MACE: Detecting Privilege Escalation Vulnerabilities in Web Applications

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Introduction

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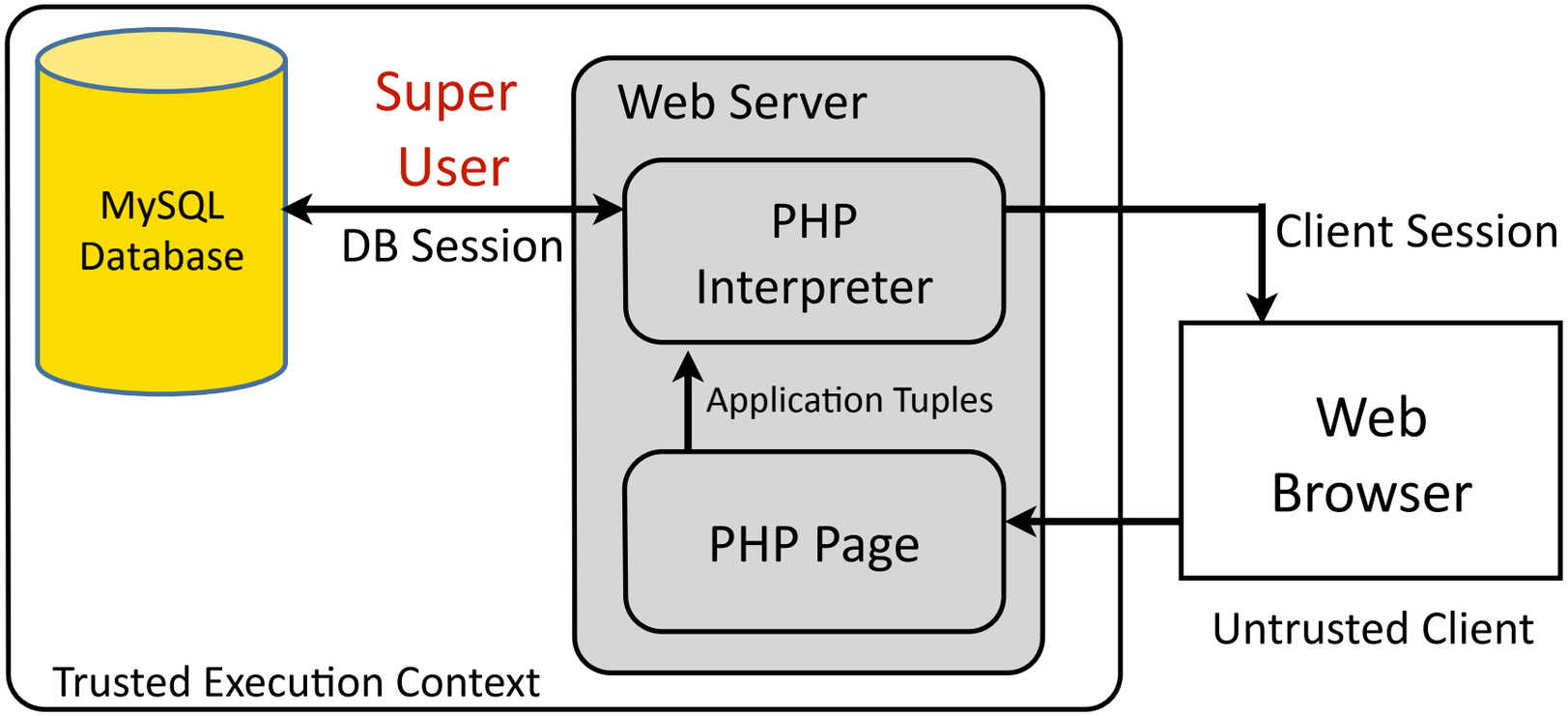
Typical Web Application Architecture

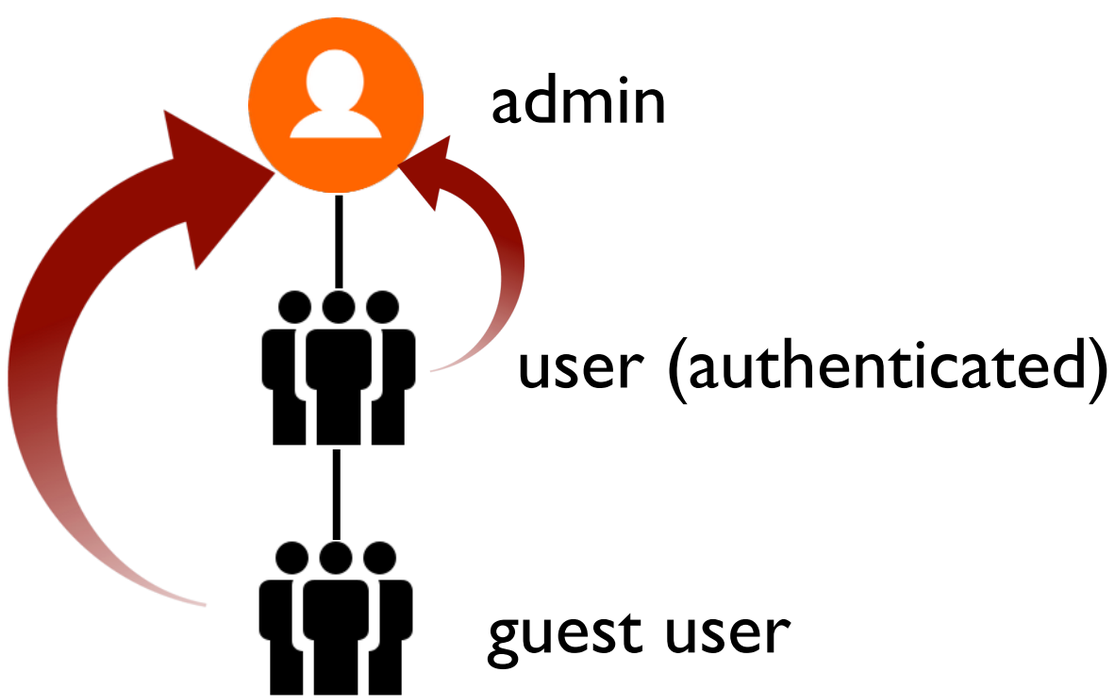
- Applications run at the privilege of the **administrator** of database
  - With highest privileges
- Typically, **no** privilege minimization

➡ Susceptible to **privilege escalation**

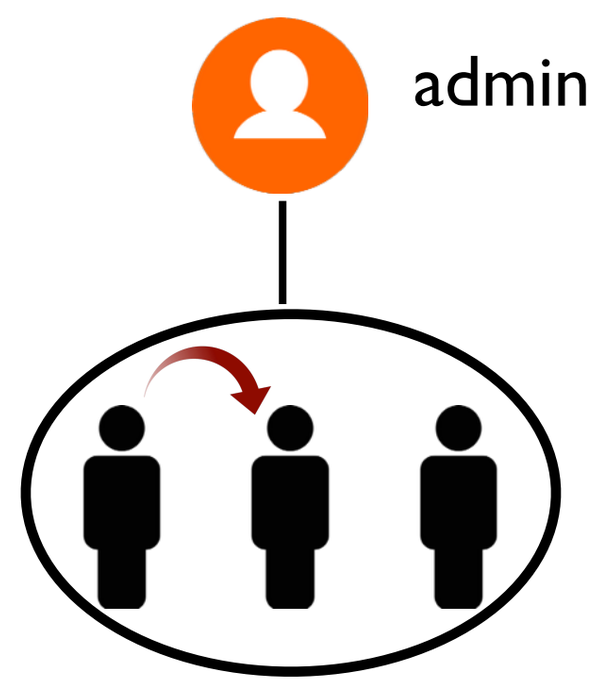


Privilege Escalation

- Vertical Privilege Escalation
  - e.g.:
    - XSS
    - Authentication Bypass



- Horizontal Privilege Escalation
- Example: Banking Website
- Can be caused by:
  - XSS, Session Fixation
  - IDs/Passwords Prediction



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Vertical Priv. Escalation - Example

Untrusted Input

```
verifyUser();
if($_GET['action'] == 'deleteAll')
    query("DELETE FROM tbl_articles");
```

Any logged-in user can delete **all** articles

```
function verifyUser(){
    if(!isset($_SESSION['userID']))
        header('Location: /login.php');
    else $userID = $_SESSION['userID'];
    return;
}
```

Should check for admin credentials

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Horizontal Priv. Escalation - Example

```
verifyUser();
if($_SESSION[$userID]['canWrite'] && $action == 'delete')
    query("DELETE FROM tbl_articles WHERE article_ID =
        '" + sanit($_GET['article_ID']) + "'");
```

Untrusted Input

- Guessing a valid article_ID
  - Hidden field in HTML code
  - Auto-increment

Any logged-in user can delete other users' articles

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Problem & Challenges

- Missing/Improper authorization checks
  - A serious security threat for web applications
  - Facilitates an attacker to perform sensitive operations
- **Problem:** How to identify missing authorization checks?
  - **Challenge 1:** No authorization policy specification available
    - The only documentation is source code
  - **Challenge 2:** Manual analysis difficult or tedious
    - Applications are large, many thousand LOC

➡ **Goal:** must infer authorization policy from code

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Inferring Access Control Rules

- How to infer policy from application, if policy implementation is not complete?
  - Intuition: For the **same** resources, in **different** access locations
    - **Same** access control rules
- Which **conditions should hold** for the user to be able to access a resource?
  - Code includes:
    - Path to the query
    - Query

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Approach

- Identify **Authorization Context**
  - **Conditions** along the path to the query: Authorization **checks**
  - **Conditions** in the query: **Access parameters**
- Resource Access Analysis
  - Building an independent access model for **each resource**
  - Compare authorization contexts within each group
  - Detect **inconsistent** accesses

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Why MACE?

- Focuses on authorization vulnerabilities
  - A more precise and flexible authorization model for resources
- Detects both
  - Vertical privilege escalation
  - Horizontal privilege escalation
    - **First tool** for automatic detection of **Horizontal Priv. Escalation**

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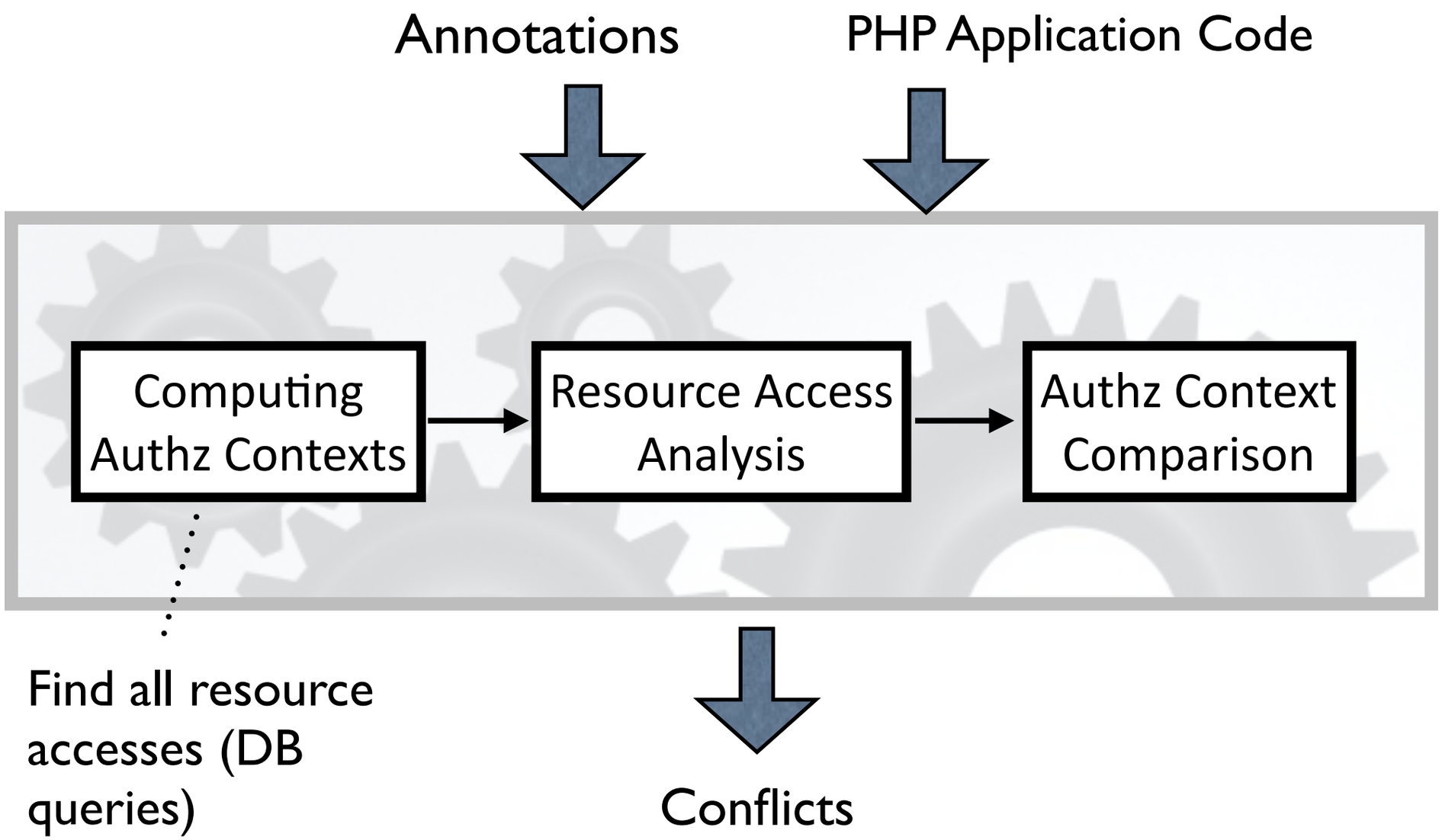
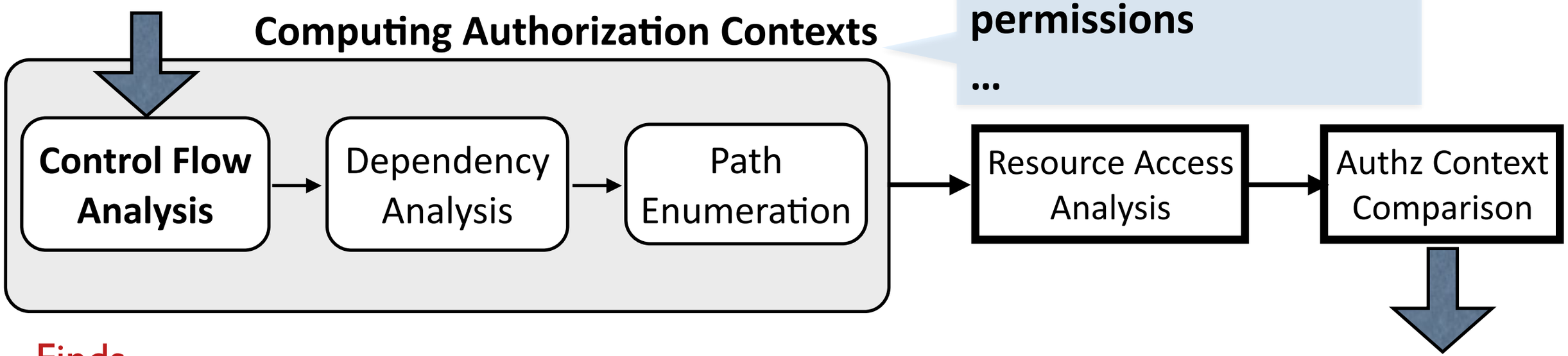


- Find all resource accesses (DB queries)
- Compute Authz Contexts for them

Computing Authorization Contexts

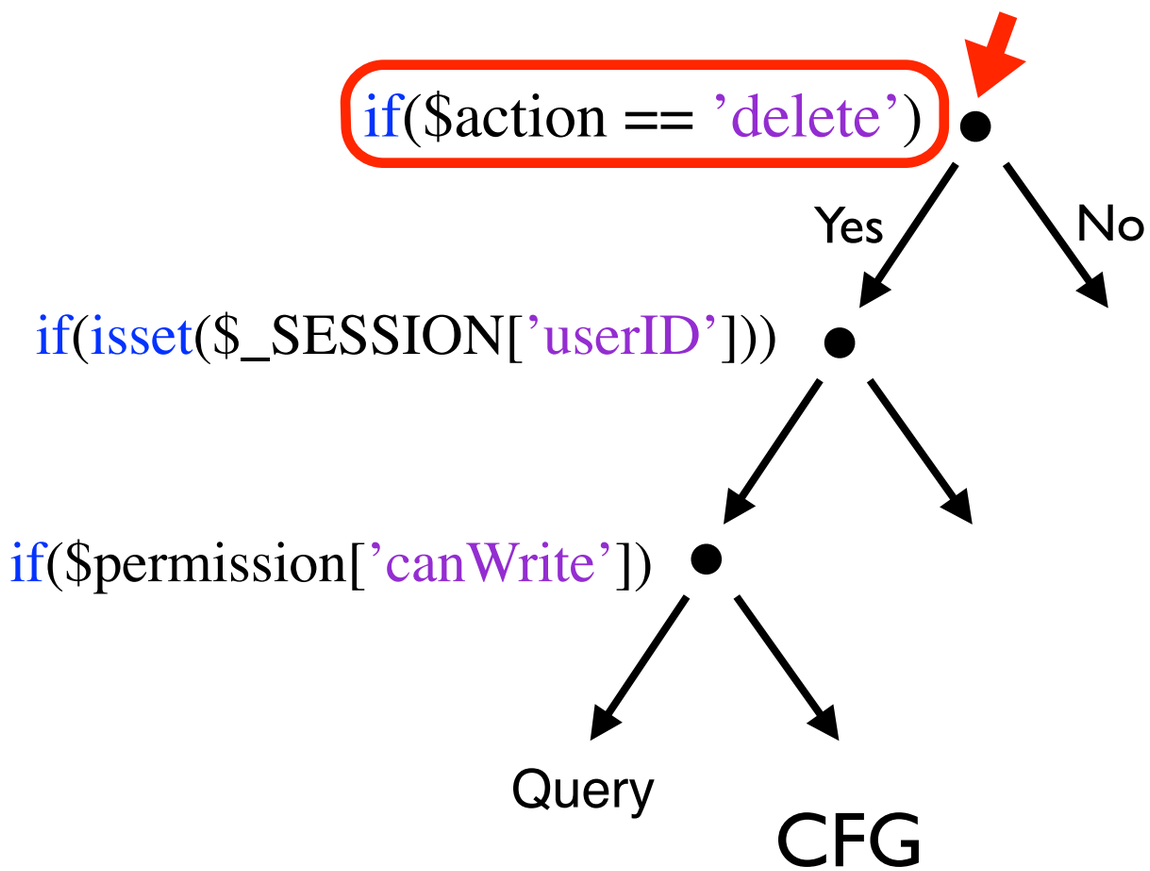
- Application Code
- Annotations



- Finds Authorization Contexts

Control Flow Analysis

- What authorization **conditions** hold at the query location?
  - **Traverse** Control Flow Graph to gather the conditions related to authorization
- Intra-procedural/Inter-procedural
- Context-sensitive, flow-sensitive



Authorization Context

Annotation

$_SESSION['userID']
$userid['level']
$permission['canWrite']

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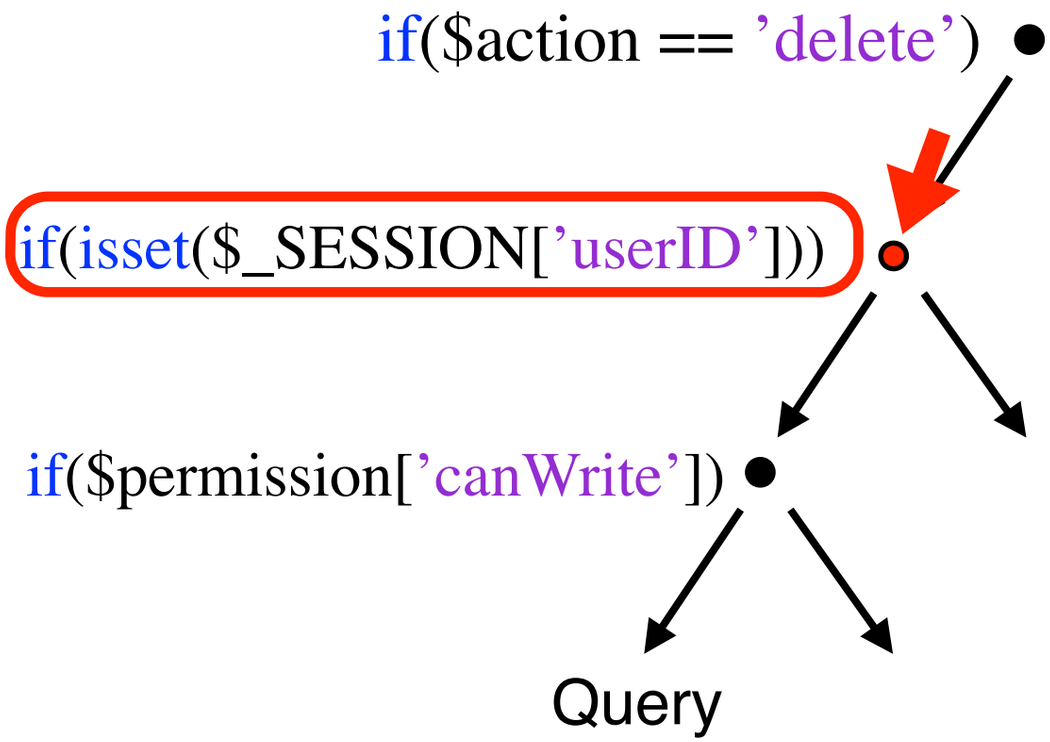
Control Flow Analysis



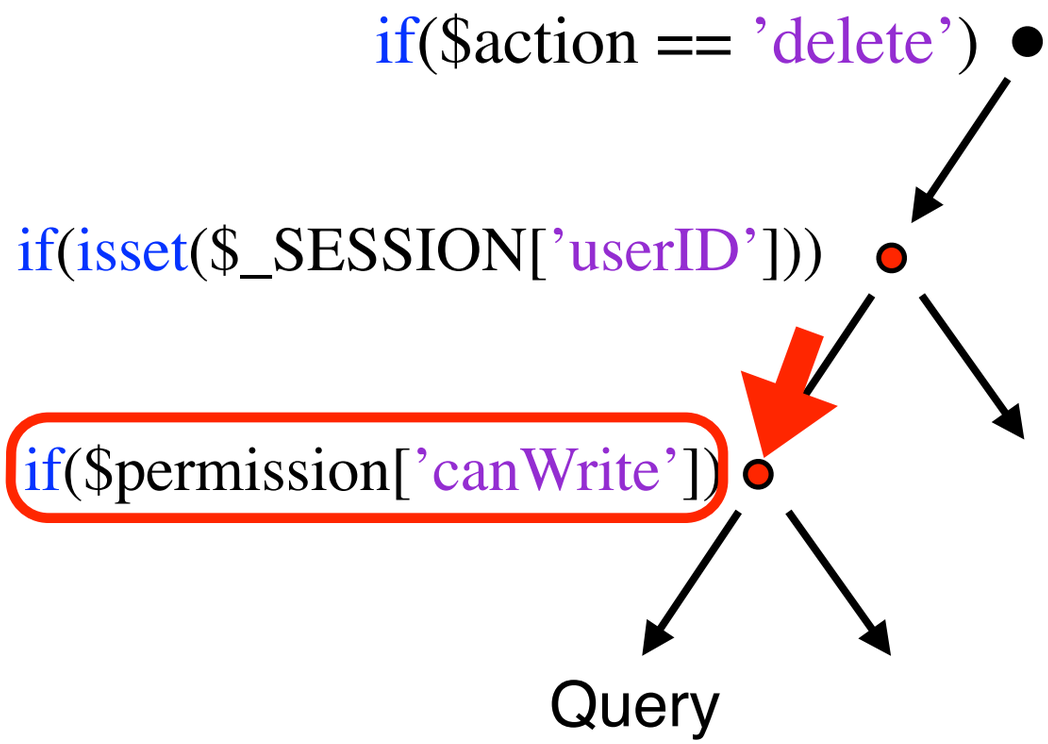
Authorization Context

isset($_SESSION['userID'])

Annotation

$_SESSION['userID']
$userid['level']
$permission['canWrite']

Control Flow Analysis



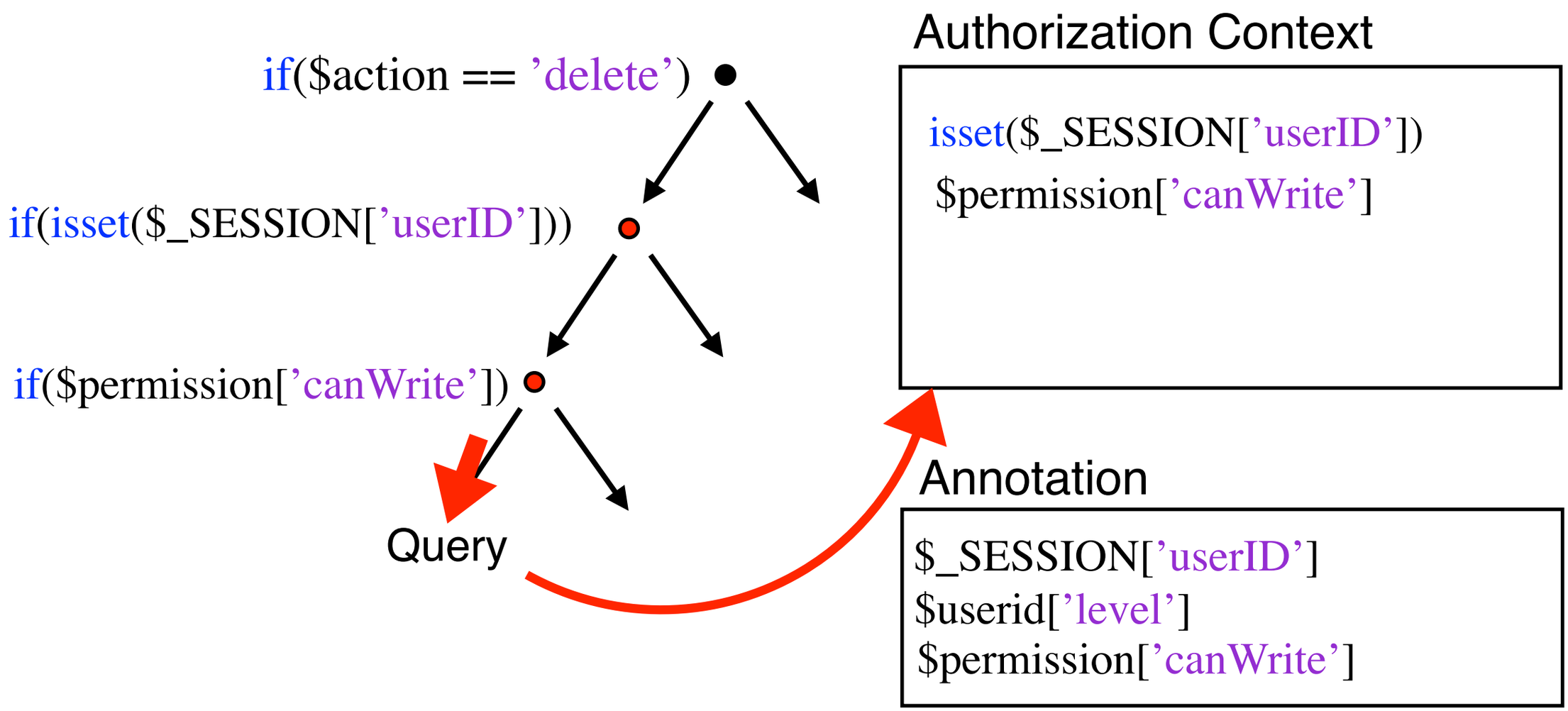
Authorization Context

```
isset($_SESSION['userID'])
$permission['canWrite']
```

Annotation

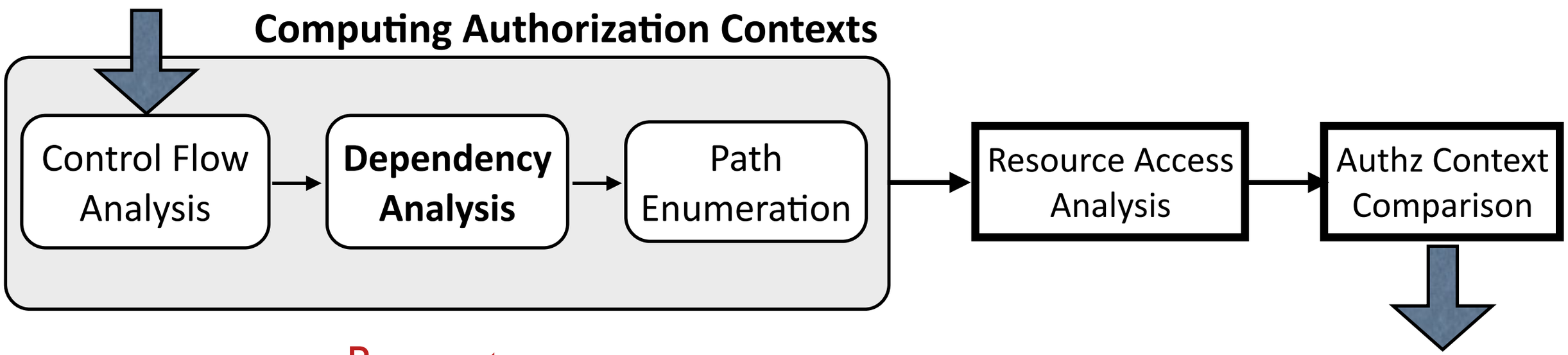
```
$_SESSION['userID']
$userid['level']
$permission['canWrite']
```

Control Flow Analysis



Computing Authorization Contexts

- Application Code
- Annotations



- Propagates Authorization Context (Values)
- Builds Symbolic Queries

Data Dependency Analysis

- Propagates Authorization Values for
  - If-statements
  - Symbolic Queries
- Intra-procedural/Inter-procedural

```
$userID = $_SESSION['userID']
query("INSERT INTO tbl_comments VALUES (
    $userID , …)");
```

Annotation

```
$_SESSION['userID']
$userid['level']
$permission['canWrite']
$userID
```

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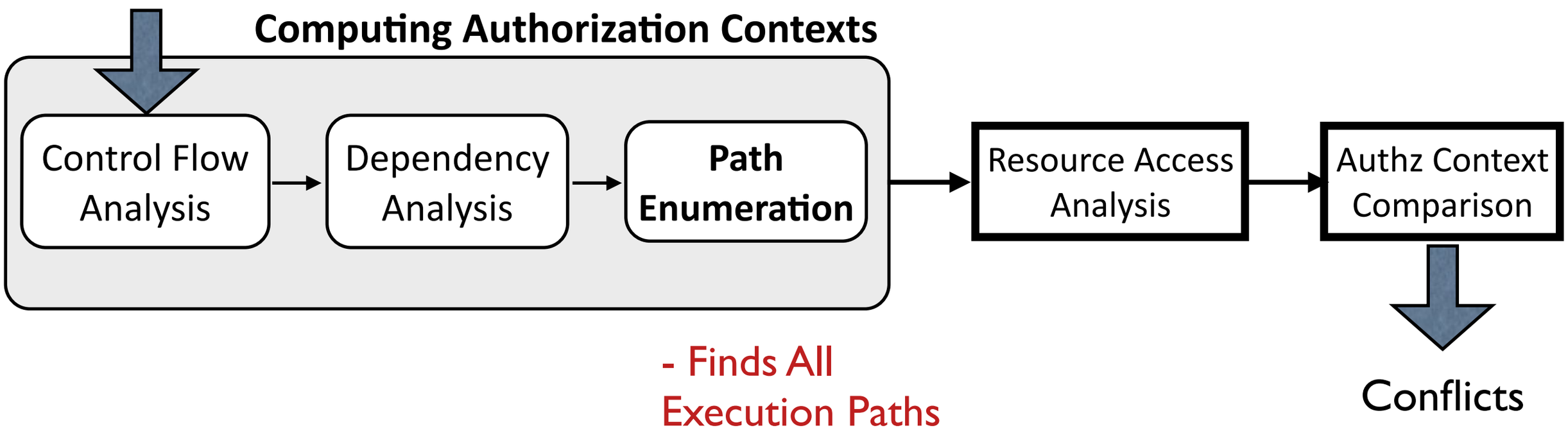
Computing Authorization Contexts

- Application Code
- Annotations



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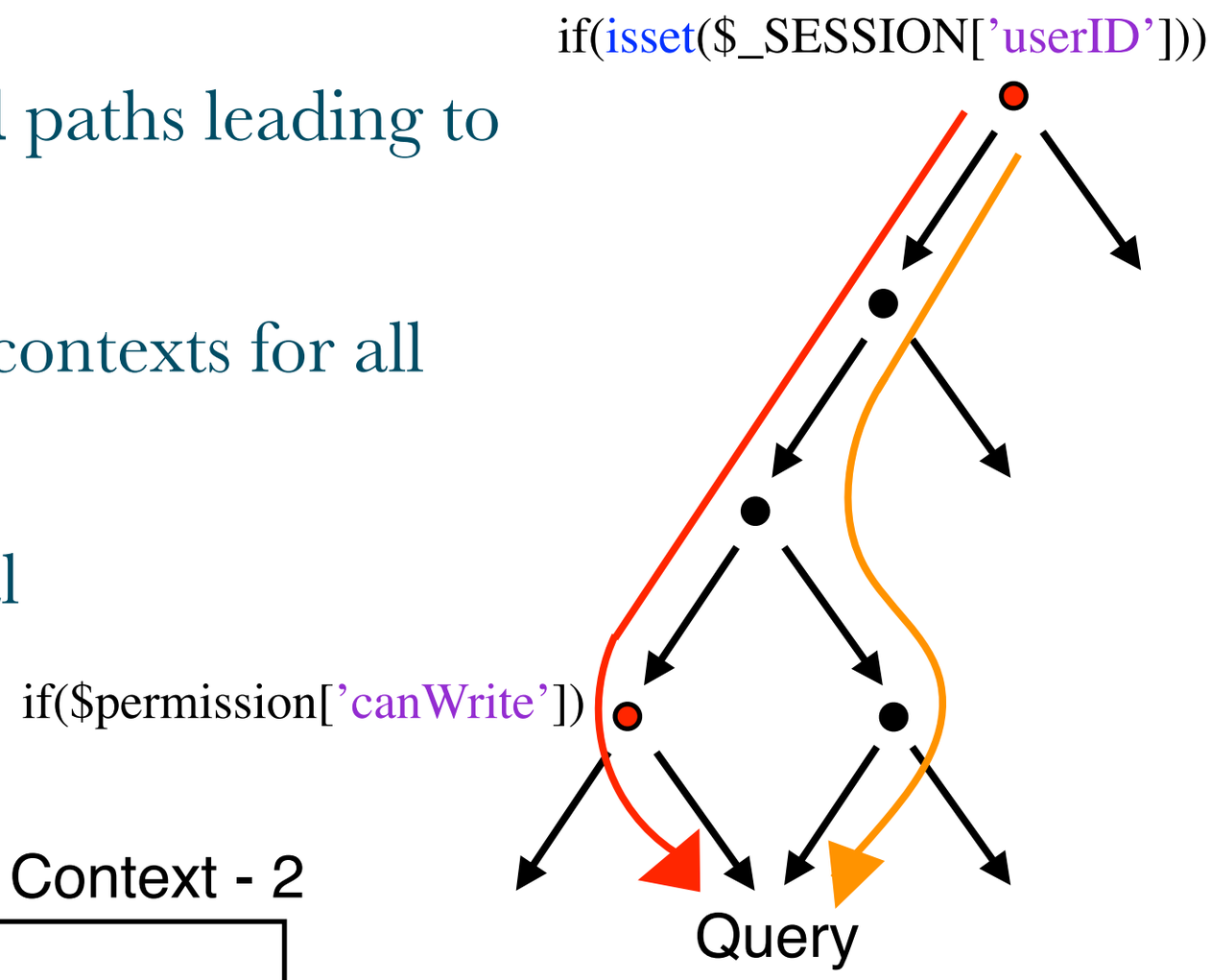
Path Enumeration

- Authorization Contexts are **path-sensitive**
- Path Enumeration enumerates **all** paths leading to queries
- Therefore we have authorization contexts for all <query, path> pairs
- Intra-procedural/Inter-procedural



Authorization Context -1

```
isset($_SESSION['userID'])
$permission['canWrite']
```

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Authorization Context - 2

```
isset($_SESSION['userID'])
```

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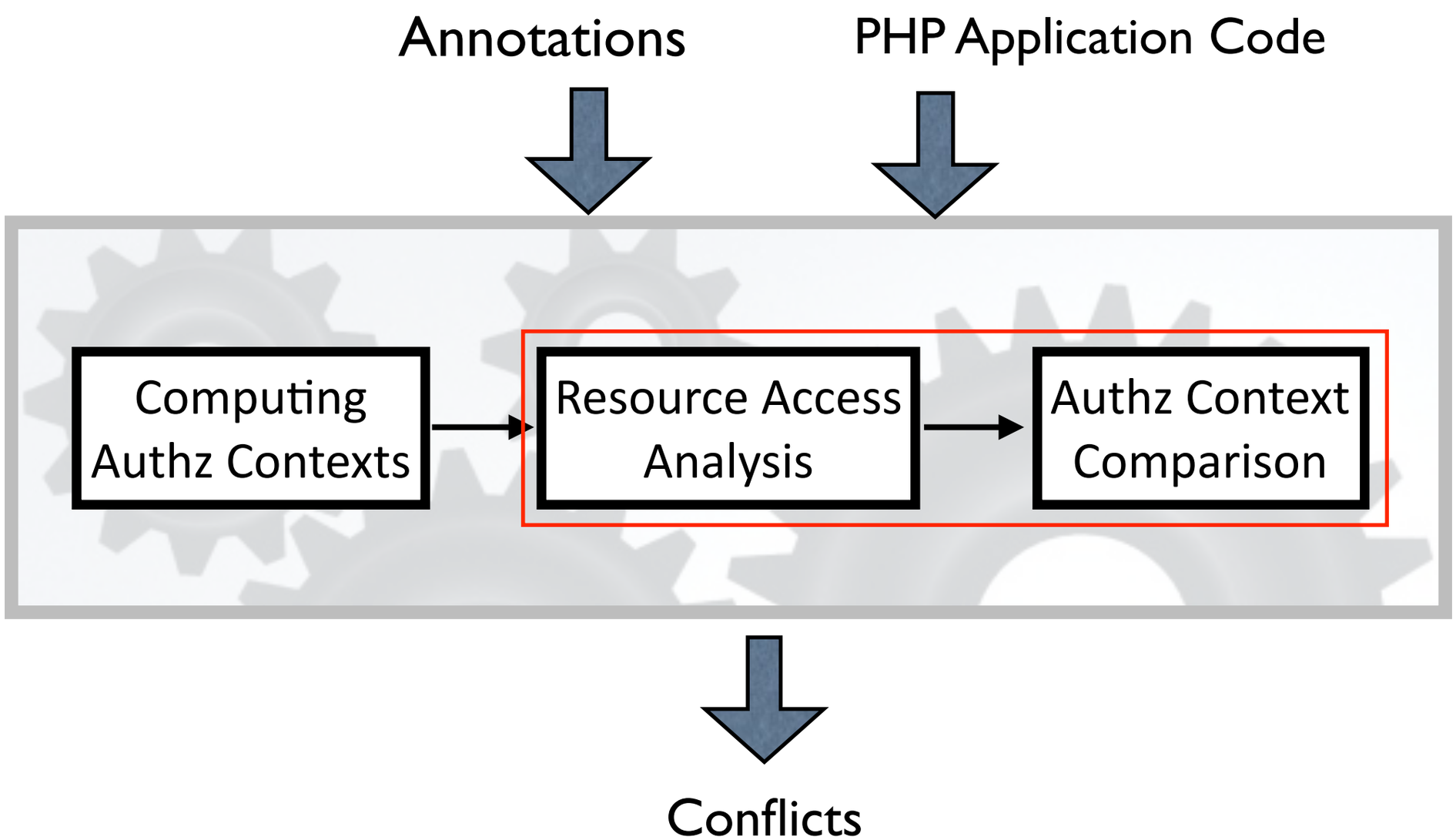
Annotations
PHP Application Code
Computing Authz Contexts
Resource Access Analysis
Authz Context Comparison
Conflicts

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Resource Access Analysis

- For each resource (DB table)
  - Gather resource access information
    - Authorization Context (Query-Path)
    - Access Parameters (Query WHERE Clause)
  - Compare authorization information
    - Insert-Insert, Insert-Update, Insert-Delete

```
query("INSERT INTO tbl_articles VALUES (
    sanit($_GET['article']),
    $_SESSION['userID'], …");
```

Authorization Context

```
isset($_SESSION['userID'])
$permission['canWrite']
. . . . . .
authorID = $_SESSION['userID']
```

≠

```
query("DELETE FROM tbl_articles WHERE
article_ID ='" + sanit($_GET['article_ID'])
+ "'");
```

Authorization Context

```
isset($_SESSION['userID'])
$permission['canWrite']
```

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Detecting Conflicts

- What is the **rationale for comparison**?
  - INSERT queries: typically the **creator** of the data **owns** the data
- Different type of conflicts show different vulnerabilities
  - Authorization Context Conflicts (conflicts in the paths)

    ➡ Vertical privilege escalation (VPE)
  - Access Parameter Conflicts (conflicts in the WHERE clause)

    ➡ Horizontal privilege escalation (HPE)

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Evaluation

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Summary of Vulnerabilities

- 7 popular small to large PHP applications (1K to 90K LOC)
- **Overall 71 vulnerabilities found**
  - **66 previously unknown** vulnerabilities detected
- **5 out of 7** applications found to be vulnerable
- **Zero false positives**

Application	Description	VPE	HPE	# of Vulns
phpns	News System	✔	✔	7
DCPPortal	CMS	✔	✔	46
DNScript	Domain Trading	-	-	0
MyBloggie	Blog	✔	✔	6
MiniBloggie	Blog	✔	-	1
SCARF	Conference Management	✔	✔	11
WeBid	Online Auction	-	-	0

- **Our results demonstrate that the approach used by MACE is effective, scalable**

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Identified Vulnerabilities

- DCPPortal
  - CMS
  - VPE: Use of cookies for authorization


```
if (UserValid($_COOKIE["dcp5_member_id"])) {
…
}
```

cookies are used to validate the users

Cookies are untrusted sources

  - HPE: Users can delete any agenda items from the shared calendar

```
if ((isset($_REQUEST["action"])) && ($_REQUEST["action"]=="delete")) {
    $sql = "DELETE FROM $t_agenda WHERE id = '".$_REQUEST["agid"]."'";
```

untrusted source

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Precision

- False Positives?
  - **Multiple** INSERT Queries with **inconsistent** Authorization Contexts
    - Which one is correct?
- False Negatives
  - SELECT Queries
    - Disclosure policy is not available
  - INSERT queries with empty authorization contexts
    - Subsequent DELETE & UPDATE queries undetected

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Performance & Scalability

- Application size: 1K to 90K
- Analysis Time
  - 95%: Dependency Analysis/Path Enumeration
  - Resource Access Analysis

	SLOC	# DB Tables	Analysis Time (s)
phpns	4.5K	13	8220
DCPPortal	**89K**	34	982
DNScript	1.5K	7	**35093**
MyBloggie	6K	5	373
MiniBloggie	1.5K	**2**	**35**
SCARF	**1K**	7	54
WeBid	27K	**47**	1492

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Related Work

- Prevention of Authorization Vulnerabilities
  - New Development Frameworks: Capsules.
  - Run-time Frameworks: **Nemesis**[5], **Diesel**[9], **Swaddler**[4], **CLAMP**[10].
  - MACE is focused on static detection of authorization vulnerabilities
- Finding Authorization Bugs in Legacy Web Applications
  - e.g.: **RoleCast**[11]
  - MACE uses a fine-grained access model
- General Vulnerability Analysis in Applications
  - Using Program Invariants, Behavioral Patterns
  - e.g.: **Waler**[7], **AutoISES**[14], **NoTamper**[1]
  - MACE focuses on authorization vulnerabilities —> better precision

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Conclusion

- **Missing/improper** authorization a serious problem for Web applications
- MACE:
  - Best-effort tool for **automatic** detection of HPE, VPEs
  - **71 total, 66 unknown** vulnerabilities were found
  - Reduces **weeks of testing** effort
- Lack of documentation about access control policies makes it challenging to detect vulnerabilities
- MACE demonstrates that it is possible to infer policies from code and use them for vulnerability detection

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Questions?

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Annotation

- How to identify the authorization variables?
  - MACE Extracts of Globals/SuperGlobals
  - Developers Confirm
  - Examples:
    - $_SESSION['user_id']
    - $userid['level']
    - $permission['can_write']

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Annotation Example - MyBloggie

- $HTTP_SERVER_VARS[REMOTE_ADDR]
- $_SERVER[REMOTE_ADDR]
- $_SERVER[HTTP_HOST]
- $_SERVER[SERVER_NAME]
- $_FILES[userfile][name]
- $_FILES[userfile][type]
- $_FILES[userfile][size]
- $_FILES[userfile][tmp_name]
- **$_SESSION[username]**
- **$_SESSION[user_id]**
- **$_SESSION[passwd]**

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Precision - False Positives?

- **Multiple** INSERT Queries with **inconsistent** Authorization Contexts
- Which one is correct?
  - Logged-in users can insert
  - Guest users can insert

```
query("INSERT INTO tbl_comments VALUES (
    $_SESSION['userID'],
    …)");
```

Authorization Context

```
isset($_SESSION['userID'])
```

≠

```
query("INSERT INTO tbl_comments VALUES (
    $_SERVER['REMOTE_ADDR'], …)");
```

Authorization Context

- Mitigation technique: Comparison with the strongest context

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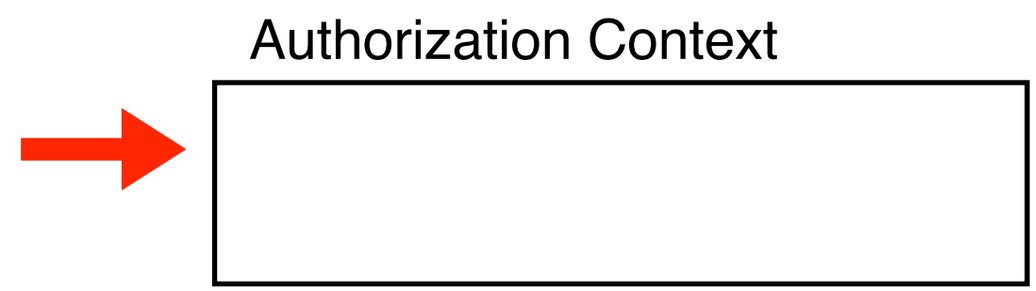
Precision - False Negatives

- SELECT Queries
- Missing Authorization Information in INSERTs

```
query("INSERT INTO tbl_articles VALUES (
    sanit($_GET['article_code']),
    $_GET['userID'],
    sanit($_GET['article_msg']))");
```



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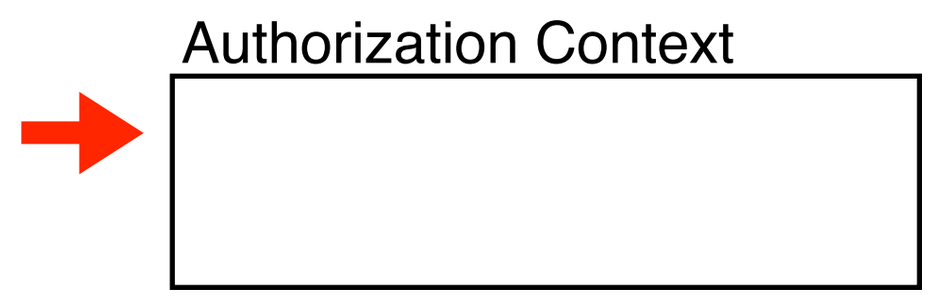
```
query("DELETE FROM tbl_articles WHERE
article_ID ='" + sanit($_GET['article_ID']) + "'");
```



- MACE reports the insert queries which have empty contexts

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Detected Violations

Application	Number of Violations		
	insert-insert	insert-update	insert-delete
phpns	0	5	2
DCPPortal	0	21	25
DNScript	0	0	0
MyBloggie	0	3	3
MiniBloggie	0	0	1
SCARF	1	8	3
WeBid	0	0	0

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