Efficient Patch-based Auditing for Web Application Vulnerabilities

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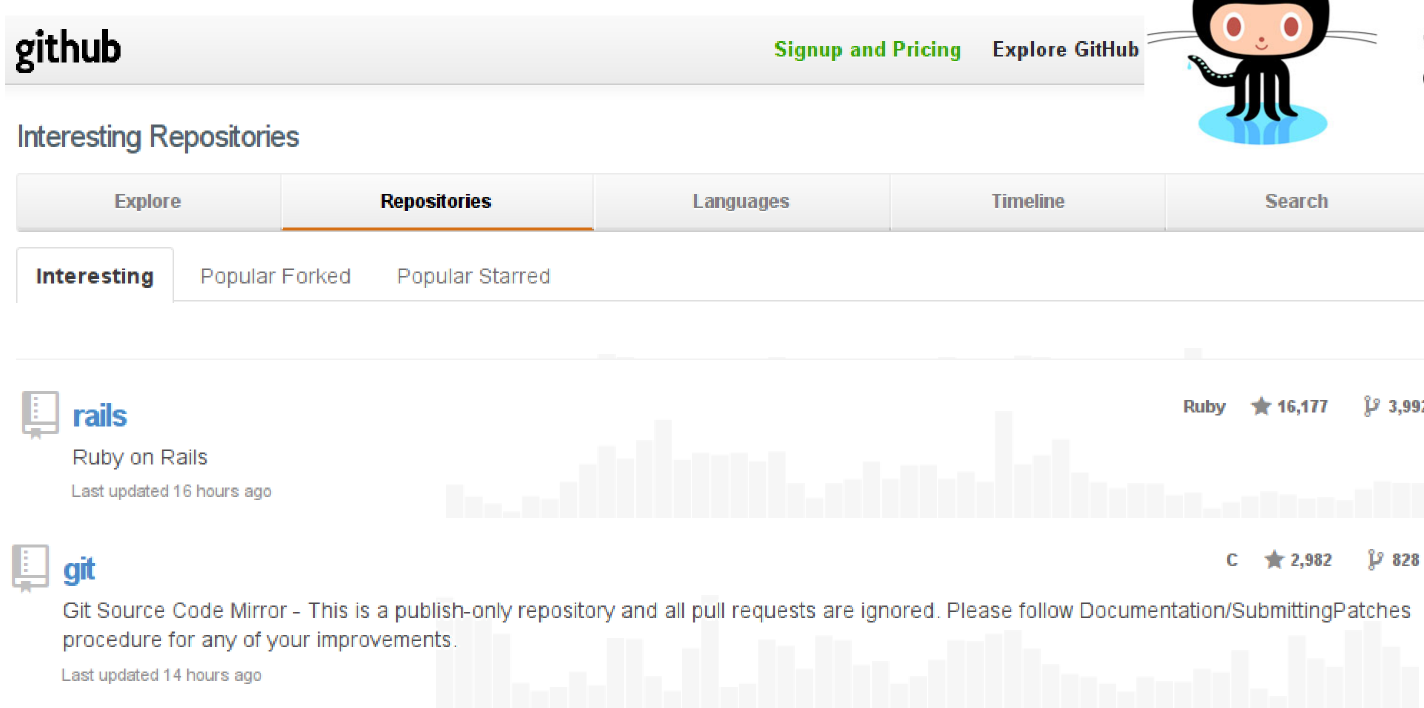
MIT CSAIL

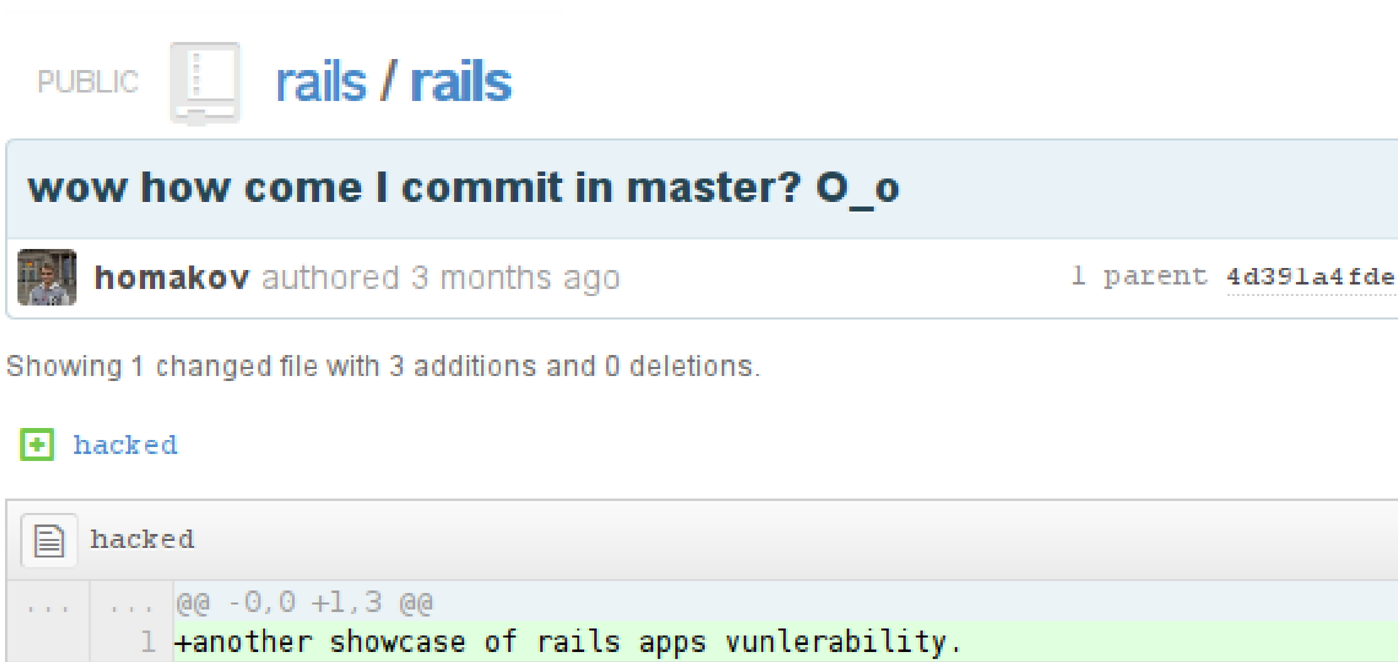
Example: Github

- Github hosts projects (git repository)
- Users have own projects
- **Authentication** based on **SSH public key**



Vulnerability: attacker can modify any user's public key

- Publicly announced in March 2012
- **Unauthorized user** modified Ruby-on-Rails project after **modifying** a developer's **public key**.

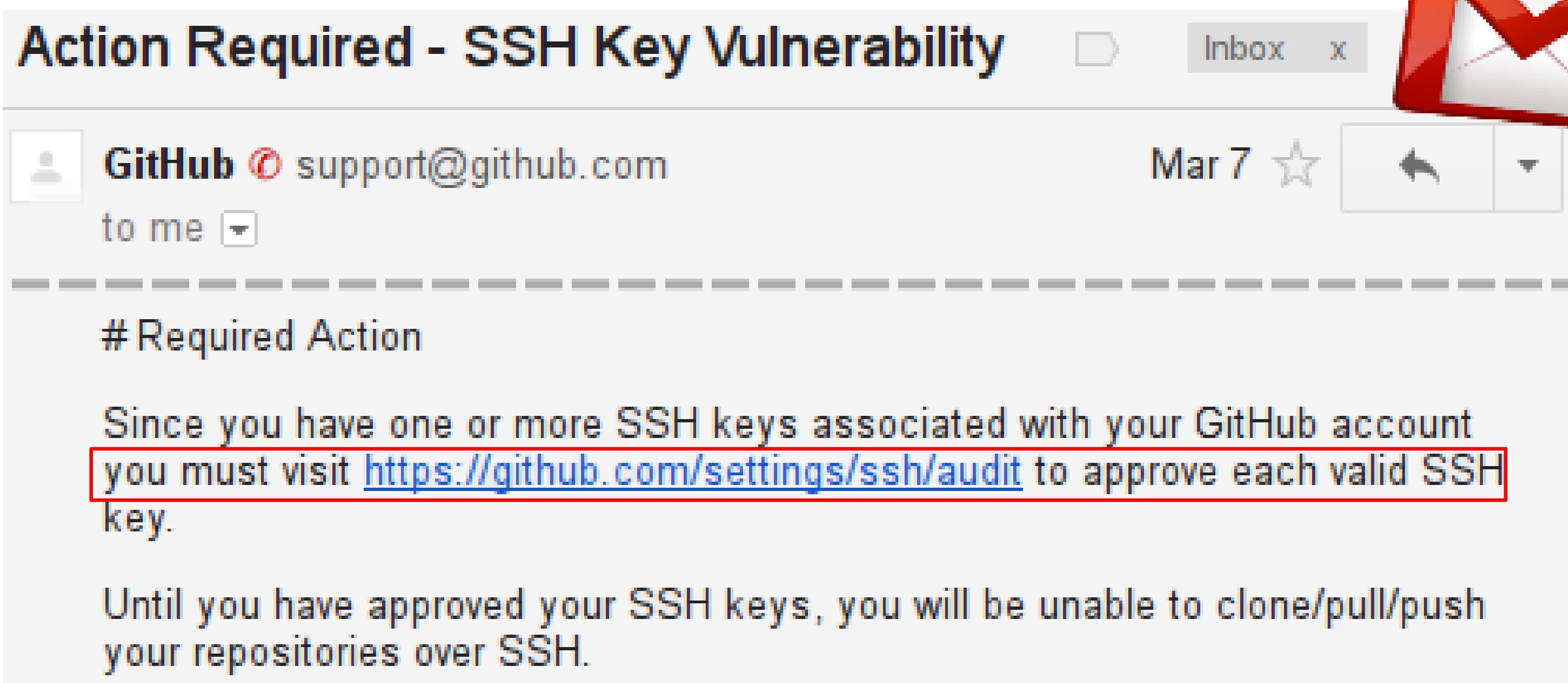


Problem: who exploited this vulnerability?

- Other attackers may have known about the vulnerability **for months or years**
- Adversaries could have modified many users' public keys, repositories, etc.
- **Ideally**, would like to detect **past attacks** that exploited this vulnerability

Github's actual response

- Immediately **blocked** all users
- **Asked** users to **audit** own public key


Action Required - SSH Key Vulnerability Inbox x

GitHub support@github.com Mar 7
to me

Required Action

Since you have one or more SSH keys associated with your GitHub account you must visit https://github.com/settings/ssh/audit to approve each valid SSH key.

Until you have approved your SSH keys, you will be unable to clone/pull/push your repositories over SSH.

Detecting past attacks is hard

- Current tools require **manual** log analysis
- Logs may be **incomplete**
- Logs may be **large** (Github: 18M req/day)

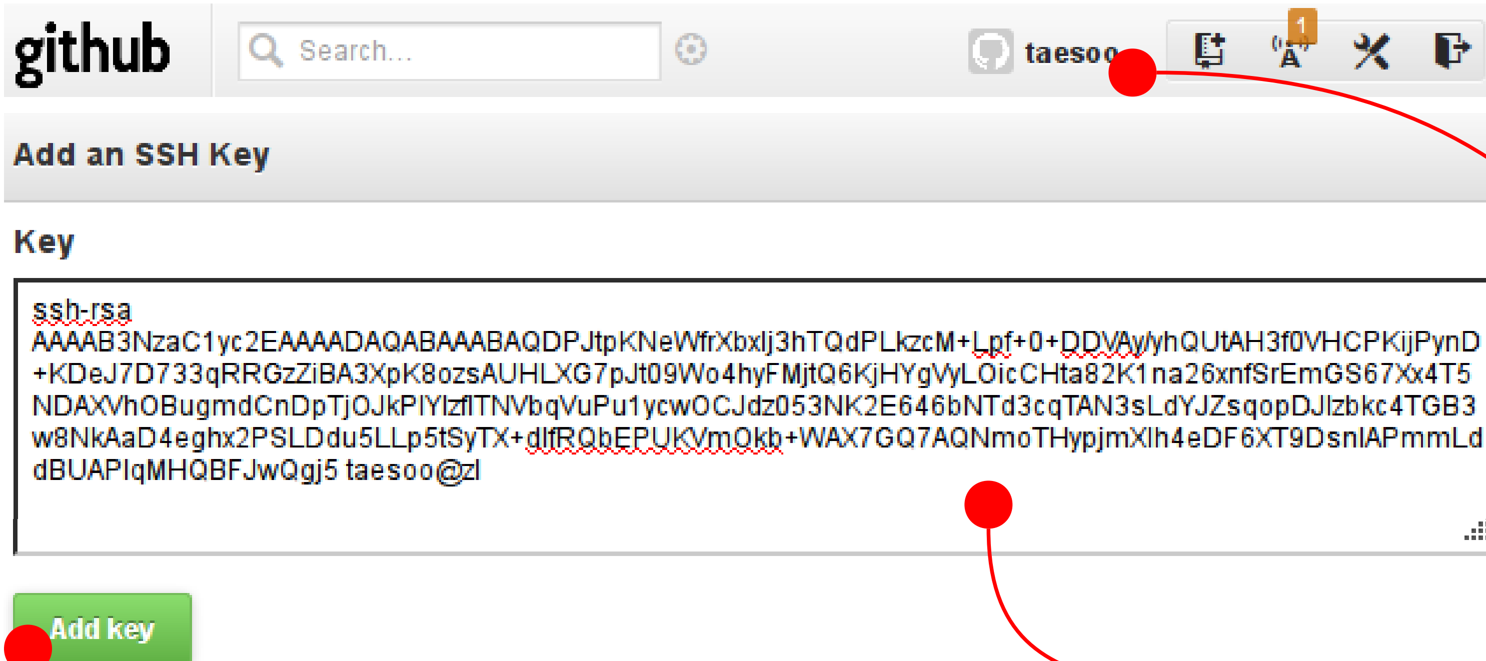
Too many vulnerabilities to inspect manually

- CVE database: 4,000 vulnerabilities per year
- Hard enough for administrator to apply patches
- Auditing each vulnerability for past attacks is impractical

Approach: automate auditing using patches

- **Insight**: security **patch** renders attack **harmless**
- **Technique**: compare execution of each request **before** and **after** patch is applied
  - Same result: no attack
  - **Different** results: **potential attack!**

Example: Github vulnerability




```
<form>
  <input type="text" name="key">
  <input type="hidden" value="taesoo" name="id" >
</form>
```

Example: Github vulnerability

```
params = {
    "key" => "ssh-rsa AAA … ",
    "id"  => "taesoo"
}
```

```
def update_pubkey
  @key = PublicKey.find_by_id(params['id'])
  @key.update_attributes(params['key'])
end
```

Example: Github vulnerability

attacker?

```
params = {
    "key" => "ssh-rsa AAA … ",
    "id"  => "taesoo"
}
```

```
def update_pubkey
  @key = PublicKey.find_by_id(params['id'])
  @key.update_attributes(params['key'])
end
```

Example: Github vulnerability

```
params = {
    "key" => "attacker's public key",
    "id"  => "victim"
}
```

Attackers can **overwrite** any user's public key, and thus can **modify** user's repositories.

```
def update_pubkey
  @key = PublicKey.find_by_id("victim")
  @key.update_attributes("attacker's public key")
end
```

Simplified patch for Github's vulnerability

```
   def update_pubkey
-    @key = PublicKey.find_by_id(params['id'])
+    @key = PublicKey.find_by_id(cur_user.id)
     @key.update_attributes(params['key'])
   end
```

Login-ed user's id

Patch-based auditing finds attack

- **Replay** each request using old(-) & new(+) code
- Attack request generates **different** SQL queries

```
  def update_pubkey
-   @key = PublicKey.find_by_id(params['id'])
+   @key = PublicKey.find_by_id(cur_user.id)
    @key.update_attributes(params['key'])
  end
```

```
- UPDATE … WHERE KEY=… ID=victim
+ UPDATE … WHERE KEY=… ID=attacker
```

Challenge: auditing many requests

- Necessary to audit **huge amount** of requests
  - Vulnerability may have existed for a long time
  - Busy web applications may have **many requests** (Github: 18M req/day)

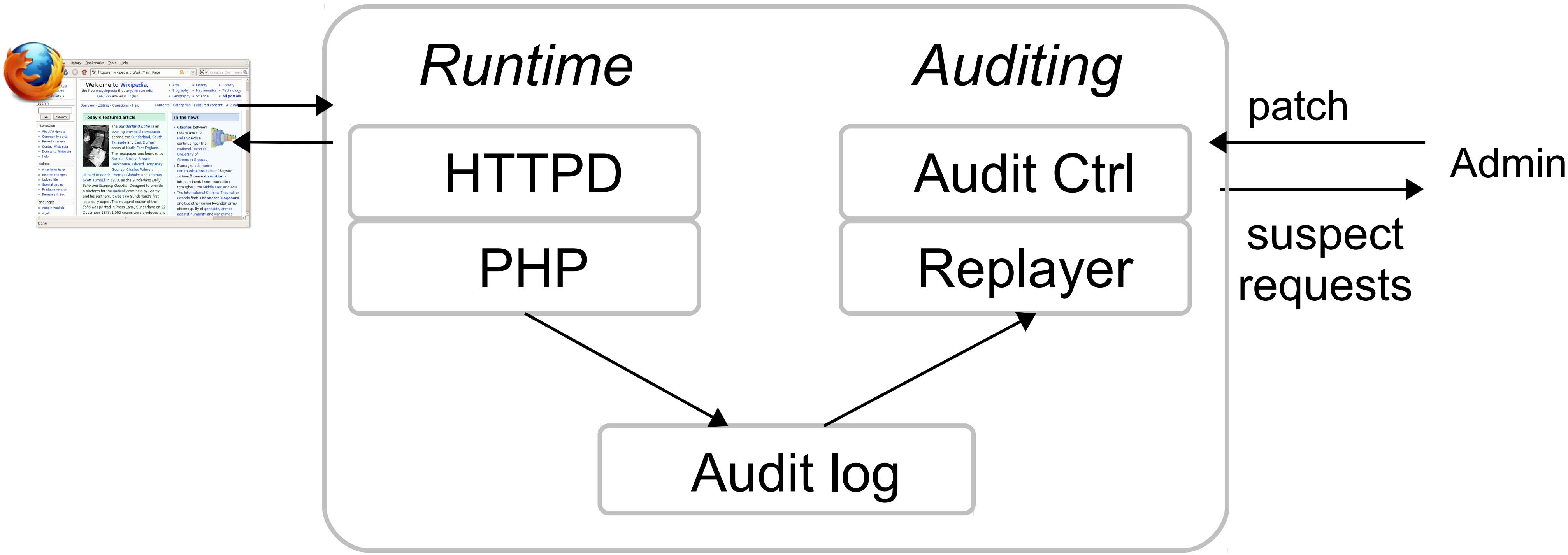
- Auditing **one** month traffic requires **two** months
  - Naive approach requires **two re-executions** (old & new code) per request

Contribution

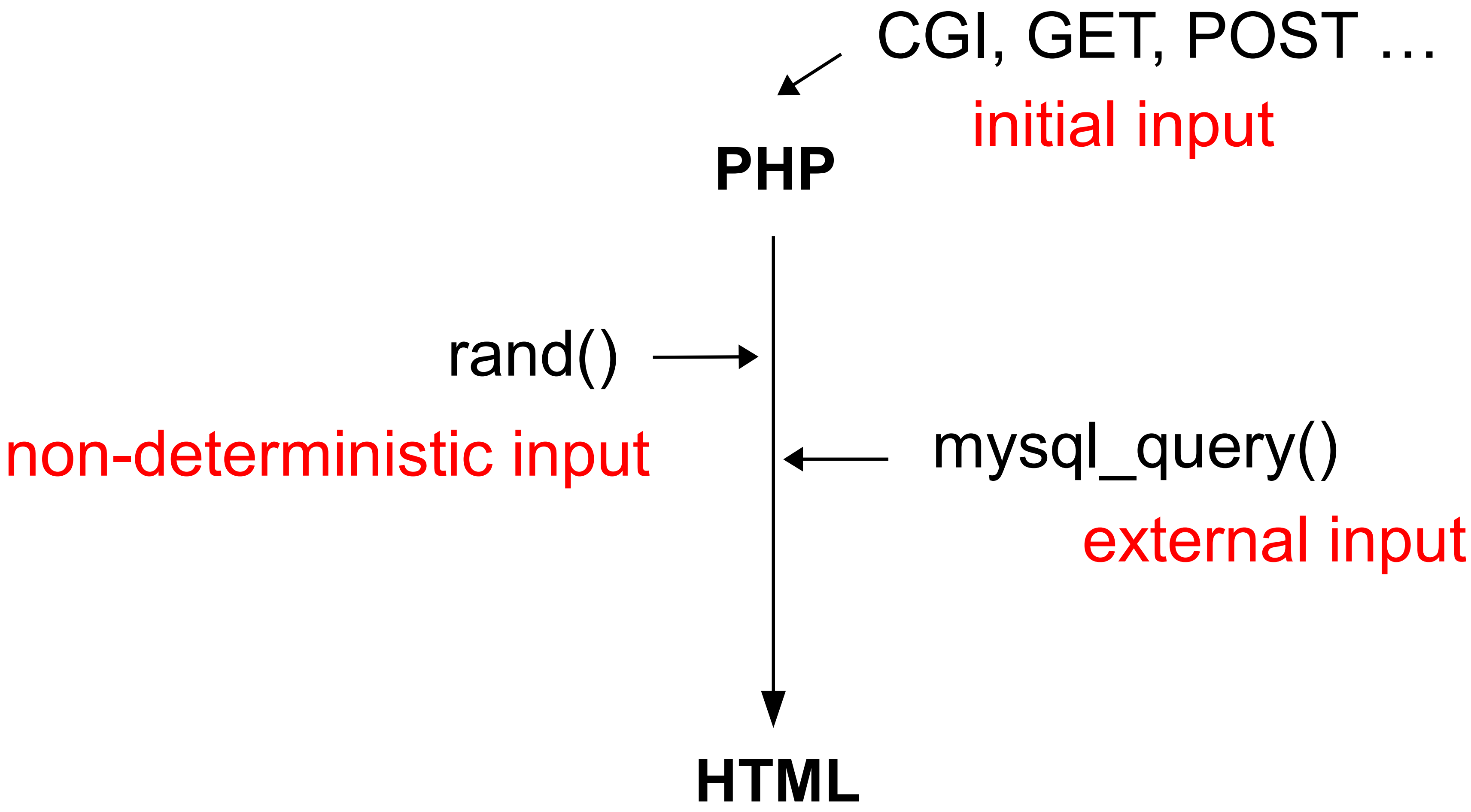
- **Efficient** patch-based auditing for web apps.

- **12 – 51x** faster than original execution for **challenging patches**
  - Worst case, auditing one month worth of requests takes 14 – 60 hours

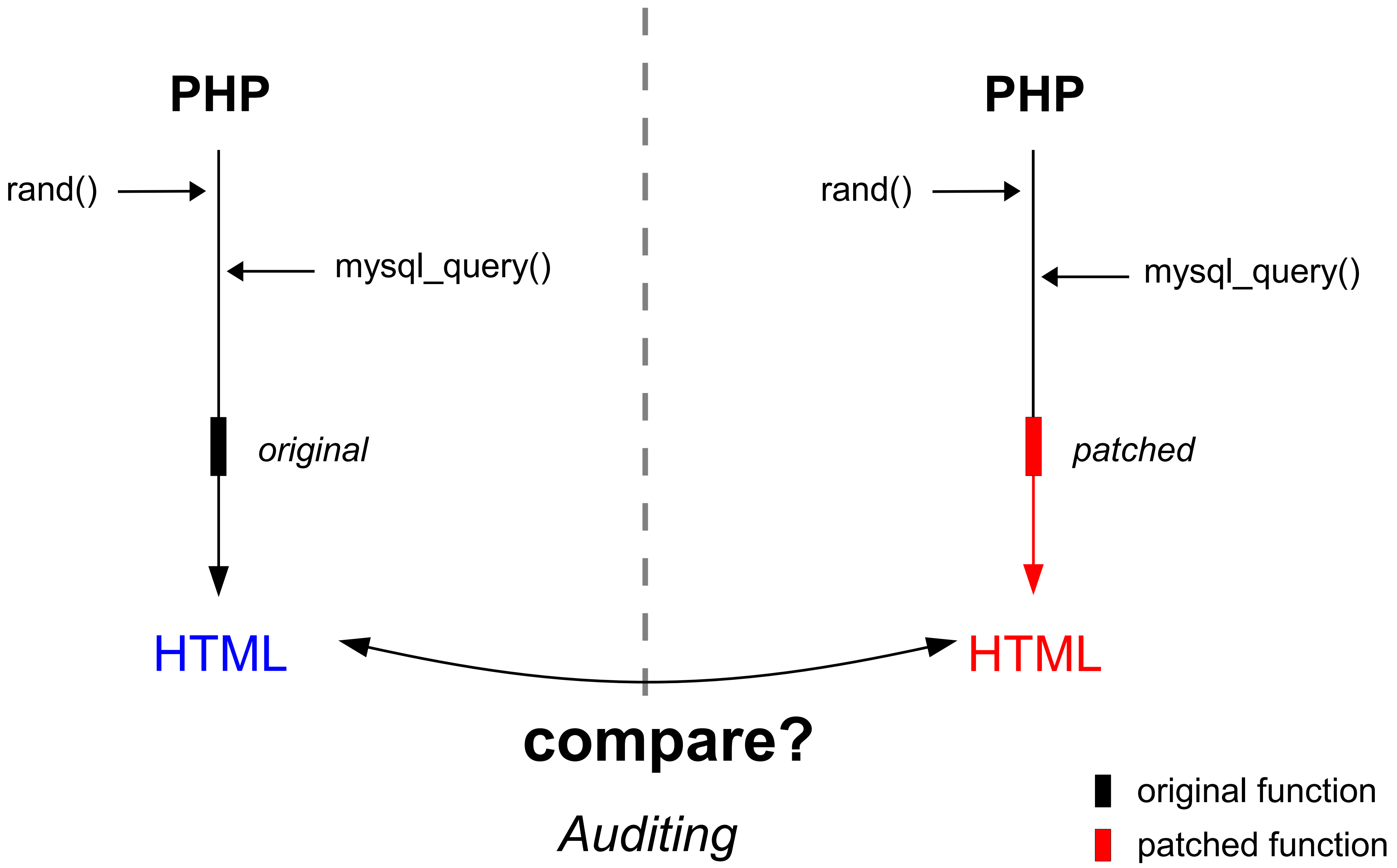
Overview of design



Logging during normal execution

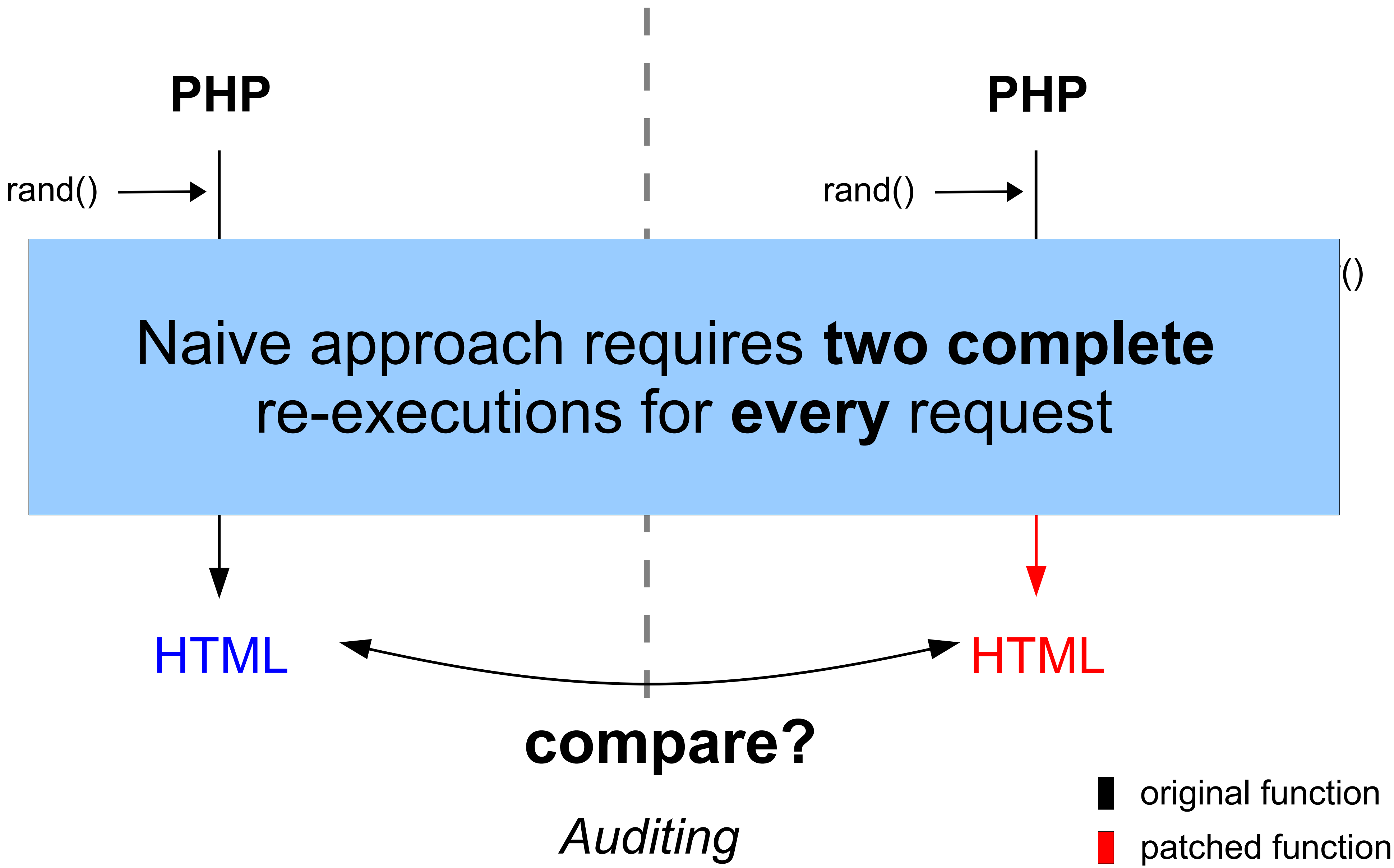


Auditing a request



Auditing

Auditing a request



Naive approach requires **two complete** re-executions for **every** request

Opportunities to improve auditing performance

- Patch might **not affect** every request
  - How to determine affected requests?
- Original and patched runs execute **common code**
  - How to **share** common code during re-execution?
- **Multiple requests** execute similar code
  - How to **reuse** similar code across **multiple** requests?

Key ideas

- **Idea 1: Control flow filtering**
  - Auditing only affected requests
- **Idea 2: Function-level auditing**
  - Sharing common code during re-execution
- **Idea 3: Memoized re-execution**
  - Reusing memoized code across multiple requests

Idea 1: Control flow filtering

- Step 1: Normal execution
  - Record the **control flow trace** (**CFT**) of each request

- Step 2: Indexing
  - Map the control flow trace (CFT) to the **basic blocks**

- Step 3: Auditing
  - Compute the **basic blocks modified** by the **patch**
  - **Filter out** requests if did **not execute** any patched basic blocks

Static analysis of source code

- Computing **basic blocks** of source code

start

```
function get_name() {
  return $_GET['name'];
}

if ($_GET['q'] == 'echo') {
  echo get_name();
}
```

Static analysis of source code

- Computing **basic blocks** of source code

```
function get_name() {
  return $_GET['name'];
}
if ($_GET['q'] == 'echo') {
  echo get_name();
}
```

start

JMP,BRK …

Recording control flow trace

- Normal execution:

  logging **control flow trace (CFT)** of each request

```
/s.php?q=test
```

```
① function get_name() {
②   return $_GET['name'];
③ }
                                'test'!='echo'
④ if ($_GET['q'] == 'echo') {
⑤   echo get_name();
⑥ }
```

start

CFT: [④,⑥] **(file, scope, func, #instruction)**

Computing executed basic blocks

- Indexing:

  computing **executed basic blocks** of each request

Basic Blocks

[①,②,③]

√ [④]

[⑤]

√ [⑥]

```
/s.php?q=test

① function get_name() {
②   return $_GET['name'];
③ }

④ if ($_GET['q'] == 'echo') {
⑤   echo get_name();
⑥ }
```

Computing modified basic blocks

- Auditing:

  compute the basic blocks **modified** by the **patch**

Basic Blocks

√ [①,②,③]

[④]
[⑤]
[⑥]

```
 ① function get_name() {
-②     return $_GET['name'];
+②     return sanitize($_GET['name']);
 ③ }

 ④ if ($_GET['q'] == 'echo') {
 ⑤     echo get_name();
 ⑥ }
```

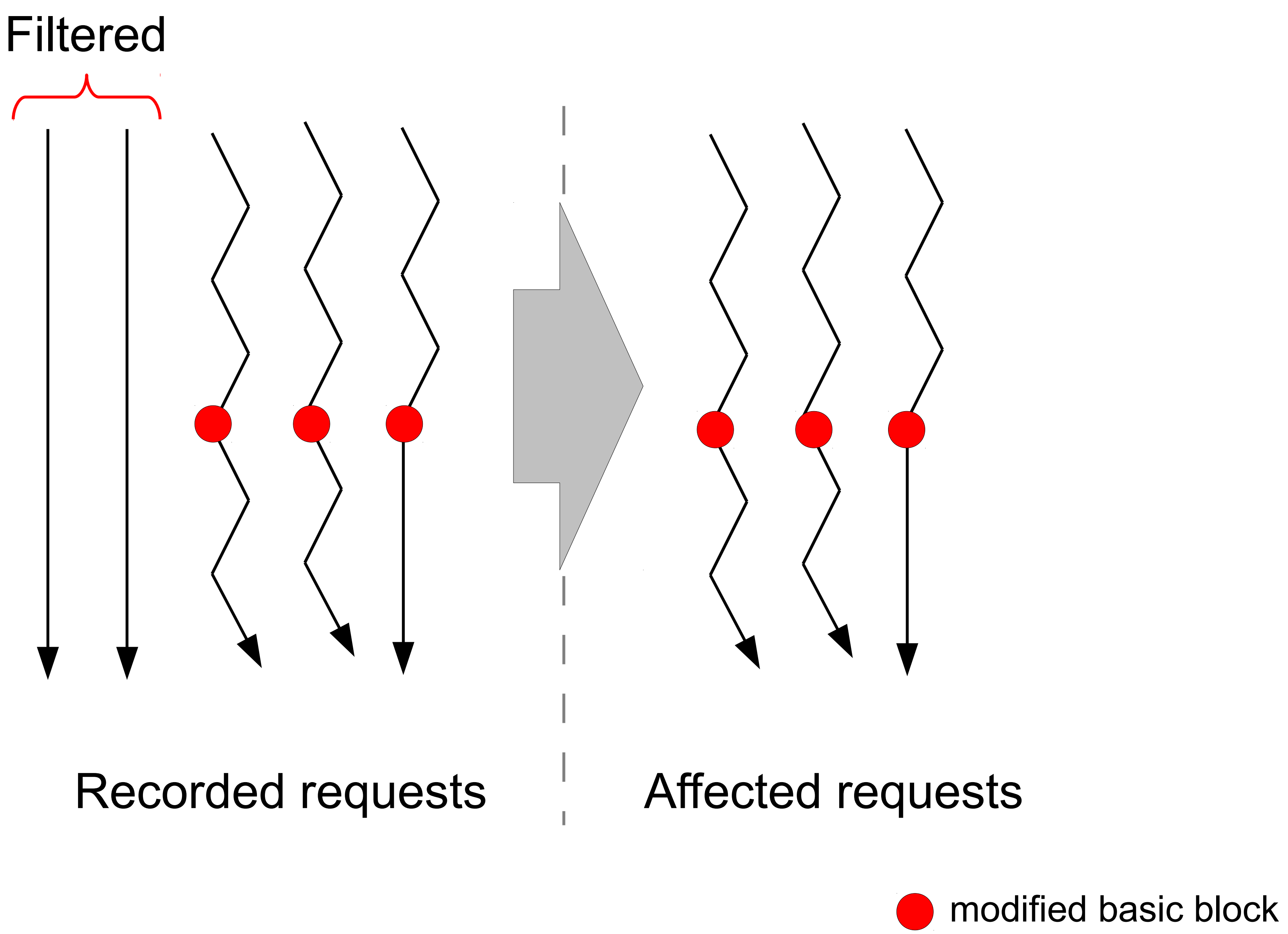
Comparing basic blocks

- Auditing:

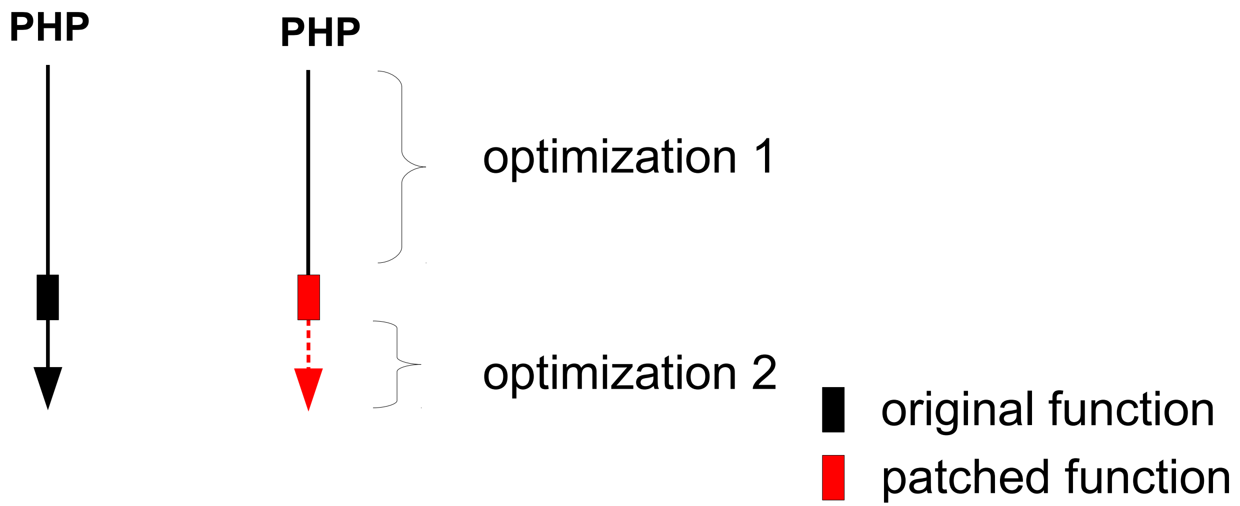
  filter out the requests that did not execute patched basic blocks

Executed	Patched
[①,②,③]	√ [①,②,③]
√ [④] [⑤] √ [⑥]	[④] [⑤] [⑥]

Summary: control flow filtering

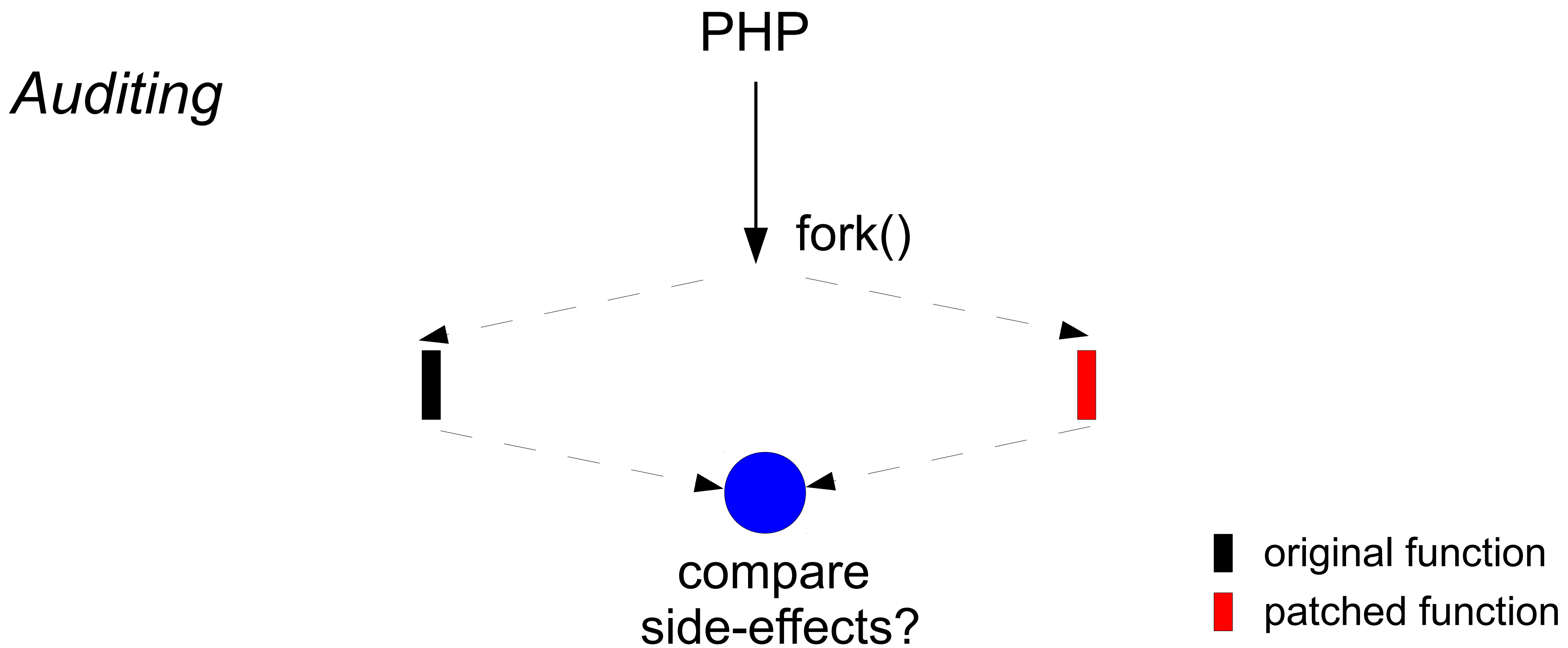


Idea 2: Function-level auditing



- Optimization 1: sharing common code
  - **Share code** up to the patched function
- Optimization 2: early termination
  - **Stop** after the last invocation of the patched functions

Function-level auditing



- **Intercept** side-effects **inside** the patched functions
- **Stop** after the **last** invocation of the patched functions
- **Compare** intercepted **side-effects**

Intercepting side-effects

global writes

(e.g., global, class)

```
class PublicKey {
  …
  function update($key) {
    $this->last = date();
    echo "updated";
    $rtn = mysql_query("UPDATE … $key …");
    return $rtn;
  }
  …
}
```

html output

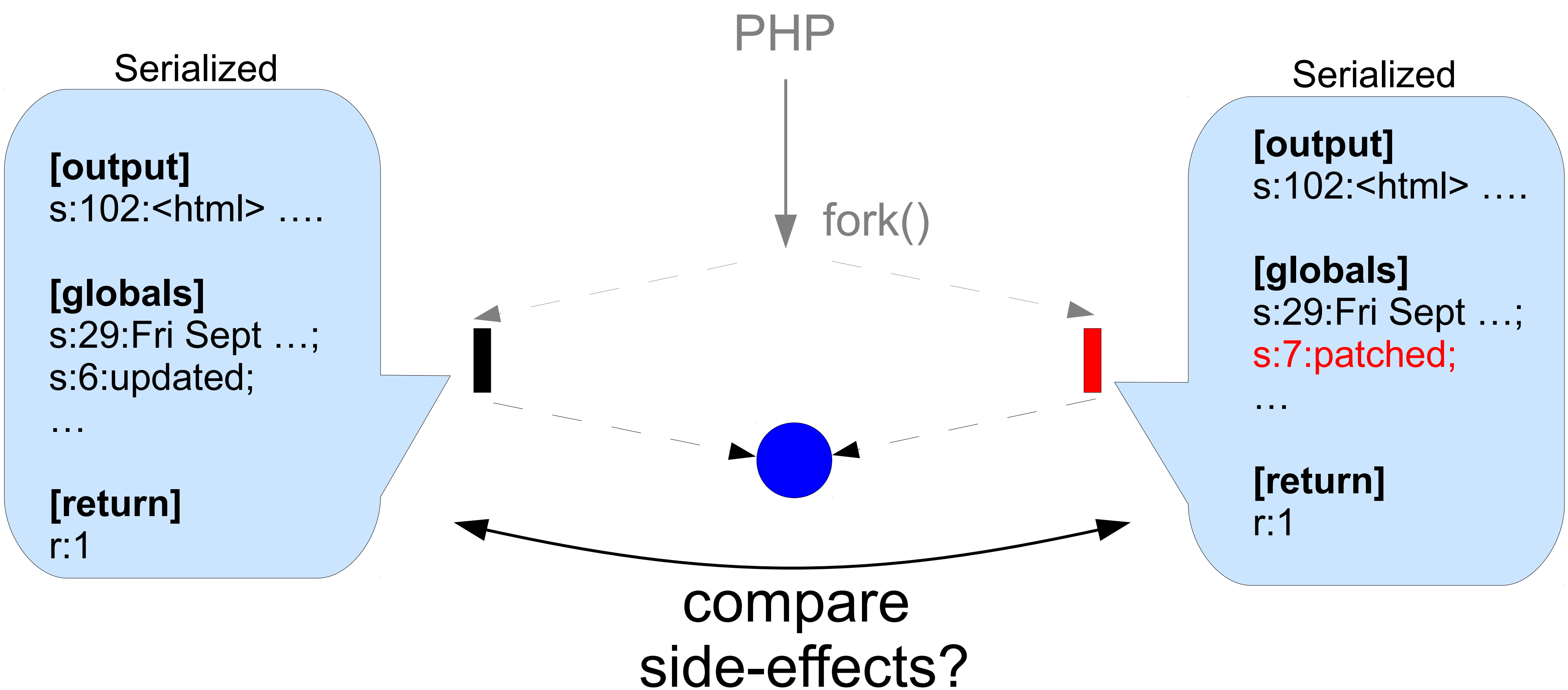
return value

external calls

(e.g., header, sql-query …)

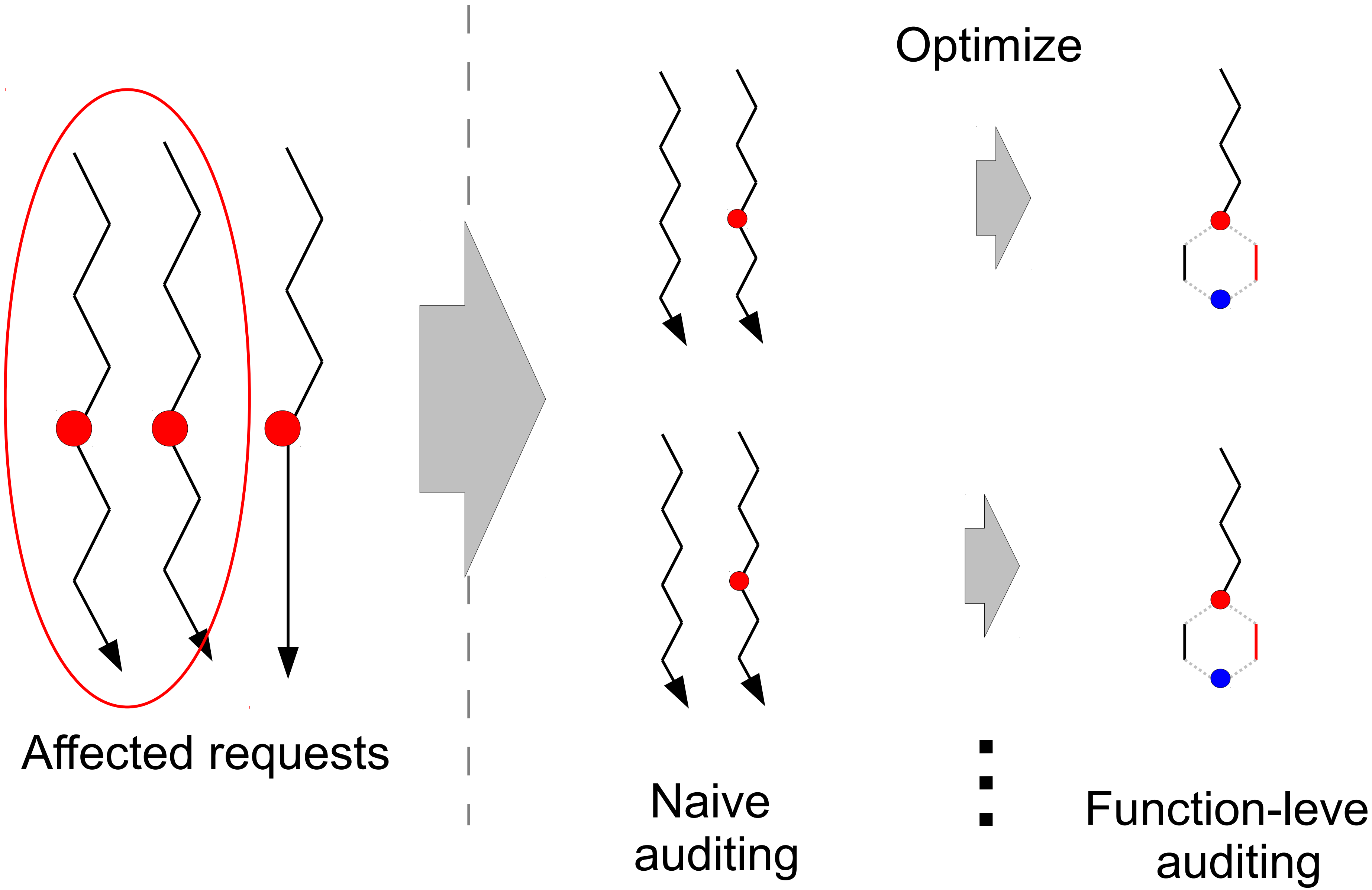
<the worst case example>

Comparing side-effects



- If **different**, **mark** the request **suspect**
- If **same**, **stop** and audit next request

Summary: function-level auditing



Idea 3: Memoized re-execution

- **Motivation**: many requests run **similar** code

```
1)/s.php?q=echo&name=alice
```

CFT: [④,⑤,①,②,③,⑥]

```
① function get_name() {
②   return $_GET['name'];
③ }
```

start

```
④ if ($_GET['q'] == 'echo') {
⑤   echo get_name();
⑥ }
```

Idea 3: Memoized re-execution

- **Motivation**: many requests run **similar** code

```
1)/s.php?q=echo&name=alice
2)/s.php?q=echo&name=bob
3)/s.php?q=echo&name=<script>…
```

CFT: [④,⑤,①,②,③,⑥]

```
① function get_name() {
②   return $_GET['name'];
③ }

start → ④ if ($_GET['q'] == 'echo') {
⑤   echo get_name();
⑥ }
```

Idea 3: Memoized re-execution

- **Motivation**: many requests run **similar** code

Control flow **group** (**CFG**)

```
1)/s.php?q=echo&name=alice
2)/s.php?q=echo&name=bob
3)/s.php?q=echo&name=<script>…
```

CFT: [④,⑤,①,②,③,⑥]

```
①  function get_name() {
②    return $_GET['name'];
③  }

④  if ($_GET['q'] == 'echo') {
⑤    echo get_name();
⑥  }
```

start →

Idea 3: Memoized re-execution

- Step 1: normal execution
  - **Record** control flow trace (**CFT**) of each request
  - **Classify** the corresponding **control flow group** (**CFG**)

- Step 2: auditing (each CFG)
  - Determine input differences among requests (**template variables**)
  - Generate a **template**: efficient way to re-execute request given an assignment of template variables
  - **Re-execute** each request using the template

Determining template variables

- **Template variables** are input differences among all requests in the same CFG
  (e.g., GET/POST, CGI variables, …)

```
1)/s.php?q=echo&name=alice
2)/s.php?q=echo&name=bob
3)/s.php?q=echo&name=<script> …
```

(e.g., $GET[name] = Template variable)

Generating a template

Template variable

```
/s.php?q=echo&name=alice
```

```
① function get_name() {
②   return $_GET['name'];
③ }

④ if ($_GET['q'] == 'echo') {
⑤   echo get_name();
⑥ }
```

start →

→ **Template**: [②,⑤]

1. Determine template variables of the CFG
2. Pick / replay a request from the CFG
3. Record instructions depending on template variables

Re-executing the template

```
1)/s.php?q=echo&name=alice
2)/s.php?q=echo&name=bob
3)/s.php?q=echo&name=<script> …
```

1. Update the template variable

   (e.g., $GET['name'] = '**bob**' and '**<script>...**')

2. Re-execute the recorded instructions in the template

```
②    return $_GET['name'];
⑤    echo return of ②;
```

Auditing with template re-execution

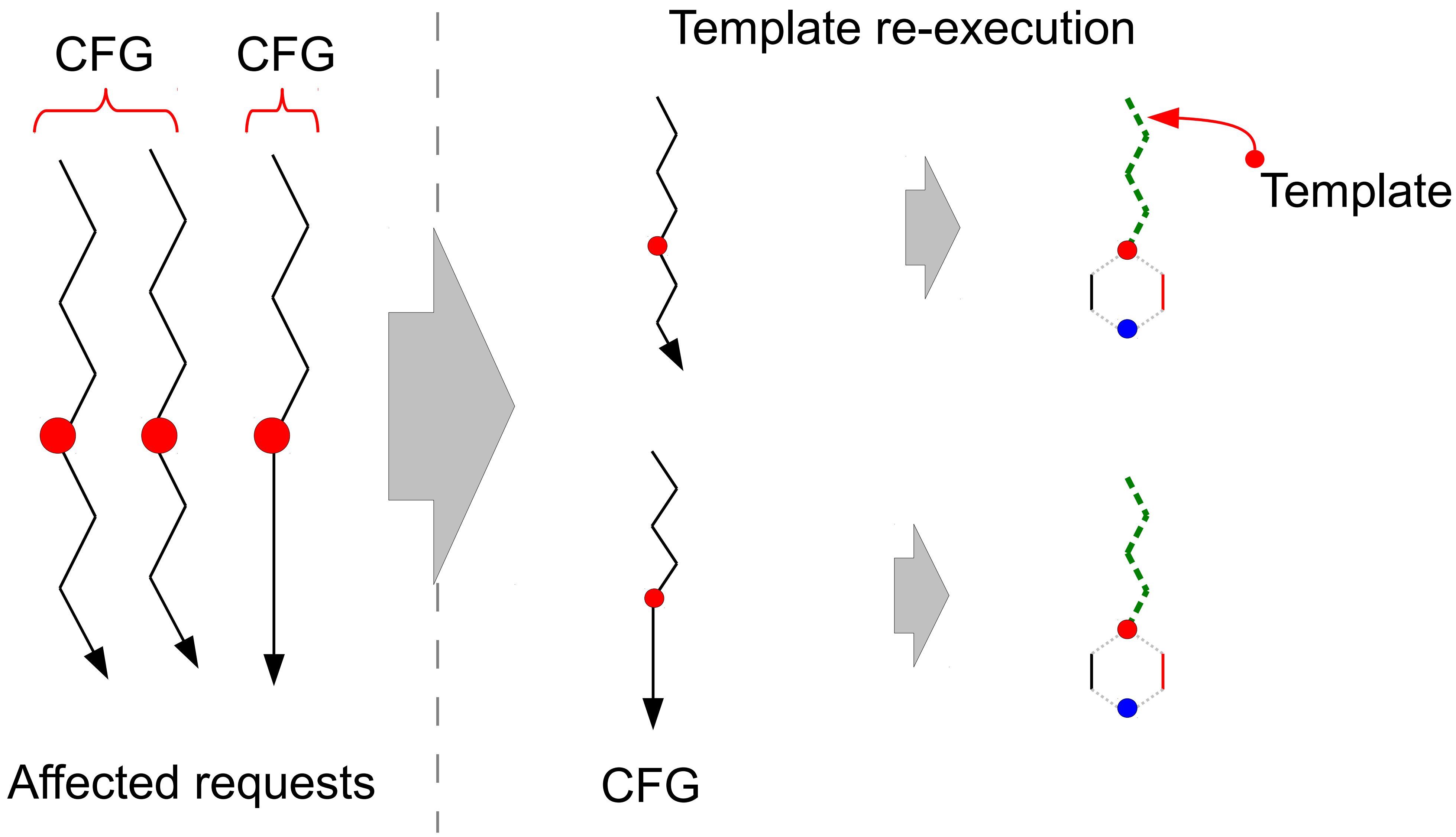
3)`/s.php?q=echo&name=<script> …`

```
 ① function get_name() {
-② ~~return $_GET['name'];~~
+②   return sanitize($_GET['name']);
 ③ }

 ④ if ($_GET['q'] == 'echo') {
 ⑤   echo get_name();
 ⑥ }
```

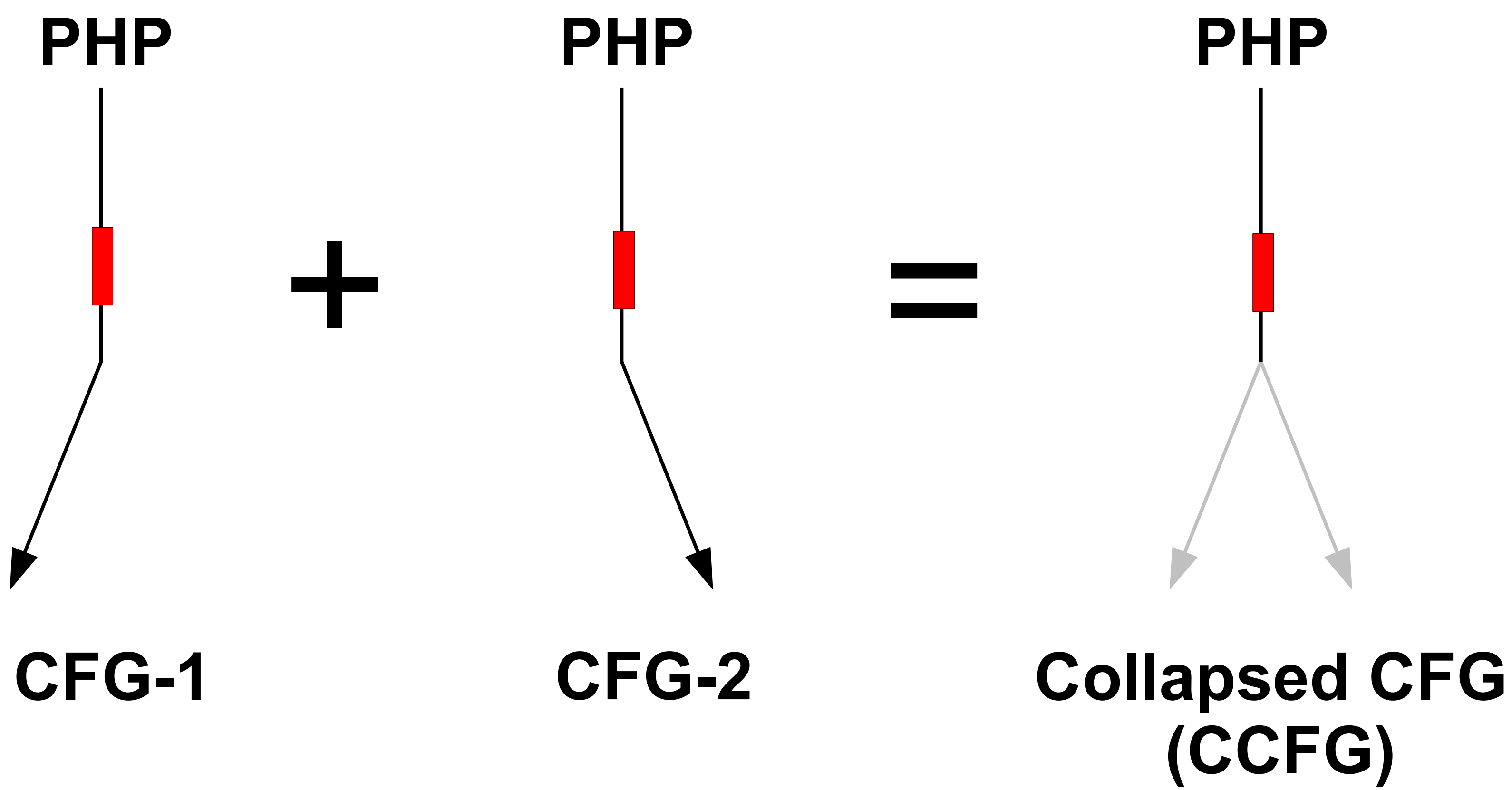
1. Given a patch
2. Re-execute the **template up to** the patched function
3. Perform **function-level auditing**

Summary: template re-execution

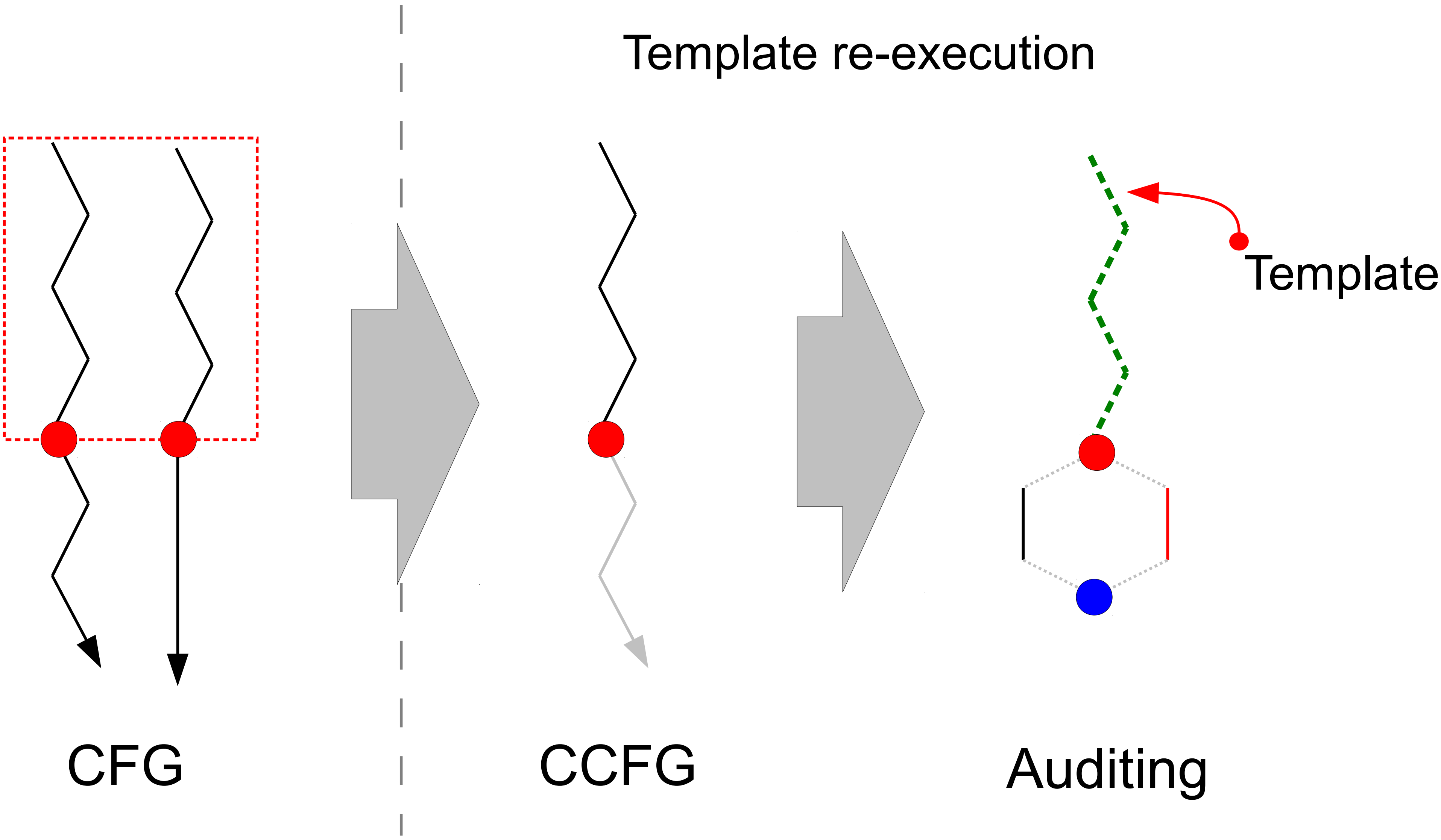


Optimization: collapsing templates

- **Motivation**: different CFGs can share common code up to the patched function (given patch)



Summary: collapsing template



Implementation

- **POIROT**: a prototype for PHP
  - Based on PHP-5.3.6
  - Using PHP Vulcan Logic Dumper
  - 15,000 LoC changes
- **No changes** in application source code

Evaluation

- Does POIROT detect attacks of **real vulnerabilities**?
- Does POIROT audit **efficiently**?
- Does POIROT impose reasonable **runtime overhead**?

POIROT detects real attacks

- **MediaWiki**: detected 5 **different types** of attacks (using *realistic* Wikipedia traces)
- **HotCRP**: detected 4 **information leak** vulnerabilities (using *synthetic* workloads)

CVE	Description	Detected?	F+
2009-4589	Stored XSS	Yes	0
2009-0737	Reflected XSS	Yes	0
2010-1150	CSRF	Yes	0
2004-2186	SQL injection	Yes	0
2011-0003	Clickjacking	Yes	100%

MediaWiki

BUG	Detected?	F+
f30eb	Yes	0
63896	Yes	0
3ff7b	Yes	0
4fb7d	Yes	0

HotCRP

POIROT efficiently audits attacks

- **34 CVEs** (security patches 2004 ~ 2011)
- Trace containing **100K** Wikipedia requests (**3.4 h**)
- Auditing time:
  - 29 CVEs: **<0.2 sec**
  - 5 CVEs: **~9.2 min** (12x ~ 51x faster than the original execution)

CVE	**Naive** Time (h)	**POIROT** Time (min)
2011-4360	6.6 h	4.5 min
2011-0537	6.6 h	4.5 min
2011-0003	7.0 h	16.5 min
2007-1055	6.8 h	16.9 min
2007-0894	8.8 h	4.0 min
29 cases*	6.9 h	0.02~0.19 s

* 2011-1766, 2010-1647, 2011-1765, 2011-1587, …

Control flow filtering is effective for many patches

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- Trace containing **100K** Wikipedia requests (**3.4 h**)
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Function-level auditing
Memoized re-execution

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Function-level auditing improves performance

- Naive: **7.3 h** → Func-level: **3.5 h**
- Re-execute **2 – 60%** (avg. **16**%) instructions

CVE	#re-exec. Instructions / #total instructions	Func-level Re-exec (hour)
2011-4360	6.4K / ~200K = 3.2%	2.4 h
2011-0537	4.8K / ~200K = 2.4%	5.3 h
2011-0003	120K / ~200K = 58.5%	5.4 h
2007-1055	5.6K / ~200K = 2.79%	2.0 h
2007-0894	25K / ~200K = 12.5%	2.9 h

Templates reduce re-executed instructions

- 100K requests → **~840 #CFG**
- Templates contain **0.1% ~ 2.7%** (avg. **0.7%**) instruction

CVE	#CFG	#instruction in a template / #total instruction
2011-4360	844	289 / 200K = 0.14%
2011-0537	834	96 / 200K = 0.05%
2011-0003	834	5,427 / 200K = 2.71%
2007-1055	844	177 / 200K = 0.09%
2007-0894	844	1,085 / 200K = 0.54%

Collapsing reduces number of templates

- 100K → **~840 #CFG → 1 ~ 589 #CCFG**
- **30.5 s** to collapse templates on average
- Auditing 100K requests (**3.4h**) → **avg. 9.2 min**

CVE	#CCFG / #CFG	Collapsing time (sec)	Memoized POIROT (min)
2011-4360	4 / 844 = 0.5%	31.0	4.5 min
2011-0537	1 / 834 = 0.1%	30.3	4.5 min
2011-0003	589 / 834 = 69.8%	30.5	16.5 min
2007-1055	2 / 844 = 0.2%	30.1	16.9 min
2007-0894	18 / 844 = 2.1%	30.4	4.0 min

POIROT imposes moderate runtime overhead

- Testing with **100K Wikipedia** requests
  - **14.1% latency** overhead
  - **15.3% throughput** overhead
  - **5.4 KB/req** storage overhead (compressed online)

Related work

- Record-and-replay with patches:
  - **Warp**: repairing web apps with retroactive patching
  - **Rad**: fork-and-compare, auditing memory writes
- Testing patched programs:
  - **TACHYON**: automatic/live patch testing
  - **Delta execution**: validate patched version (split/merge)
- Program slicing (adjustable computation):
  - **Static slicing**: all stmts. that possibly affect the variable
  - **Dynamic slicing**: all stmts. that really affected the variable

Conclusion

- POIROT: efficient patch-based auditing system
  - Detected real attacks in MediaWiki / HotCRP without any modification
  - 12 – 51x faster than original execution
- Three partial re-execution techniques
  - Control flow filtering
  - Function-level auditing
  - Memoized re-execution