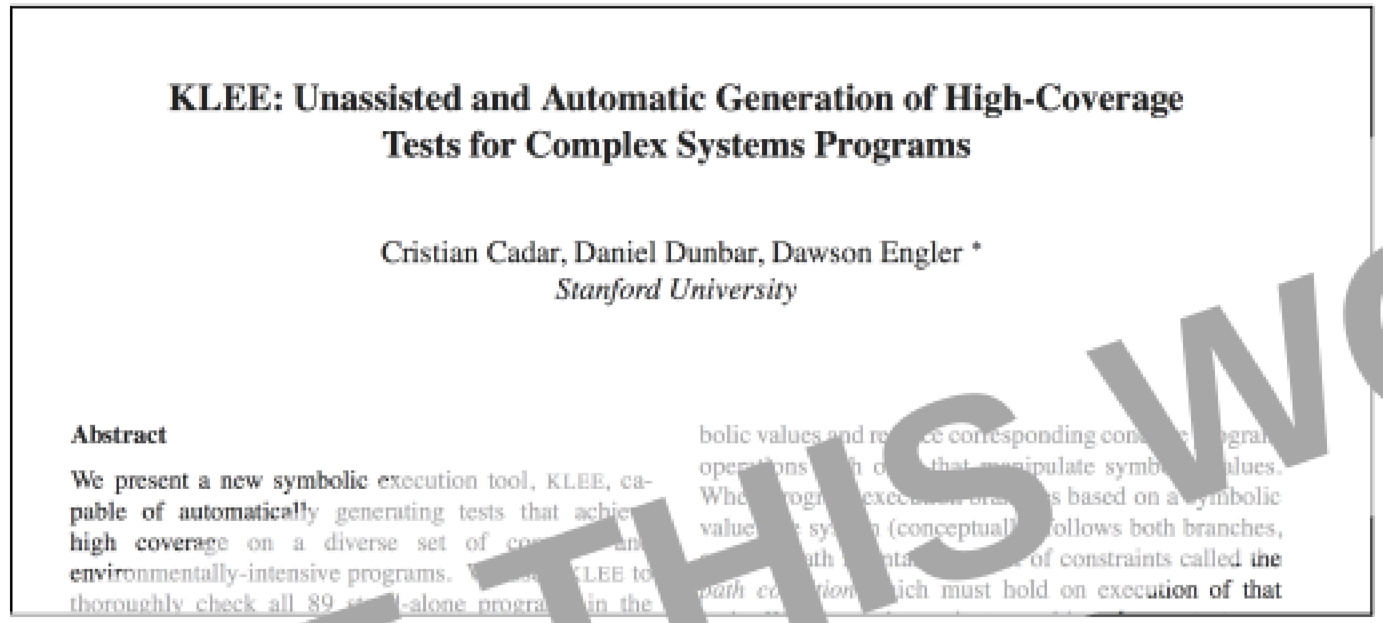

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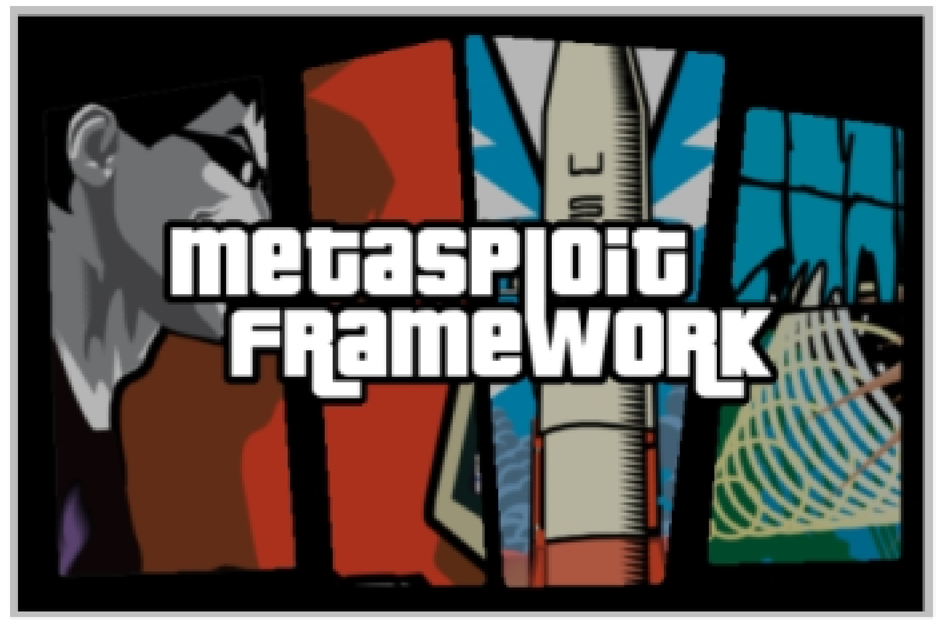

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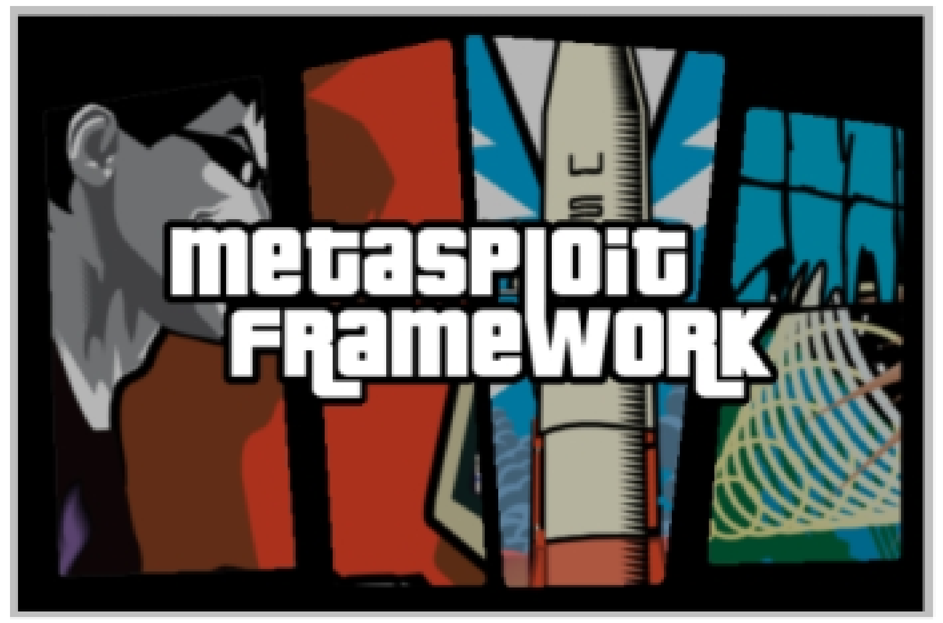

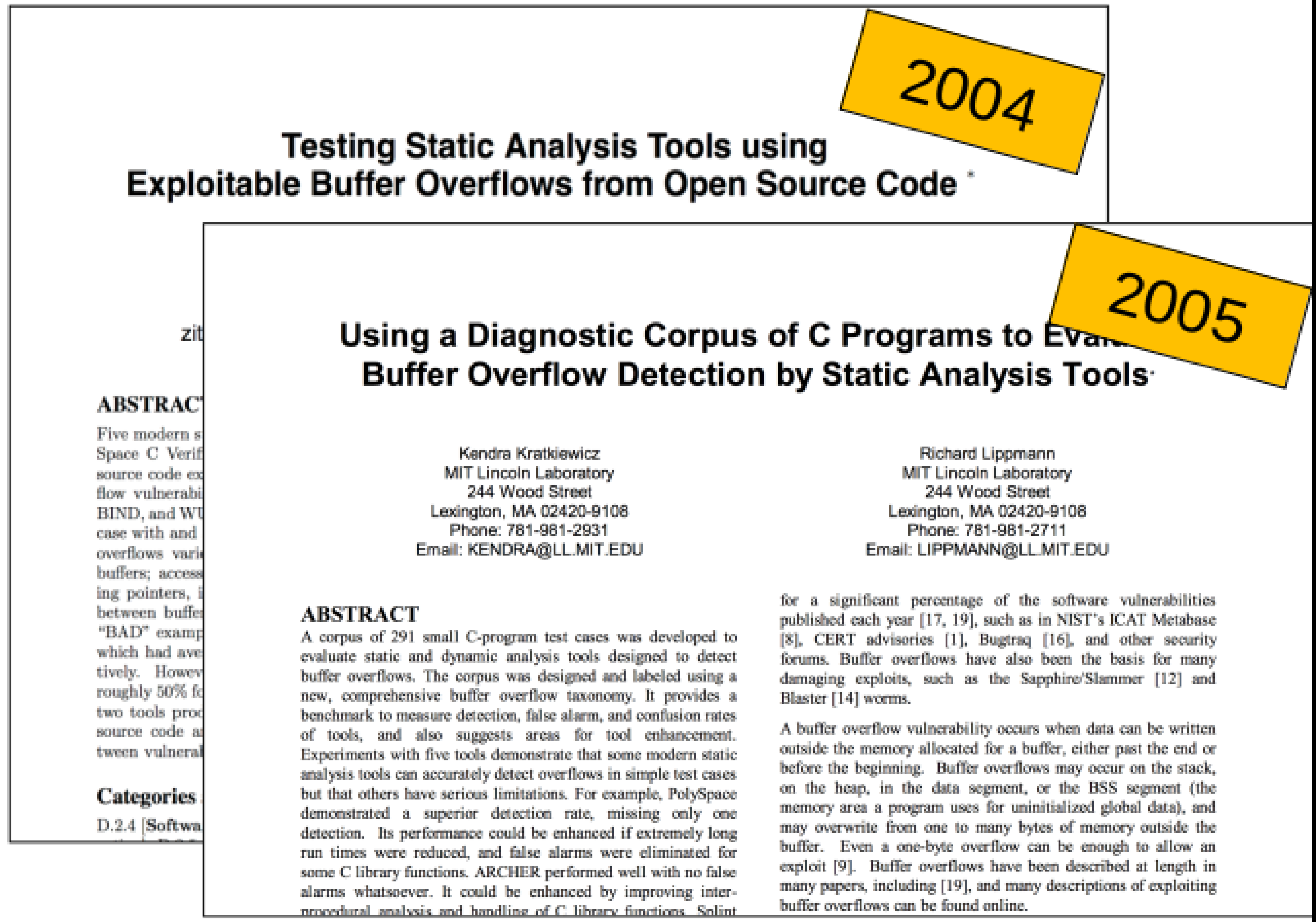

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MIT Lincoln Laboratory
244 Wood Street
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ABSTRACT

A corpus of 291 small C-program test cases was developed to evaluate static and dynamic analysis tools designed to detect buffer overflows. The corpus was designed and labeled using a new, comprehensive buffer overflow taxonomy. It provides a benchmark to measure detection, false alarm, and confusion rates of tools, and also suggests areas for tool enhancement. Experiments with five tools demonstrate that some modern static analysis tools can accurately detect overflows in simple test cases but that others have serious limitations. For example, PolySpace demonstrated a superior detection rate, missing only one detection. Its performance could be enhanced if extremely long run times were reduced, and false alarms were eliminated for some C library functions. ARCHER performed well with no false alarms whatsoever. It could be enhanced by improving inter-procedural analysis and handling of C library functions. Splint

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A buffer overflow vulnerability occurs when data can be written outside the memory allocated for a buffer, either past the end or before the beginning. Buffer overflows may occur on the stack, on the heap, in the data segment, or the BSS segment (the memory area a program uses for uninitialized global data), and may overwrite from one to many bytes of memory outside the buffer. Even a one-byte overflow can be enough to allow an exploit [9]. Buffer overflows have been described at length in many papers, including [19], and many descriptions of exploiting buffer overflows can be found online.

Existing vulnerability corpora

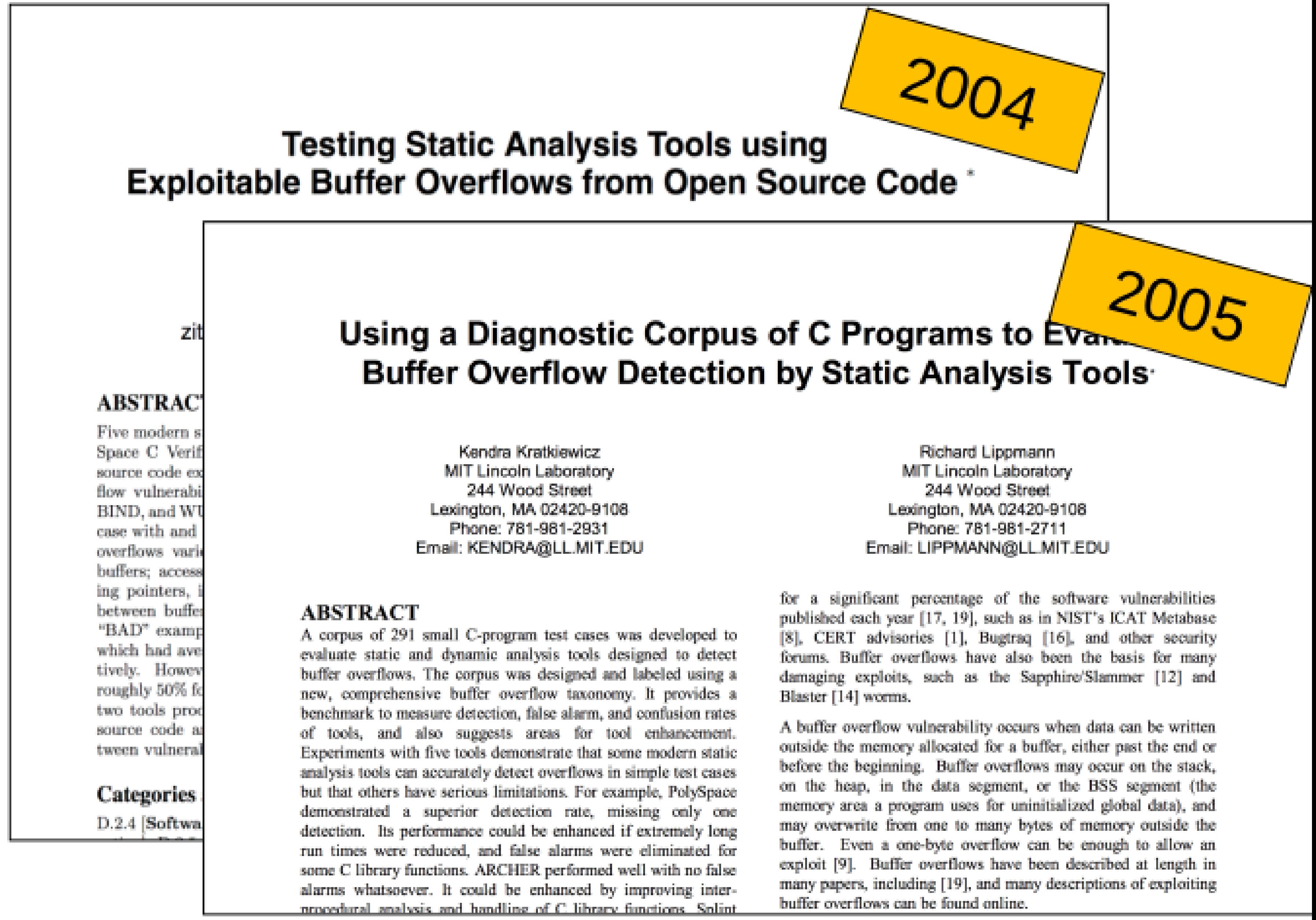
National Vulnerability Database
nvd.nist.gov

CVE

SAMATE
NIST
National Institute of Standards and Technology

EXPLOIT DATABASE

metasploit FRAMEWORK



2004

Testing Static Analysis Tools using
Exploitable Buffer Overflows from Open Source Code *

zit

ABSTRACT

Five modern s
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Categories

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2005

Using a Diagnostic Corpus of C Programs to Eval
Buffer Overflow Detection by Static Analysis Tools *

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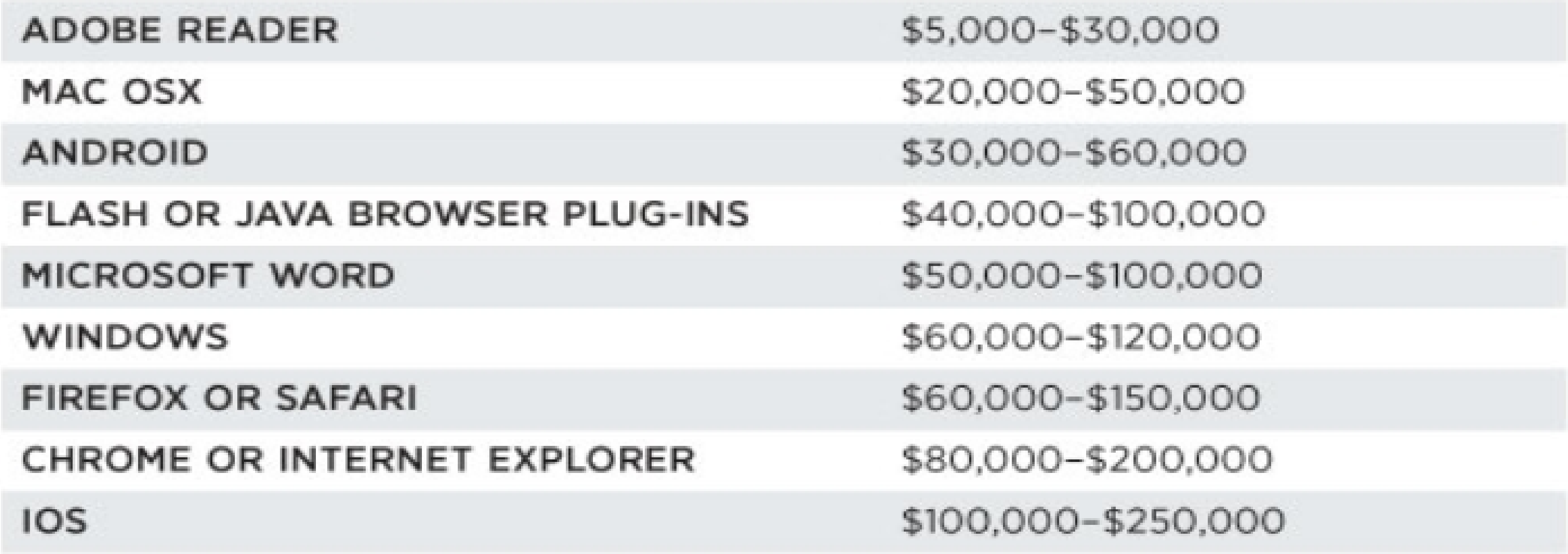
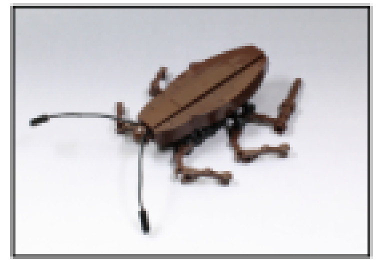


ADOBE READER	$5,000–$30,000
MAC OSX	$20,000–$50,000
ANDROID	$30,000–$60,000
FLASH OR JAVA BROWSER PLUG-INS	$40,000–$100,000
MICROSOFT WORD	$50,000–$100,000
WINDOWS	$60,000–$120,000
FIREFOX OR SAFARI	$60,000–$150,000
CHROME OR INTERNET EXPLORER	$80,000–$200,000
IOS	$100,000–$250,000

Forbes, 2012

Vulnerability corpora sources

Source	Cost	Realism	Yield
Accident		High	Tiny
Search	$$$$	Med-High	Low
Injection	$$	Med	Low-Med
Synthesis	$	Low	High



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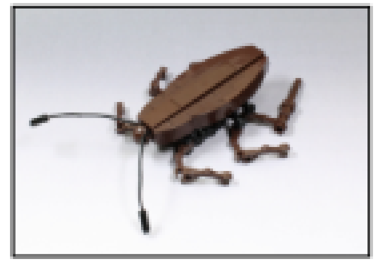

LAVA

LAVA concept

- **Vulnerability corpus requirements**
  - ❑ **Cheap and plentiful**
  - ❑ **Realistic**
  - ❑ **Triggering input**
  - ❑ **Manifest only for one or very few inputs**
  - ❑ **Security-critical effect**

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- Caveats
  - Works only on source
  - C programs
  - Linux
  - Buffer overflows

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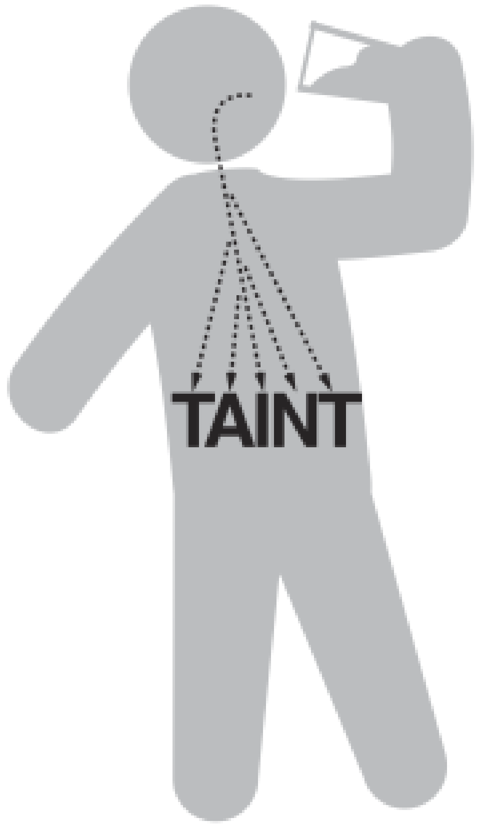
- Caveats
  - Works only on source
  - C programs
  - Linux
  - Buffer overflows

- Large-scale Automated Vulnerability Addition
  - Uses static and dynamic analysis to find attacker-controlled data that can be used to introduce new code that creates a bug
  - Change program and input at same time to insert bugs in known places
  - Special sauce: new taint-based measures

Dynamic taint analysis

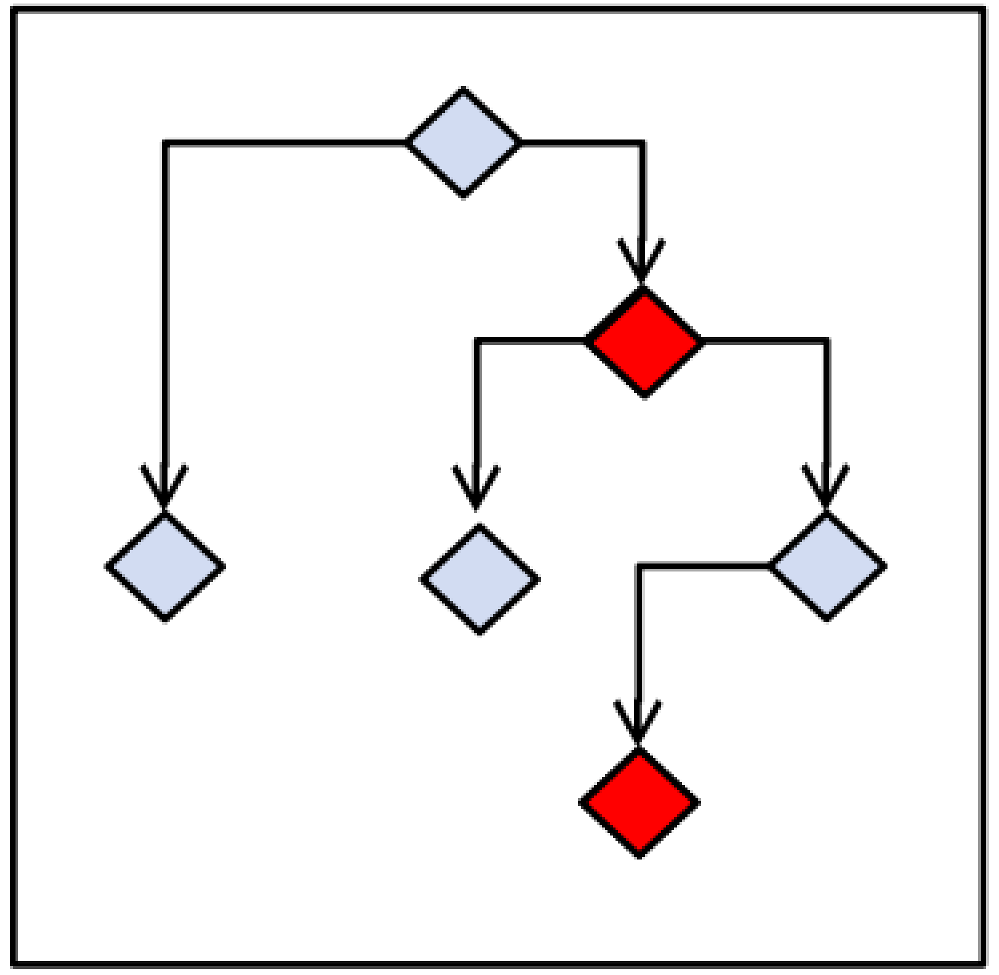
- **PANDA dynamic taint**
  - **Whole system (all processes + kernel)**
  - **Works on binaries**
  - **Includes all library code**
  - **Oddball x86 instructions all analyzed including FPU and SSE**
  - **Many labels supported: Every byte in 10MB file**
  - **Labels combine into sets to represent computation**
  - **Fast (enough). 50-100x**



https://github.com/panda-re

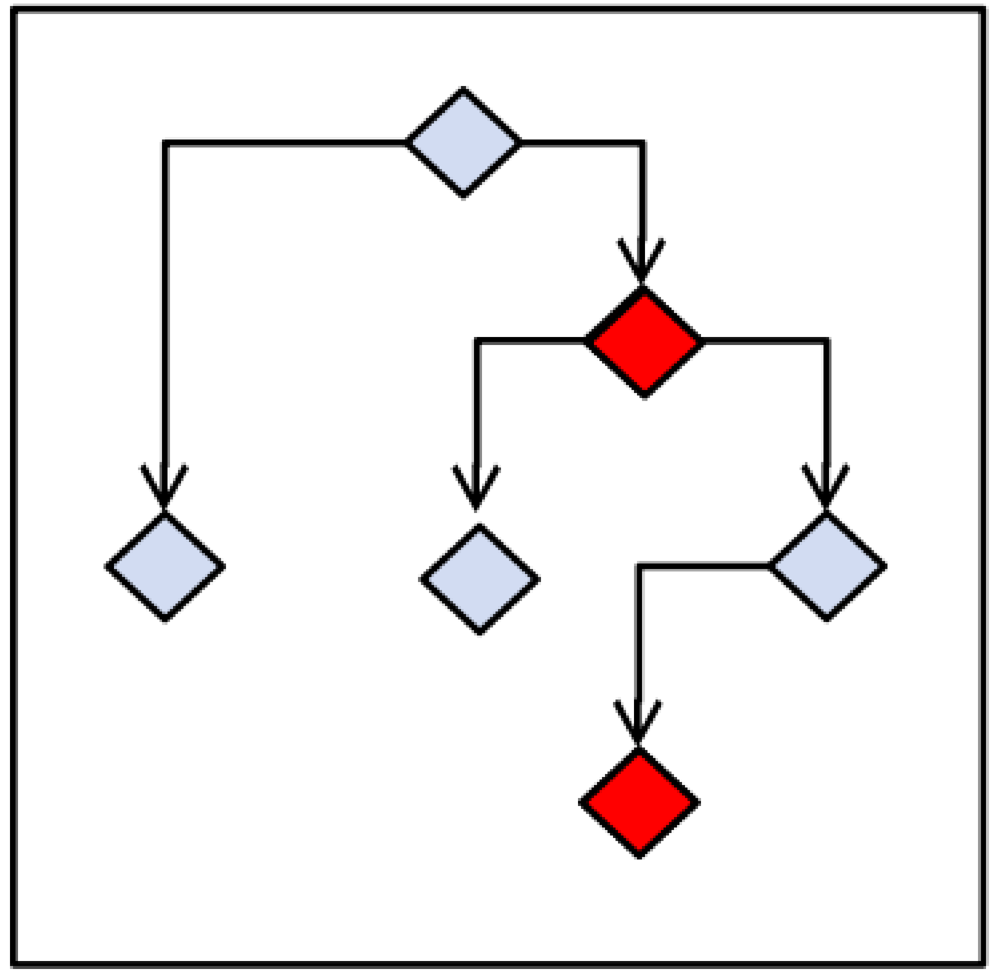
Taint-based measures

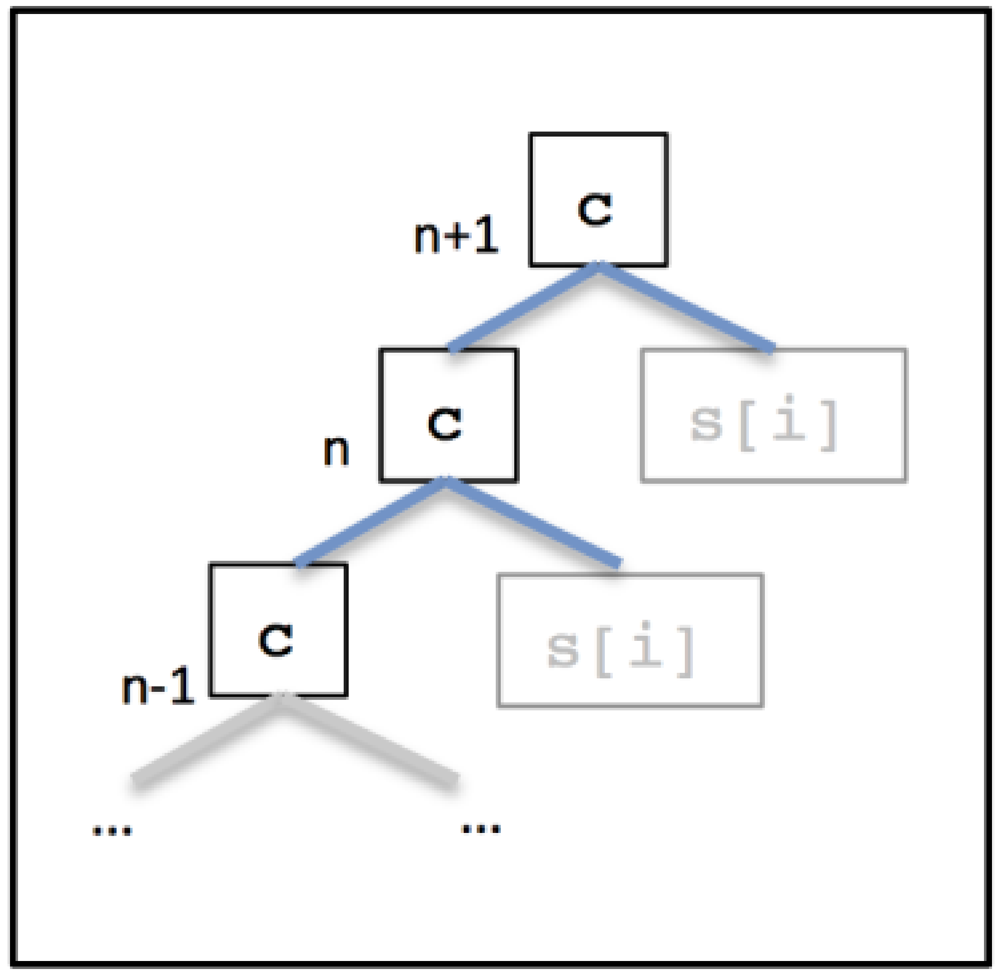
Taint-based measures



Liveness:
Number of branches an input byte is used to decide.
How much effect upon control flow do specific input bytes have?

Taint-based measures





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How complicated a function of input bytes is an lval?

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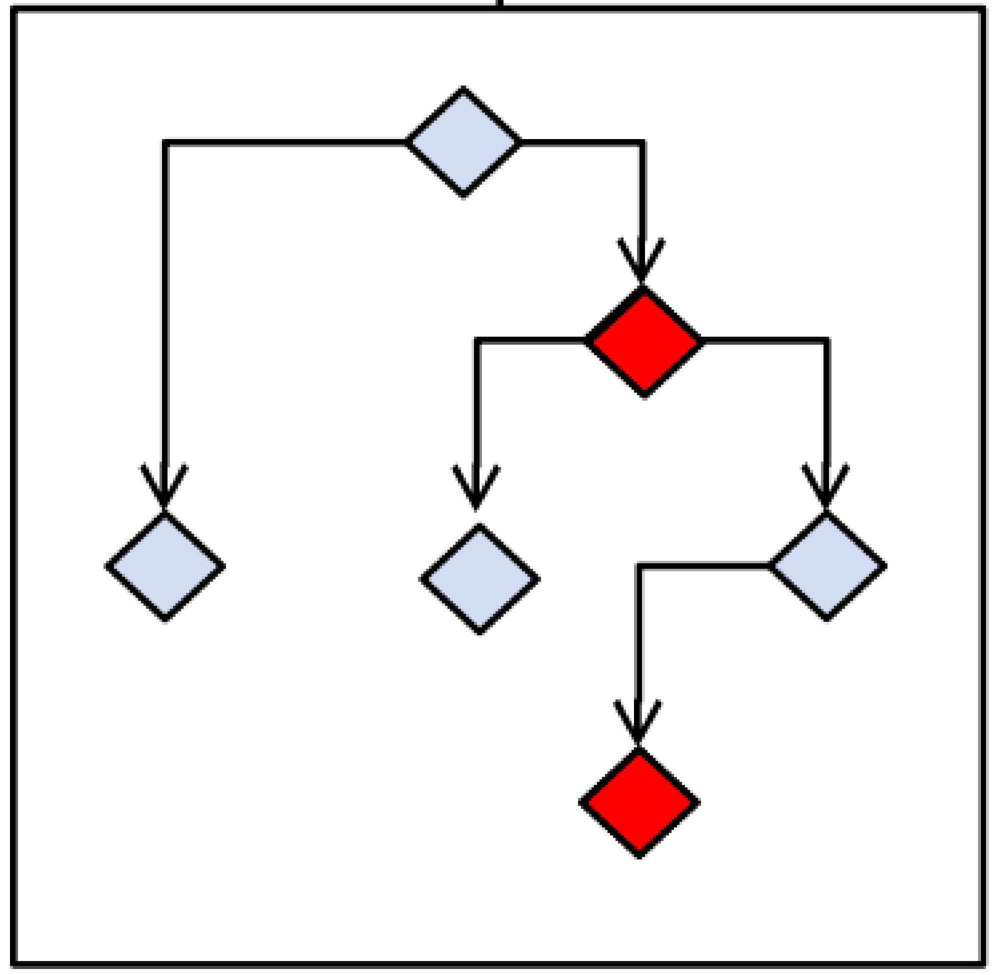

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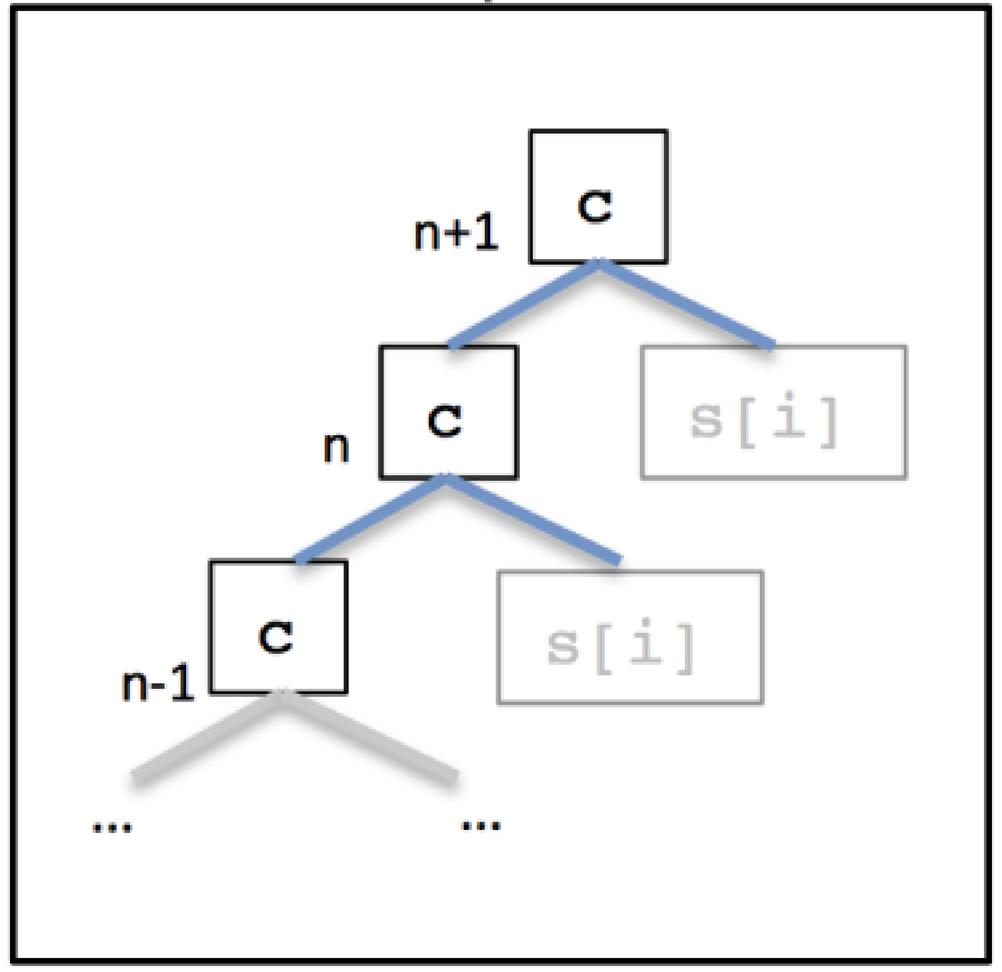
DEAD, UNCOMPLICATED, and AVAILABLE data (DUA)

Attacker-controlled data that can be used to create a vulnerability



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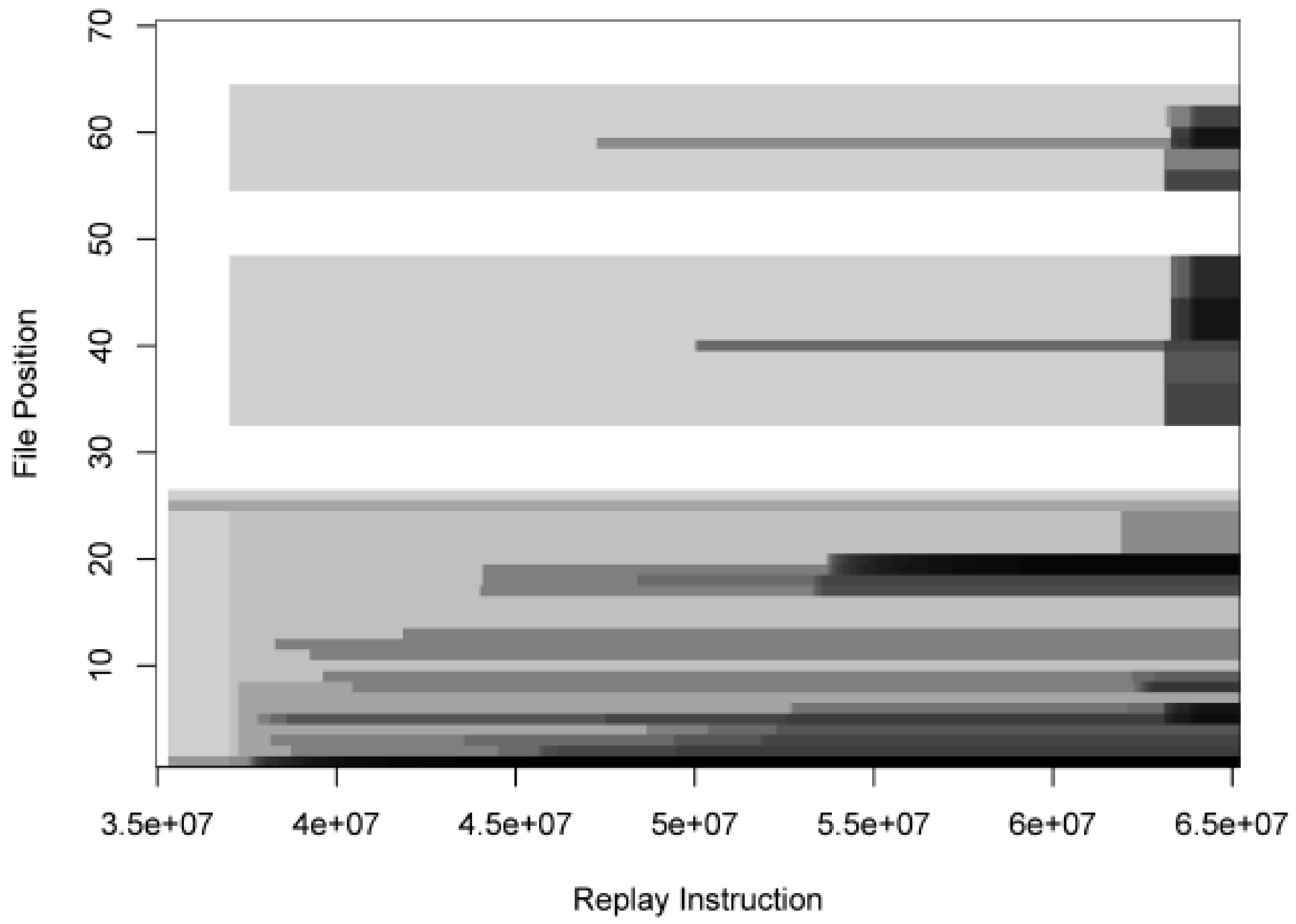

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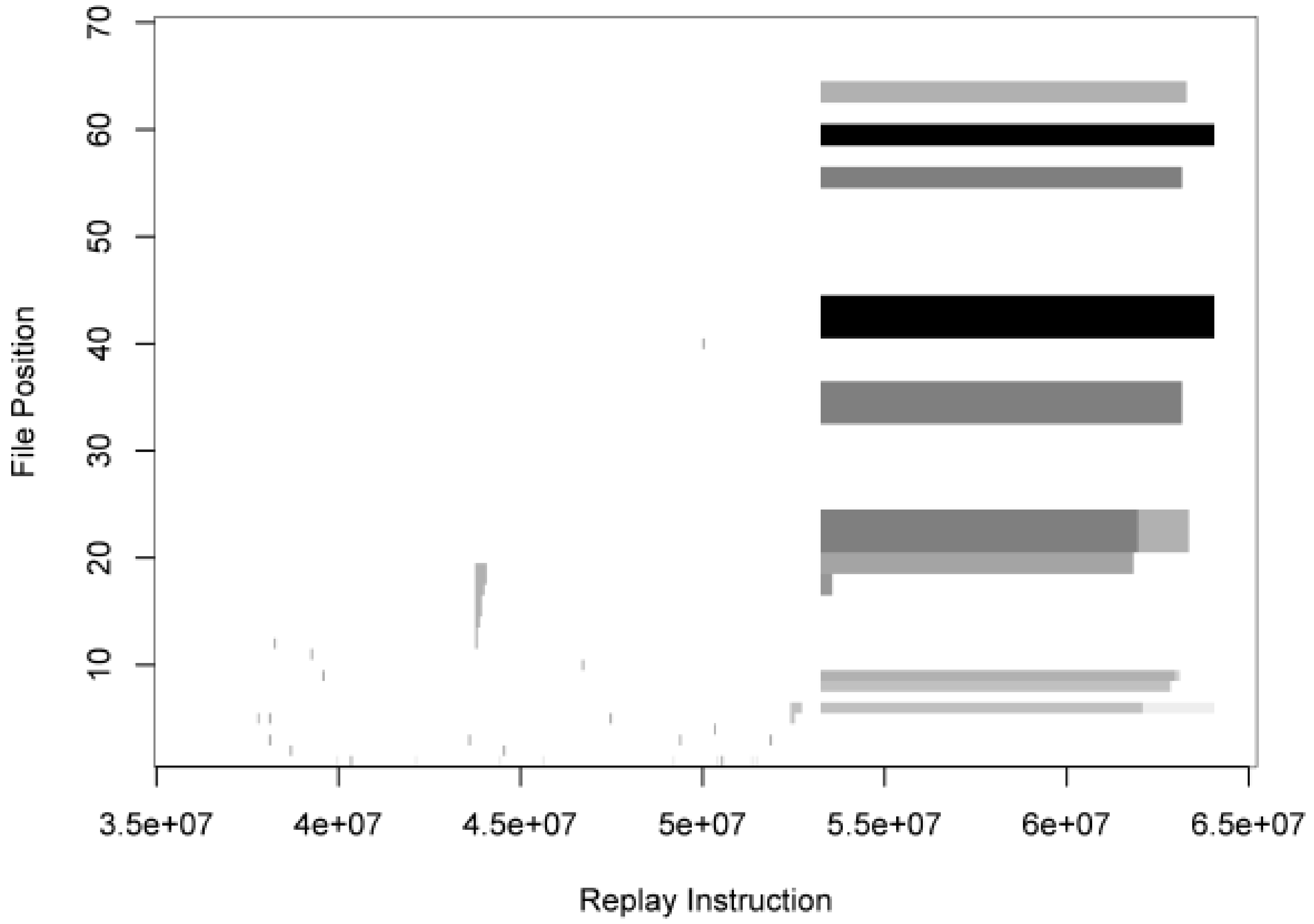

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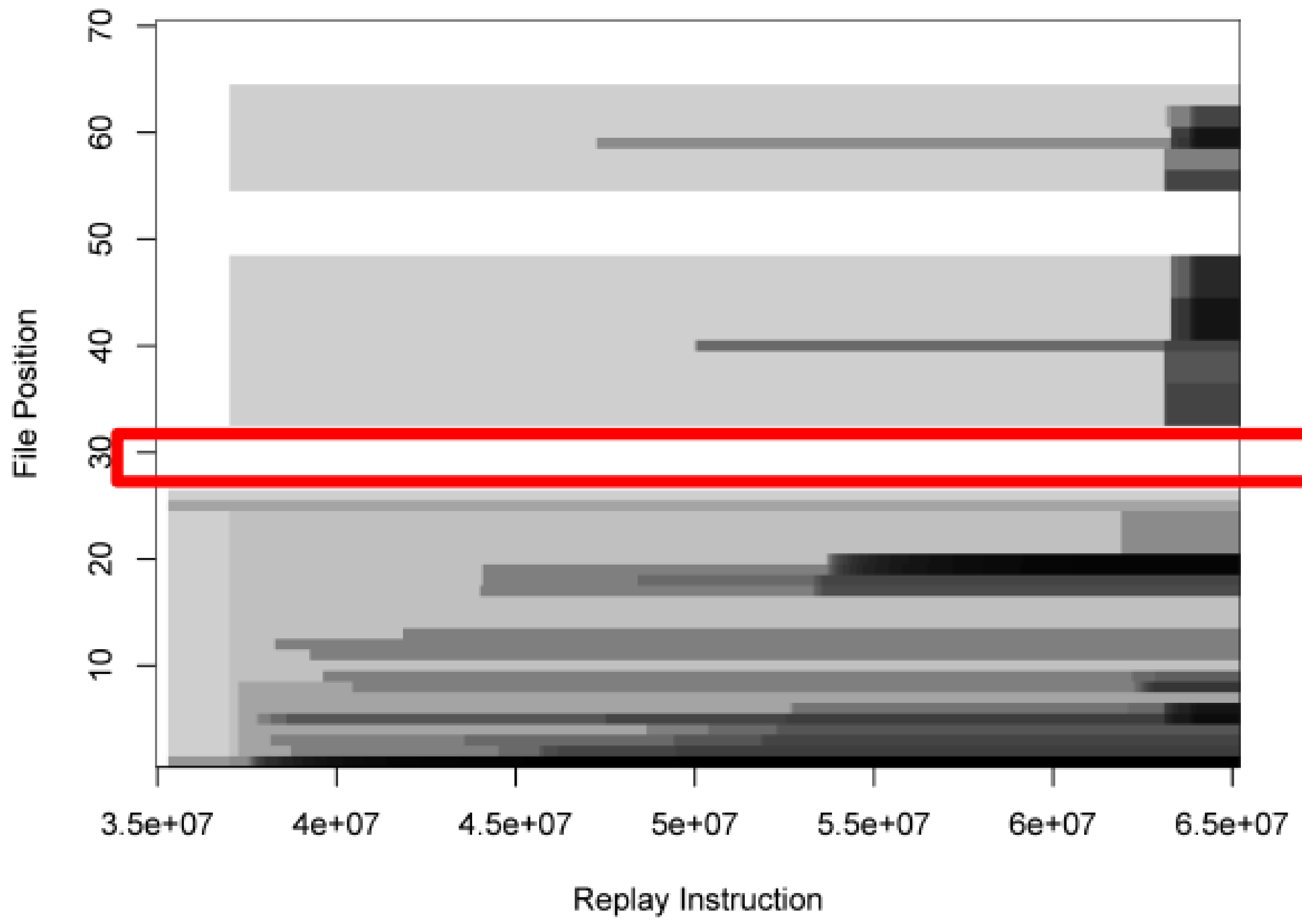

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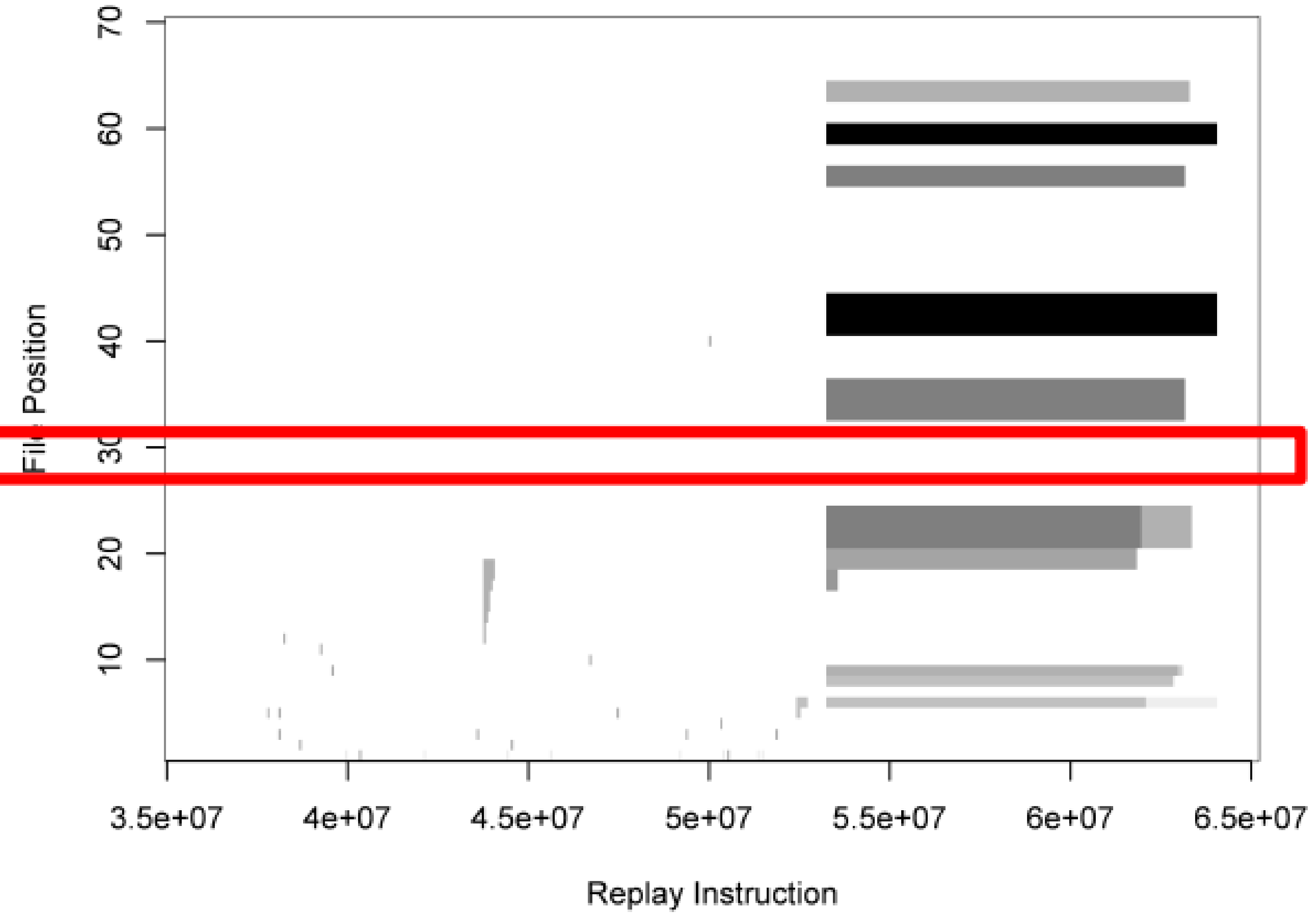

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LAVA Taint-based bug injection

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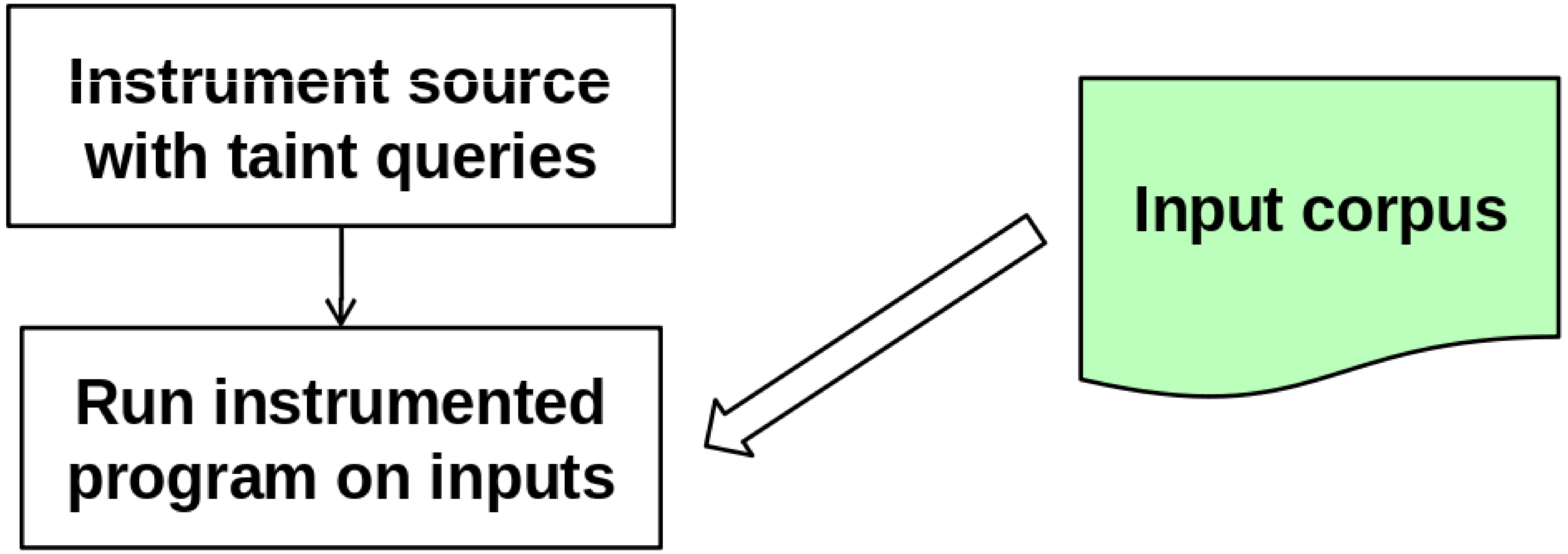
Clang

Instrument source
with taint queries

LAVA Taint-based bug injection

Clang

PANDA record

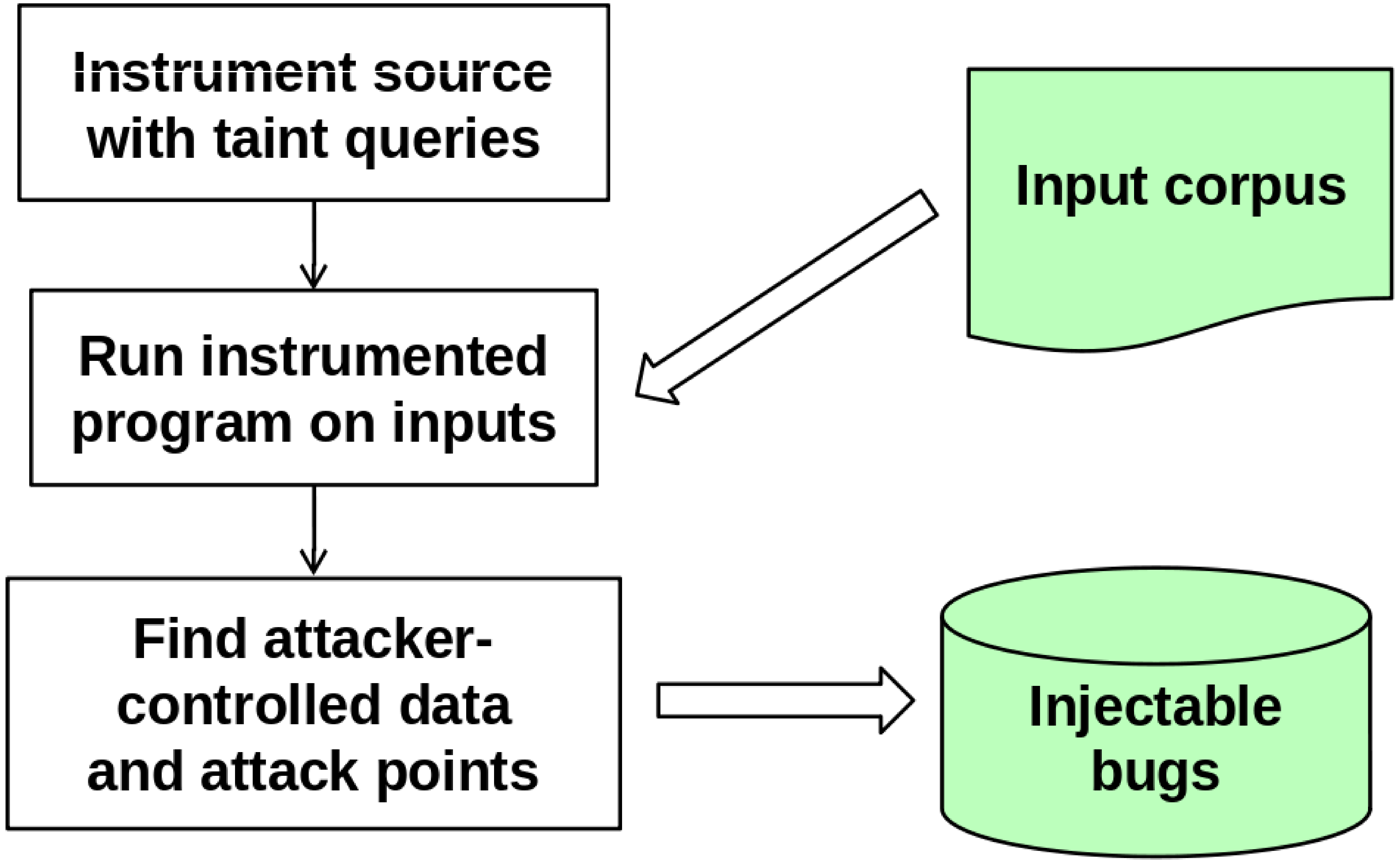


~~Instrument source~~ with taint queries

Run instrumented program on inputs

Input corpus

LAVA Taint-based bug injection



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PANDA replay + taint analysis

Find attacker-controlled data and attack points

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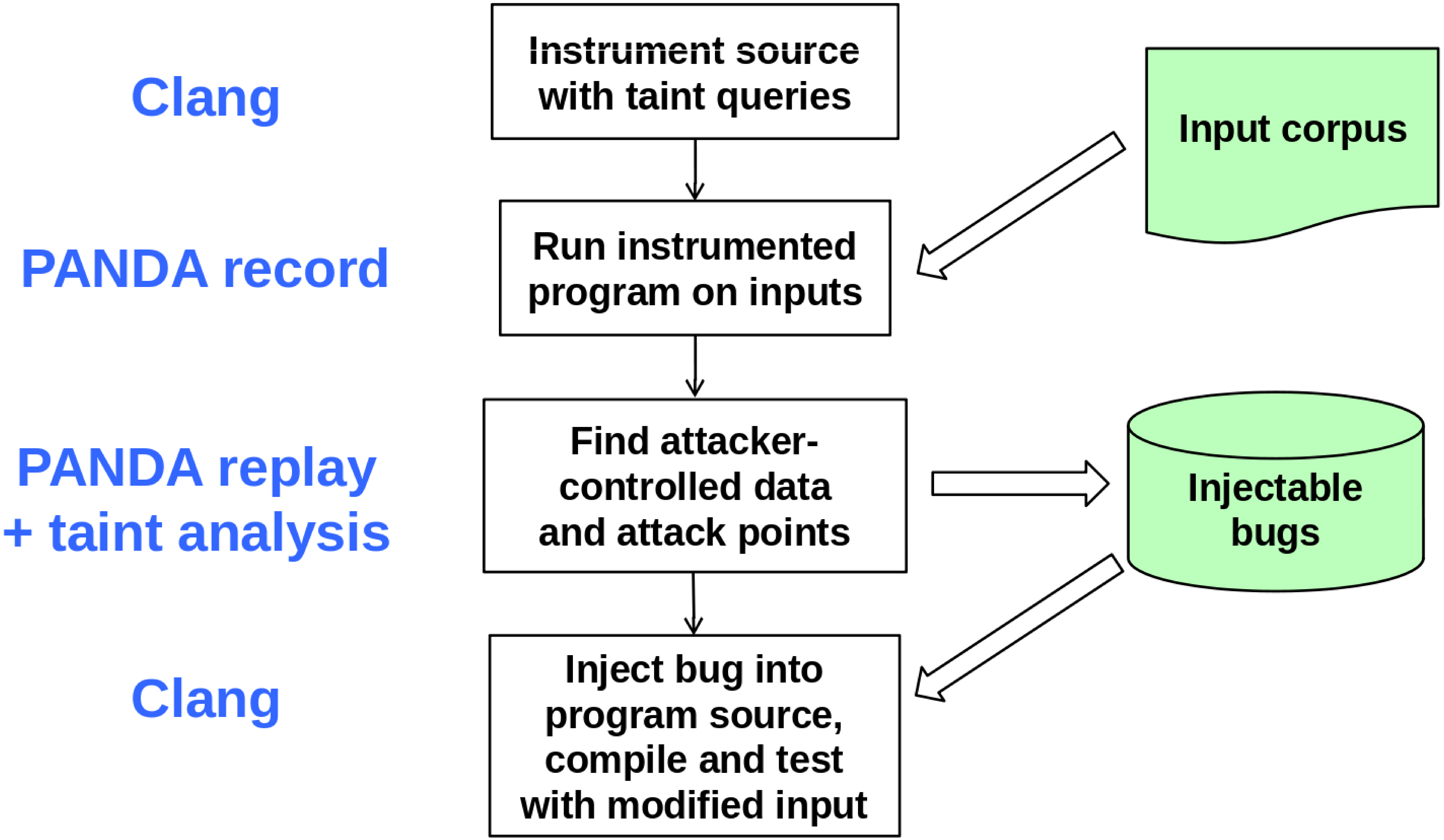

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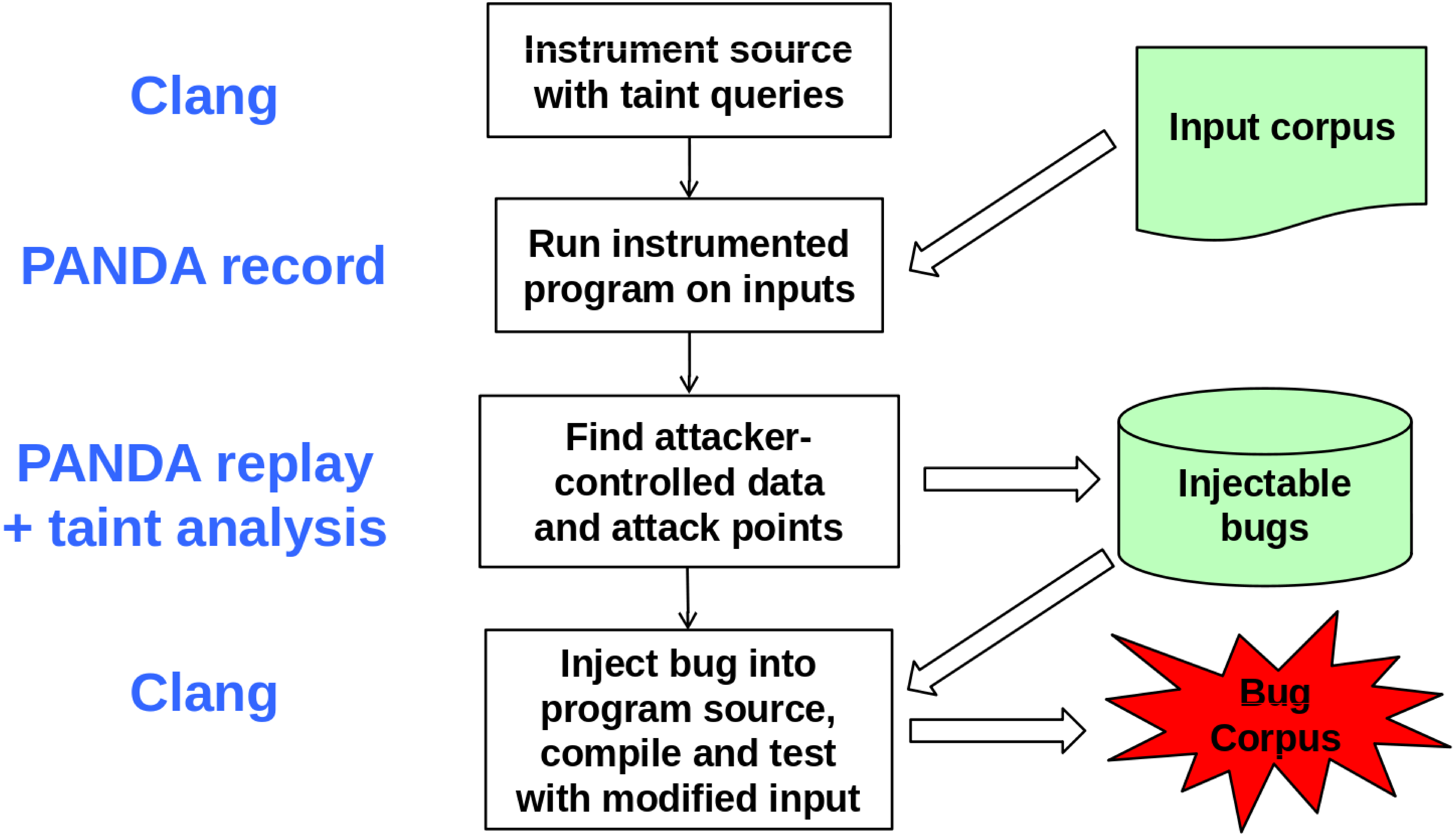

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encoding.c 115: } else if (looks_extended(buf, nbytes,
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- PANDA taint analysis tells us that bytes 0-3 in the buffer `buf` at line 115 of `src/encoding.c` is attacker-controlled
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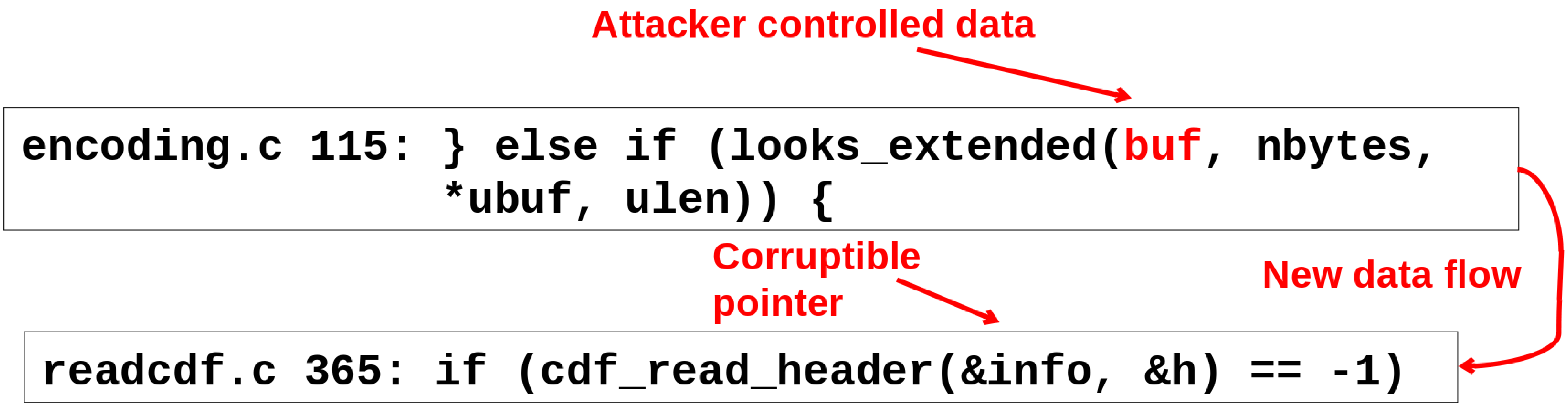

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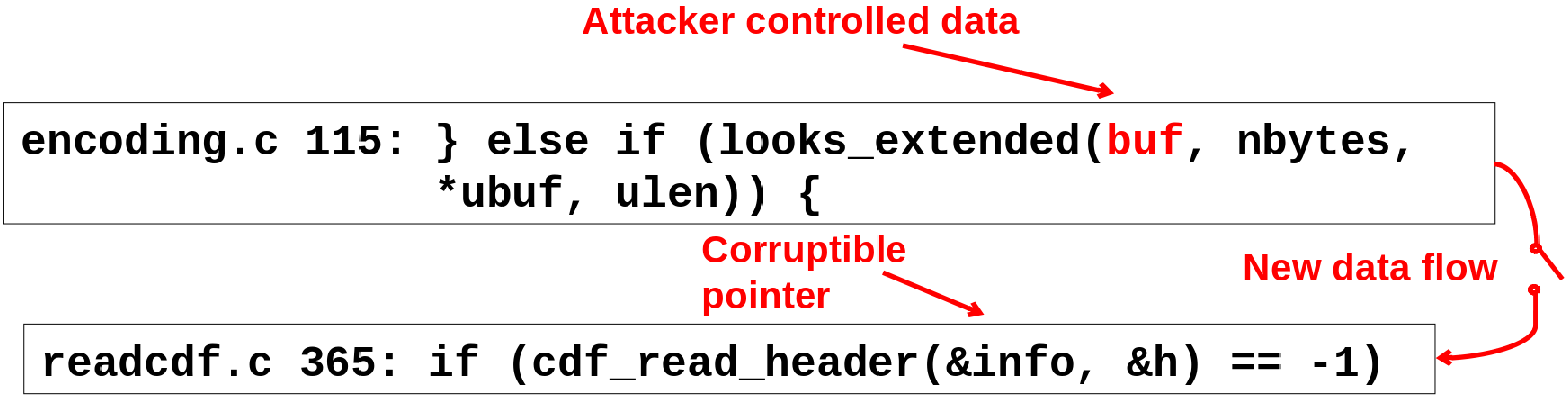

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```
// encoding.c:
} else if
  (({int rv =
       looks_extended(buf, nbytes, *ubuf, ulen);
     if (buf) {
       int lava = 0;
       lava |= ((unsigned char *)buf)[0];
       lava |= ((unsigned char *)buf)[1] << 8;
       lava |= ((unsigned char *)buf)[2] << 16;
       lava |= ((unsigned char *)buf)[3] << 24;
       lava_set(lava);
    }; rv; })) {
```

```
// readcdf.c:
if (cdf_read_header
    ((&info) + (lava_get()) *
      (0x6c617661 == (lava_get()) || 0x6176616c == (lava_get())),
       &h) == -1)
```

Vulnerability injection effectiveness

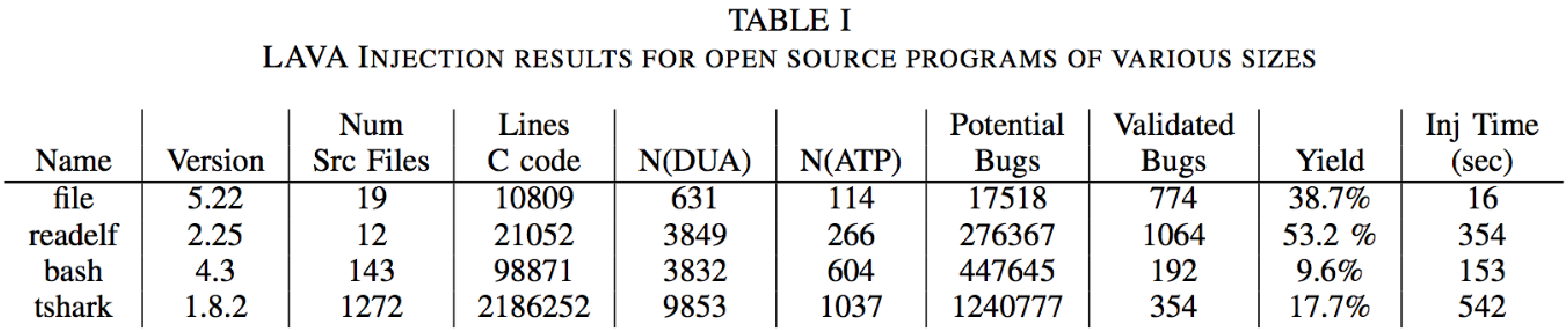
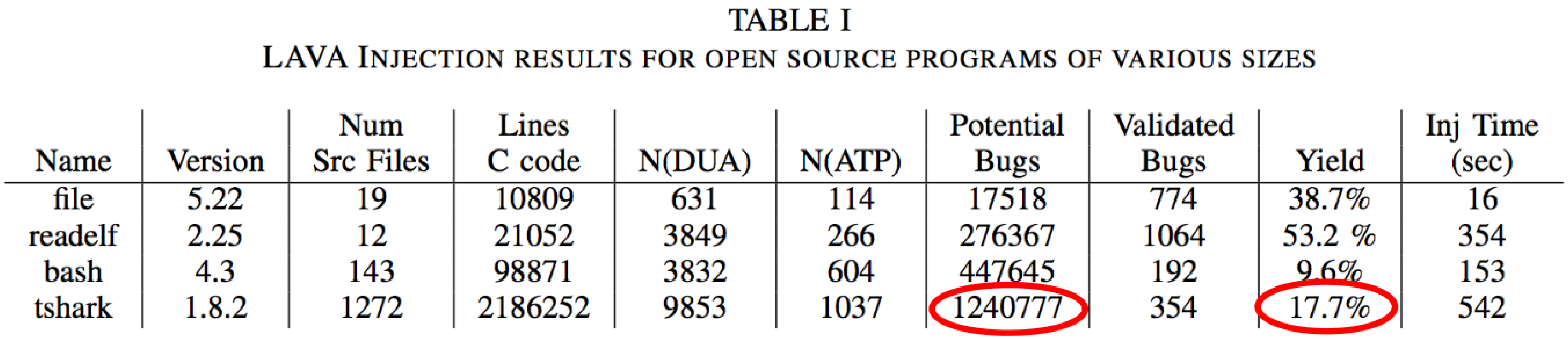


TABLE I
LAVA INJECTION RESULTS FOR OPEN SOURCE PROGRAMS OF VARIOUS SIZES

Name	Version	Num Src Files	Lines C code	N(DUA)	N(ATP)	Potential Bugs	Validated Bugs	Yield	Inj Time (sec)
file	5.22	19	10809	631	114	17518	774	38.7%	16
readelf	2.25	12	21052	3849	266	276367	1064	53.2 %	354
bash	4.3	143	98871	3832	604	447645	192	9.6%	153
tshark	1.8.2	1272	2186252	9853	1037	1240777	354	17.7%	542

- Four open source programs 10K -> 2M LOC
- 2000 injection attempts per target (of over 1M)
- LAVA yield (validated injected bugs): 10->50%
- Over 2000 bugs injected

Vulnerability injection effectiveness



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Over 200K possible?

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Using LAVA to evaluate tools

- Created two corpora using LAVA
  - LAVA-1 programs containing individual bugs of varying difficulty
  - LAVA-M programs each with more than one bug

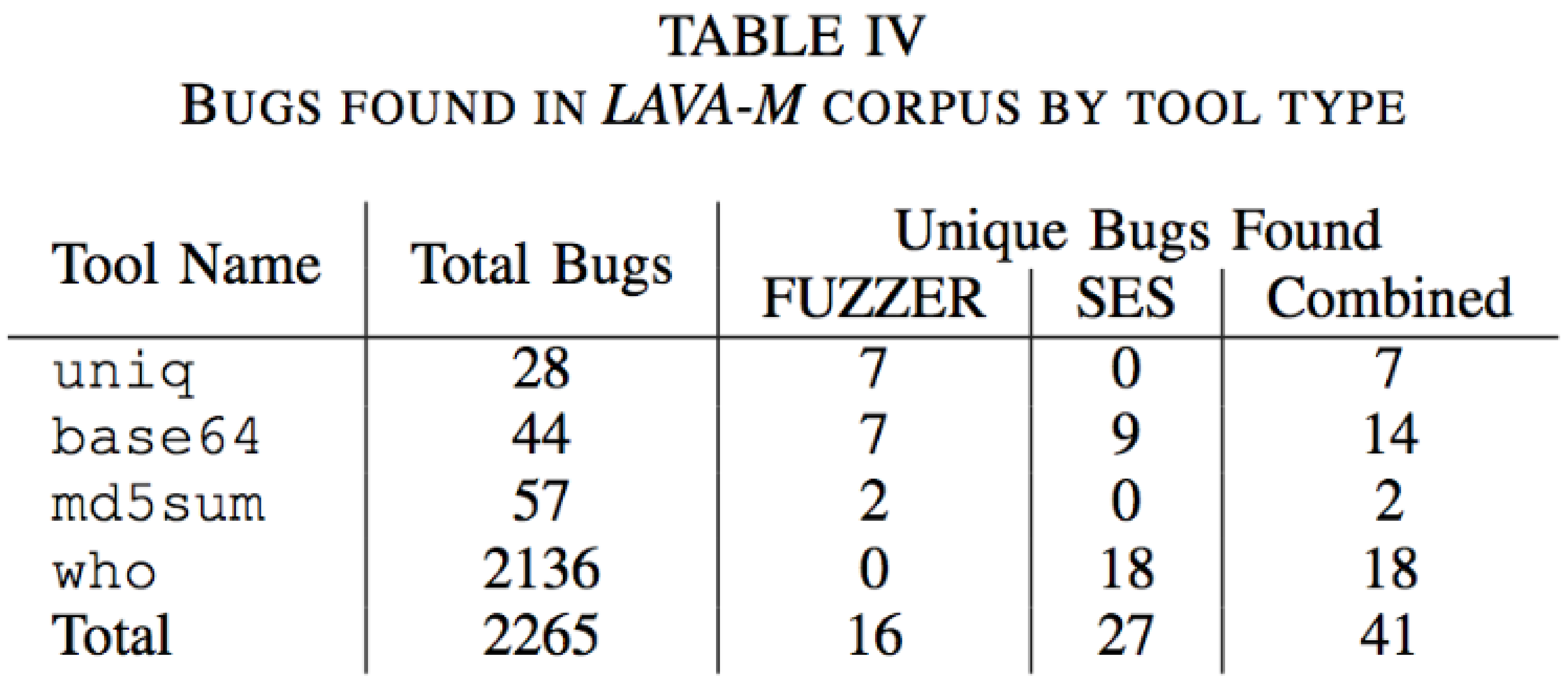

TABLE IV
BUGS FOUND IN *LAVA-M* CORPUS BY TOOL TYPE

Tool Name	Total Bugs	Unique Bugs Found		
		FUZZER	SES	Combined
`uniq`	28	7	0	7
`base64`	44	7	9	14
`md5sum`	57	2	0	2
`who`	2136	0	18	18
Total	2265	16	27	41

- Evaluated two open-source vulnerability discovery tools by ability to detect LAVA bugs
  - Fuzzer
  - Symbolic execution + SAT solving

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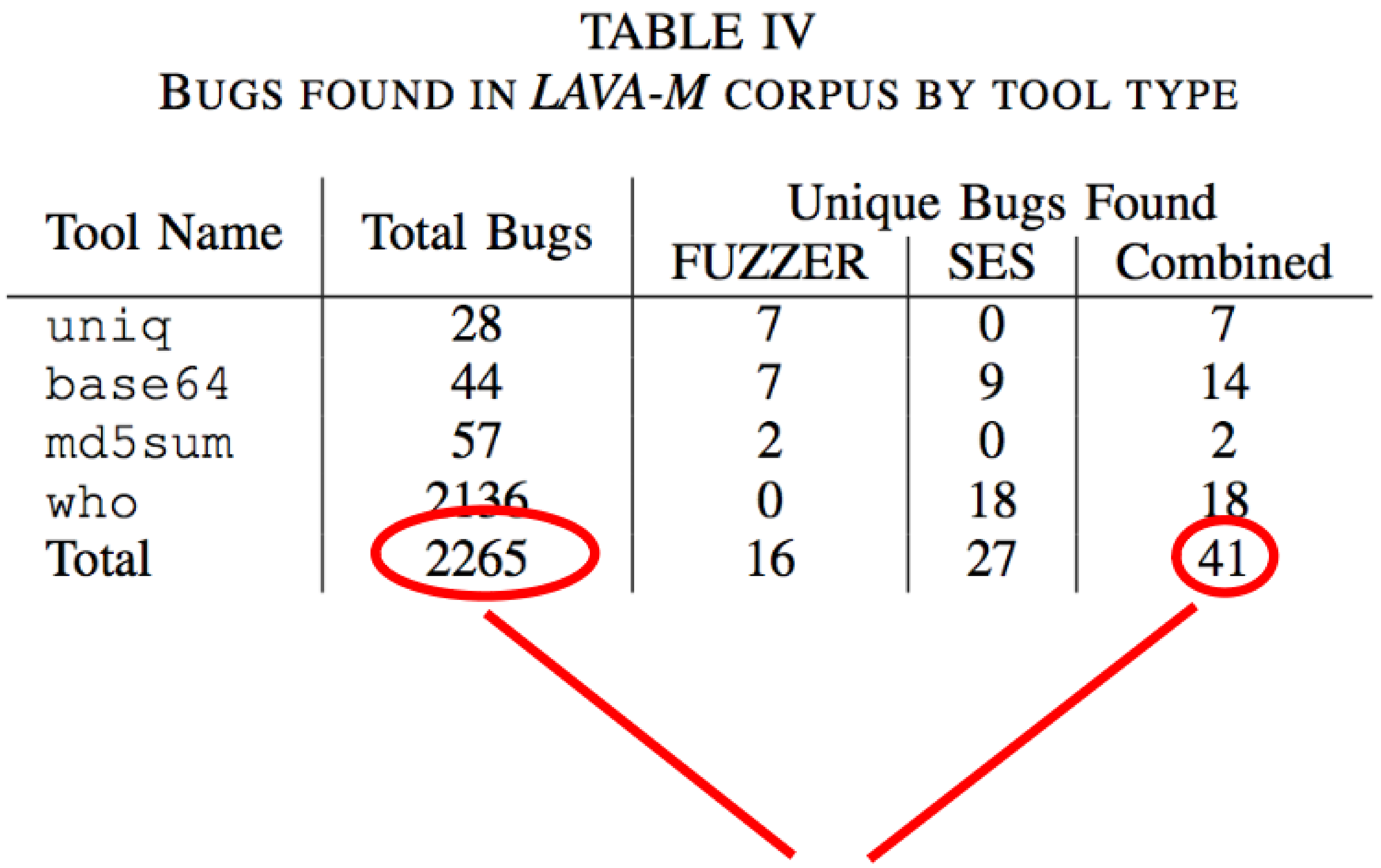

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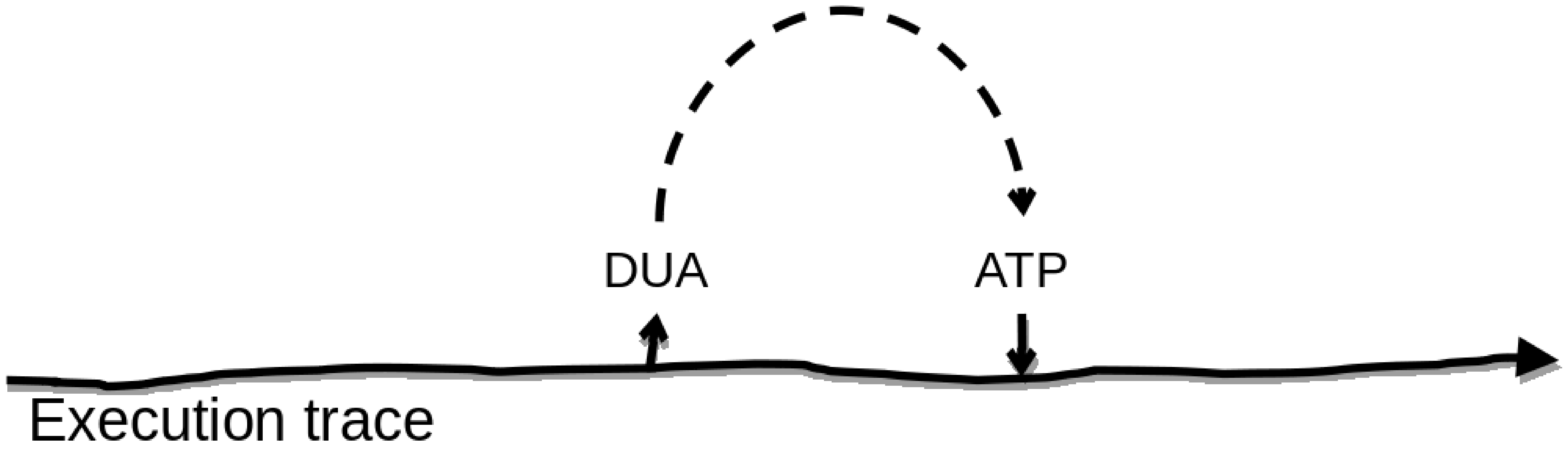
Detection < 2%

LAVA vulnerability realism

Realism is a concern. But hard to quantify

One possible measure is the fraction of the trace that is unaffected by LAVA yet must be analyzed correctly to discover the vulnerability

LAVA's bugs are inserted, generally quite far along in the trace. If anything we need some easier ones



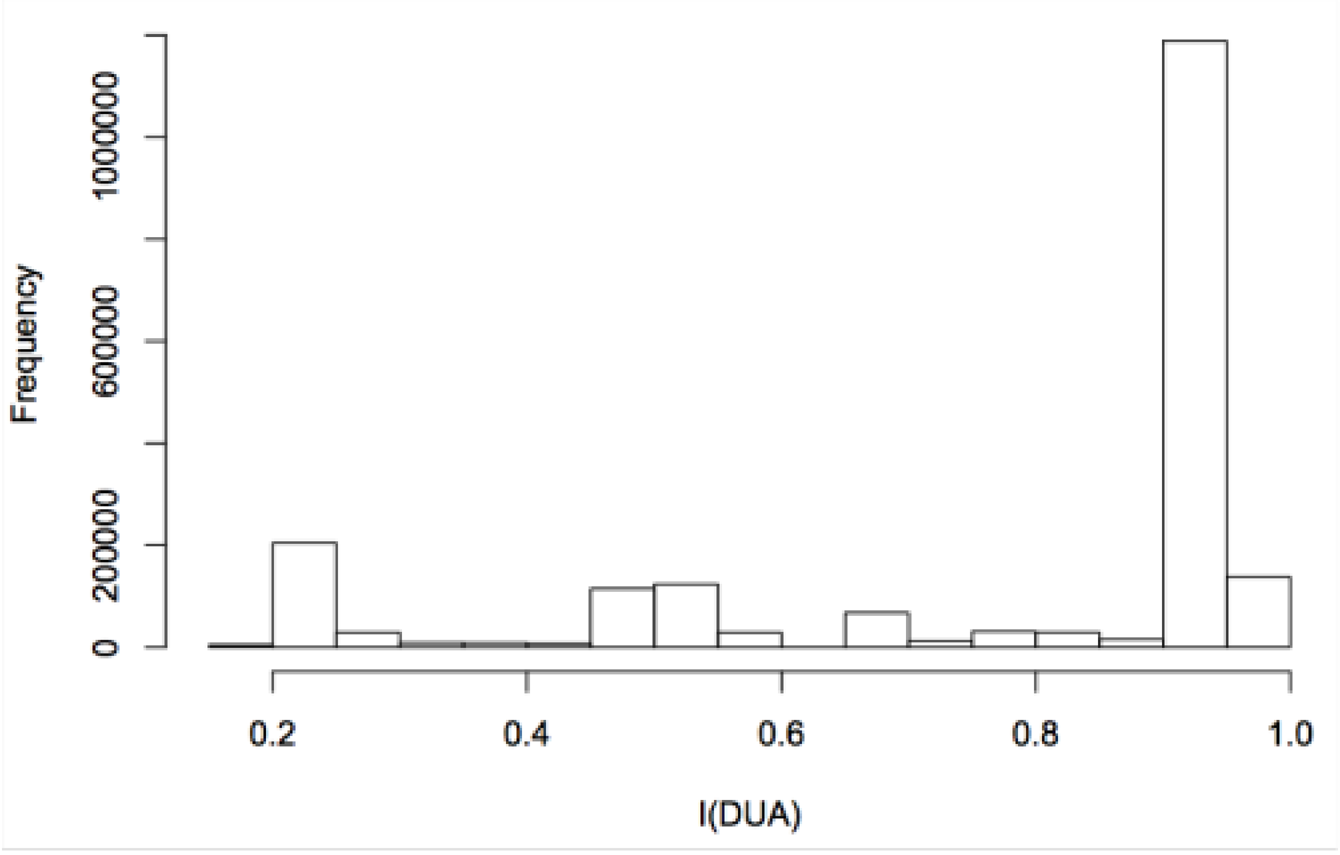


Fig. 8. Normalized DUA trace location

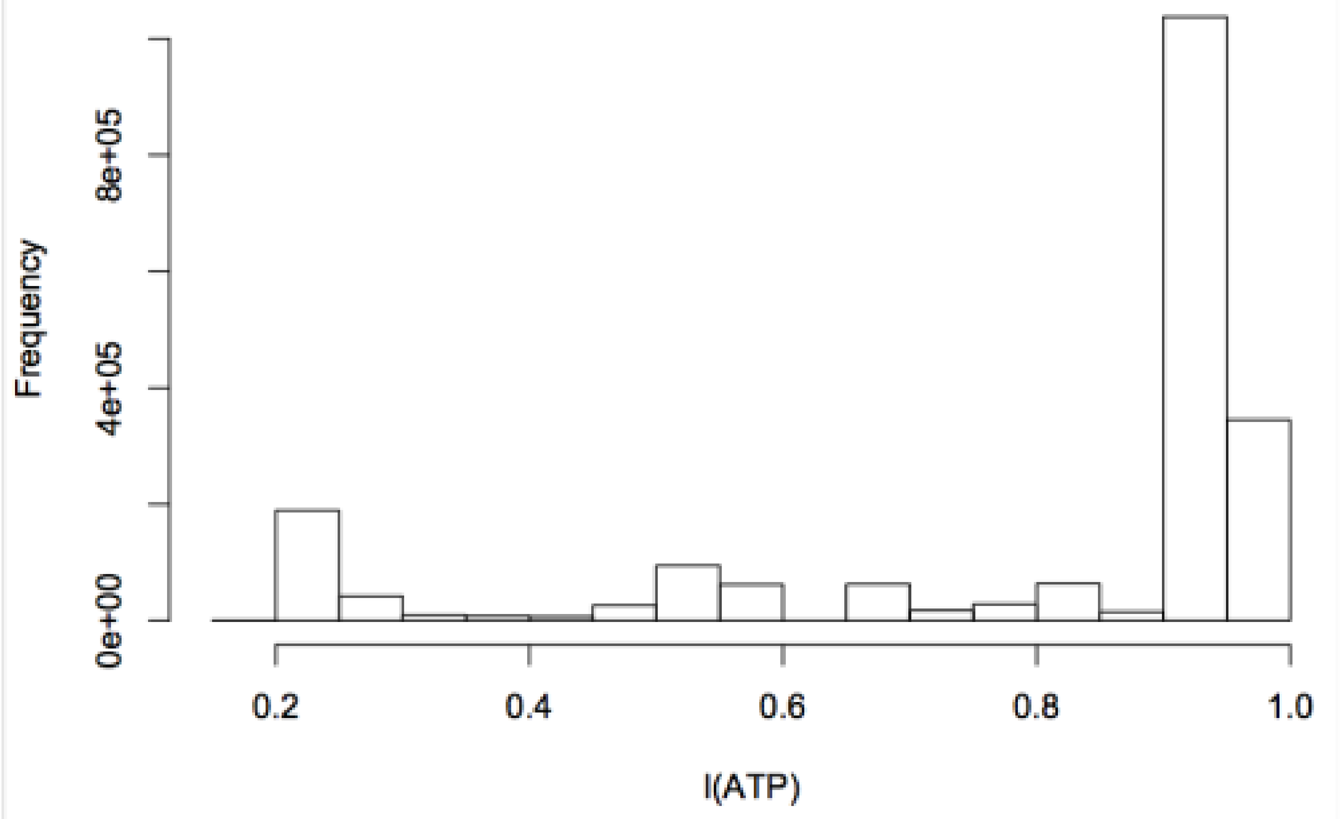


Fig. 9. Normalized ATP trace location

Summary and future directions

- **Summary**
  - **Working system automates construction of large corpora for study and assessments**
  - **Novel taint-based measures are key: liveness and TCN**
- **Future directions**
  - **Continuous on-line competition to encourage self-eval**
  - **Use in security competitions like Capture the Flag to re-use and construct challenges on-the-fly**
  - **Assess and improve realism of LAVA bugs**
  - **More types of vulnerabilities**
  - **More interesting effects (exploitable ones)**