APISan: Sanitizing API Usages through Semantic Cross-checking

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APIs in today's software are plentiful yet complex

- Example: OpenSSL
  - 3841 APIs in [v1.0.2h]
  - 3718 in [v1.0.1t] -> 3841 in [v1.0.2h] (**+123** APIs)
  - OpenSSH uses **158** APIs of OpenSSL

Complex APIs result in programmers' mistakes

- Problems in documentation
  - Incomplete: e.g., low details in hostname verification
  - Long: e.g., 43K lines in OpenSSL documentation
  - Lack: e.g., internal APIs

- Lack of automatic tool support
  - e.g., missing formal specification and precise semantics

Problem: API misuse can cause security problems

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OpenSSL

#2008-016 multiple OpenSSL signature verification API misuse

Description:

Several functions inside the OpenSSL library incorrectly check the result afte

This bug allows a malformed signature to be treated as a good signature rather t

The flaw may be exploited by a malicious server or a man-in-the-middle attacl
validation.

→ MITM

Problem: API misuse can cause security problems

mozilla
Firefox

Vulnerability Summary for CVE-2015-7199

Original release date: 11/05/2015

Last revised: 11/05/2015

Source: US-CERT/NIST

Overview

The (1) AddWeightedPathSegLists and (2) SVGPathSegListSMILType::Interpolate functions
attackers to cause a denial of service (memory corruption) or possibly have unspecified oth

→ Code execution

Problem: API misuse can cause security problems

→ Privilege Escalation

Today's practices to help programmers

- Formal method
  - Problem: lack of specification

- Model checking
  - Problem: manual, lack of semantic context

- Symbolic execution
  - Problem : failed to scale for large software

Promising approach: finding bugs by using existing code

- “Bugs as deviant behavior” [OSDI01]
  - Syntactic template: e.g., check NULL on malloc()
- “Juxta” [SOSP15]
  - Inferring correct semantics from multiple of implementations
  - File system specific bug finding tool

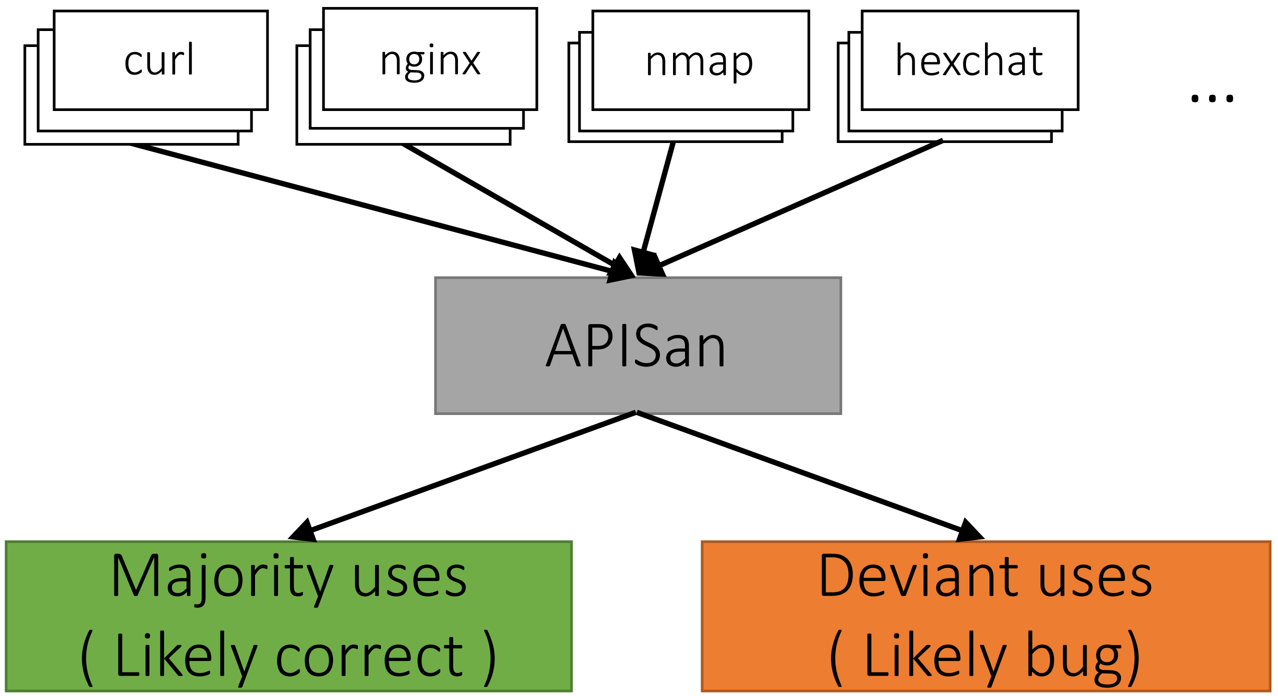
Promising approach: finding bugs by using existing code

- “Bugs as deviant behavior”[OSDI01]
  - Syntactic template: e.g., check NULL on malloc()

Research goal: can we apply this method to *any* kind of software *without manual efforts*?

Our idea: comparing API usages in various implementation

- Example: finding OpenSSL API misuses



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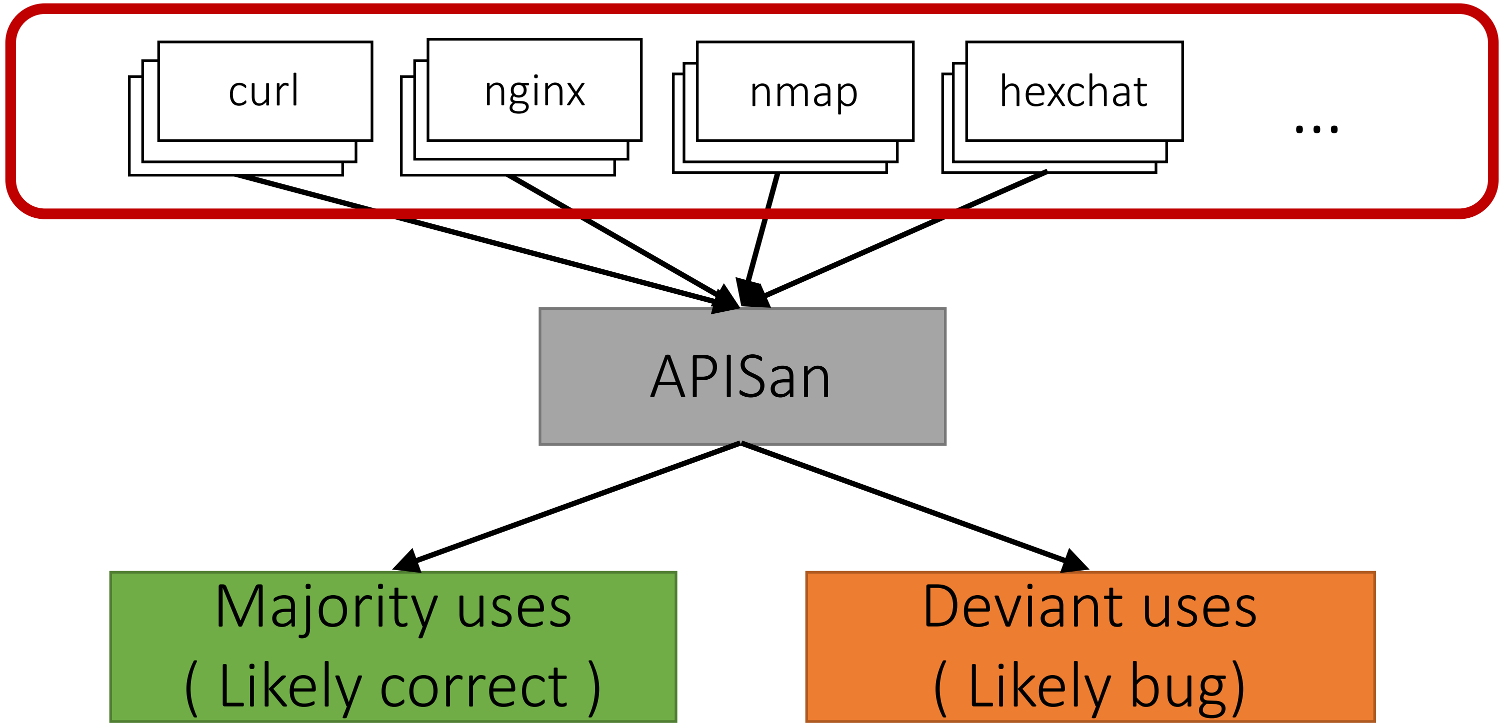

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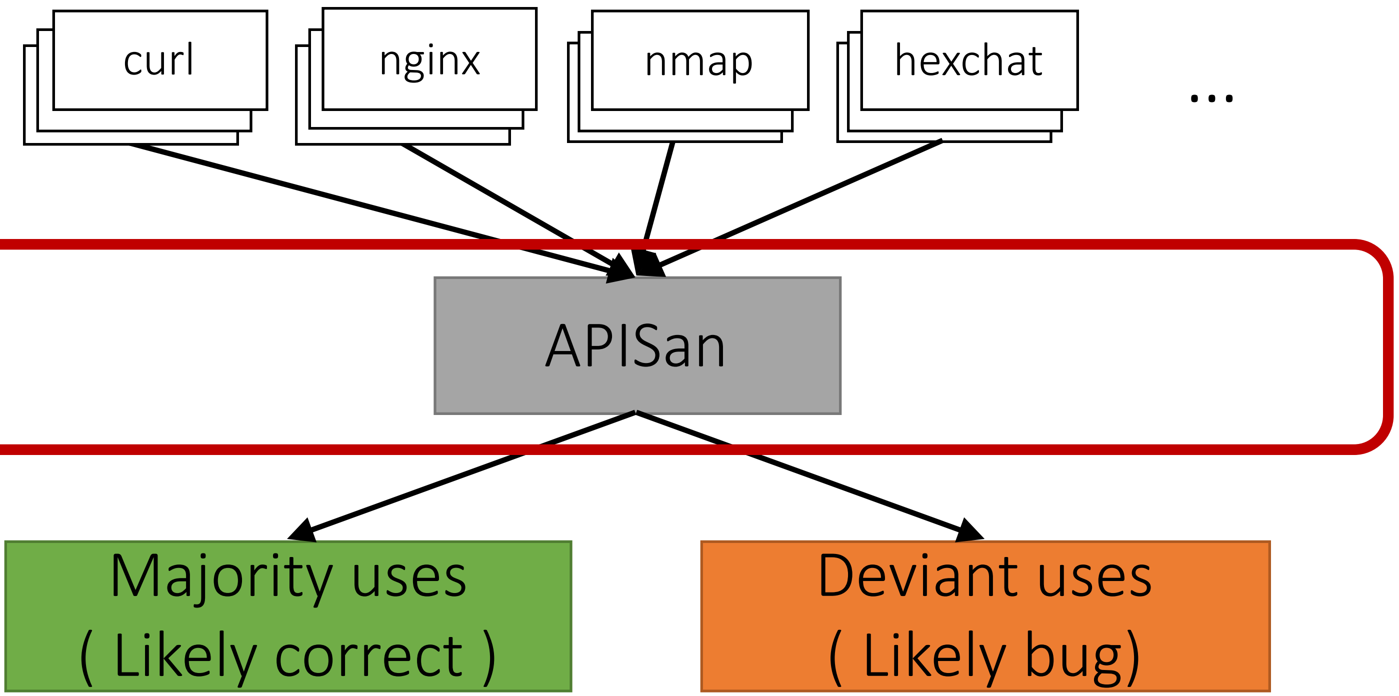

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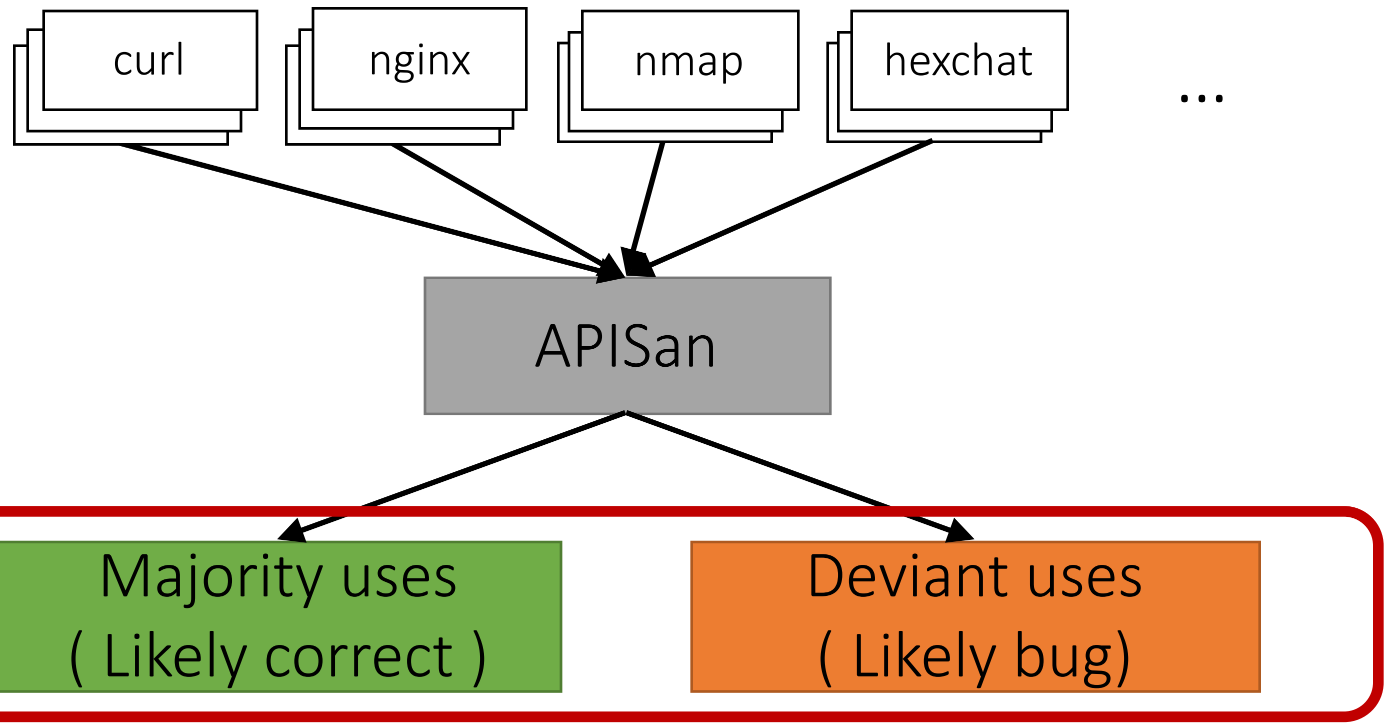

Our approach is very promising

- Effective in finding API misuses
  - 76 new bugs
- Scale to large, complex software
  - Linux kernel, OpenSSL, PHP, Python, etc.
  - Debian packages

Technical Challenges

- API uses are too different from impl. to impl.
- Subtle semantics of the correct API uses
- Large, complex code using APIs

Example: OpenSSL API uses

- SSL_get_verify_result()
  - Get result of peer certificate verification

```
if (SSL_get_verify_result() == X509_V_OK) { ... }
```

Example: OpenSSL API uses

- SSL_get_verify_result()
  - Get result of peer certificate verification
  - no peer certificate → always returns X509_V_OK

```
if (SSL_get_verify_result() == X509_V_OK) { ... }
```

Example: OpenSSL API uses

- SSL_get_verify_result()
  - Get result of peer certificate verification
  - **no peer certificate → always returns X509_V_OK**

```
if (SSL_get_verify_result() == X509_V_OK
      && SSL_get_peer_certificate() != NULL ) { … }
```

Example: a correct implementation using OpenSSL API

```
cert = SSL_get_peer_certificate(handle);
if (!cert) {…}
err = SSL_get_verify_result(handle);
if (err == X509_V_OK) { … }
```

curl

Example: a correct implementation using OpenSSL API

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Example: a correct implementation using OpenSSL API

Semantically same with correct usage

```
if (SSL_get_verify_result() == X509_V_OK
 && SSL_get_peer_certificate() != NULL ) { … }
```

Example: a correct implementation using OpenSSL API

Correct

```
cert = SSL_get_peer_certificate(handle);
if (!cert) {...}
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```

curl

Example: providing various implementations using OpenSSL

Correct

```
cert = SSL_get_peer_certificate(handle);
if (!cert) {…}
err = SSL_get_verify_result(handle);
if (err == X509_V_OK) { … }
```

curl

```
if (SSL_get_verify_result(conn) != X509_V_OK)
    return NGX_OK;
cert = SSL_get_peer_certificate(conn);
if (cert) { … }
```

nginx

```
cert = SSL_get_peer_certificate(ssl);
if (cert == NULL)
    return 0;
if (SSL_get_verify_result(ssl) != X509_V_OK) {…}
```

nmap

```
err = SSL_get_verify_result(ssl);
switch(err) {
  case X509_V_OK:
    cert = SSL_get_peer_certificate(ssl);
```

hexchat

Example: providing various implementations using OpenSSL

Correct

```
cert = SSL_get_peer_certificate(handle);
if (!cert) {…}
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if (SSL_get_verify_result(conn) != X509_V_OK)
    return NGX_OK;
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nmap

```
err = SSL_get_verify_result(ssl);
switch(err) {
  case X509_V_OK:
    cert = SSL_get_peer_certificate(ssl);
    // if (cert) is missed
```

hexchat

Example: providing various implementations using OpenSSL

Correct

```
cert = SSL_get_peer_certificate(handle);
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if (err == X509_V_OK) { … }
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curl

Correct

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if (SSL_get_verify_result(conn) != X509_V_OK)
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if (cert == NULL)
   return 0;
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Incorrect

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err = SSL_get_verify_result(ssl);
switch(err) {
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   // if (cert) is missed
```

hexchat

Example: providing various implementations using OpenSSL

Correct

```
cert = SSL_get_peer_certificate(handle);
if (!cert) {…}
```

Correct

```
if (SSL_get_verify_result(conn) != X509_V_OK)
   return NGX_OK;
```

Can we distinguish between *correct* implementations and *buggy* implementations?

```
   return 0;
if (SSL_get_verify_result(ssl) != X509_V_OK) {…}
```

nmap

```
case X509_V_OK:
  cert = SSL_get_peer_certificate(ssl);
  // if (cert) is missed
```

hexchat

Challenge 1: API usages are different from each other

Correct

```
cert = SSL_get_peer_certificate(handle);
if (!cert) {…}
err = SSL_get_verify_result(handle);
if (err == X509_V_OK) { … }
```

curl

Correct

```
if (SSL_get_verify_result(conn) != X509_V_OK)
   return NGX_OK;
cert = SSL_get_peer_certificate(conn);
if (cert) { … }
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nginx

Correct

```
cert = SSL_get_peer_certificate(ssl);
if (cert == NULL)
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Incorrect

```
err = SSL_get_verify_result(ssl);
switch(err) {
 case X509_V_OK:
   cert = SSL_get_peer_certificate(ssl);
   // if (cert) is missed
```

hexchat

Challenge 2: subtle semantics of the correct API usages

Correct

```
cert = SSL_get_peer_certificate(handle);
if (!cert) {…}
err = SSL_get_verify_result(handle);
if (err == X509_V_OK) { … }
```

curl

Correct

```
if (SSL_get_verify_result(conn) != X509_V_OK)
    return NGX_OK;
cert = SSL_get_peer_certificate(conn);
if (cert) { … }
```

nginx

Correct

```
cert = SSL_get_peer_certificate(ssl);
if (cert == NULL)
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nmap

Incorrect

```
err = SSL_get_verify_result(ssl);
switch(err) {
  case X509_V_OK:
    cert = SSL_get_peer_certificate(ssl);
    // if (cert) is missed
```

hexchat

Challenge3 : Large, complex code using APIs

- On average, more than 100K LoC
  - curl : 110K LoC
  - nginx : 127K LoC
  - nmap: 169K LoC
  - hexchat: 61K LoC

- Linux : > 1M LoC

Challenge3 : Large, complex code using APIs

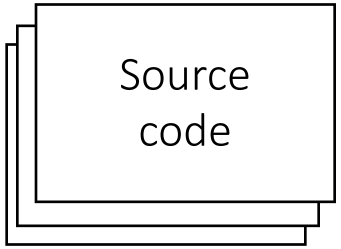
```
cert = SSL_get_peer_certificate(handle);
if (!cert) {…}
err = SSL_get_verify_result(handle);
if (err == X509_V_OK) { … }
```

curl (simplified)

```
cert = SSL_get_peer_certificate(handle);
if (!cert) {…}
...
len = BIO_get_mem_data(mem, (char **) &ptr);
infof(data, " start date: %.*s\n", len, ptr);
rc = BIO_reset(mem);
...
err = SSL_get_verify_result(handle);
if (err == X509_V_OK) { … }
```

curl

Overview of APISan



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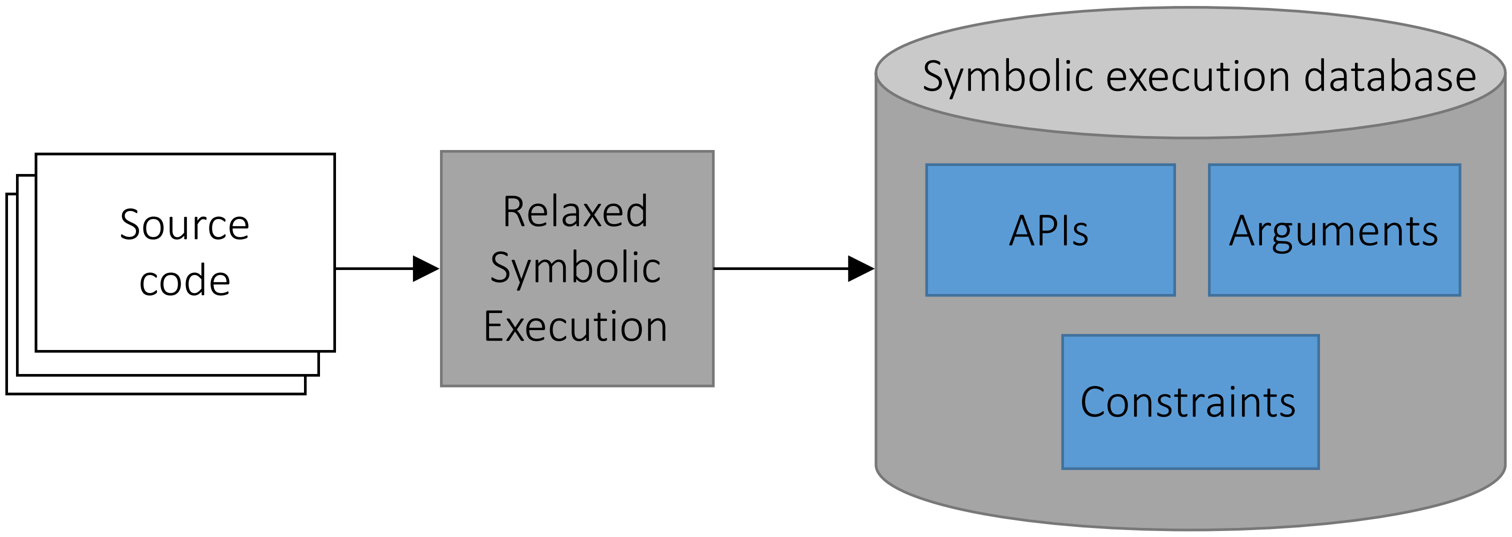

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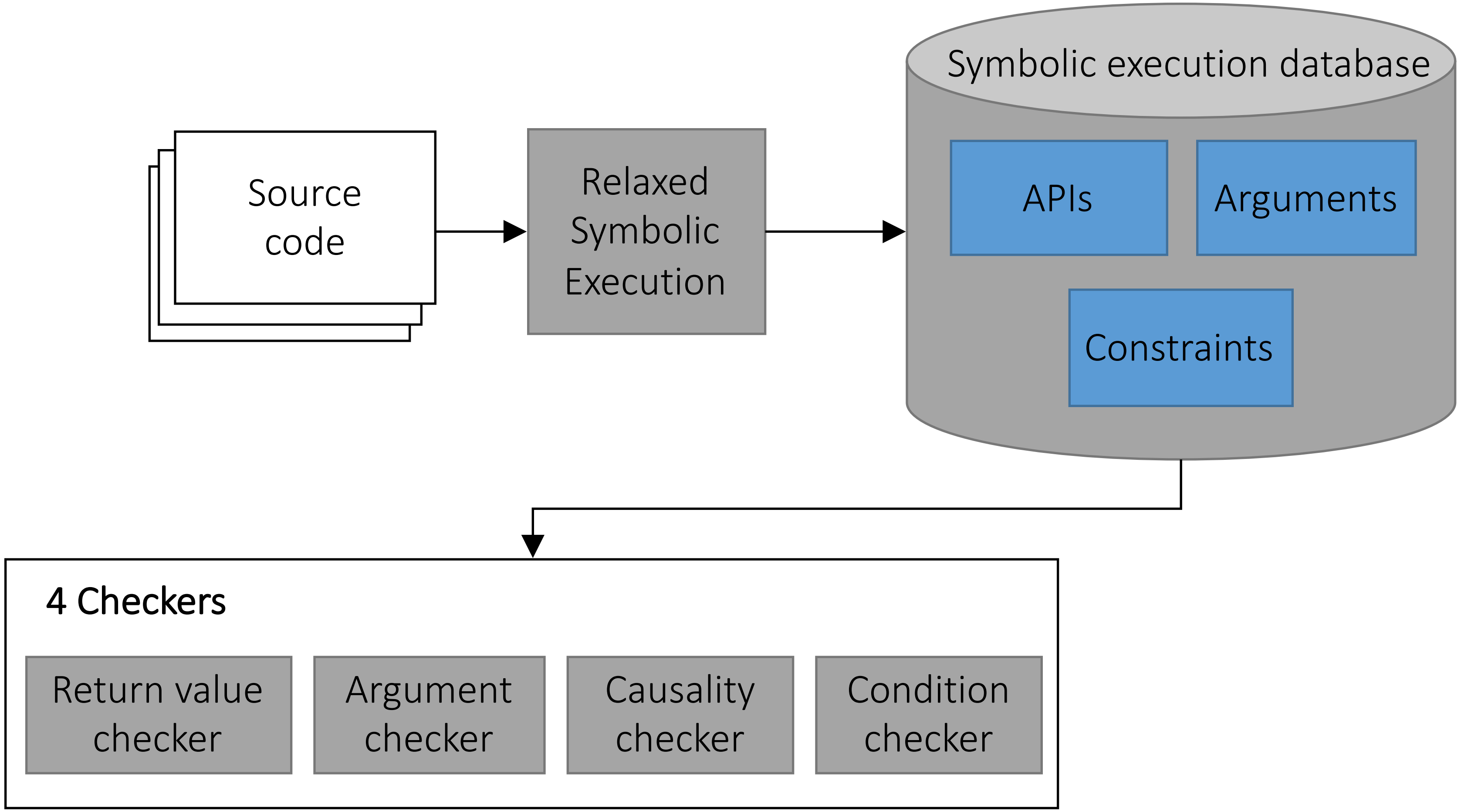

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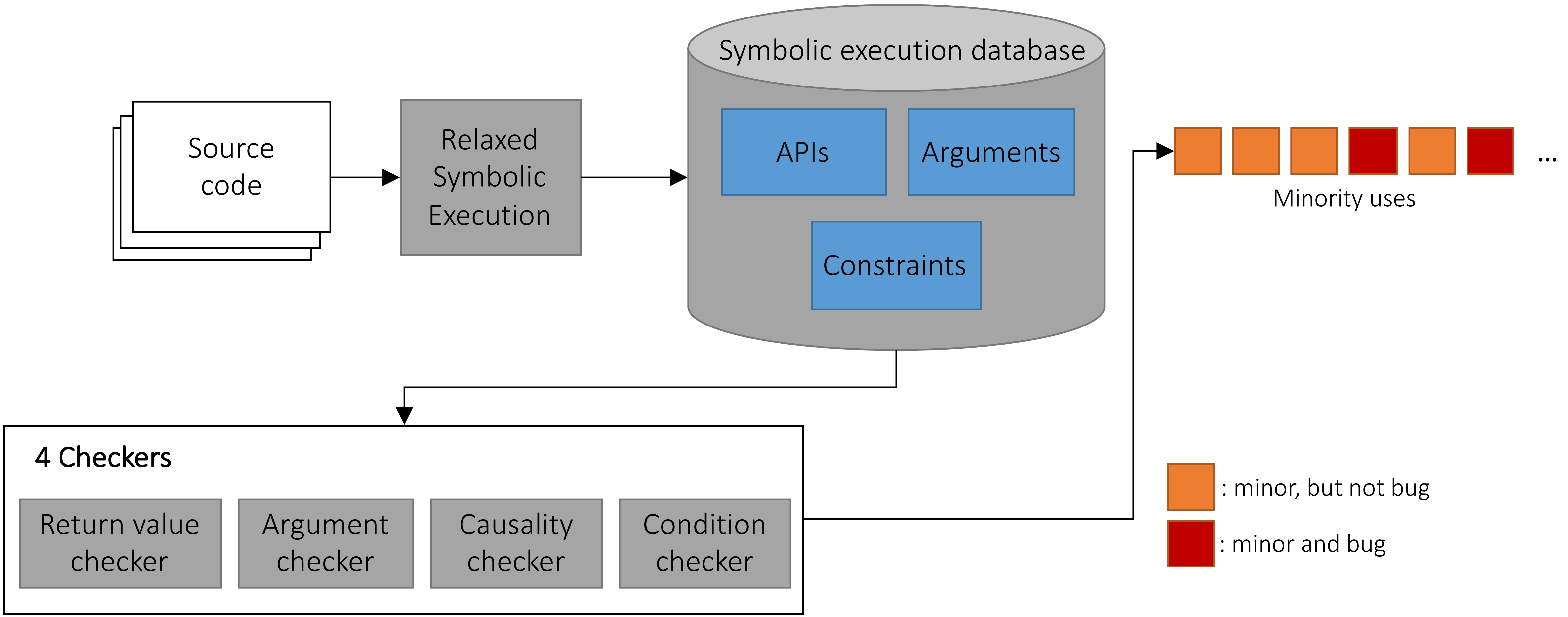

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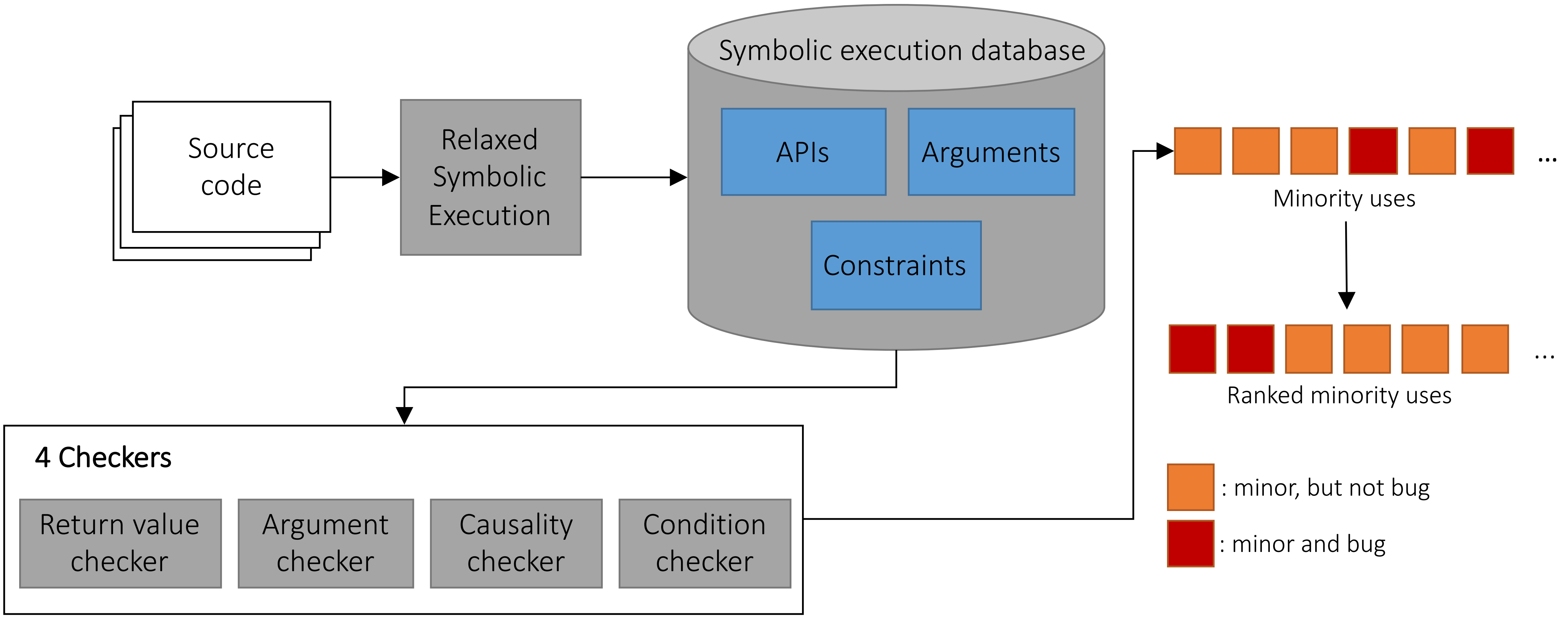

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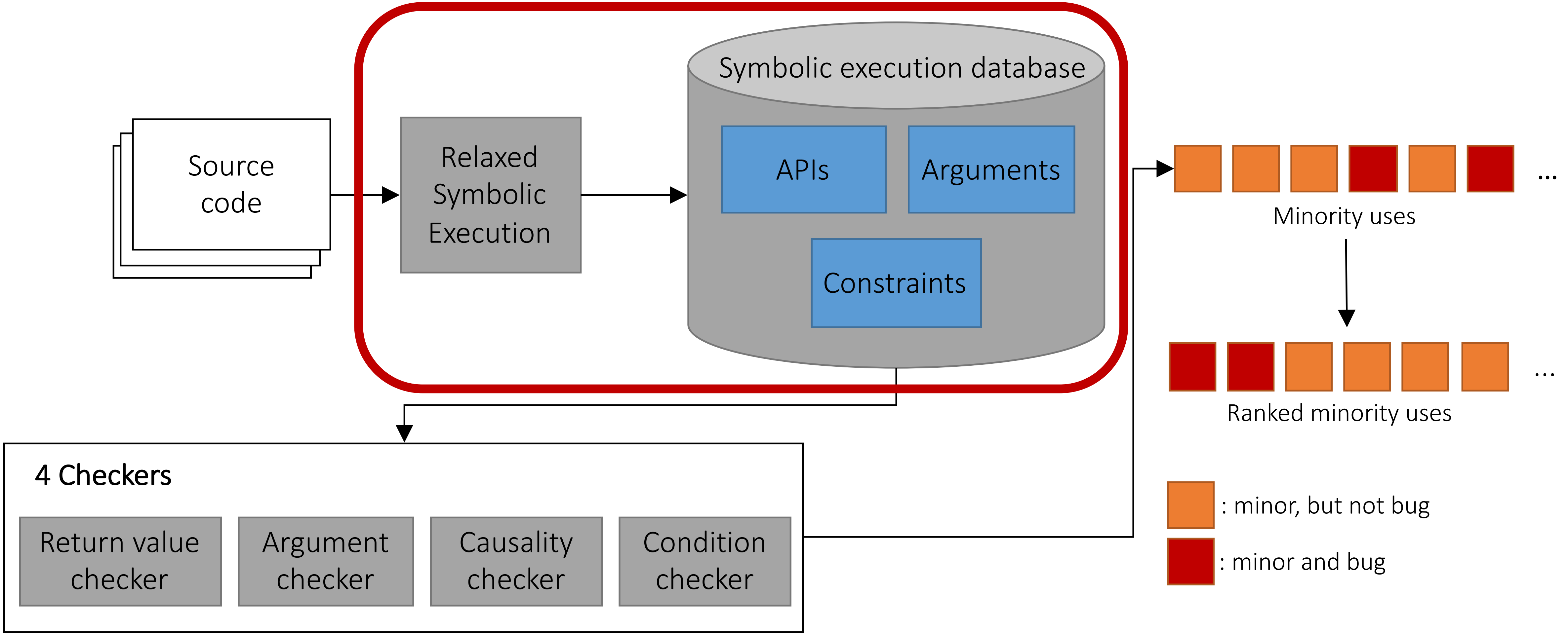

Symbolic execution can be relaxed in finding API contexts

- Symbolic execution is not scalable
  - Path explosion
  - SMT is expensive, naturally NP-complete
- Methods to relax symbolic execution
  - Limiting inter-procedural analysis
  - Removing back edges
  - Range-based

Method 1: Limiting inter-procedural analysis

- How APIs are used O
- How APIs are implemented X

```
cert = SSL_get_peer_certificate(handle);
if (!cert) {…}
err = SSL_get_verify_result(handle);
if (err != X509_V_OK) { … }
```

Method 2: Removing back edges

- API contexts can be captured within loops
  - e.g., malloc() and free() are matched inside a loop

```
~~for(…) {~~
  cert = SSL_get_peer_certificate(handle);
  if (!cert) {…}
  err = SSL_get_verify_result(handle);
  if (err != X509_V_OK) { … }
}
```

Method 3: Range-based

- Most of arguments & return values are integer

```
cert != NULL ∧ err == X509_V_OK
```

```
cert = {[-MAX, -1] , [1, MAX]}
err  = {[X509_V_OK, X509_V_OK]}
```

- Clang uses range-based symbolic execution

Building per-path symbolic abstractions

- Path-sensitive, context-sensitive
- Record symbolic abstractions
  - API calls
  - Symbolic expression of arguments
  - Constraints

Examples: Building per-path symbolic abstractions from source code

```
cert = SSL_get_peer_certificate(handle);
if (!cert) {…}
err = SSL_get_verify_result(handle);
if (err == X509_V_OK) { … }
```

Source code

Symbolic abstractions

Examples: Building per-path symbolic abstractions from source code

```
cert = SSL_get_peer_certificate(handle);
if (!cert) {…}
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if (err == X509_V_OK) { … }
```

Source code

Call	SSL_get_peer_certificate(handle)

Symbolic abstractions

Examples: Building per-path symbolic abstractions from source code

```
cert = SSL_get_peer_certificate(handle);
if (!cert) {…}
err = SSL_get_verify_result(handle);
if (err == X509_V_OK) { … }
```

Source code

Call	SSL_get_peer_certificate(handle)
Constraint	SSL_get_peer_certificate(handle) = {[-MAX, -1], [1, MAX]}

Symbolic abstractions

Examples: Building per-path symbolic abstractions from source code

```
cert = SSL_get_peer_certificate(handle);
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Source code

Call	SSL_get_peer_certificate(handle)
Constraint	SSL_get_peer_certificate(handle) = {[-MAX, -1], [1, MAX]}
Call	SSL_get_verify_result(handle)

Symbolic abstractions

Examples: Building per-path symbolic abstractions from source code

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cert = SSL_get_peer_certificate(handle);
if (!cert) {…}
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```

Source code

Call	SSL_get_peer_certificate(handle)
Constraint	SSL_get_peer_certificate(handle) = {[-MAX, -1], [1, MAX]}
Call	SSL_get_verify_result(handle)
Constraint	SSL_get_verify_result(handle) = {[X509_V_OK, X509_V_OK]}

Symbolic abstractions

Examples: Building per-path symbolic abstractions from source code

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cert = SSL_get_peer_certificate(handle);
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Examples: Building per-path symbolic abstractions from source code

```
cert = SSL_get_peer_certificate(handle);
if (!cert) {…}
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Source code

Symbolic Abstractions #1

Examples: Building per-path symbolic abstractions from source code

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Source code

Symbolic Abstractions #1

Symbolic Abstractions #2

Examples: Building per-path symbolic abstractions from source code

```
cert = SSL_get_peer_certificate(handle);
if (!cert) {…}
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if (err == X509_V_OK) { … }
```

Source code

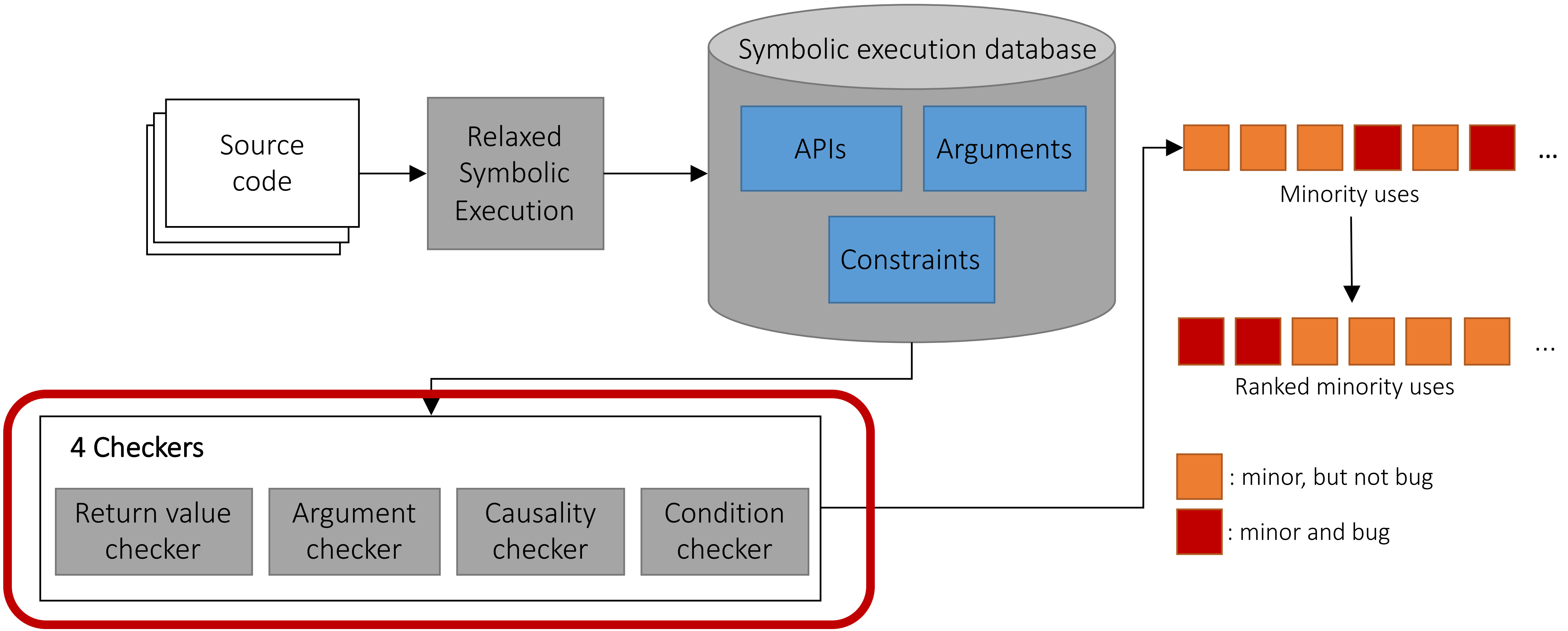
Symbolic Abstractions #1

Symbolic Abstractions #2

Symbolic Abstractions #3

….

Overview of APISan



Four semantic contexts have security implications

- Orthogonal, essential, security-related contexts
  - Return value
  - Arguments
  - Causality
  - Condition

Context 1: Return value

- Return computation result or execution status

- NULL dereference
- Privilege escalation
  - e.g, Windows, CVE-2014-4113

```
ptr = malloc(size)
if (!ptr){ … }
```

Context 2: Arguments

- Inputs for calling APIs and their relationship

- Format string bug
- Memory corruption

```
printf(buf);
```

```
ptr = malloc(size1);
memcpy(ptr, src, size2);
```

Context 3: Causality

- Causal relationship between APIs

- Deadlock
- Memory leak

```
lock();
unlock();
```

```
malloc();
free();
```

Context 4: Condition

- Implicit pre- and post condition for calling APIs
- MITM

```
if (SSL_get_verify_result() == X509_V_OK &&
        SSL_get_peer_certificate() != NULL)
```

Extract contexts from symbolic abstractions

- Symbolic abstractions contains
  {APIs, Arguments, Constraints}

- Return value ← Constraints
- Arguments ← Arguments
- Causality ← APIs
- Condition ← Constraints + APIs

Extract contexts from symbolic abstractions

- Symbolic abstractions contains
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- Condition ← Constraints + APIs

Example: extract condition contexts from symbolic abstractions

Call	SSL_get_peer_certificate(handle)
Constraint	SSL_get_peer_certificate(handle) = {[-MAX, -1], [1, MAX]}
Call	SSL_get_verify_result(handle)
Constraint	SSL_get_verify_result(handle) = {[X509_V_OK, X509_V_OK]}

curl

Any constraint or call

Line numbers when event is called

Event	Line
SSL_get_verify_result = {[X509_V_OK, X509_V_OK]}	{curl}
Constraint	**Line**
SSL_get_peer_certificate = {[-MAX, -1], [1, MAX]}	{curl}
...	....

Example: extract condition contexts from symbolic abstractions

Call	SSL_get_verify_result(conn)
Constraint	SSL_get_verify_result(handle) == {[X509_V_OK, X509_V_OK]}
Call	SSL_get_peer_certificate(conn)
Constraint	SSL_get_peer_certificate(conn) != {[-MAX, -1], [1, MAX]}

nginx

Event	Line
SSL_get_verify_result = {[X509_V_OK, X509_V_OK]}	{curl, **nginx**}
Constraint	Line
SSL_get_peer_certificate = {[-MAX, -1], [1, MAX]}	{curl, **nginx**}
...	....

Example: extract condition contexts from symbolic abstractions

Call	SSL_get_peer_certificate(ssl)
Constraint	SSL_get_peer_certificate(ssl) = {[-MAX, -1], [1, MAX]}
Call	SSL_get_verify_result(ssl)
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nmap

Event	Line
SSL_get_verify_result = {[X509_V_OK, X509_V_OK]}	{curl, nginx, **nmap**}
Constraint	**Line**
SSL_get_peer_certificate = {[-MAX, -1], [1, MAX]}	{curl, nginx, **nmap**}
...	....

Example: extract condition contexts from symbolic abstractions

Call	SSL_get_verify_result(ssl)
Constraint	SSL_get_verify_result(ssl) = {[X509_V_OK, X509_V_OK]}
Call	SSL_get_peer_certificate(ssl)

hexchat

Event	Line
SSL_get_verify_result = {[X509_V_OK, X509_V_OK]}	{curl, nginx, nmap, **hexchat**}
Constraint	**Line**
SSL_get_peer_certificate = {[-MAX, -1], [1, MAX]}	{curl, nginx, nmap}
...	....

Example: find majority & minority usages from contexts

Event	Line
SSL_get_verify_result = {[X509_V_OK, X509_V_OK]}	{curl, nginx, nmap, hexchat, …}
Constraint	**Line**
SSL_get_peer_certificate = {[-MAX, -1], [1, MAX]}	{curl, nginx, nmap, …}
…	….

Example: find majority & minority usages from contexts

Event	Line
SSL_get_verify_result = {[X509_V_OK, X509_V_OK]}	{curl, nginx, nmap, hexchat, …}
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Majority uses
(Likely correct)

Example: find majority & minority usages from contexts

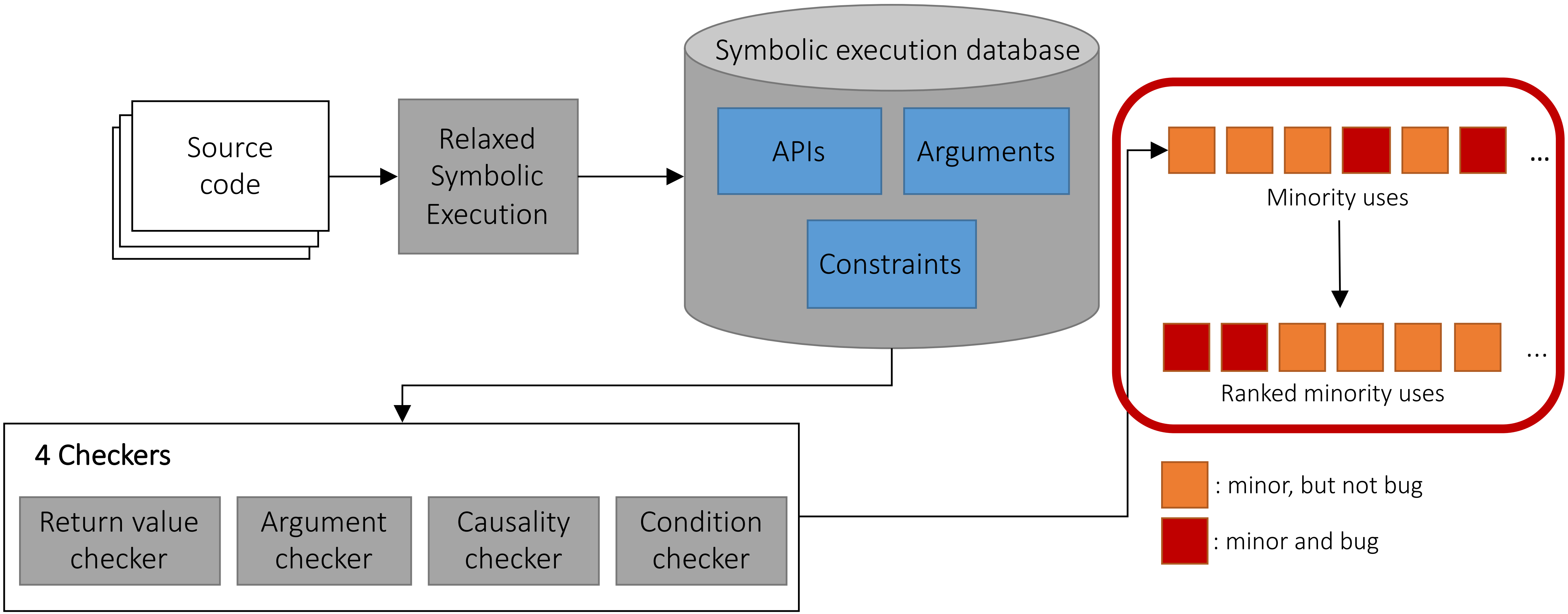
Event	Line
SSL_get_verify_result = {[X509_V_OK, X509_V_OK]}	{curl, nginx, nmap, hexchat, ...}
Constraint	**Line**
SSL_get_peer_certificate = {[-MAX, -1], [1, MAX]}	{curl, nginx, nmap, ...}
...	....

Majority uses
(Likely correct)

Deviant uses
(Likely bug)

= total_event – majority_use = **{hexchat, ...}**

Overview of APISan



False positives can be happened in majority analysis

- Lack of inter-procedural analysis
  - e.g., check a return value of malloc() inside a function
- Correlation ≠ Causation
  - e.g., fprintf() is used for printing debug messages when open() is failed
- Correct minor uses
  - e.g., strcmp() == 0, strcmp() > 0

Ranking can mitigate false positives

- More majority pattern repeated, more bug-likely
  - e.g., 999 majority, 1 minority > 10 majority, 1 minority
- General information
  - e.g., most of allocation functions have “alloc” in their names and are required to check their return values
- Domain specific knowledge
  - e.g., SSL APIs start with a string “SSL”

Our approach is formalized as a general framework

$$
\begin{array}{rcl}
\textsf{SymbolicContexts}\,(f) & = & \{\ (t,i,C)\ \mid\ t \in \mathbb{D} \wedge i \in [1..|t|] \wedge t[i] \equiv \textbf{call}\, f(*) \wedge C = \textsc{Contexts}(t,i)\ \} \\
\textsf{Frequency}\,(f,c) & = & \{\ (t,i)\ \mid\ \exists C:\ c \in C \wedge (t,i,C) \in \textsf{SymbolicContexts}(f)\ \} \\
\textsf{Majority}\,(f) & = & \{\ c\ \mid\ |\textsf{Frequency}(f,c)|\ /\ |\textsf{SymbolicContexts}(f)| \geq \theta\ \} \\
\textsf{BugReports}\,(f) & = & \{\ (t,i,C)\ \mid\ (t,i,C) \in \textsf{SymbolicContexts}(f) \wedge C \cap \textsf{Majority}(f) = \emptyset\ \} \\
\textsf{BugReportScore}\,(f) & = & 1 - |\textsf{BugReports}(f)|\ /\ |\textsf{SymbolicContexts}(f)| + \textsc{Hint}(f)
\end{array}
$$

$$
\begin{array}{rcl}
\textsf{returnValueContexts} & = & \lambda(t,i).\ \{\ \bar{r} \mid \exists j:\ t[j] \equiv \textbf{assume}(e,\bar{r}) \wedge \langle \textbf{ret}, i\rangle \in \mathit{retvars}(e)\ \} \\
\textsf{argRelationContexts} & = & \lambda(t,i).\ \{\ (u,v) \mid t[i] \equiv \textbf{call} * (\bar{e}) \wedge \mathit{argvars}(\bar{e}[u],t) \cap \mathit{argvars}(\bar{e}[v],t) \neq \emptyset\ \} \\
\textsf{causalityContexts}\langle\bar{r}\rangle & = & \lambda(t,i).\ \{\ g \mid \exists j: t[j] \equiv \textbf{assume}(e,\bar{r}) \wedge \langle \textbf{ret}, i\rangle \in \mathit{retvars}(e) \wedge \exists k > j: t[k] \equiv \textbf{call}\, g(*)\ \} \\
\textsf{conditionContexts}\langle\bar{r}\rangle & = & \lambda(t,i).\ \{\ (g,\bar{r}') \mid \exists j: t[j] \equiv \textbf{assume}(e,\bar{r}) \wedge \langle \textbf{ret}, i\rangle \in \mathit{retvars}(e) \wedge \exists k > j: t[k] \equiv \textbf{call}\, g(*) \wedge \\
 & & \qquad \exists l: t[l] \equiv \textbf{assume}(e',\bar{r}') \wedge \langle \textbf{ret}, k\rangle \in \mathit{retvars}(e')\ \} \\
\textsf{defaultHint} & = & \lambda f.\ 0 \qquad \textsf{nullDerefHint} = \lambda f.\ \text{if } (f\text{'s name contains } \mathit{alloc}) \text{ then } 0.3 \text{ else } 0
\end{array}
$$

Implementation of APISan

- 9K LoC in total
  - Symbolic database generation : 6K LoC of C/C++ (Clang 3.6)
  - APISan library : 2K LoC of Python

- Checkers : 1K LoC of Python
  - Return value checker : 131 LoC
  - Argument checker : 251 LoC
  - …

Evaluation questions

- How effective is APISan in finding new bugs?
- How easy to use and easy to extend?
- How effective is APISan’s ranking system?

APISan is effective in finding bugs

- Found 76 new bugs in large, complex software
  - Linux kernel, OpenSSL, PHP, Python, and Debian packages
- Security implication
  - e.g., CVE-2016-5636: Python zipimporter heap overflow (Code execution in Google App Engine)

APISan is easy to use without any manual annotation

- To generate symbolic context database

```
$ apisan make                      # use existing build command
```

- Run a checker

```
$ apisan --checker=cpair           # cpair : causality checker
```

- Run a checker (inter-application)

```
$apisan --checker=cpair --db=app1, app2
```

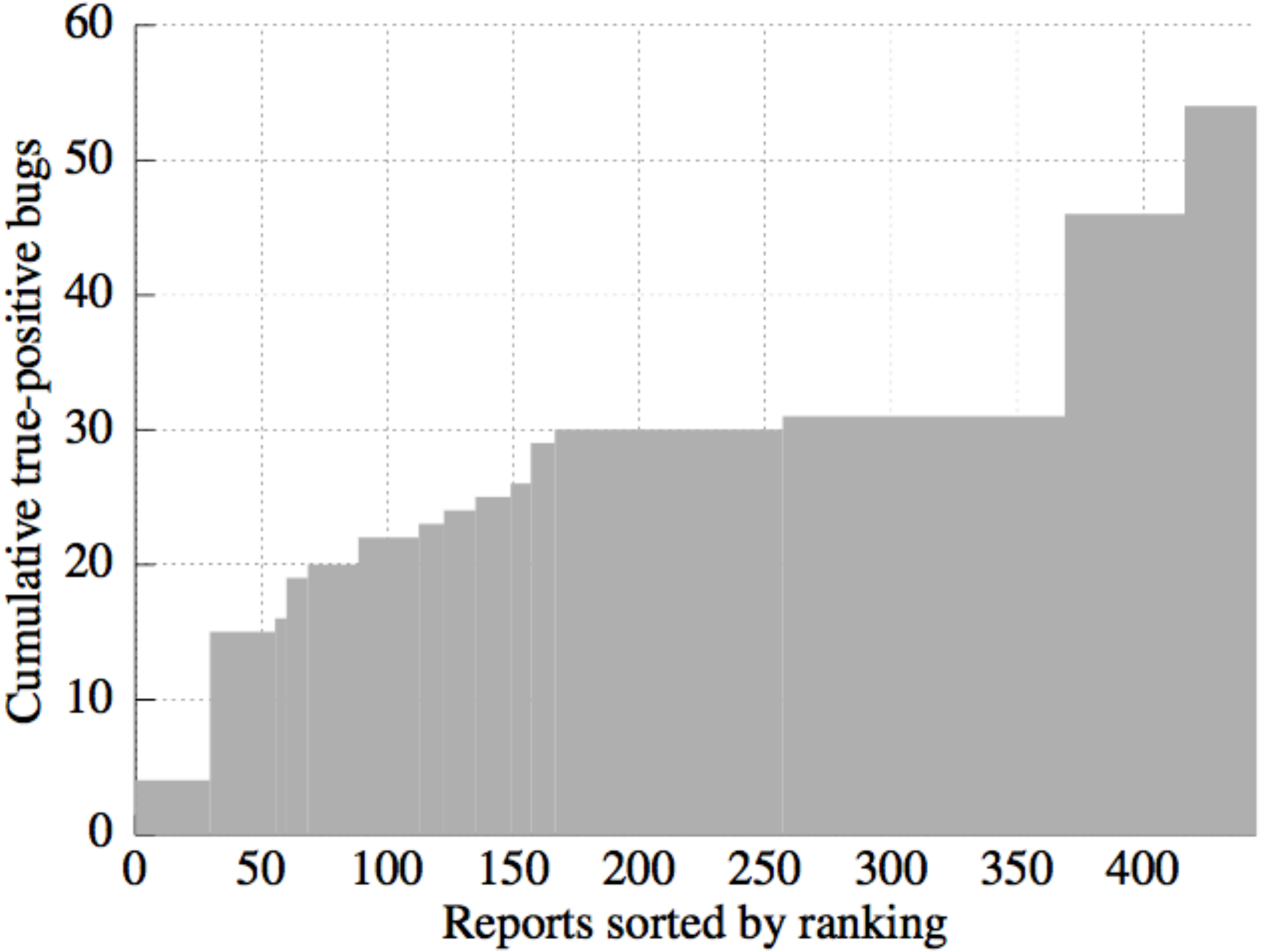
APISan is easy to extend

- e.g., Integer overflow check
- Integer overflow sensitive APIs
  - Have security implications when integer overflow happens
  - e.g., memory allocation functions
- Integer overflow ← Arguments + Constraints
  - If arguments contains binary operators
    → check integer overflow within given constraints

Check integer overflow with APISan

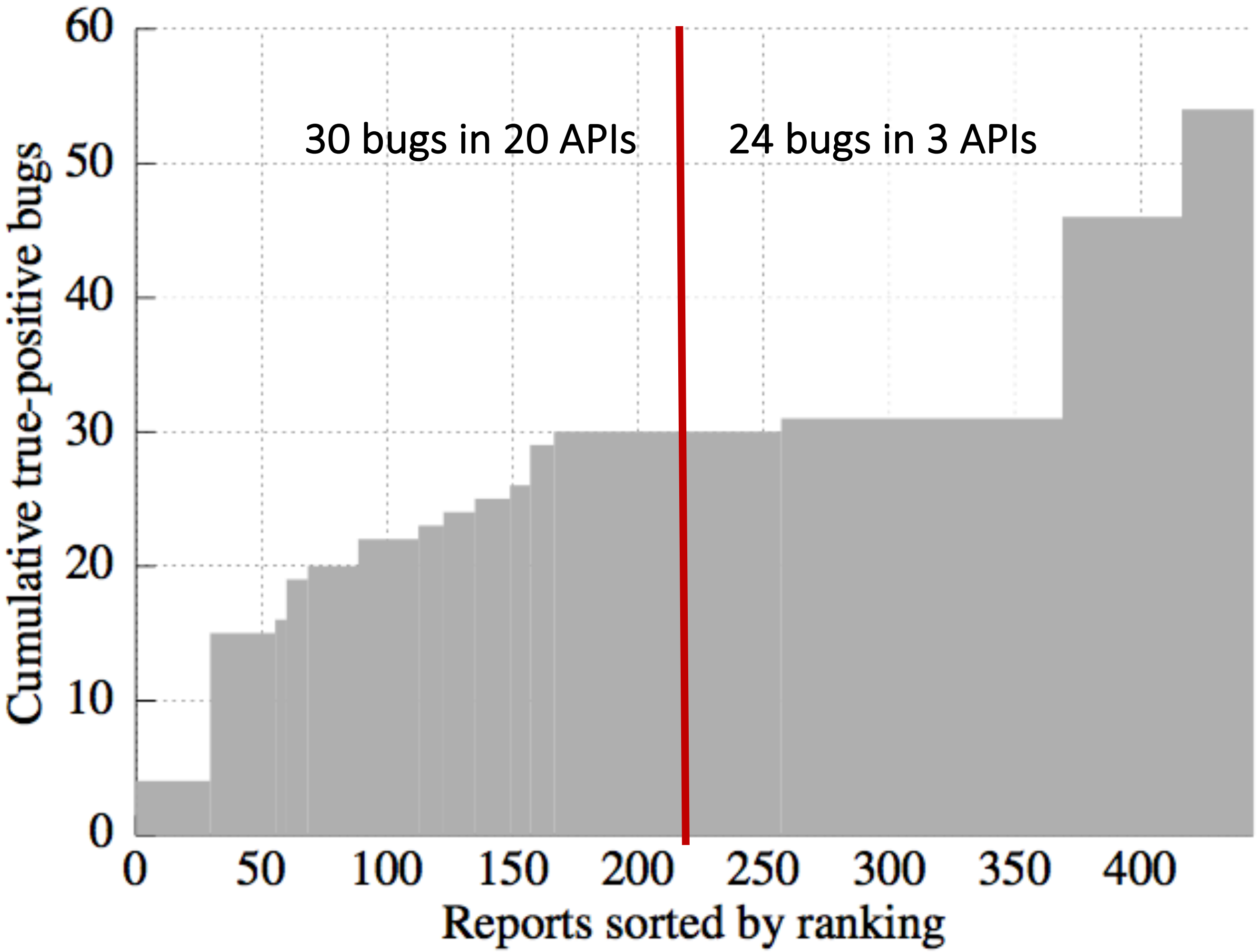
- Collect all integer overflows
- Ranking strategy
  - More integer overflow prevented by constraints
    → APIs are likely integer overflow sensitive
  - Incorrect constraints > Missing constraints
    ; Missing constraints can be caused by limited analysis
- Found 6 integer overflows (167 LoC)

APISan's ranking system is effective



- Linux Kernel
  with Return Value Checker
- Total 2,776 reports
- Audited 445 reports
- Found 54 bugs

APISan's ranking system is effective



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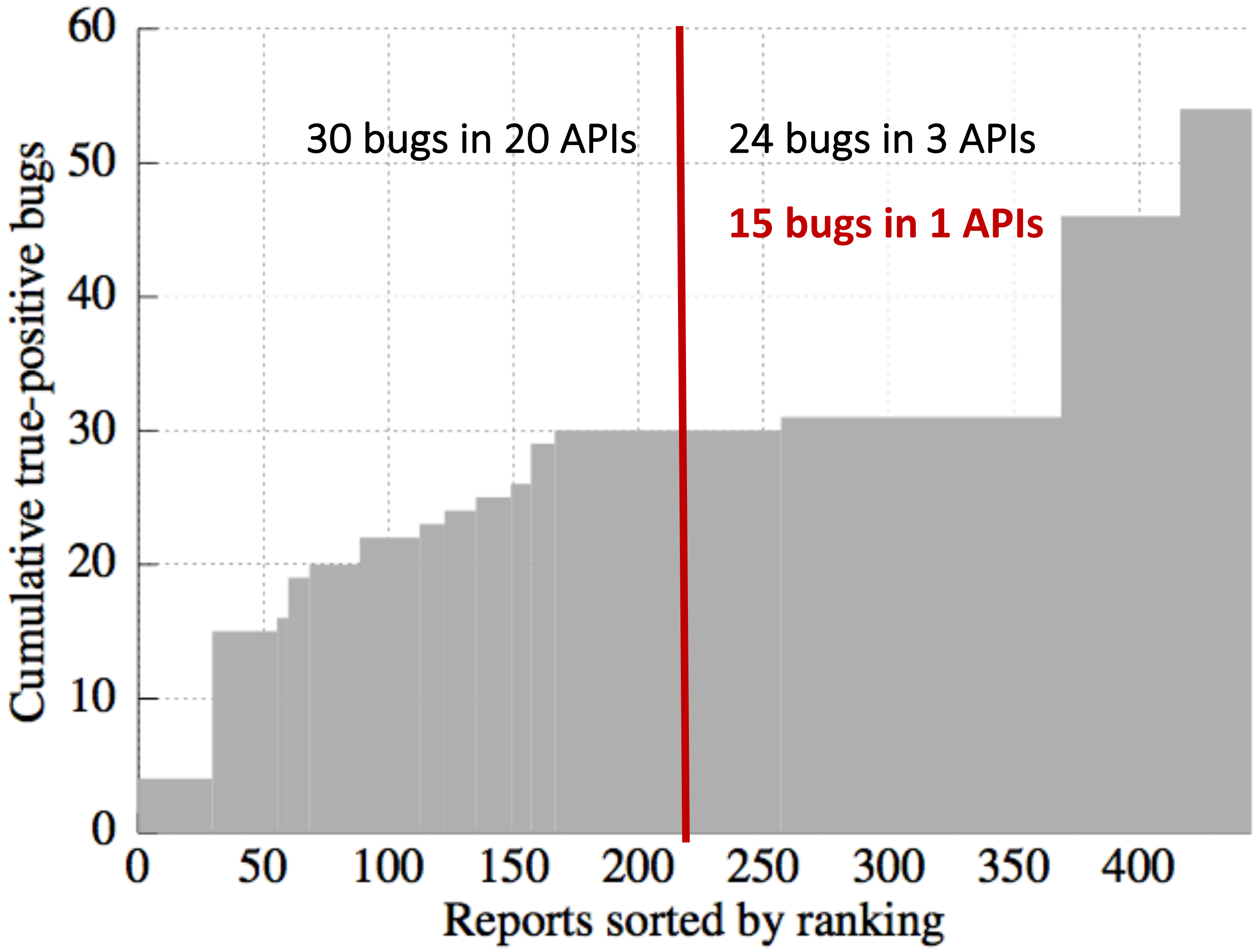

- Linux Kernel
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Limitation

- No soundness & No completeness
- High false positive rate : > 80%
- Too slow to frequently analyze
  - 32-core Xeon server with 256GB RAM
  - For Linux kernel,
    Generating database : 8 hours
    Each checker: 6 hours
- Not fully resolve path explosion
  - stopped in functions which have path explosion

Conclusion

- APISan: an automatic way for finding API misuse
  - Effective: Finding 76 new bugs
  - Scalable: Tested with Linux kernel, Debian packages, etc
- APISan *WILL* be released as open source
  - https://github.com/sslab-gatech

Thank you!

Questions?