Preventing Security Bugs Through Software Design

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If I had a dollar for every time someone writes an XSS…

Why so Many Bugs?

- Developer education doesn't solve the problem
  - Very large number of potentially vulnerable code sites
  - Security concerns orthogonal to primary developer focus
  - Sometimes quite subtle
- Bugs are hard to find after the fact
  - Complex, whole-system data-flows
- Low confidence in security assessment

Don't Blame the Dev, Blame the API

Preventing SQL Injection

SQL Injection

```
String getAlbumsQuery = "SELECT … WHERE " +
    " album_owner = " + session.getUserId() +
    " AND album_id = " + servletReq.getParameter("album_id");
ResultSet res = db.executeQuery(getAlbumsQuery);
```

Existing Best Practices

- Prepared Statements
  - Developers forget → potential bug
  - ```
    dbConn.prepareStatement(
        "... WHERE foo = " + req.getParameter("foo"));
    ```
  - (yes, not making this up)
- Structural Query Builders
  - Cumbersome for complex statements
    ```

A Simple, Safe Query API

- Desired: Query has no data-flow dependency on untrusted input
- Implied by: Query is concatenation of application-controlled strings

QueryBuilder

```
public class QueryBuilder {
  private StringBuilder query;

  /** ... Only call with compile-time-constant arg!!! ... */
  public QueryBuilder append(
      @CompileTimeConstant String sqlFragment) {...}

  public String getQuery() { return query.build(); }
}
```

Preventing API Misuse

- Developers don't always read documentation
  - `qb.append(`
    `"WHERE album_id = " + req.getParameter("album_id"));`
- Enforce `@CompileTimeConstant` annotation via javac-integrated checker [github.com/google/error-prone, Aftandilian et al, SCAM '12]
- ```
  java/com/google/.../Queries.java:194: error: [CompileTimeConstant]
  Non-compile-time constant expression passed to parameter with
  @CompileTimeConstant type annotation.
      "WHERE album_id = " + req.getParameter("album_id"));
                          ^
  ```
  ```

Code Refactoring

```
// Before
String sql = "SELECT ... FROM ...";
sql += "WHERE A.sharee = :user_id";

if (req.getParam("rating")!=null) {
  sql += " AND A.rating >= " +
      req.getParam("rating");
}

Query q = sess.createQuery(sql);
q.setParameter("user_id", ...);
```

```
// After
QueryBuilder qb = new QueryBuilder(
    "SELECT ... FROM ...");
qb.append("WHERE A.sharee = :user_id");
qb.setParameter("album_id", ...);

if (req.getParam("rating")!=null) {
  qb.append(" AND A.rating >= :rating");
  qb.setParameter("rating", ...);
}

Query q = qb.build(sess);
```

Practice

- Implemented inherently-safe Builder APIs for F1 [SIGMOD '12, VLDB '13] (C++, Java), Spanner [OSDI '12] (C++, Go, Java), and Hibernate.
- Refactored all existing call-sites across Google
  - Few person-quarters effort
- Removed `executeQuery(String)` methods
  - Hibernate: Errorprone checker to constrain Hibernate API use
- No more SQL injection!

Exceptional Use Cases

- E.g.: Command-line query tool
- Provide potentially-unsafe, unconstrained API
  - Subject to security review,
  - enforced using visibility whitelists [bazel.io/docs/build-encyclopedia.html#common.visibility]
  - Needed rarely (1-2% of call sites)

Preventing XSS

Ad-Hoc HTML Markup Creation

```
var escapedCat = goog.string.htmlEscape(category);
var jsEscapedCat = goog.string.escapeString(escapedCat);
catElem.innerHTML = '<a onclick="createCategoryList(\'' +
        jsEscapedCat + '\')">' + escapedCat + '</a>';
```

What if `category == "');xssPlayload();//"`

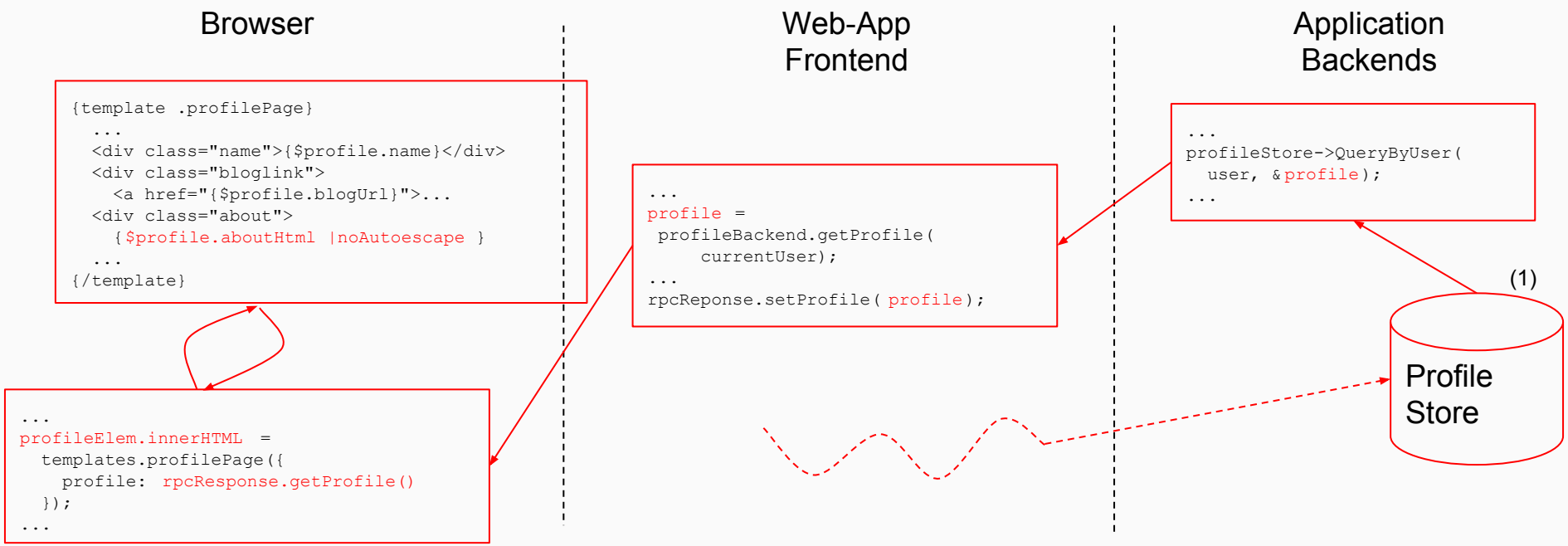
Missing/Incorrect HTML Template Directives

```
{template .profilePage}
  …
  <div class="name">{$profile.name}</div>
  <div class="bloglink">
    <a href="{$profile.blogUrl}">...
  <div class="about">
    {$profile.aboutHtml |noAutoescape}
  …
{/template}
```

Missing/Incorrect HTML Template Directives

```
{template .profilePage}
  …
  <div class="name">{$profile.name}</div>
  <div class="bloglink">
    <a href="{$profile.blogUrl |sanitizeUrl}">...
  <div class="about">
    {$profile.aboutHtml |noAutoescape}
  …
{/template}
```

Complex, Whole-System Dataflows



Strictly Contextually Autoescaping Template Systems

- Template system infers correct **context-sensitive** sanitization/escaping [Samuel et al, CCS '13]
- No escaping directives/modifiers (the **strict** part)
- Recursive

Strict Contextual Template

```
{template .profilePage autoescape="strict"}
  …
  <div class="name">{$profile.name}</div>
  <div class="bloglink">
    <a href="{$profile.blogUrl}">...
  <div class="about">
    {$profile.aboutHtml}
  …
{/template}
```

Strict Contextual Template

```
{template .profilePage autoescape="strict"}
  …
  <div class="name">{$profile.name |escapeHtml}</div>
  <div class="bloglink">
    <a href="{$profile.blogUrl |sanitizeUrl|escapeHtml}">...
  <div class="about">
    {$profile.aboutHtml |escapeHtml}
  …
{/template}
```

Types to Designate Safe Content

- Simple wrappers for string
- Context-specific type contracts
  - SafeHtml
  - SafeUrl
  - TrustedResourceUrl
  - SafeStyle
  - SafeStyleSheet
  - SafeScript
- Similar types in Google Web Toolkit, ca 2009.

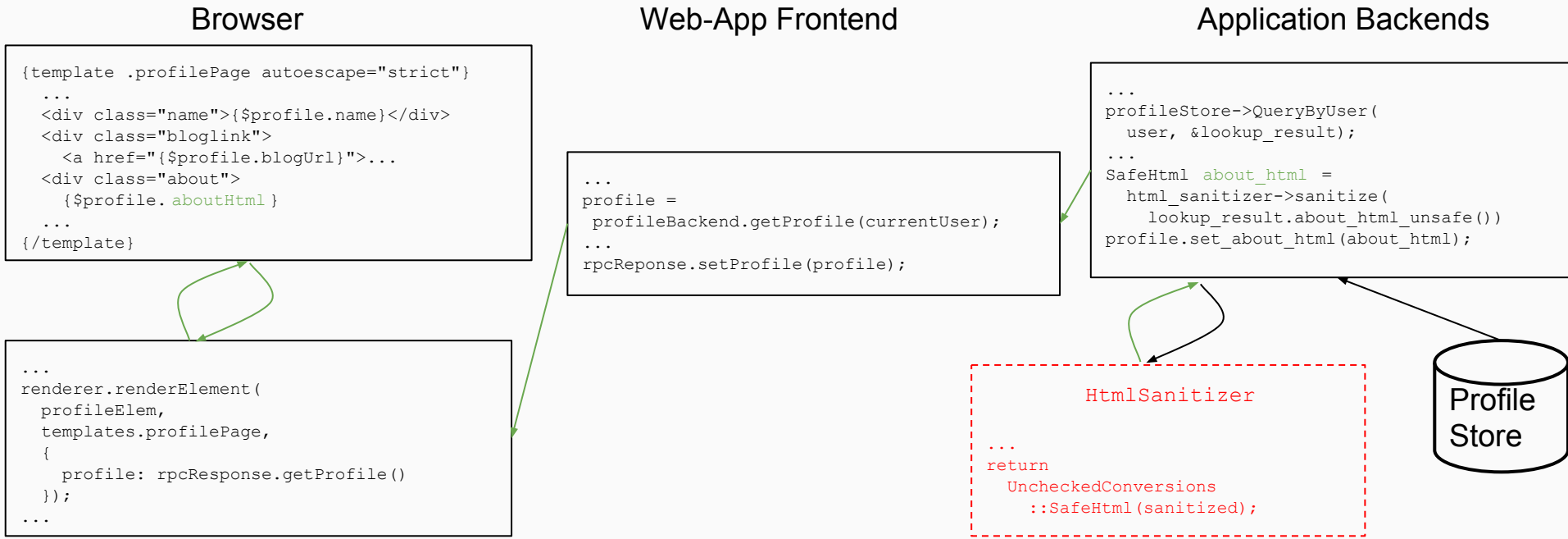
Creating Safe-Content-Typed Values

- Inherently-Safe Builders/Producers
  - Structural builders
  - Strict template evaluation
- Unchecked Conversions
  - Subject to security review (BUILD-visibility)
  - Guidelines on appropriate use -- reviewability & local reasoning

Disallow Injection-Prone Sinks

- `.innerHTML`, server-side responses, etc.
- Static enforcement
  - Javascript conformance pass in Closure Compiler
  - Errorprone
  - Reviewed white-lists

Putting it all Together



Practical Application

- Strict contextual escaping in Closure Templates et al.
- Adopted in several flagship Google applications
- Drastic reduction in bugs
  - One case: **~30 XSS** in 2011, **None** (*) since Sep 2013
- More background: [Kern, CACM 9/'14]

Caveats/Limitations

- Type system
  - Reflection, casts, loose visibility
  - But: Idiomatic usage patterns matter!
- No formal guarantees
  - Correctness properties ultimately based on human reasoning
  - But: By design, **local** reasoning, and drastically reduced scope
  - But: In practice, most bugs found in application code
- Pathological uses: Control-flow dep. effectively implies Data-flow dep.
  - But: Threat model -- Non-malicious programmer

Lessons Learnt

It's OK to change code!

Strings are Bad

Unless Proven Otherwise

Types

Simple Static Checks

Don't Track "Taint",
Make or Track "Safe"

Simple, Safe, Familiar-ish APIs (>98%)

Review-Gated Unsafe API (<2%)

Build on Existing Tooling

Benefits

(Potentially) Vulnerable Code never even Written/Checked-in

Confines Bug Potential into Very Small Portion of Codebase

Drastic Reduction in Bugs Observed

Drastic Reduction in Review Burden

Increased Confidence in Correctness

It's all about API Design

Questions?