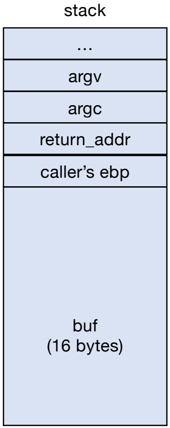
SelectiveTaint: Efficient Data Flow Tracking With Static Binary Rewriting

Sanchuan Chen, Zhiqiang Lin, and Yinqian Zhang

USENIX Security 2021

Dynamic Taint Analysis

```
include <string.h>
void main(int argc, char **argv){
char buf[16];
strcpy(buf, argv[1]);
return;
}
```



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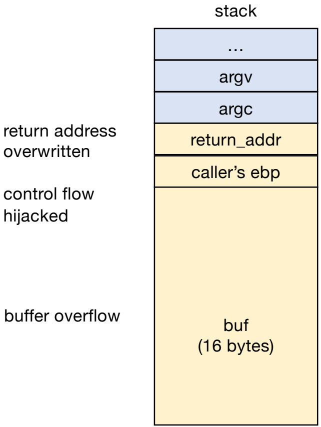


stack

...

argv

argc

return_addr

caller's ebp

buf
(16 bytes)

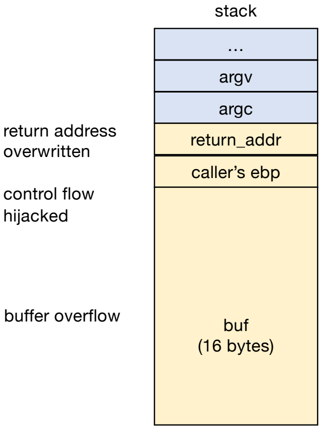
return address
overwritten

control flow
hijacked

buffer overflow

Dynamic Taint Analysis

```
include <string.h>
void main(int argc, char **argv){  <-- Taint Source
char buf[16];
strcpy(buf, argv[1]);            <-- Taint Propagation
return;                          <-- Taint Sink
}
```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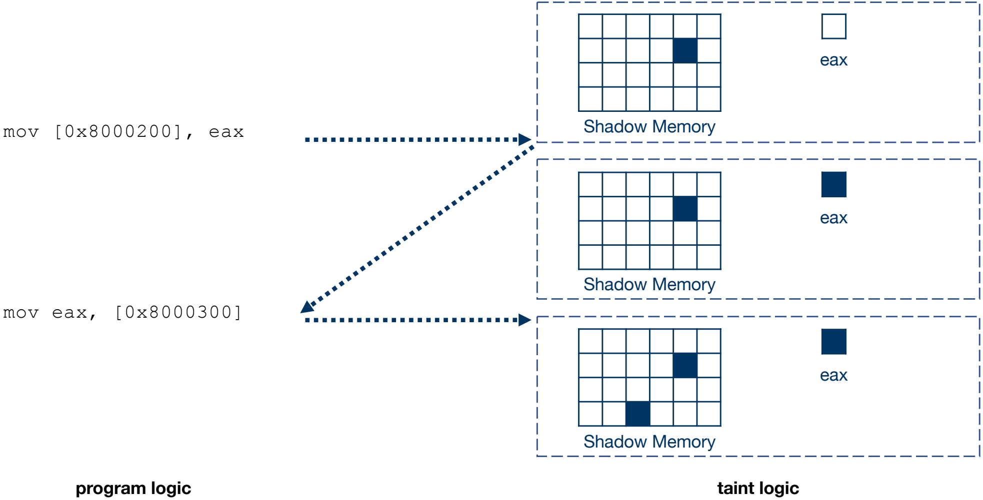

```
mov [0x8000200], eax
```

```
mov eax, [0x8000300]
```

program logic

taint logic

High Performance Overhead

Performance

Dynamic taint analysis frameworks often have a **high performance overhead**, which stop them from deploying in real world computer systems.

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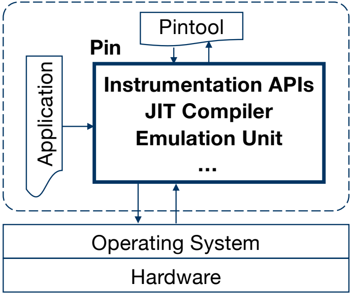
Dynamic taint analysis frameworks often have a **high performance overhead**, which stop them from deploying in real world computer systems.

Example

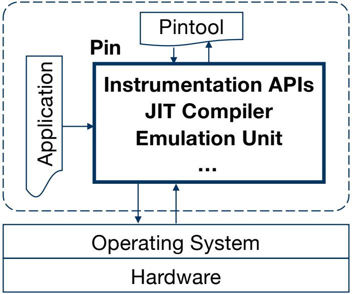
A dynamic taint analysis framework called `libdft` imposes about **4x** slowdown for `gzip` when compressing a file.

Reason 1: Dynamic Instruction Instrumentation



Architecture of Intel Pin

Reason 1: Dynamic Instruction Instrumentation



Architecture of Intel Pin

Insight 1

Taint logic can be instrumented **statically** via static binary rewriting.

Reason 2: Over Instrumentation

Example

```
test eax, eax
```

This instruction will not affect any memory location or general register and does not propagate taint.

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Example

`test eax, eax`

This instruction will not affect any memory location or general register and does not propagate taint.

Insight 2

Taint logic can be instrumented **selectively** via value set analysis.

Static and Selective Instrumentation

Static Taint Analysis

Selective and static instrumentation is performed at **compile time**, which is equivalent to perform **static taint analysis**.

Research Questions

RQ: How to perform this static taint analysis?

$\Downarrow$

RQ: How to reason about aliasing relation in binary code?

Static and Selective Instrumentation

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⇓

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Value Set Analysis

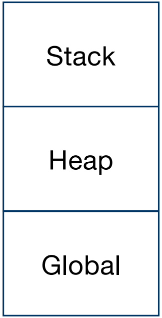
Value set analysis

Value set analysis (VSA) is a static binary analysis technique, which over-approximates **the set of possible values** for data objects at each program point.

Value Set Analysis

Memory Regions

VSA separates the memory space into three disjoint memory spaces: global, stack, heap regions.

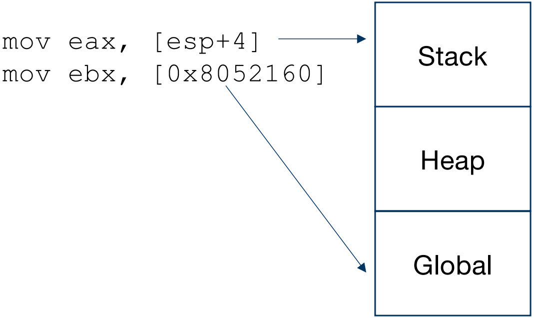


Value Set Analysis

Value Sets

VSA computes the region and value sets based on:

1. instruction semantics



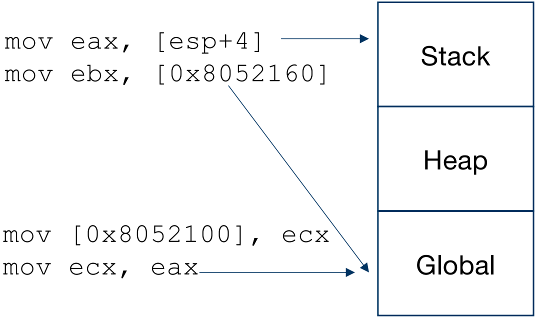
```
mov eax, [esp+4]
mov ebx, [0x8052160]
```

Value Set Analysis

Value Sets

VSA computes the region and value sets based on:

1. instruction semantics
2. data flow analysis



```
mov eax, [esp+4]
mov ebx, [0x8052160]

mov [0x8052100], ecx
mov ecx, eax
```

Static and Selective Instrumentation

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Selective and static instrumentation is performed at **compile time**, which is equivalent to perform **static taint analysis**.

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SelectiveTaint Approach

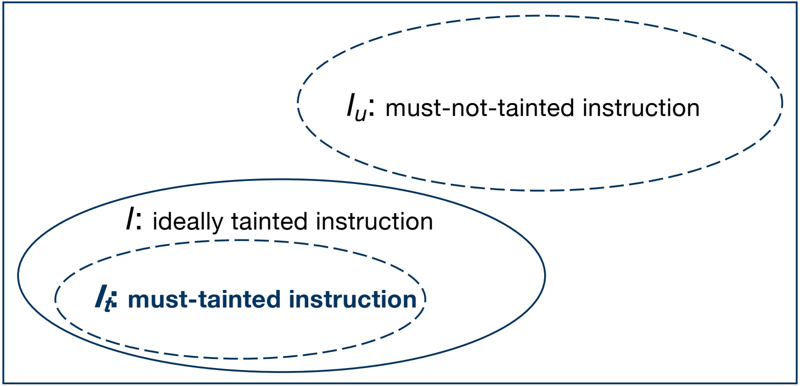
Strawman approach

Strawman approach identifies a **must-tainted** instruction set I_t using VSA. However, VSA loses precision due to incomplete CFG and aliasing.

Our approach

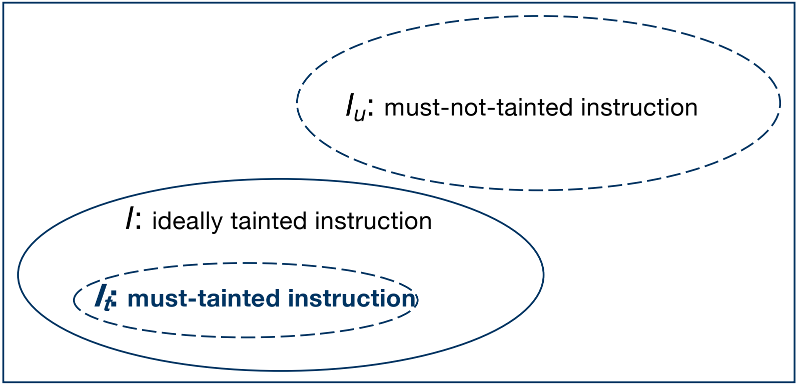
Our approach **conservatively** identifies a **must-not-tainted** instruction set I_u using VSA and taint the others.

SelectiveTaint Approach



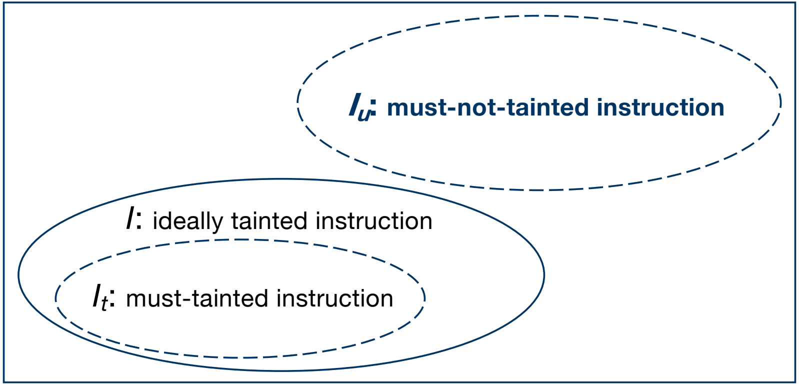
must-tainted analysis → imprecise

SELECTIVETAINT Approach



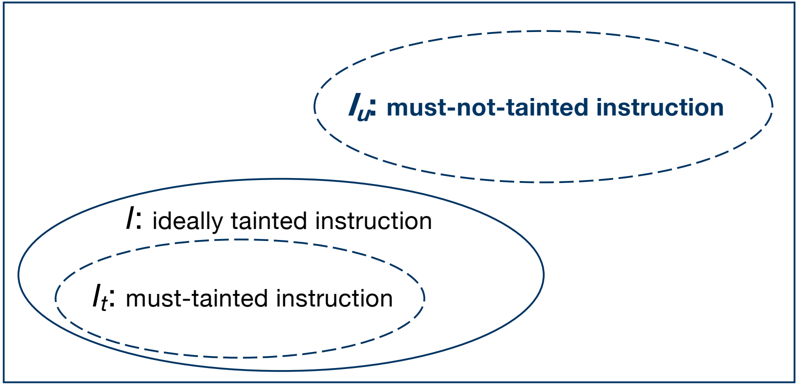
conservative must-tainted analysis → under-taint

SELECTIVETAINT Approach



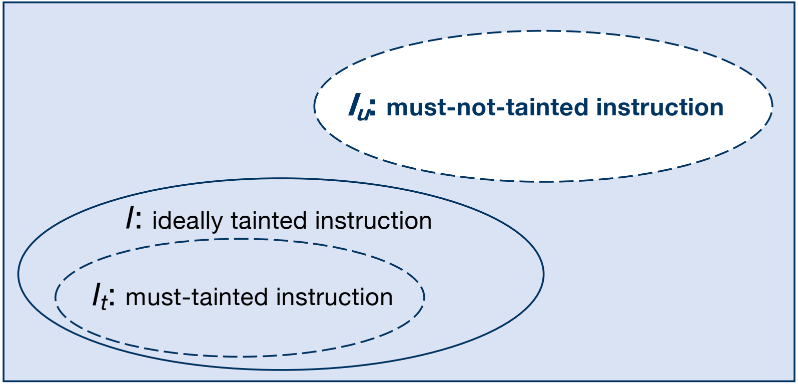
must-not-tainted analysis → imprecise

SELECTIVETAINT Approach



conservative must-not-tainted analysis → over-taint

SELECTIVETAINT Approach



I_u: must-not-tainted instruction

I: ideally tainted instruction

I_t: must-tainted instruction

We perform a conservative must-tainted analysis and taint the rest.

Identification Policy

Unreachable instructions

Removed from must-not-tainted set

```
<version_etc_arn>:
804b7a0: push ebp
```

Potentially tainted instructions

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```
8055c3c: call 8048f30 <__IO_getc@plt>
8055c41: mov eax, edx
```

Untainted operand instructions

Added to must-not-tainted set

```
8096a07: inc ebp
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None taint-propagation instructions

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```
8062456: jmp 806238b <mbslen+0x8b>
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Formal Proof of Must-not-tainted Analysis

Primary Inference Rules

$$\textsc{Unreachable}\ \frac{\nexists i_s \in source,\ i_s \rightsquigarrow i,\ i \rightsquigarrow i_s}{\mathcal{I}_u\ -\!\!=\ \{i\}} \qquad \textsc{UnknownOperand}\ \frac{\exists o \in op(i),\ V[o] = (\bot,\bot,\bot)}{\mathcal{I}_u\ -\!\!=\ \{i\}}$$

$$\textsc{UntaintedOperand}\ \frac{\forall o \in op(i),\ V[o] \subseteq \mathcal{V}_u}{\mathcal{I}_u\ \cup\!\!=\ \{i\}} \qquad \textsc{NonPropagateOpcode}\ \frac{\forall o \in op(i),\ V[o] \overset{i}{\equiv} V[o]}{\mathcal{I}_u\ \cup\!\!=\ \{i\}}$$

Formal Proof of Must-not-tainted Analysis

Auxiliary Inference Rules

Control-flows:

$$\textsc{Reachable}\ \frac{succ(i_1,\ i_2)}{i_1\ \rightsquigarrow\ i_2} \qquad \textsc{TransReachable}\ \frac{succ(i_1,\ i_2) \quad succ(i_2,\ i_3)}{i_1\ \rightsquigarrow\ i_3}$$

Operands:

$$\textsc{LiteralOperand}\ \frac{l\ \in\ op(i) \quad l\ :\ \texttt{literal}}{\mathcal{V}_u\ \cup\!=\ V[l]} \qquad \textsc{LabelOperand}\ \frac{l\ \in\ op(i) \quad l\ :\ \texttt{label}}{\mathcal{V}_u\ \cup\!=\ V[l]}$$

$$\textsc{TaintSource}\ \frac{o\ \in\ taintedop(i_s) \quad i_s\ \in\ source}{\mathcal{V}_u\ -\!=\ V[o]} \qquad \textsc{TaintPropagate}\ \frac{o_1\ \in\ sourceop(i) \quad o_2\ \in\ destop(i) \quad V[o_1]\ \subseteq\ \mathcal{V}_u}{\mathcal{V}_u\ -\!=\ V[o_2]}$$

Opcodes:

$$\textsc{PCRegChangeOpcode}\ \frac{V[pc]\ {}^{i}\ V[pc] \quad \forall o\ \in\ op(i),\ V[o]\ \overset{i}{\equiv}\ V[o]}{\mathcal{I}_u\ \cup\!=\ \{i\}}$$

$$\textsc{StatusRegChangeOpcode}\ \frac{V[status]\ {}^{i}\ V[status] \quad \forall o\ \in\ op(i),\ V[o]\ \overset{i}{\equiv}\ V[o]}{\mathcal{I}_u\ \cup\!=\ \{i\}}$$

Formal Proof of Must-not-tainted Analysis

Theorem 1

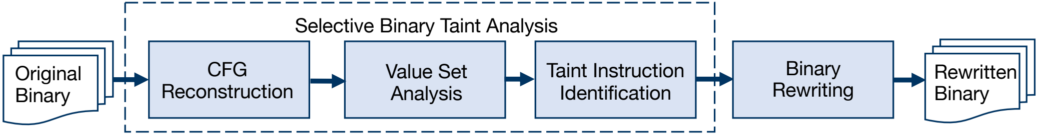
Must-not-tainted analysis is sound, except for the precision loss due to imprecise CFG and VSA results.

Proof

We prove this theorem with induction.

1. In the first iteration, I_u is $\emptyset$, must-not-tainted analysis is sound.
2. We next prove if the kth iteration, must-not-tainted analysis is sound, it also holds for the (k+1)th iteration.

Design


Selective Binary Taint Analysis

Original Binary

CFG Reconstruction

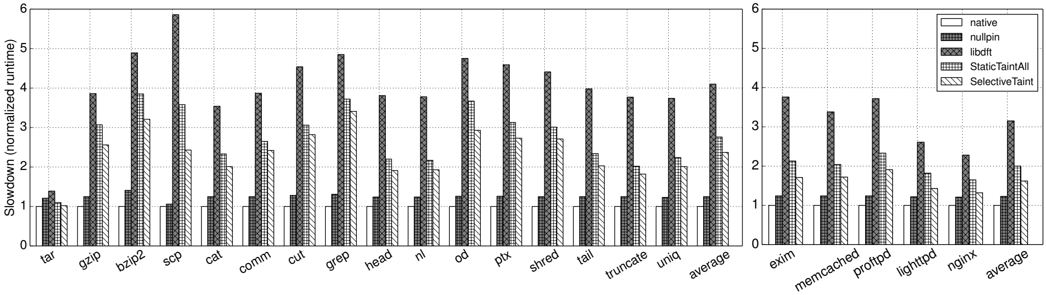
Value Set Analysis

Taint Instruction Identification

Binary Rewriting

Rewritten Binary

Performance Evaluation



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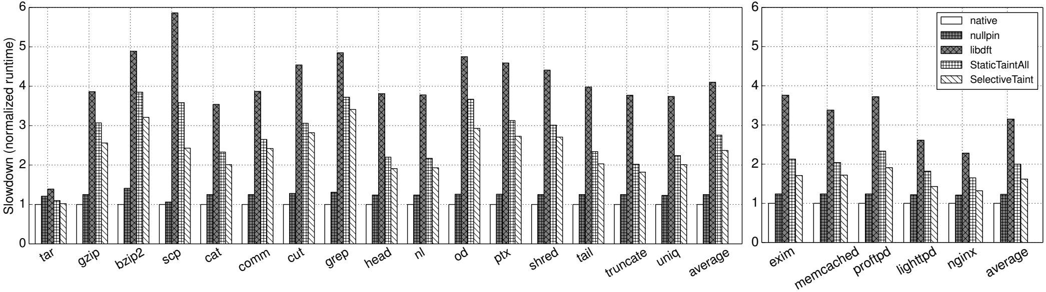

Results

On average **1.7x** faster than libdft.

Functionality Evaluation

Program	Category	Vulnerability	CVE ID	STATICTAINTALL	SELECTIVETAINT
SoX 14.4.2	Sound Processing Utilities	Buffer Overflow	CVE-2019-8356	✓	✓
TinTin++ 2.01.6	Multiplayer Online Game Client	Buffer Overflow	CVE-2019-7629	✓	✓
dcraw 9.28	Raw Image Decoder	Buffer Overflow	CVE-2018-19655	✓	✓
ngiflib 0.4	GIF Format Decoding Library	Buffer Overflow	CVE-2018-11575	✓	✓
Gravity 0.3.5	Programming Language Interpreter	Buffer Overflow	CVE-2017-1000437	✓	✓
MP3Gain 1.5.2	Audio Normalization Software	Buffer Overflow	CVE-2017-14411	✓	✓
NASM 2.14.02	Assembler and Disassembler	Double Free	CVE-2019-8343	✓	✓
Jhead 3.00	Exif Jpeg Header Manipulation Tool	Integer Underflow	CVE-2018-6612	✓	✓
Nginx 1.4.0	Web Server	Buffer Overflow	CVE-2013-2028	✓	✓

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ngiflib 0.4	GIF Format Decoding Library	Buffer Overflow	CVE-2018-11575	✓	✓
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Results

Detected **all nine** tested vulnerability as libdft.

Dynamic Taint Analysis

Papers	Year	Static	Dynamic	Hardware	Parallel/Offline	Neural Network
Suh et al. [SLD04]	2004		✓	✓		
Newsome et al. [NS05]	2005		✓			
Clause et al. [CLO07]	2007		✓			
Bosman et al. [BSB11]	2011		✓			
Kemerlis et al. [KPJK12]	2012		✓			
Jee et al. [JPK$^+$12]	2012		✓			
Jee et al. [JKKP13]	2013		✓		✓	
Ming et al. [MWX$^+$15]	2015	✓	✓			
Ming et al. [MWW$^+$16]	2016	✓	✓		✓	
Banerjee et al. [BDCN19]	2019	✓	✓			
She et al. [SCS$^+$20]	2020	✓	✓			✓
SelectiveTaint [CLZ21]	2021	✓				

Related Work

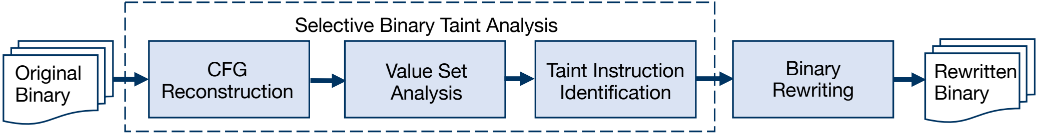
Binary Rewriting

Uroboros [WWW15], Ramblr [WSB+17], Multiverse [BLH18], Probabilistic Disassembly [MKS+19], Ddisasm [FMS20], dyninst [BM11].

Alias Analysis on Binary

Points-to relations with Datalog [BN06], abstract address sets [DMW98], symbolic value sets [ABZT98].

Summary



SELECTIVETAINT

- Static and selective instruction instrumentation
- Conservative must-not-tainted analysis

The source code is available at `https://github.com/OSUSecLab/SelectiveTaint`. Email: {chen.4825, lin.3021}@osu.edu, yinqianz@acm.org

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