Precisely Characterizing Security Impact in a Flood of Patches via Symbolic Rule Comparison

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Driven to Discover®

Why do we need to identify security bugs?

Motivation

- The overwhelming number of bugs reports
  - Mozilla: ~ 300 bugs reports per day
  - Linux kernel: More than 900K commits have been made
    - ~165 git commits per day

...

Motivation

- The overwhelming number of bugs reports
- Patch propagation in derivative programs is hard and expensive
    - Example: Many projects are derived from the Linux kernel

Motivation

- The overwhelming number of bugs reports
    - Security bugs may not be fixed timely, and attackers have opportunities to exploit these security bugs
- Patch propagation in derivative programs is hard and expensive

Maintainers are prioritizing to fix security bugs.
Unrecognized security bugs may be left unpatched!

Our goal:

Identify patches that are for security bugs

How to identify patches for security bugs?

Traditional approaches:

- Text-mining
  - Analyze textual information of patches to find security-related keywords.

- Statistical analysis
  - Differentiate patches of security bugs from general bugs by using statistical information.

Limitations:

1. Bad precision.
2. Cannot know the security impacts of bugs.

Limitations of traditional approaches:

CVE-2014-8133 Permission bypass

```
commit 41bdc78544b8a93a9c6814b8bbbfef966272abbe
Author: Andy Lutomirski <luto@amacapital.net>
Date:   Thu Dec 4 16:48:16 2014 -0800

    x86/tls: Validate TLS entries to protect espfix

    Installing a 16-bit RW data segment into the GDT defeats espfix.
    AFAICT this will not affect glibc, Wine, or dosemu at all.

    Signed-off-by: Andy Lutomirski <luto@amacapital.net>
    Acked-by: H. Peter Anvin <hpa@zytor.com>
    Cc: stable@vger.kernel.org
    Cc: Konrad Rzeszutek Wilk <konrad.wilk@oracle.com>
    Cc: Linus Torvalds <torvalds@linux-foundation.org>
    Cc: security@kernel.org <security@kernel.org>
```

We prefer a program analysis--based method

- Understand the semantics of patches and bugs precisely
- A bug is a security bug if it causes *security impacts* when triggered.
- A patch is for a security bug when it blocks the security impacts

How to know if a patch blocks security impacts?

A security impact = A security-rule violation

Security rules are coding guidelines used to prevent security bugs.

Security-rule violations cause security impacts.
We thus check if a patch blocks security-rule violations

Common security rules

Rule 1: In-bound access

Read & write operations should be within the boundary of the current object.

Rule 2: No use after free

An object pointer should not be used after the object has been freed.

Rule 3: Use after initialization

A variable should not be used until it has been initialized.

Rule 4: Permission check before sensitive operations

Permissions should be checked before performing sensitive operations, such as I/O operations.

Violations for common security rules

Rule 1: In-bound access

↓ violation

Out-of-bound access

Rule 2: No use after free

↓ violation

Use-after-free

Rule 3: Use after initialization

↓ violation

Uninitialized use

Rule 4: Permission check before sensitive operations

↓ violation

Permission bypass

A patch blocks security impacts if:

If we can prove the following conditions:

Condition 1: The unpatched version of code violates a security rule.

Condition 2: The patched version of code does **not** violate the security rule.

Challenge:

How to precisely determine the security-rule violations?

Intuition:

We can leverage **two unique properties** of **under-constrained symbolic execution**.

Property 1: Constraints model violations

Security-rule violations can be modeled as constraints

Example:

Buffer access: Buffer[Index];

Constraints for out-of-bound access:

Index $\geqslant$ ***UpBound***, and/or ***Index*** $\leqslant$ ***LowBound***

Property 2: Conservativeness

Under-constrained symbolic execution is conservative.

- False-positive solutions
  - If the constraints are solvable, this can be a false positive.
- Proved unsolvability
  - If it cannot find a solution against constraints, they are indeed unsolvable.

Leverage the properties for determining the security-rule violations

- Patch-related operations can be modeled as symbolic constraints

- To show the patched version won't violate a security rule
  - To prove "**violating**" is unsolvable
- To show the unpatched version will violate the security rule
  - To prove "**non-violating**" is unsolvable

Our approach: Symbolic rule comparison

1. Construct opposite constraint sets for the patched and unpatched version
   a. Patched version: Construct constraints for violating security rules
   b. Unpatched version: Construct constraints for not violating security rules
2. Check the ***unsolvability*** of these constraint sets
3. Confirm the patches for security bugs if both constraint sets are unsolvable

Rationale behind our approach

- For a security rule, the patched version NEVER violate it
    - This means that the patched version is in a safe state

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- The patch changes the code from an unsafe state to a safe state
  - Precisely confirmed with property 2

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  - This means that the unpatched version is in an unsafe state
- The patch changes the code from an unsafe state to a safe state

The patch fixed a security bug with the security impact that corresponding to the security rule violation.

A concrete example

STEP 1: Symbolically analyzing patched code

```
// CVE-2012-6712
int iwl_sta_ucode_activate(... , u8 sta_id) {
+       if (sta_id >= IWLAGN_STATION_COUNT) {
+               IWL_ERR(priv, "invalid sta_id %u", sta_id);
+               return -EINVAL;
+       }

        if (!(priv->stations[sta_id].used ))
                IWL_ERR(priv,"Error active station id %u "
                    "addr %pM\n",
                    sta_id, priv->stations[sta_id].sta.sta.addr);

        ...
        return 0;
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Identify security operations.

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Extract critical variable.

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Slicing

Identify vulnerable operations.

STEP 2: Collecting and construct constraints for patched code

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+     }

      if (!(priv->stations[sta_id].used ))
              IWL_ERR(priv,"Error active station id %u "
                  "addr %pM\n",
                  sta_id, priv->stations[sta_id].sta.sta.addr);

      ...
      return 0;
}
```

Collecting constraints

Constraints source	Constraints
Security operations	sta_id < IWLAGN_STATION_COUNT
Slice	N/A
Artificial constraints (Security rules)	sta_id >= Bound of priv->stations

Violating security rules

STEP 3: Solving constraints for patched code

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// CVE-2012-6712
int iwl_sta_ucode_activate(... , u8 sta_id) {
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These constraints are unsolvable!

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                    sta_id, priv->stations[sta_id].sta.sta.addr);

        ...
        return 0;
}
```

The patched version **won't** violate the security rule.

These constraints are unsolvable!

STEP 1’: Symbolically analyzing unpatched code

```
// CVE-2012-6712
int iwl_sta_ucode_activate(... , u8 sta_id) {





        if (!(priv->stations[sta_id].used ))
                IWL_ERR(priv,"Error active station id %u "
                   "addr %pM\n",
                   sta_id, priv->stations[sta_id].sta.sta.addr);

        ...
        return 0;
}
```

Identify vulnerable operations.

STEP 1’: Symbolically analyzing unpatched code

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int iwl_sta_ucode_activate(... , u8 sta_id) {





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        ...
        return 0;
}
```

Extract critical variable.

Identify vulnerable operations.

STEP 1’: Symbolically analyzing unpatched code

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        ...
        return 0;
}
```

Slicing

Extract critical variable.

Identify vulnerable operations.

STEP 2’: Collecting and construct constraints for unpatched code

```
// CVE-2012-6712
int iwl_sta_ucode_activate(... , u8 sta_id) {






        if (!(priv->stations[sta_id].used ))
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Collecting constraints

Constraints source	**Constraints**
Security operations	-
Slice	-
Artificial constraints (Security rules)	sta_id < Bound of priv->stations

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Collecting constraints

Constraints source	Constraints
Security operations	sta_id >= IWLAGN_STATION_COUNT
Slice	-
Artificial constraints (Security rules)	sta_id < Bound of priv->stations

Non-violating security rules

STEP 3’: Solving constraints for unpatched code

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// CVE-2012-6712
int iwl_sta_ucode_activate(... , u8 sta_id) {
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        return 0;
}
```

Slicing & Collecting constraints

Constraints source	Constraints
Security operations	sta_id >= IWLAGN_STATION_COUNT
Slice	-
Artificial constraints (Security rules)	sta_id < Bound of priv->stations

These constraints are also unsolvable!

STEP 3': Solving constraints for unpatched code

```
// CVE-2012-6712
int iwl_sta_ucode_activate(... , u8 sta_id) {




        if (!(priv->stations[sta_id].used ))
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        ...
        return 0;
}
```

The unpatched version MUST violate the security rule.

These constraints are also unsolvable!

STEP 4: Symbolic rules comparison

- The constraints for patched version are unsolvable!
  - "Violating security rules" is unsolvable
  - Patched version does not have an out-of-bound access

- The constraints for unpatched version are unsolvable!
  - "NOT violating security rules" is unsolvable
  - Unpatched version has out-of-bound accesses

Conclusion: The patch blocks an out-of-bound access.

Advantages of our approach

- Very few false positives --- Special use of under-constrained symbolic execution
  - ***97%*** precision rate

- Determine security impacts of bugs
  - By detecting security rules violations, it can identify security bugs and also their security impacts

- Easy to extend
  - To cover more kinds of security impacts, users just need to model more types of security rules

Implementation

- Our prototype: SID
  - Based on LLVM

- Currently support five types of common security impacts
  - Out-of-bound access, permission bypass, uninitialized use, use-after-free, and double-free

Evaluation

Performance

- We analyzed 54K patches
- The experiments were performed on a desktop with 32GB RAM and 6 core Intel Xeon CPU
- The analysis takes an average of 0.83 seconds for each patch.

False-positive and false-negative analysis

- Few false positives
  - We confirmed 227 security bugs with 8 false-positive cases.
- False negatives (can be reduced)
  - 53% false negatives.
  - Most of them are caused by incomplete coverage for security and vulnerable operations.

Security evaluation for identified security bugs

- Security impacts
  - Already confirmed by SID

- Reachability
  - Check the call chain from entry points to vulnerable functions

Security evaluation for identified security bugs

- Vulnerability confirmation for CVE
  - ***54*** CVEs confirmed out of 227 identified bugs.
  - 117 security bugs are still under review.

- Reachability analysis for security bugs
  - ***28*** dynamically confirmed bugs (fuzzers).
  - ***154*** are reachable from attacker controllable entry points, such as system calls.

- ***21*** security bugs still unpatched in the Android kernel.

Conclusions

- Timely patching of security bugs requires the determination of security impacts
  - Patch propagation is hard and expensive
  - So maintainers have to prioritize to fix the security bugs.
- We exploit the properties of under-constrained symbolic execution for the determination
  - Our novel approach: **Symbolic rule comparison**
- Identified many overlooked security bugs in the kernel
  - They may cause critical security consequences

Security impacts, security rules violation, and fixes

Main security impacts	Security rules violation	Common fixes
Out-of-bound access (16.5%)	Read/Write out of boundary	Add bound check (79%)
Uninitialized use (13.7%)	Use before initialization	Add initialization (78%)
Permission bypass (21.9%)	Sensitive operations without perm check	Add permission check (59%)
Use-after-free, double-free (4.3%)	Use freed pointer	Add nullification (32%)
...	...	...

(See II. BACKGROUND)

Modeling different types of security bugs

Security operation	Patched version	Unpatched version
Pointer nullification	$FLAG_{CV} = 1$	$FLAG_{CV} = 0$
Initialization	$FLAG_{CV} = 1$	$FLAG_{CV} = 0$
Permission check	$FLAG_{CV} = 1$	$FLAG_{CV} = 0$
Bound check	$CV < UpBound$, or $CV > LowBound$	$CV \geqslant UpBound$, resp. $CV \leqslant LowBound$

Constraints for security operations from patches. $Flag_{CV}$: Flag symbol; CV: critical variable ; UpBound: checked upper bound; LowBound: checked lower bound.

Modeling different types of security bugs

Security rules	Patched version	Unpatched version
No use after free	$FLAG_{CV} = 0$	$FLAG_{CV} = 1$
Use after initialization	$FLAG_{CV} = 0$	$FLAG_{CV} = 1$
Permission check before sensitive operations	$FLAG_{CV} = 0$	$FLAG_{CV} = 1$
In-bound access	$CV \geqslant MAX$, or/and $CV \leqslant MIN$	$CV < MAX$, resp. $CV > MIN$

Constraints from security rules. $Flag_{CV}$: Flag symbol; CV: critical variable; MAX: maximum bound of the buffer; MIN: minimum bound of the buffer

Generality of patch model

- The existence of three key components in vulnerabilities
  - ***77%*** vulnerabilities contains all of three key components
  - ***11%*** vulnerabilities contains part of key components
- After extending, SID can support the security-impact determination for them (See VII. DISCUSSION)

What is the common model of patches for security bugs?

Common patch model and key components

// Unpatched program

```
Vulnerable_operation(Critical variable, … ) ;
```

Common patch model and key components

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Vulnerable_operation(Critical variable, … ) ;
```

Violate security rules

Common patch model and key components

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```
Vulnerable_operation(Critical variable, … ) ;
```

Violate security rules → Security impacts

Common patch model and key components

```
// Patched program
Security_operation(Critical variable, … );
+ Vulnerable_operation(Critical variable, … ) ;
```

Violate security rules → Security impacts

Common patch model and key components

```
// Patched program
Security_operation(Critical variable, … );
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```

Fix

Violate security rules → Security impacts

Common patch model and key components

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Security_operation(Critical variable, … );
+ Vulnerable_operation(Critical variable, … ) ;
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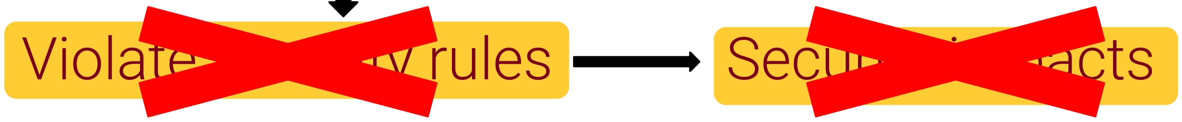
→ Fix



NOT Violate security rules