CHALMERS
UNIVERSITY OF TECHNOLOGY

SecArchUnit: Extending ArchUnit to support validation of security architectural constraints

Master's Thesis in Software Engineering

MARCUS RANDEVIK
PATRIK OLSON

Department of Computer Science and Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020

Master's thesis 2020:NN

SecArchUnit: Extending ArchUnit to support validation of security architectural constraints

MARCUS RANDEVIK
PATRIK OLSON

Department of Computer Science and Engineering
Division of Software Engineering
Chalmers University of Technology
Gothenburg, Sweden 2020

SecArchUnit: Extending ArchUnit to support validation of security architectural constraints
MARCUS RANDEVIK
PATRIK OLSON

© MARCUS RANDEVIK, PATRIK OLSON, 2020.

Supervisor: Riccardo Scandariato, Computer Science and Engineering
Examiner: Michel Chaudron, Computer Science and Engineering

Master's Thesis 2020:NN
Department of Computer Science and Engineering
Division of Software Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2020

Todo list

Outline chapters 3
Add additional information on the process of deriving at the full list, see comment 6
Reformulate everything as constraints 8
Present each of the final constraints, see notes in comment 8
add word for what is greater 10
Perhaps change the number of mentioned entries 11
Patrik 12
Patrik 12
Show rule definition for each constraint 13
Show how each constraint is used in our toy app 13
Specific example that requires additional information 16
Show rule definition for each constraint 16
Show how each constraint is used in our toy app 16
Specific example that requires an extension 18
Detail the extensions we made 18
Show rule definition for each constraint 18
Show how each constraint is used in our toy app 18
adjust sections as necessary 19

An Informative Headline describing the Content of the Report
A Subtitle that can be Very Much Longer if Necessary
MARCUS RANDEVIK
PATRIK OLSON
Department of Computer Science and Engineering
Chalmers University of Technology

Abstract

Lorem ipsum dolor sit amet, consectetur adipisicing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur. Excepteur sint occaecat cupidatat non proident, sunt in culpa qui officia deserunt mollit anim id est laborum.

Keywords: lorem, ipsum, dolor, sit, amet, consectetur, adipisicing, elit, sed, do.

Acknowledgements

Lorem ipsum dolor sit amet, consectetur adipisicing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur. Excepteur sint occaecat cupidatat non proident, sunt in culpa qui officia deserunt mollit anim id est laborum.

Name Familyname, Gothenburg, Month Year

Contents

Todo list **iii**

List of Figures **xi**

List of Tables **xii**

1 Introduction **1**
1.1 Scope 2
1.2 Research questions 2
1.3 Research contribution 2
1.4 Limitations 2
1.5 Thesis outline 3

2 Background **4**
2.1 Software architecture 4
2.2 Architectural security constraints 4
2.3 ArchUnit 4
2.4 Architectural conformance monitoring 4

3 Methodology **5**
3.1 Data collection 5
3.2 Processing 6
3.3 Validation 6
3.3.1 Solution Proposal 6
3.3.2 Controlled Experiment 6
3.3.2.1 Performance metrics 7
3.3.2.2 Projects used in evaluation 7

4 Selection of Architectural Security Constraints **8**
4.1 Collection of Security Measures 8
4.2 Final Selection 8
4.2.1 Log all security events ✓ 8
4.2.2 Enforce AuthN/AuthZ at single point 10
4.2.3 Messages are sent from a central point 11
4.2.4 Validate user input 11
4.2.5 Restrict thread spawning 11
4.2.6 Sensitive information must stay within trust boundary 12

4.2.7 Secrets must not be exposed in log messages 12

5 Enforcing Constraints 13

5.1 Support in ArchUnit as-is 13
5.1.1 Log all security events 13
5.1.2 Enforce AuthN/AuthZ at single point 15
5.1.3 Messages are sent from a central point 16
5.2 With Additional Information in Code 16
5.2.1 Validate user input 16
5.2.2 Restrict thread spawning 17
5.3 With Extensions to ArchUnit 17
5.3.1 Extensions 18
5.3.2 Constraints 18

6 Evaluation 19

6.1 Selection of systems 19
6.2 Comparison with SonarQube 19

Bibliography 20

List of Figures

5.1 An example of a system, for the purpose of illustrating how the constraints are applied. 14

List of Tables

4.1 Security constraints and their related CIAA goals. 9
4.2 Constraints that have been selected for enforcement. 9

6.1 Results from running both tools on ATM simulator. 19

1

Introduction

In the age of an ever more digitalized world, ensuring the security of software systems becomes an increasingly more critical task. The increased severeness is true in particular, as systems are being developed based on the principle of permanent connectivity [1]. Services ranging from those offered by governmental agencies to that of social media are always connected to the open internet, potentially creating a large surface of attack. Although the great importance of a securely designed system is widely known, developing a secure system is a challenging task as far from all software engineers are security specialists, or for that matter, particularly educated in security aspects [2].

Introducing a weakness into a system can be done in every part of the software development lifecycle. An early introduction often leads to a more costly fix as the scope of the flaw is increased [3]. Typically, weaknesses are categorized as either implementation bugs (e.g. buffer overflow) or design flaws (e.g. client-side validation) where the later commonly has a more extensive scope and is the responsibility of the architect [4]. However, this binary division might be too simplified as it assumes a securely designed is correctly implemented, meaning that there is no discrepancy between the "intended architecture" and the actual one found in the source code. Jasser [5] considers violations of the architectural security design as a third type of category with a comparable impact to that of design flaws.

Deviations from the intended architecture are not unique to the initial implementation of a system. Over time, subsequent changes made to the system, often due to new requirements, frequently lead to further disparency called software erosion [6]. Proponents of the agile methodology also somewhat worsen the problem of erosion as the reduction of upfront design severely hinders the design of the architecture [7]. Many of the tools and techniques produced by academia to try and remedy the frequent violations of architectural design have failed to gain much adoption in the industry [6]. Of the few that have, architectural design documentation is the most prominent and widely included in numerous software processes. While the technique is well adopted, performing it formally to allow for automatic compliance monitoring is seldomly done, which causes developers to rely on the less scalable method of manual reviews [6].

A recently developed tool called ArchUnit[1] has provided architects with the capability to express architectural constraints trough Java unit testing frameworks. ArchUnit is not the first tool developed for architectural conformance checking. It possibly is, however, the first to leverage already existing testing infrastructure (Unit testing) in a manner that allows for testing over time. In its current form, ArchUnit has not provided any explicit functionality to test security constraints. Thus, the objective of this thesis is to explore the feasibility of expressing and enforcing typical security architectural constraints trough ArchUnit.

1.1 Scope

This study focuses on architectural measures that aid in fulfilling a security goal. Moreover, these measures should be possible to enforce through static analysis of Java bytecode. Any measures related to the configuration (of an application or operating system), the file-system, or other run-time properties that cannot be validated through static code analysis are deemed to be out of scope.

1.2 Research questions

To fulfill the objective of the study, the following research questions have been defined:

- RQ1: What architectural security constraints can be validated using the tool?
- RQ2: What modifications can be made to the tool in order to facilitate the validation of additional constraints?

1.3 Research contribution

This study aims to show how architectural security constraints can be validated with the help of a static analysis tool. The thesis demonstrates applications of the tool to several open source systems, over time, in an evaluation of its efficacy and precision in terms of detecting violations of constraints.

1.4 Limitations

The thesis, and the modified version of ArchUnit, is not aimed at being a complete solution for all security architectural constraints. Instead, the study is performed to provide an initial evaluation of the possibility of using ArchUnit as an alternative to already existing techniques of static conformance checking.

The principle of ArchUnit may very well apply to programming languages other than Java. Though, the limited scope of the thesis makes it unfeasible to provide functionality to analyze source-code in additional languages.

---

[1] https://www.archunit.org/

1.5 Thesis outline

The remainder of this report is structured as follows.

Outline chapters

Chapter 2: Provides a general background to the topic of software architecture and architectural security constraints. In addition, the ArchUnit framework is introduced and compared to previously developed tools for architectural conformance.

Chapter 3: design of our evaluation, how systems are chosen, the protocol for testing the tool, how to assert the ground truth, process of mapping constraints to rules

Chapter 4: composing the architectural constraints, our final constraints, what they prevent and how they are expressed

Chapter 5: expressing and enforcing constraints with the tool, the identification of missing information / tool features

Chapter 6: results from the empirical validation

Chapter 6: discussion, answer our research questions

Chapter 7: conclusion

2

Background

This chapter...

2.1 Software architecture

[8], [9], [10], [11], [12],

2.2 Architectural security constraints

[13], [1], [14],

Security goals, CIAA...

2.3 ArchUnit

,

2.4 Architectural conformance monitoring

[15], [16], [17], [18], [6], [19], [20], [21],

3

Methodology

This chapter describes the adopted method for collecting relevant constraints, relating these to the common security-goals of CIAA, and later mapping them to functionality within ArchUnit. Second, this chapter presents the validation plan for expressing security constraints with ArchUnit (as is) by means of an illustration and for expressing additional constraints by means of a controlled experiment.

3.1 Data collection

The relevance of the security architectural constraints included in the study was ensured by performing a review of security measures and common weaknesses and compiling the result to a list of constraints. Completeness was not the primary goal of the review, but rather to provide a set of constraints derived from previous knowledge. Presented below are the three sources used to form the final list.

CAWE catalog: The Common Architectural Weakness Enumeration catalog [22] details 224 common weaknesses in security architectures. Each entry has a description of the weakness and exemplifications of how it could manifest itself in the source code, when applicable. In some entries, there are recommendations on what techniques can be used to detect the weakness, along with mitigation strategies.

Security patterns: Similar to the usage of general design patterns made famous in [23], security patterns provide a reusable and domain-independent solution to a known problem. More specifically, this study focused on security patterns for the design phase, as defined in [2]. While the security pattern repository[1] lists over 170 security patterns, not all are provided with sufficient detail or at the appropriate level of abstraction. As a result, the report by Scandariato et al. [24] which provides a filtered list of patterns.

Security rules: Architectural security rules constrain the implementation of a system while being less solution-oriented compared to security patterns. Eden and Kazman differentiate architectural security rules from those defined on a level of source code based on two criteria, locality and intension/extension [25]. Architectural rules are both non-local and intensional, meaning that they affect all or several parts of the system while having “infinitely-many possible instances”. In [5], Jasser presents a catalog of architectural security rules. Although the entire catalog of 150 security rules is not yet available, the initial list of 22 included in the paper was used in our study.

---

[1] http://sefm.cs.utsa.edu/repository/

3.2 Processing

Each of the three sources where intially review individually

Security measures that we deem difficult to enforce through static analysis, or are otherwise unrelated to security architecture, are discarded upfront. Applicable security measures are categorized according to the security goal that they aim to fulfill. Measures that are similar in nature are combined and presented as a single measure. Additionally, measures defined as the absence of certain functionality are deemed as less important due to the increased difficulty of enforcement [14].

Add additional information on the process of deriving at the full list, see comment

3.3 Validation

The validation of our results will be performed in two ways, depending on whether or not a constraint required any modification of ArchUnit or additional information in the source-code. The latter category carries a higher degree of scientific value thus motivating a more thorough validation procedure. In the sections below, both types of procedures will be described.

3.3.1 Solution Proposal

As described in section 2.3, ArchUnit already provides functionality to perform conformance testing of architectural constraints. However, it is unclear whether the framework supports the enforcement of security architectural constraints. The mapping of security architectural constraints to that of rules in ArchUnit allows us to perform a *proposal of solution* as described in [26]. This type of validation is intended to propose a novel or significantly improved technique without rigorous validation. Instead, a proof of concept or small example is used to facilitate later validation.

3.3.2 Controlled Experiment

In contrast to constraints which may be implemented through already existing functionality, those requiring extension to either the API or additional information within the source-code are not guaranteed to reliably detect violations of the intended architecture. Therefore, validation is performed using a laboratory experiment [27] in order to increase the precision of the measurement.

Integration with already existing testing frameworks is a prominent advantage of ArchUnit. As testing is generally performed overtime to ensure that a system does not degrade, the focus of the experiment is to determine whether ArchUnit can detect changes to security architectural constraints between two versions.

3.3.2.1 Performance metrics

The imbalance between the designer, who needs to ensure that every single aspect of a system is secure, and the attacker, who needs to succeed only once, influences the metrics chosen to represent how well the extension to ArchUnit performs. Precision and recall were the metrics of choice, with the greater importance placed on the latter.

3.3.2.2 Projects used in evaluation

Systems to be included in the validation needed to fulfill two mandatory criteria. First and foremost was the fact that they need open source and written in Java as the static analysis of ArchUnit relies on the source-code. Secondly, there needed to be at minimum two different snapshots in order to fulfill the goal of comparing subsequent changes to a system.

In addition to the mandatory criteria, other aspects were also considered to reduce bias in the validation process. Systems which had already been analyzed in previous literature [28, 18] would provide an existing architecture and its security analysis, which we leverage as ground truth in our experiment. Additionally, systems which have a well documented architecture and security requirements and were within a reasonable size can further help mitigate potential internal validity threats.

4

Selection of Architectural Security Constraints

This chapter describes the methodology of collecting a final list of security constraints from three sources.

4.1 Collection of Security Measures

The processed collection of security measures can be seen in Table 4.1.

Reformulate everything as constraints

4.2 Final Selection

As explained in Section 1.4, the aim is not to demonstrate the enforceability of as many constraints as possible, but rather to investigate the feasibility of using the tool in this manner. To that end, a subset of the full list of security constraints is selected for enforcement. The final list contains 7 architectural security constraints, as this allows us to cover at least one constraint from each goal. The selected constraints can be seen in Table 4.2. The remainder of this section presents each selected constraint in further detail.

Present each of the final constraints, see notes in comment

4.2.1 Log all security events ✓

Description: In any system, several components either directly change or process data, which represents the system's asset, or indirectly by invoking other components to act on its behalf. In either case, the request to perform a particular action originates from an actor (user or external process) who should later be held accountable. As a consequence, the system should log a security event before performing an action that could breach the specified security policies. Although the term security event has become somewhat ambiguous, the definition used in the context of this report comes from the SANS Institute: "An event is an observable occurrence in an information system that actually happened at some point in time." [1]

Typical enforcement: The usage of the *audit interceptor* forces all requests from

---

[1] `https://www.sans.org/reading-room/whitepapers/incident/events-incidents-646`

ID	Constraint	Goal
1	Exceptions shown to the client must be sent to a sanitizer ✓	Confidentiality
2	Sensitive information must not bleed to components with lower security classification ✓	Confidentiality
3	Sensitive information must be encrypted before transmission ✓	Confidentiality
4	Every outbound message must be sent from a single component responsible for transmissions ✓	Confidentiality
5	Data that passes a trust boundary must first be sent to a component responsible for hiding or removing sensitive data ✓	Confidentiality
6	Secrets must not be exposed in log messages ✓	Confidentiality
7	The system must not provide functionality to decrypt secured log messages ✓	Confidentiality
8	Output passing between components must be validated against its specification	Integrity
9	Input from a user must pass through a component validating the data ✓	Integrity
10	The session object must not be accessible to the user ✓	Integrity
11	Components must store its state as restorable checkpoints ✓	Availability
12	Spawning of threads must be limited or throttled ✓	Availability
13	The system must not have multiple points of access ✓	Accountability
14	At least one checkpoint must be initialized after successful authentication and authorization ✓	Accountability
15	Methods related to security events must call the logger ✓	Accountability
16	Authentication and authorization must each be enforced in a single component ✓	Accountability
17	Security relevant log messages must be encrypted and immutable	Accountability

Table 4.1: Security constraints and their related CIAA goals.

#	$\#_{4.1}$	Constraint
1	15	Methods related to security events must call the logger
2	16	Authentication and authorization must each be enforced in a single component
3	4	Every outbound message must be sent from a single component responsible for transmissions
4	9	Input from a user must pass through a component validating the data
5	12	Spawning of threads must be limited or throttled
6	2	Sensitive information must not bleed to components with lower security classification
7	6	Secrets must not be exposed in log messages

Table 4.2: Constraints that have been selected for enforcement.

a user to first be sent to a component responsible for logging the request and later forwarding it to the intended target.

Sources: CAWE 223/778, Jasser rule 5, Security pattern *Audit interceptor*

Attack scenario: A typical scenario where the logging of security events increases a system's resilience to attacks is that of failed login attempts. An attacker may try and guess the credentials of a user by employing a brute-force attack. During the attack, the attacker performs several failed attempts at guessing the credentials, (hopefully) causing the system to either increase the time between repeated attempts or lock the account entirely though with the added effect of decreased availability for the intended user. Although this type of defense temporarily hinders the attacker, a log of failed attempts facilities the detection of malicious actors and enables administrators to impose more permanent measures.

4.2.2 Enforce AuthN/AuthZ at single point

Description: Any system that has more than one user needs to incorporate functionality for authentication (AuthN), as well as authorization (AuthZ) if the privileges between users differ. The difficulty in complex systems where components handle different functionality, thus receiving separate requests and creating multiple entry points, is the fact that the components may have been designed to use various mechanisms of authentication. Instead, AuthN/AuthZ should be delegated to a single component to ensure consistent behavior across all entry points.

Typical enforcement: Designing a single component responsible for AuthN/AuthZ mechanisms across several points of entry. Several third-party libraries exist that provide such features as well as language extending specifications such as Jakarta EE (formerly J2EE).

Sources: CAWE 288/420/592, Security pattern *Authentication enforcer* and *Authorization enforcer*

Attack scenario: In system where the following conditions are true:

- There are multiple points of entry;
- There are different mechanisms to provide AuthN/AuthZ, some having a greater certainty that a user is

  add word for what is greater

- and all points of entry share the same session object

An attacker may try and gain access to the least trusted point of entry and later use the granted authority to access services or operation normally requiring a greater level of trust.

4.2.3 Messages are sent from a central point

✓

Description: Communication with external actors, whether they are a client connecting to a server, or the system requesting data from a third party, is commonly performed over insecure networks. Encryption is the preferred method of securing such communication against potential attackers. However, it is challenging to implement an encryption algorithm correctly as a seemingly small deviation might affect the algorithm's mathematical soundness. Having a single component responsible for any outbound communication reduces the risk of introducing an implementation error, potentially causing an otherwise sound algorithm to be insecure.

Typical enforcement: A single component is responsible for establishing, performing, and closing external communications. This component may be a part of a network library or implemented inside of the system.

Sources: Jasser rule 11

Attack scenario: A banking system may properly use a delegated component for the transmission of some of the most critical data (e.g. credit card numbers) but fail to do so for others (e.g. bank account numbers). An attacker who monitors network traffic at an open wireless network can thus intercept the packets and directly read and/or alter the data sent between the user and the system. If the user were to initiate a money transfer, the attacker could potentially change the recipient's account number.

4.2.4 Validate user input

Description: The ability to receive and process user input is fundamental to every computer system. However, the same input is also the primary source of untrusted data as an attacker possesses full control of what the system receives. Assuming that all data passed to a system is safe to process can have severe consequences when interpreting user input as a part of a query, often referred to as injection. In order to prevent an attacker from compromising the system by injection, all user input must be validated.

Typical enforcement:

Perhaps change the number of mentioned entries

Sources: CAWE 20/59/74-79/88-91/93-99/138/150/349/352/472/473/502/601//641/643/652/790-797/942, Security pattern *input guard*

Attack scenario:

4.2.5 Restrict thread spawning

Description: Computers have finite resources in terms of memory, CPU time and network bandwidth. Systems should be designed with this in mind, employing measures to avoid exhausting the computer's resources. This constraint limits the number of threads that can be spawned on behalf of actors, which could otherwise lead to exhaustion of the CPU.

Typical enforcement: Dispatching tasks to a pool of worker threads that is not allowed to grow beyond a fixed size. Moreover, various mechanisms are employed to throttle or limit requests such that a single actor cannot occupy all of the allotted threads.

Sources: CAWE 770

Attack scenario: An attacker may initiate many requests that are each handled by the system in a separate thread. By initiating requests at a higher rate than the server is able to process them, the resources at the server are eventually exhausted. This leads to a denial of service to any legitimate actors attempting to access the system.

4.2.6 Sensitive information must stay within trust boundary

Patrik

Description:

Typical enforcement:

Sources: CAWE 488

Attack scenario:

4.2.7 Secrets must not be exposed in log messages

Patrik

Description: Many systems handle secrets that should never touch permanent storage. A password is perhaps the most common example of such a secret. While great care can be taken on the design level to ensure that these secrets are not stored to disk, they may still be exposed unintentionally through log messages. In order to prevent such exposure, messages that are sent to the logger must not contain secrets.

Typical enforcement: A typical approach is to manually review log statements and ensure that they do not expose any secrets. As for automated enforcement, various information flow analysis tools, like JOANA[2], can be employed to detect these types of information leaks within a system.

Sources: CAWE 359/532, Jasser rule 13

Attack scenario: Log messages may be accessible to actors who are not otherwise granted direct access to the secrets. By exploiting an unintentional leak of secrets into the log messages, an attacker could systematically extract these without facing the intended restrictions.

---

[2] `https://pp.ipd.kit.edu/projects/joana/`

5

Enforcing Constraints

This chapter explains how the constraints are expressed and validated with the tool. The constraints are divided into three distinct categories. The first category contains the constraints that are possible to express in ArchUnit as-is. The second category describes constraints that are enforceable with the help of additional information in source code. The third and final category details constraints that require an extension of ArchUnit to be possible to enforce.

5.1 Support in ArchUnit as-is

ArchUnit contains an extensive vocabulary for expressing typical architectural constraints. These constraints are typically composed of three parts. The first part indicates the type of Java construct that should be inspected. These constructs include classes, methods, fields and constructors. The second part contains a predicate that selects a subset of these constructs. The third part defines the condition that must hold true for all the selected constructs.

An example of a rule defined solely using this standard vocabulary can be seen in Listing 5.1, where each of the three aforementioned parts of the constraint has been separated into their own line. The rule is a simple example of complete mediation, where some internal classes must only be accessed through a mediator.

```
ArchRule rule = classes()
    .that().resideInAPackage("..internal..")
    .should().onlyBeAccessed().byAnyPackage("..mediator..");
```

Listing 5.1: Example of a rule that is expressed with the standard vocabulary.

In cases where this vocabulary is not sufficient for expressing a constraint, there is a possibility to define custom predicates and conditions over any given construct and supplying these as arguments to the `that()` and `should()` methods.

Show rule definition for each constraint

Show how each constraint is used in our toy app

5.1.1 Log all security events

This constraint is expressed with the assumption that there are services, in the form of classes, that are responsible for performing security related events. Any publicly

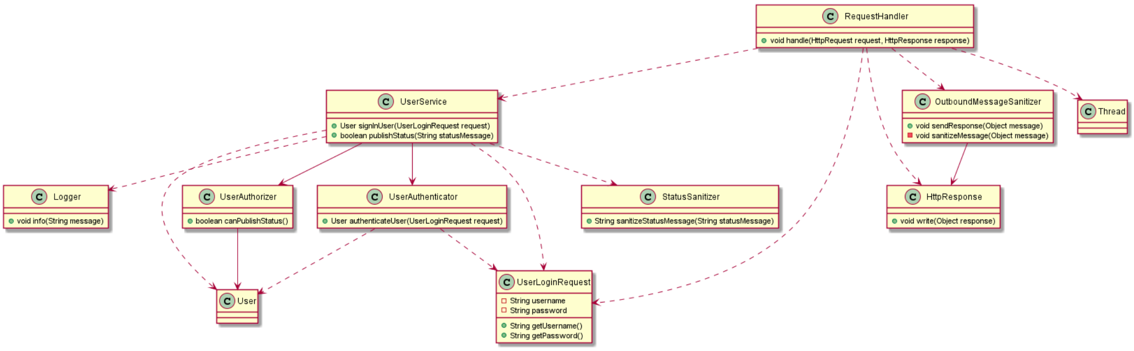
RequestHandler
void handle(HttpRequest request, HttpResponse response)
UserService
User signInUser(UserLoginRequest request)
boolean publishStatus(String statusMessage)
OutboundMessageSanitizer
void sendResponse(Object message)
void sanitizeMessage(Object message)
Thread
Logger
void info(String message)
UserAuthorizer
boolean canPublishStatus()
UserAuthenticator
User authenticateUser(UserLoginRequest request)
StatusSanitizer
String sanitizeStatusMessage(String statusMessage)
HttpResponse
void write(Object response)
User
UserLoginRequest
String username
String password
String getUsername()
String getPassword()

Figure 5.1: An example of a system, for the purpose of illustrating how the constraints are applied.

accessible methods in these services perform a security event and must therefore contain a call to the logging facility.

The definition of the architectural rule can be seen in Listing 5.2. The predicate that selects the security services, and the class that is responsible for logging, are passed as arguments to the architectural rule. This leaves no need for injecting information into the source code of the target system. Furthermore, by using a predicate to select the security services, the developer is left with some flexibility in how they decide to apply the constraint. As opposed to a plain list of classes, a predicate can match all classes belonging to a specific package or following a set naming scheme, minimizing the need for revisiting the constraint as the system evolves.

```java
ArchRule logSecurityEvents(
        DescribedPredicate<? super JavaClass>
            securityServicesDescriptor,
        Class<?> logger) {
    return methods()
        .that().haveModifier(JavaModifier.PUBLIC)
        .and().areDeclaredInClassesThat(securityServicesDescriptor)
        .should(callMethod(declaredIn(logger)));
}
```

Listing 5.2: Rule definition for constraint 1.

In the example system, illustrated in Figure 5.1, the logging facility is the class named `Logger` while the only security service is the `UserService` class. An application of the constraint on this system can be as simple as the one shown in Listing 5.3.

```java
@ArchTest
ArchRule logSecurityEvents = SecArchUnit
    .logSecurityEvents(type(UserService.class), Logger.class);
```

Listing 5.3: Application of constraint 1 to the example system.

5.1.2 Enforce AuthN/AuthZ at single point

The second constraint is defined in terms of two concepts: an authentication point and an authentication enforcer. Authentication is performed through a method call to the authentication enforcer, which is a class whose sole responsibility is to authenticate an actor. This call should occur at the authentication point, and at no other points in the system, for the sake of ensuring a uniform authentication mechanism throughout the system. Authorization is enforced in the same manner, with the concepts of an authorization point and an authorization enforcer.

The definition of the second constraint is detailed in Listing 5.4. The constraint is defined as two separate rules, for the sake of clarity, but their implementations are identical.

```
ArchRule enforceAuthenticationAtCentralPoint(
        Class<?> authenticationPoint,
        Class<?> authenticator) {
    return CompositeArchRule.of(
        theClass(authenticationPoint)
            .should(callMethod(declaredIn(authenticator)))
    ).and(
        methods()
            .that().areDeclaredIn(authenticator)
            .should(onlyBeAccessedBy(authenticationPoint))
    );
}

ArchRule enforceAuthorizationAtCentralPoint(
        Class<?> authorizationPoint,
        Class<?> authorizer) {
    return enforceAuthenticationAtCentralPoint(
        authorizationPoint,
        authorizer
    );
}
```

Listing 5.4: Rule definition for constraint 2.

In the example system, the authentication and authorization points are both situated in the `UserService` class while authentication and authorization are enforced by the classes `UserAuthenticator` and `UserAuthorizer` respectively. The application of the rule can be seen in Listing 5.5.

```
@ArchTest
ArchRule enforceAuthentication = SecArchUnit
    .enforceAuthenticationAtCentralPoint(UserService.class,
       UserAuthenticator.class);

@ArchTest
ArchRule enforceAuthorization = SecArchUnit
    .enforceAuthorizationAtCentralPoint(UserService.class,
       UserAuthorizer.class);
```

Listing 5.5: Application of constraint 2 to the example system.

5.1.3 Messages are sent from a central point

...

```
ArchRule sendOutboundMessagesFromCentralPoint(
        Class<?> sendingPoint,
        DescribedPredicate<? super JavaClass> senderDescriptor) {
    return methods()
        .that().areDeclaredInClassesThat(senderDescriptor)
        .and(haveAtLeastOneParameter)
        .should(onlyBeAccessedBy(sendingPoint));
}
```

Listing 5.6: Rule definition for constraint 3.

5.2 With Additional Information in Code

Some of the architectural constraints require that the developer injects additional information into the source code.

In some cases, this information is simply an indicator that says something about an entire class. Naming the class with a specific suffix is one approach to accomplish this. Another approach is to implement an empty interface, which is the technique used with Java's `Serializable`[1] interface.

In other cases, however, the information may be required for methods of arbitrary signatures and even specific fields. For the purposes of flexibility and minimal obtrusiveness, any extra information is expressed in the form of annotations. These can be applied to classes, fields, methods and parameters without changing the underlying architecture of the system.

Specific example that requires additional information

Show rule definition for each constraint

Show how each constraint is used in our toy app

5.2.1 Validate user input

...

---

[1] https://docs.oracle.com/javase/7/docs/api/java/io/Serializable.html

```
public static ArchRule validateUserInput() {
    return codeUnits()
        .that().areAnnotatedWith(UserInput.class)
        .should(performDirectOrIndirectValidation);
}
```

Listing 5.7: Rule definition for constraint 4.

5.2.2 Restrict thread spawning

While resources is a broad term, this constraint focuses on preventing the exhaustion of CPU and memory resources through the creation of new threads and processes. As such, every block of code that contains a call to the `start()` method of a `Thread`[2] or any of its subclasses, must be marked as containing a resource restriction mechanism. The same rule is applied for calls to `ProcessBuilder.start()`[3] and `Runtime.exec()`[3], which lead to the creation of new processes.

The marking is done with the help of an annotation, either on the relevant method or the entire class. The decision of how the restriction mechanism is implemented is left to the developer of the system.

```
public static ArchRule limitResourceAllocation() {
    return noClasses()
        .that().areNotAnnotatedWith(ResourceRestriction.class)
        .should().callMethodWhere(
            aThreadIsStartedWithoutRestriction
        ).orShould().callMethodWhere(
            aProcessIsStartedWithoutRestriction
        );
}
```

Listing 5.8: Rule definition for constraint 5.

5.3 With Extensions to ArchUnit

In the current ArchUnit API, a rule that aims to constrain access to a method (or field) must be expressed in terms of the type signatures of the source and target methods. Some of our constraints require knowledge about the type signature of the object that is being passed as a parameter. This is a non-issue when fields and method parameters are of the same types as the objects being passed to them. However, in cases where a method signature accepts a "more general" type, such as an `Object`, there is no way for ArchUnit to constrain the types of the objects that are actually being passed as arguments.

ArchUnit builds its representation of the architecture using ASM[4], a Java bytecode analysis framework. This framework contains functionality for keeping track of the stack and local variables while analyzing the instructions of a method. With knowledge of the type signatures of the references on the stack at the time of a method call or field assignment, it is possible to determine the type signatures of objects passed as method arguments or an object being assigned to a field. Our extension provides this additional information in ArchUnit's representation of accesses to fields and methods, which the rule definitions can then make use of.

---

[2] https://docs.oracle.com/javase/7/docs/api/java/lang/Thread.html

[3] https://docs.oracle.com/javase/7/docs/api/java/lang/Process.html

[4] `https://asm.ow2.io/`

Specific example that requires an extension

5.3.1 Extensions

Detail the extensions we made

5.3.2 Constraints

Show rule definition for each constraint

Show how each constraint is used in our toy app

Do not allow sensitive information to bleed to other components

...

Do not log secrets

...

6

Evaluation

adjust sections as necessary

6.1 Selection of systems

6.2 Comparison with SonarQube

...

The results from this comparison can be seen in Table 6.1.

Tool	**TP**	**FP**	**FN**	**Precision**	**Recall**
SecArchUnit	19	1	2	0.95	0.90
SonarQube plugin	17	1	4	0.94	0.81

Table 6.1: Results from running both tools on ATM simulator.

Bibliography

[1] M. Felderer, M. Büchler, M. Johns, A. D. Brucker, R. Breu, and A. Pretschner, "Security Testing," in *Advances in Computers.* Elsevier, 2016, vol. 101, pp. 1–51. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0065245815000649

[2] N. Yoshioka, H. Washizaki, and K. Maruyama, "A survey on security patterns," *Progress in Informatics*, no. 5, p. 35, Mar. 2008. [Online]. Available: http://www.nii.ac.jp/pi/n5/5_35.html

[3] G. Mcgraw, "Software security," *IEEE Security & Privacy Magazine*, vol. 2, no. 2, pp. 80–83, Mar. 2004. [Online]. Available: http://ieeexplore.ieee.org/document/1281254/

[4] I. Arce, K. Clark-Fisher, N. Daswani, J. DelGrosso, D. Dhillon, C. Kern, T. Kohno, C. Landwehr, G. McGraw, B. Schoenfield, and others, "Avoiding the top 10 software security design flaws," *IEEE Computer Society*, 2014.

[5] S. Jasser, "Constraining the Implementation Through Architectural Security Rules: An Expert Study," in *Product-Focused Software Process Improvement*, X. Franch, T. Männistö, and S. Martínez-Fernández, Eds. Cham: Springer International Publishing, 2019, vol. 11915, pp. 203–219. [Online]. Available: http://link.springer.com/10.1007/978-3-030-35333-9_15

[6] L. de Silva and D. Balasubramaniam, "Controlling software architecture erosion: A survey," *Journal of Systems and Software*, vol. 85, no. 1, pp. 132–151, Jan. 2012. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0164121211002044

[7] J. van Gurp and J. Bosch, "Design erosion: problems and causes," *Journal of Systems and Software*, vol. 61, no. 2, pp. 105–119, Mar. 2002. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0164121201001522

[8] D. Garlan and M. Shaw, "AN INTRODUCTION TO SOFTWARE ARCHITECTURE," in *Series on Software Engineering and Knowledge Engineering.* WORLD SCIENTIFIC, Dec. 1993, vol. 2, pp. 1–39. [Online]. Available: http://www.worldscientific.com/doi/abs/10.1142/9789812798039_0001

[9] A. Jansen and J. Bosch, “Software Architecture as a Set of Architectural Design Decisions,” in *5th Working IEEE/IFIP Conference on Software Architecture (WICSA’05)*. Pittsburgh, PA, USA: IEEE, 2005, pp. 109–120. [Online]. Available: http://ieeexplore.ieee.org/document/1620096/

[10] L. Bass, P. Clements, and R. Kazman, *Software architecture in practice*, 3rd ed., ser. SEI series in software engineering. Upper Saddle River, NJ: Addison-Wesley, 2013.

[11] R. Scandariato, K. Yskout, T. Heyman, and W. Joosen, “Architecting software with security patterns,” Katholieke Universiteit Leuven, Belgium, Tech. Rep. CW 515, Apr. 2009.

[12] P. H. Nguyen, K. Yskout, T. Heyman, J. Klein, R. Scandariato, and Y. Le Traon, “SoSPa: A system of Security design Patterns for systematically engineering secure systems,” in *2015 ACM/IEEE 18th International Conference on Model Driven Engineering Languages and Systems (MODELS)*. Ottawa, ON, Canada: IEEE, Sep. 2015, pp. 246–255. [Online]. Available: http://ieeexplore.ieee.org/document/7338255/

[13] M. Broy, J. Grünbauer, and C. A. R. Hoare, Eds., *Software system reliability and security*, ser. NATO security through science series. Amsterdam ; Washington, DC: IOS Press, 2007, no. v. 9, oCLC: ocn127107624.

[14] C. Haley, R. Laney, J. Moffett, and B. Nuseibeh, “Security Requirements Engineering: A Framework for Representation and Analysis,” *IEEE Transactions on Software Engineering*, vol. 34, no. 1, pp. 133–153, Jan. 2008. [Online]. Available: http://ieeexplore.ieee.org/document/4359475/

[15] J. Aldrich, C. Chambers, and D. Notkin, “ArchJava: connecting software architecture to implementation,” in *Proceedings of the 24th International Conference on Software Engineering. ICSE 2002*. Orlando, FL, USA: ACM, 2002, pp. 187–197. [Online]. Available: http://ieeexplore.ieee.org/document/1007967/

[16] M. Abi-Antoun and J. M. Barnes, “Analyzing Security Architectures,” in *Proceedings of the IEEE/ACM International Conference on Automated Software Engineering*, ser. ASE ’10. New York, NY, USA: ACM, 2010, pp. 3–12, event-place: Antwerp, Belgium. [Online]. Available: http://doi.acm.org/10.1145/1858996.1859001

[17] D. Luckham and J. Vera, “An event-based architecture definition language,” *IEEE Transactions on Software Engineering*, vol. 21, no. 9, pp. 717–734, Sep. 1995. [Online]. Available: http://ieeexplore.ieee.org/document/464548/

[18] M. Abi-Antoun and J. Aldrich, “Static extraction and conformance analysis of hierarchical runtime architectural structure using annotations,” in *Proceeding of the 24th ACM SIGPLAN conference on Object oriented programming systems languages and applications - OOPSLA 09*. Orlando,

Florida, USA: ACM Press, 2009, p. 321. [Online]. Available: http://dl.acm.org/citation.cfm?doid=1640089.1640113

[19] J. Knodel and D. Popescu, “A Comparison of Static Architecture Compliance Checking Approaches,” in *2007 Working IEEE/IFIP Conference on Software Architecture (WICSA’07)*. Mumbai, India: IEEE, Jan. 2007, pp. 12–12. [Online]. Available: http://ieeexplore.ieee.org/document/4077029/

[20] A. Jansen, J. Bosch, and P. Avgeriou, “Documenting after the fact: Recovering architectural design decisions,” *Journal of Systems and Software*, vol. 81, no. 4, pp. 536–557, Apr. 2008. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S016412120700194X

[21] Hong Yan, D. Garlan, B. Schmerl, J. Aldrich, and R. Kazman, “DiscoTect: a system for discovering architectures from running systems,” in *Proceedings. 26th International Conference on Software Engineering*. Edinburgh, UK: IEEE Comput. Soc, 2004, pp. 470–479. [Online]. Available: http://ieeexplore.ieee.org/document/1317469/

[22] J. C. S. Santos, K. Tarrit, and M. Mirakhorli, “A Catalog of Security Architecture Weaknesses,” in *2017 IEEE International Conference on Software Architecture Workshops (ICSAW)*. Gothenburg, Sweden: IEEE, Apr. 2017, pp. 220–223. [Online]. Available: http://ieeexplore.ieee.org/document/7958491/

[23] E. Gamma, Ed., *Design patterns: elements of reusable object-oriented software*, ser. Addison-Wesley professional computing series. Reading, Mass: Addison-Wesley, 1995.

[24] R. Scandariato, K. Yskout, T. Heyman, and W. Joosen, “A system of security patterns,” Katholieke Universiteit Leuven, Belgium, Tech. Rep. CW 469, Dec. 2006.

[25] A. Eden and R. Kazman, “Architecture, design, implementation,” in *25th International Conference on Software Engineering, 2003. Proceedings.* Portland, OR, USA: IEEE, 2003, pp. 149–159. [Online]. Available: http://ieeexplore.ieee.org/document/1201196/

[26] R. Wieringa, N. Maiden, N. Mead, and C. Rolland, “Requirements engineering paper classification and evaluation criteria: a proposal and a discussion,” *Requirements Engineering*, vol. 11, no. 1, pp. 102–107, Mar. 2006. [Online]. Available: http://link.springer.com/10.1007/s00766-005-0021-6

[27] K.-J. Stol and B. Fitzgerald, “The ABC of Software Engineering Research,” *ACM Transactions on Software Engineering and Methodology*, vol. 27, no. 3, pp. 1–51, Sep. 2018. [Online]. Available: http://dl.acm.org/citation.cfm?doid=3276753.3241743

[28] S. Peldszus, K. Tuma, D. Struber, J. Jurjens, and R. Scandariato, “Secure Data-Flow Compliance Checks between Models and Code Based on

Automated Mappings,” in *2019 ACM/IEEE 22nd International Conference on Model Driven Engineering Languages and Systems (MODELS)*. Munich, Germany: IEEE, Sep. 2019, pp. 23–33. [Online]. Available: https://ieeexplore.ieee.org/document/8906984/