UNIVERSITÄT PASSAU

Secure Code Generation for Web Applications

Martin Johns

ISL, Universität Passau
martin.johns@uni-passau.de

ISL Institute of IT-Security and Security Law

Outline

1. Past activities
2. String-based code injection
3. Secure code generation

Outline

1. **Past activities**
2. String-based code injection
3. Secure code generation

Me, myself, and I

Martin Johns

- Worked as a developer for quite a while
  - Wrote a considerable amount of insecure code
- Joined Prof. Posegga's group in 2005 to work in the Secologic project
  - Joint project with SAP, Commerzbank, and Eurosec
  - Goal: Establishing the state of the art in software security
  - http://www.secologic.org
- Since 2007 further research projects
  - ScanStud, evaluation static analysis, with Siemens CERT
  - FLET, language-based security for web apps, with SAP Research
  - ORKA, dynamic access control (project management), with Fraunhofer and others
- Personal focus on web application security

WebAppSec: Mitigation

XSS/Session Hijacking

- Protection against XSS-based session hijacking attacks
- Implementation: Server-side reverse proxy
- [Johns, ESORICS 06]

Cross-site Request Forgery

- Client-side protection against CSRF attacks
- Implementation: Proxy, browser extension
- [Johns & Winter, OWASP EU 06]

Browser-based attacks on intranet resources

- Protection of intranet resources against JS malware and DNS rebinding attacks
- Implementation: Browser extension
- [Johns & Winter, DIMVA 07], [Johns, JICV 08]

WebAppSec: Detection and prevention

Cross-site Scripting detection

- Server-side detection of XSS exploits through passive HTTP monitoring
- [Johns, Engelmann, Posegga, ACSAC 08]

Static analysis

- Evaluation of commercial static analysis tools
- Joint work with the Siemens CERT, presented at OWASP EU 08

Detection of string-based code injection

- Instruction set randomization for web applications
- [Johns & Beyerlein, ACM SAC 07]

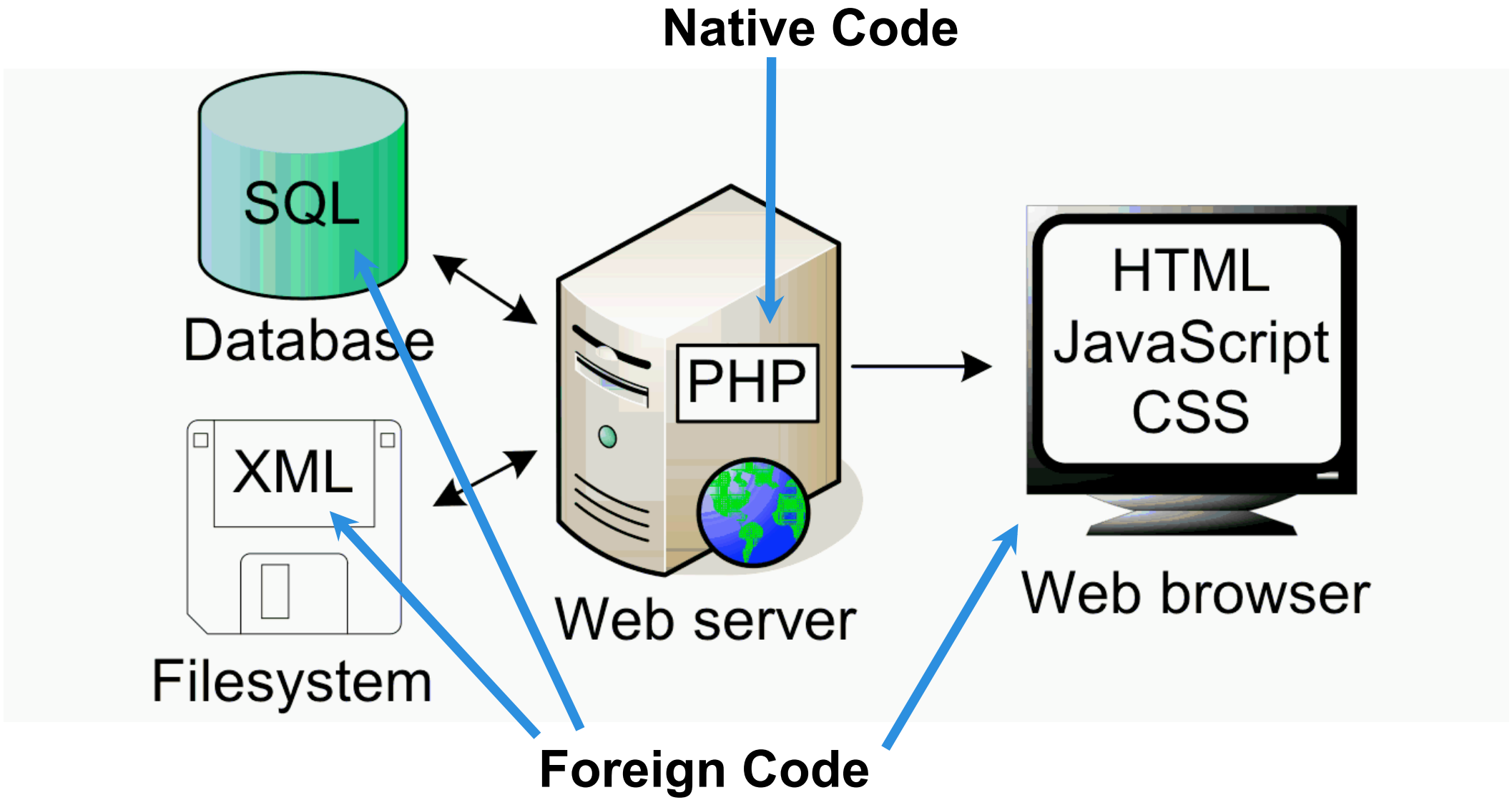
Language-base prevention of code injection vulnerabilities

- Topic of today's talk

Outline

1. Past activities
2. **String-based code injection**
3. Secure code generation

Web application architecture



String based code injection

Today's most prevalent security bug pattern

- Affects foreign code creation

Types

- Cross-site scripting
- SQL injection
- Shell injection
- Path traversal
- XPath injection, LDAP injection, JSON injection, …

String based code injection

Dynamic code assembly

```
$pass = $_GET[“password”];

$sql = “SELECT * FROM Users WHERE Passwd = ‘” + $pass + “’”;
```

String based code injection

wget http://site.com/login?password=‘%20OR%20’1’=‘1

```
$pass = $_GET[“password”];

$sql = “SELECT * FROM Users WHERE Passwd = ‘” + $pass + “’”;
```

String based code injection

wget http://site.com/login?password=‘%20OR%20’1’=‘1

```
$pass = “’ OR ‘1’=‘1”;

$sql = “SELECT * FROM Users WHERE Passwd = ‘’ OR ‘1’=‘1’”
```

String based code injection

The programmer's view:

```
$pass = $_GET[“password”];

$sql = “SELECT * FROM Users WHERE Passwd = ‘” + $pass + “’”;
```

Code **Data**

String based code injection

The database's view:

```
$pass = $_GET["password"];

$sql = "SELECT * FROM Users WHERE Passwd = '" + $pass + "'";
```

String based code injection

The database's view:

```
$pass = "' OR 1=1";

$sql = "SELECT * FROM Users WHERE Passwd = '' OR '1'='1'";
```

⇒ **Implicit foreign code creation through string-serialization**

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1. Past activities
2. String-based code injection
3. **Secure code generation**
   - **General approach**
   - **Datatype**
   - **Design and Implementation**
   - **Evaluation**
   - **Conclusion**

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General approach

Similarities within the bug pattern:

- **String-based foreign code assembly**
- [Unmediated interfaces to the external interpreters]

Solving the problem on the programming language level

- **Goal: Secure dynamic foreign code assembly**
- **“How do we need to extend/modify the existing practice to reliably prevent the vulnerability class?”**

Methodology

- **Removal of the vulnerability class’ fundamental requirements**
  - **Exchange the string type for code assembly**
  - Abstract all direct interfaces to external interpreters
    - Offering a secure alternative is not enough

Design objectives

Do not invent a new language

- The developed concepts should be applicable for any modern programming language

Closely mimic the foreign syntax

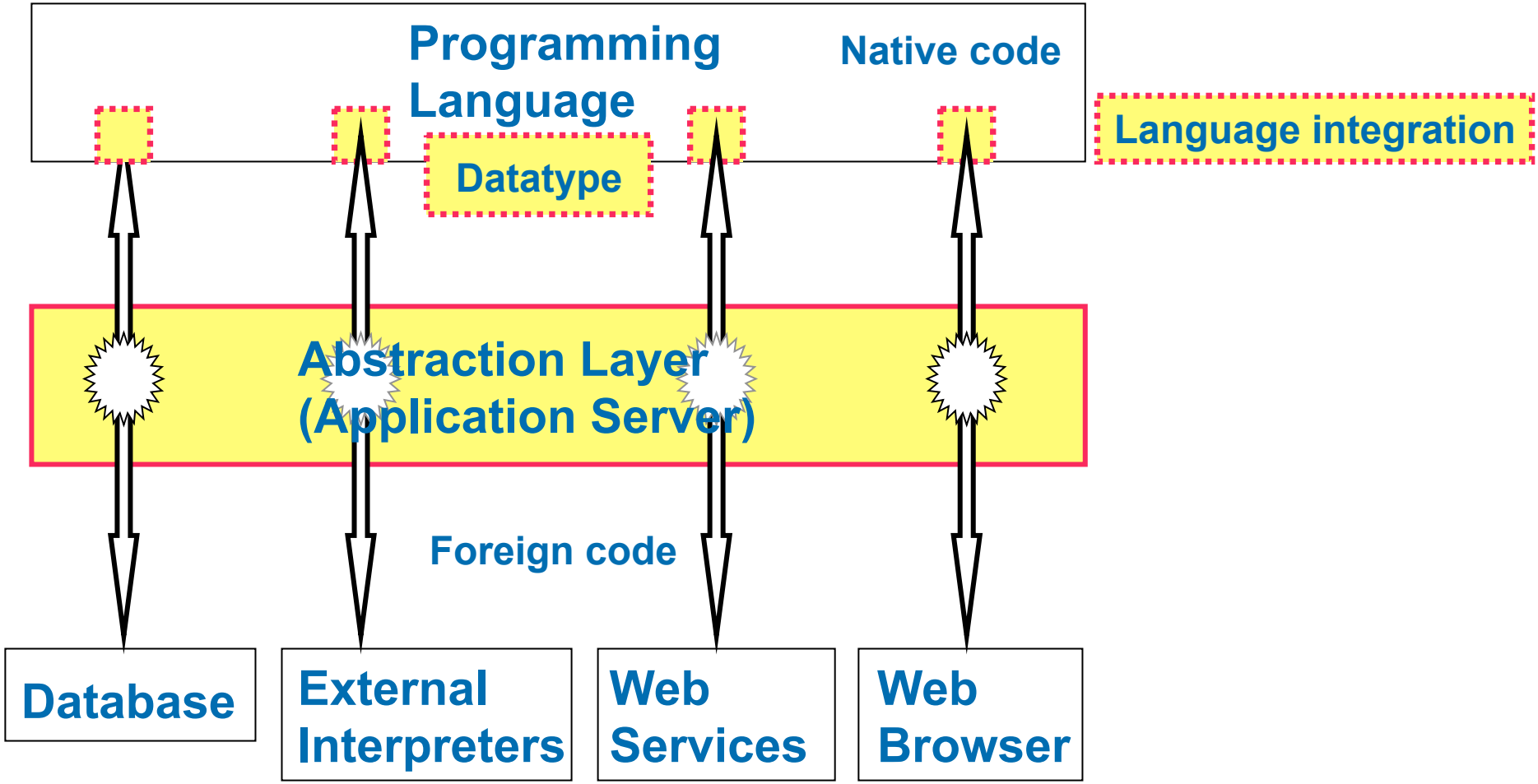
- Respect the design decisions of the language's inventors
- No additional training costs

Maintain the flexibility of the String type

- Dynamic assembly of foreign code is a powerful tool

→ Keep the programmers happy

Key components (I)



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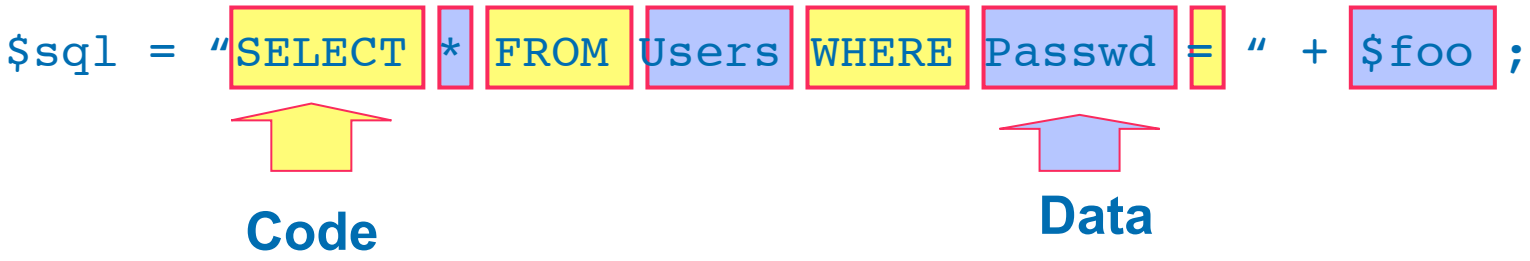
The datatype

“Foreign Language Encapsulation Type” (FLET)

- Part of the native language
- Capable of encapsulating foreign code
- Provides strict separation between *data* and *code*



Objectives

- Code-elements should only be created explicitly
  - Instead of “take this string and treat it as code” the programmer has to specify the exact syntactic purpose of each element

Formal considerations (I)

Type systems for security properties

- **Dominant focus: Confidentiality**
- **Bell-LaPadula model [Bell & LaPadula 73]**
  - **Multilevel security**
    - Simplest case: public/secret
  - **Information flow constraints**
    - Simple Security Property (no read-up)
    - *-Property (no write-down)
- **[Denning & Denning 77], enforcement through static program analysis**
- **[Volpano & Smith 96], formalizes Denning's approach through a type system**
  - ***public* is a subtype of *secret***
  - **Compile time enforcement through type checking**

Formal considerations (II)

Biba model [Biba 77]

- Dual model to Bell-LaPadula
- Enforces integrity constraints
  - No information flows form *low* to *high* integrity
- Two axioms
  - Simple Integrity Axiom (no read-down)
  - *-Integrity Axiom (no write-up)
- Can be modeled analogous to [Volpano & Smith 96]

Applying this to our case

Our problem can be abstracted into integrity constraints

- Code elements == high integrity
- Data elements == low integrity
- Code injection ⇒ information flow from low integrity to high integrity

Prevention of direct flows from low to high

- Indirect flows have to be possible (Example: Wiki)
- Concentration on the *-Integrity axiom
- Hence, we only require a subset of Volpano's typing rules

Question:

- Definition of data/code element?

Identifying language elements

Needed: Mapping data/code to syntactical elements

```
$sql = "SELECT * FROM Users WHERE Passwd = 'foobar' ";
```

General token-classes, derived from foreign grammar

- **Static-elements**
  - Names defined in the language's grammar
  - E.g., keywords, punctuators, tag-names,…
- **Identifier-elements**
  - Names defined on compile time
  - E.g., variable, function or table names

Not to be defined on runtime ⇒ *code*

- **Values**
  - Values vary on run-time
  - E.g., strings, integers, attribute-values, …

OK to be defined on runtime ⇒ *data*

Resulting data & integrity types

Three additional native datatypes to represent foreign syntax elements

- `code-token`, **represents foreign static- and identifier-elements**
- `data-token`, **represents foreign data-elements**
- `FLET`, **container type, representing a token stream**

Two integrity classes

- ***CT*** **(assigned to code-tokens)**
- ***DT*** **(assigned to data-tokens, strings, integers, floats,…)**

Subtype relationship: $CT \subseteq DT$

$$(\text{subtype})\ \frac{\Gamma \vdash e : \tau \qquad \tau \subseteq \tau'}{\Gamma \vdash e : \tau'} \qquad (\text{assignment})\ \frac{\Gamma \vdash e : \tau\ var \qquad \Gamma \vdash e' : \tau}{\Gamma \vdash e := e' : \tau\ cmd}$$

Resulting integrity types (II)

Claim

- By using the typing rules from [Volpano & Smith 96] that enforce the *-Axiom, *CT*-typed expressions cannot be defined by *DT*-typed values

Proof

- By induction through typing rules

⇒ As attacker controlled data enters the application typed *DT*, it can not end up in a *CT* (code) context

The FLET

FLET is modeled as a type-conserving container
⇒ Sequence of data- and code-elements (tokenstream)

$$(\text{FLET})\ \frac{\Gamma \vdash e_i : \tau_i \qquad \tau_i \in \{DT, CT\} \qquad i \in 1...n}{\Gamma \vdash FLET(e_1 : \tau_1, ..., e_n : \tau_n)}$$

$$(\text{retrieval})\ \frac{\Gamma \vdash M : FLET(e_1 : \tau_1, ..., e_n : \tau_n) \qquad \tau_i \in \{DT, CT\} \qquad i, j \in 1...n}{\Gamma \vdash M.e_j : \tau_j}$$

⇒ Within the native language, data and code are cleanly separated

- **Final serialization step is done outside of the language's scope**

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Implementation target

J2EE/HTML/JavaScript

Interesting implementation target

- XSS is one of the most pressing issues today
- Two distinct foreign syntaxes (HTML, JavaScript)
- Many non-trivial injection attack-vectors

Language Integration (I)

“How do we fill the FLET?”

- Incorporation of the foreign language elements into the native language

Three approaches

- API
- Extending the native language’s grammar
- Usage of a pre-processor

Language integration (I)

API approach

```
SQLFlet q = new SQLQuery("SELECT").addMetaChar("*")
                .addKeyWord("FROM").addString("Users");
```

Advantages:

- No additional means necessary (besides creating the API)
- No changes in the native language's syntax, compiler or interpreter

Disadvantages:

- Cumbersome syntax (esp. in the case of complex languages)
- Hard to maintain code
- Programmer's acceptance is doubtable

Language integration (II)

Extending the native language's grammar:

```
SQLFlet q = SELECT * FROM Users;
```

Advantages:

- Strong mimicking of the foreign language's syntax
- Good support for compile time checking
- Almost no learning curve

Disadvantages:

- Requires profound changes in the native language's syntax, compiler or interpreter

→LINQ

Language integration (III)

Usage of a pre-processor:

```
SQLFlet q = $$ SELECT * FROM Users; $$
```

Advantages:

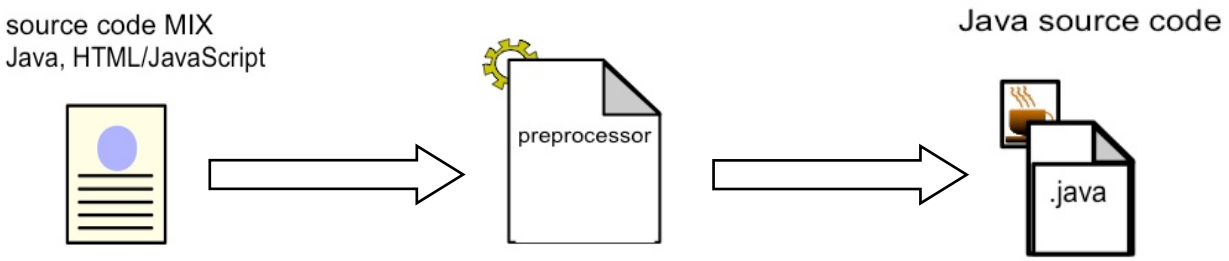
- Strong mimicking of the foreign language's syntax
- Integration of the complete foreign syntax
- Almost no learning curve for developers

Disadvantages:

- Compiled code != source code
- Requires changes in the build process or the language's compiler
- Poor support for compile-time checking of the foreign syntax

Practical realization

Source-to-source translation that translates foreign code into an Java API representation



- The pre-processor locates and parses the foreign code into tokens
- Then it generates the corresponding API calls which instantiate the token-elements and add them to the FLET container

API design

Code elements

- **Completely static instantiation calls**

```
FLET.addJS_Keyword() ⇒
    f.addJS_while()
```

Identifier elements

- **Definition through static values**

```
FLET.addJSIdentifier(const string) ⇒
    f.addJSIdentifier("document")
```

Data elements

- **Definition through native types**

```
FLET.addJS_data(string) ⇒
  f.addJS_data(native_var)
```

Implementing the preprocessor

Simple meta-syntax for mixing foreign and native code

```
String name = request.getParameter("name");
HTMLFlet h $=$ <b>Hallo $data(name)$</b> $$
```

Translated to native Java (using the FLET API)

```
String name = request.getParameter("name");
HTMLFlet h = new HTMLFlet();
h.addOpeningTag_b();
h.addText("Hallo ").addText(name);
h.addClosingTag_b();
```

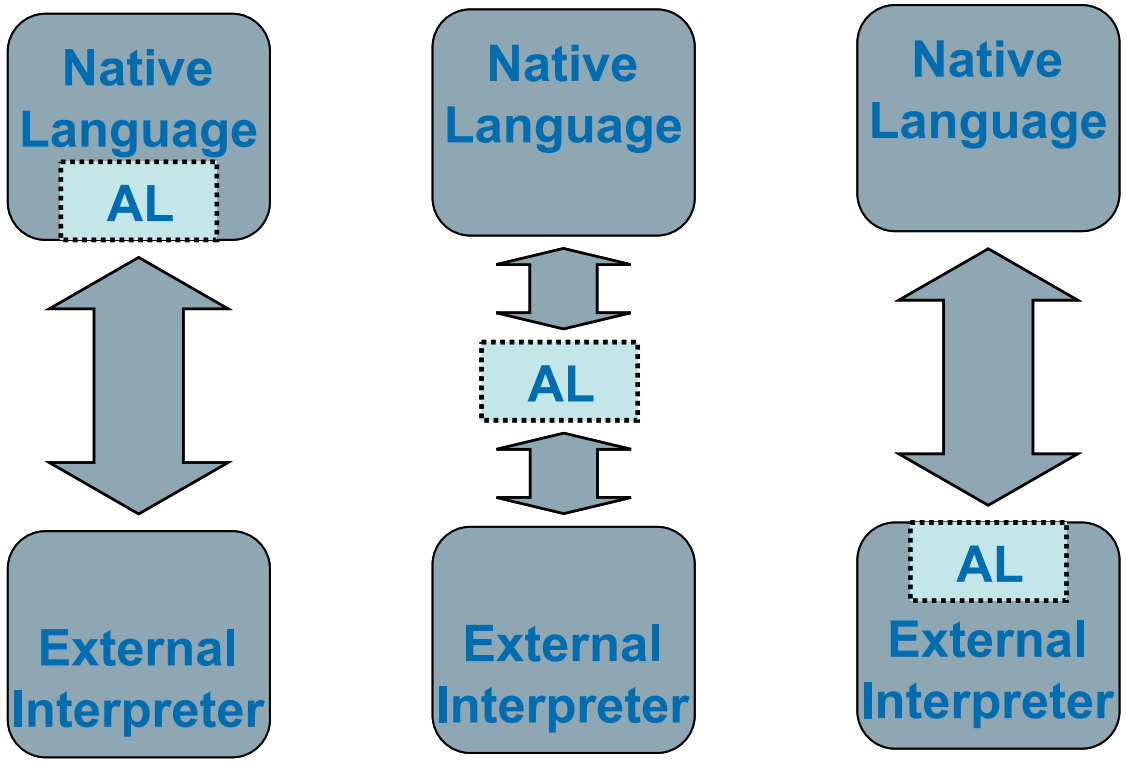
Furthermore

- Meta-syntax for simple FLET operations, such as concatenation
- API calls for splitting, searching, and iterating FLETs

Abstraction Layer: Position

Three possible positions :

- Integral part of the native language
- As a standalone intermediate entity
- Part of the external entity



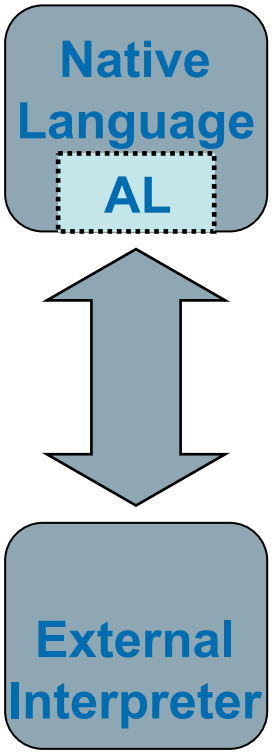
Abstraction Layer: Position (II)

Decision for the prototype:

- Implementation within the native language's runtime environment

Reasons:

- Integration on the server side
- Convenient interface to the FLET
- No deployment problems



FLET serialization

The actual communication is still character-based

- **The FLET has to be securely serialized**

Strategies

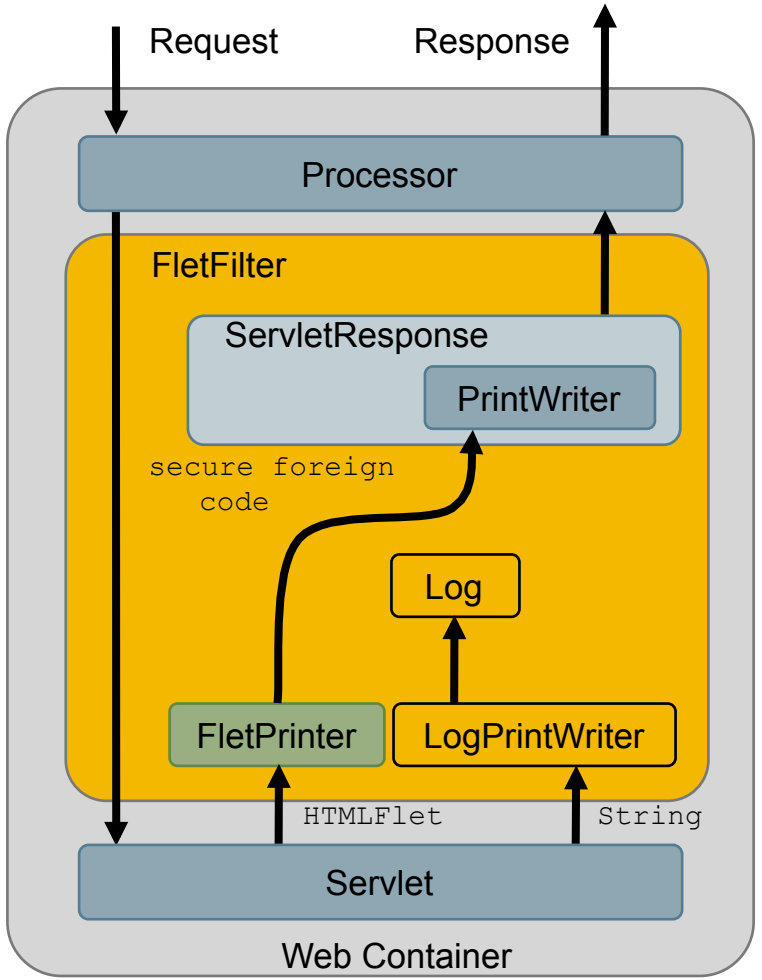
- **Translation into non-executable representation**
  - **If the foreign language provides such a representation**
    - HTML: Entities (&...;)
    - URLs: Percent-encoding (%..)
    - JavaScript: various, e.g., String.fromCharCode()
  - **Current code context is significant**
    - Applicable representation might depend on this context
    - Reliable context information through FLET available
- **Comparison of parse trees**
  - **[Su & Wasserman 06]**
  - **Replacement of data-values with dummy-values**

Implementation

Project with SAP Research

J2EE filter

- Intercepts outbound communication
- Provides a FLET-based interface
- The legacy string-based interface is rerouted to log
- Uses only standard J2EE techniques
- Easy deployment



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Evaluation (I)

Protection Evaluation

- Servlet that blindly echos user-provided data back into various HTML/JavaScript contexts
- Tested against documented XSS attack techniques

```
protected void doGet(HttpServletRequest req, HttpServletResponse resp)
  throws IOException {
    String bad = req.getParameter("data");
   [...]
    HTMLFlet h $=$ <h3>Protection test</h3> $$
    h $+$ Text: $data(bad)$ <br /> $$
    h $+$ Link: <a href="$data(bad)$">link</a> <br /> $$
    h $+$ Script: <script>document.write($data(bad)$);</script><br /> $$
   [...]
    FletPrinter.write(resp, h);    // Writing the FLET content
    resp.getWriter().println(bad); // Testing if the legacy interface
                                   // is correctly disabled
}
```

Evaluation (II)

JSPWiki

- Mature J2EE wiki engine
- ~ 70.000 LoC in 365 java/jsp-files
- Good evaluation target
  - Non-trivial dynamic HTML generation
  - No database backend

Porting to FLET

- 103 files had to be adapted
- ~ 1 person-week

Result

- Chosen version (2.4.103) had several XSS issues
- After porting, these issues were resolved

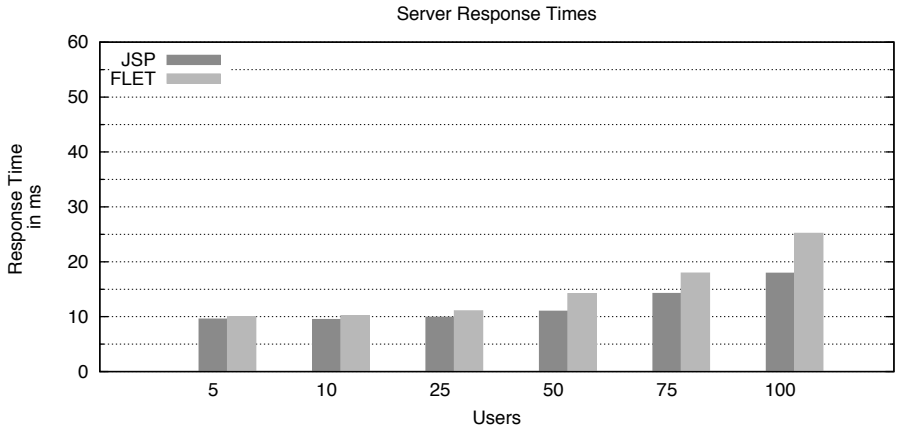
Evaluation (III)

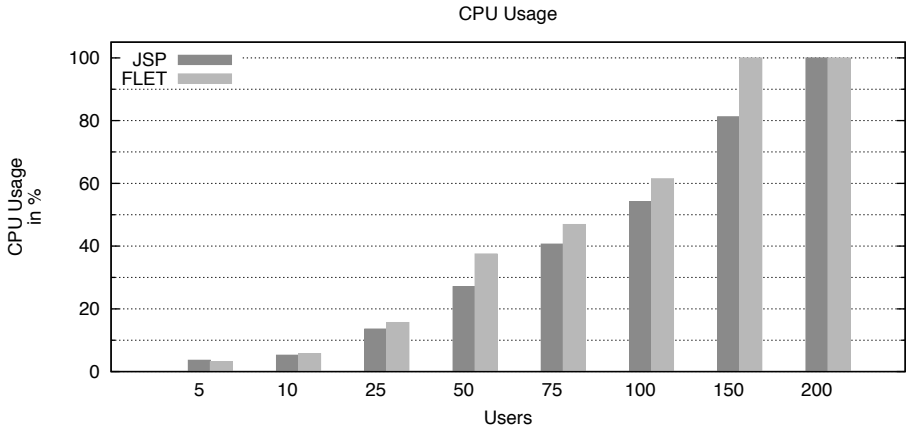
Performance Evaluation

- Test machine: Windows XP running Apache Tomcat
- Measuring tool: HP Loadrunner simulating various, increasing numbers of simultaneous users

Result

- Average observed runtime overhead: up to 25%





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Conclusion

Our approach

- reliably prevents string-based code injection,
- can be used for existing languages/frameworks/servers,
- allows integration of the complete foreign syntax,
- preserves (most of) the string-type conventions,
- and is applicable for all foreign language types
  - Query, mark-up, general purpose, hybrid, …
- Furthermore, given a grammar and a token/type mapping, preprocessor and API could (in theory) be generated automatically

The end

Thanks for your attention

martin.johns@uni-passau.de

Related work

Preprocessor-based integration of foreign code

- SQLJ, Embedded SQL

API-based integration

- DOM, SQLDom

Direct integration

- LINQ, EAX

Dynamic taint tracking

- [Nguyen-Tuong et al. 05], [Pietraszek & Berghe 05], [Xu et al. 06]

During development

- Static taint tracking [Huang et al. 04], [Livshits & Lam 05], [Jovanovic et al. 06]
- Static ISR [Boyd & Keromytis 04], Prepared Statements

Taint analysis

Dynamic tainting

- Establishing on runtime if untrusted data ends up in security sensitive places
- To be effective, it has to be implemented on the character level (a.k.a. *precise tainting*)
  - This requires a low-level alteration of the String datatype
  - Hard to do as every single function that handles strings has to be instrumented
- Can't be implemented on a source code level
  - Source code of the language's interpreter is therefore required
- Relies on sanitation functions that remove the taint-flag
  - String-based code assembly remains
  - Would not have prevented the Samy-worm

FLET and LINQ

LINQ

- Foreign code integration on a semantical level
- Excellent
- Very good support for static checking of foreign code's correctness
- Complete foreign syntax coverage is hard to achieve
- Focus on data-centric foreign code (SQL, XML)
  - General purpose/hybrid languages?

FLET

- Foreign code integration on a purely syntactical level
- Covers the full foreign syntax
- Flexible
- Can be implemented without changing the native compiler
- Uniform foreign code assembly method regardless of the actual foreign laguage

Extension of the formal model

Problem:

- By implementing the FLET through an API we allow a flow from strings to identifier-tokens
- This is not typeable in our current system

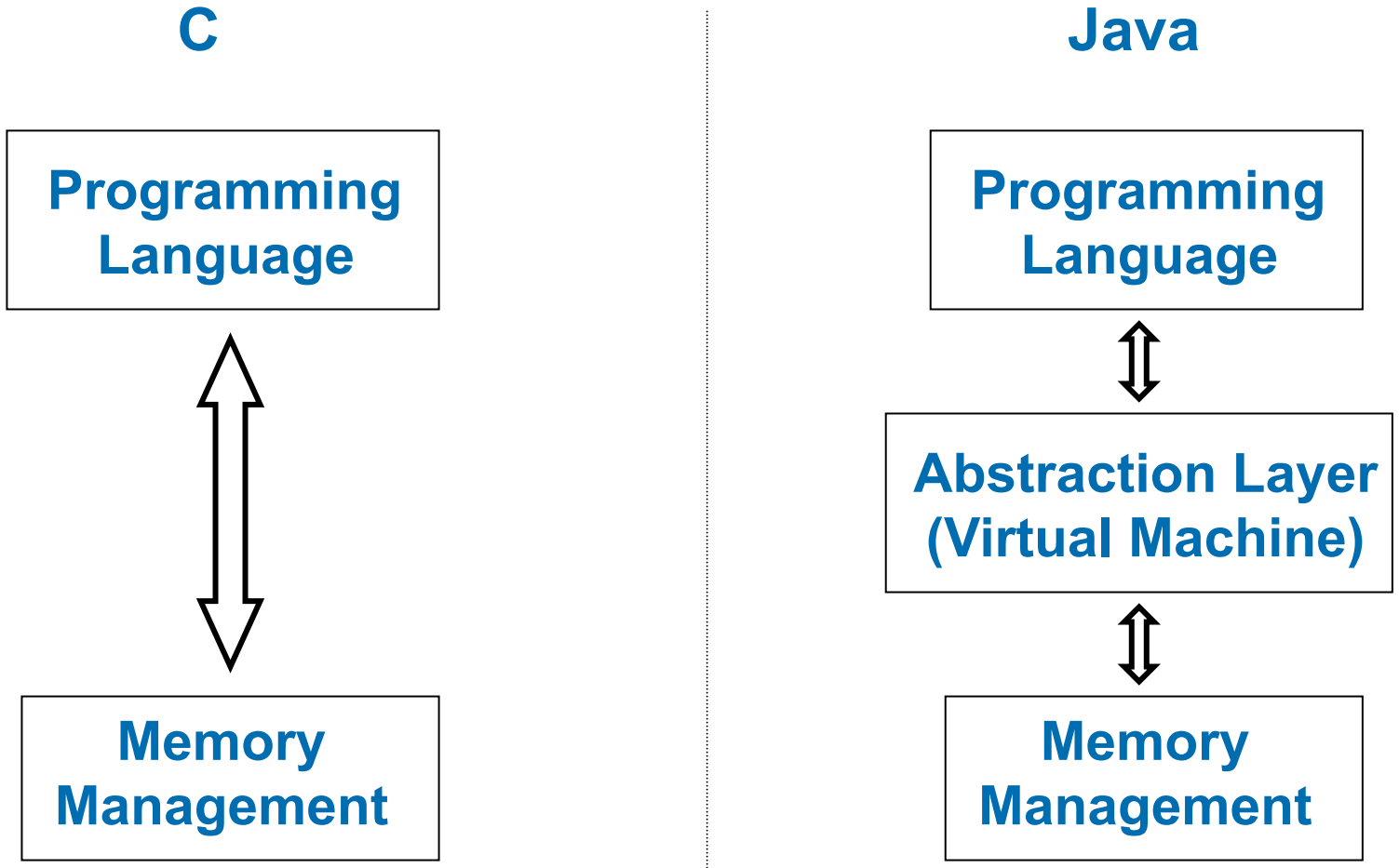
Solution: Three integrity types

- *DT*: Code-tokens
- *IT*: Identifier-tokens, constant strings
- *DT*: Date-tokens, all other native value

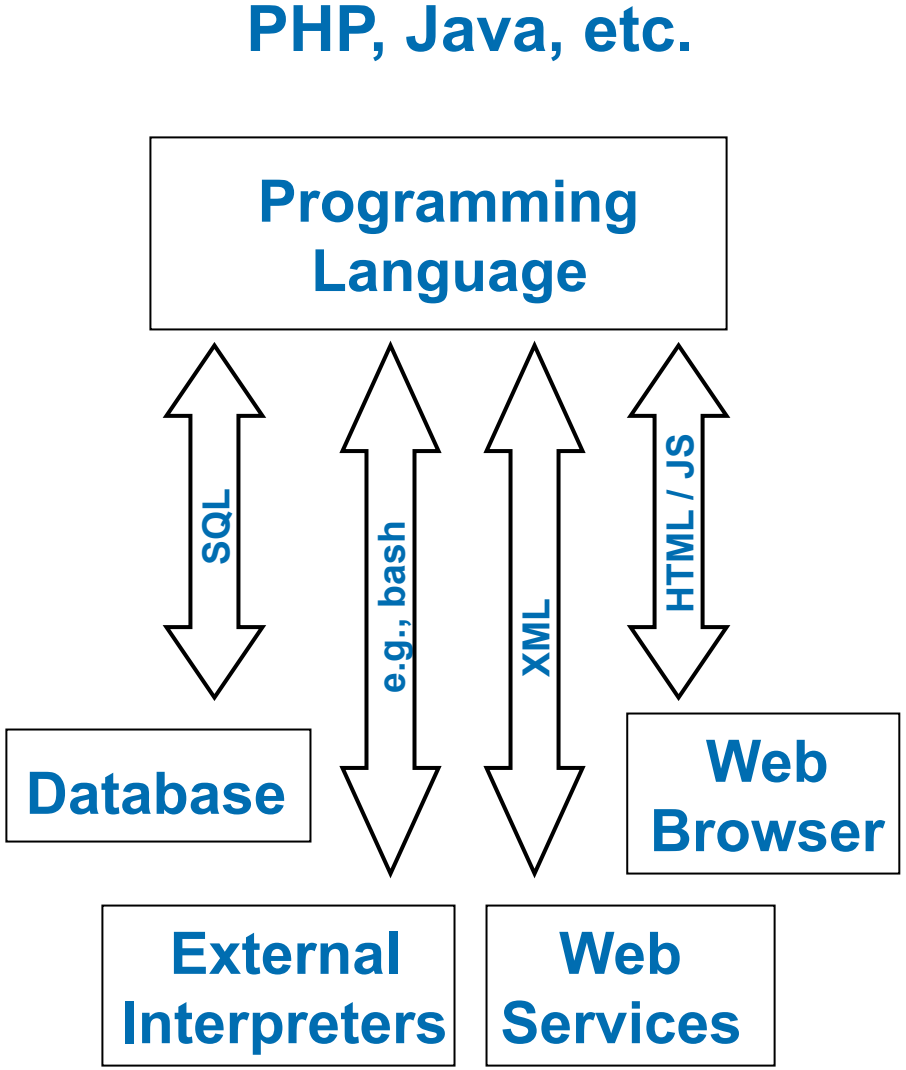
Subtyping relationship

$$CT \subseteq IT \subseteq DT$$

Initial motivation



Initial motivation



?

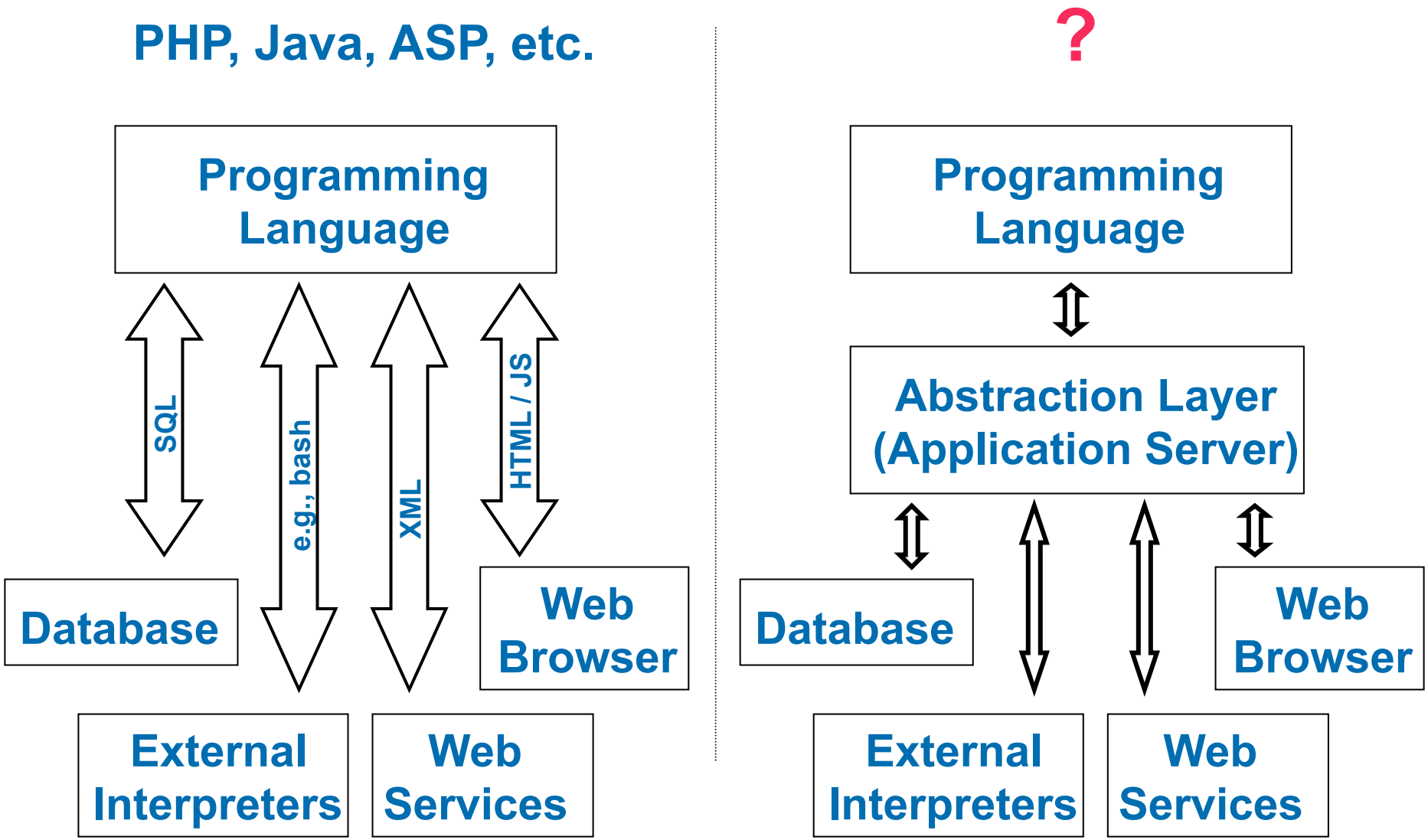
Observation

- **Desired data/code separation is actually only one-way**
  - **Stack traces, error-messages, etc.**
- **No definition of code-elements through data-values**

⇒ Constraints on information flow

Type	Description	Integrity level
DT	Data	low
CT	Code	high
$FLET$	Record-type	$(\tau_1, ..., \tau_n), \tau_i \in \{high, low\}$

Motivation


PHP, Java, ASP, etc.
Programming Language
SQL
e.g., bash
XML
HTML / JS
Database
Web Browser
External Interpreters
Web Services
?
Programming Language
Abstraction Layer (Application Server)
Database
Web Browser
External Interpreters
Web Services

String based code injection

The native compiler/interpreter's view:

```
$pass = $_GET[“password”];

$sql = “SELECT * FROM Users WHERE Passwd = ‘” + $pass + “’”;
```

String **String** **String**

Software Security

Lessons learned from C security

When it comes to code-based security issues, there are three general approaches:

- Mitigation
  - Limit the adversaries abilities even when a vulnerability exists
  - Stack Guards, DEP, ASLR, etc.
- Detection
  - In the source code, e.g., static analysis
  - During execution, e.g., taint tracking
- Prevention
  - Removal of the root cause
  - CCured, Java vs. C

WebAppSec: Prevention

Topic of today's talk…