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Large-Scale Empirical Studies to Assess Static Type Systems

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Abstract

The main goal of a static type system is to prevent certain kind of errors from happening at run-time. A type system is formulated as a set of constraints that gives any expression or term in a program a well-defined type. Yet they provide the means to circumvent their constraints through the *unsafe intrinsics* and *casting* mechanisms.

We want to understand to what degree JAVA's type system is useful. To that end, we plan to empirically study how these two mechanisms — unsafe intrinsics and casting — are used by developers. Our study focus on how these features are used in JAVA, given its wide usage and relevance for both research and industry.

We have devised (for the JAVA's Unsafe API) and we plan to devise (for casting) usage patterns. We believe that having usage patterns can help us to better categorize use cases and thus understanding how those features are used. These patterns can provide an insight on how the language is being used by developers in real-world applications.

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Contents

Chapter 1

Introduction

In programming language design, the main goal of a *static* type system is to prevent certain kind of errors from happening at run-time. A type system is formulated as a set of constraints that gives any expression or term in a program a well-defined type. As Pierce [2002] states: "A type system can be regarded as calculating a kind of *static* approximation to the run-time behaviors of the terms in a program." These constraints are enforced by the *type-checker* either when compiling or linking the program. Thus, any program not satisfying the constraints stated within a type system is simply rejected by the type-checker.

Nevertheless, often the static approximation provided by a type system is not precise enough. Being static, the analysis done by the type-checker needs to be conservative. It is preferably to reject programs that are valid, but their validity cannot be ensured by the type-checker, rather than accept some invalid programs. But there are situations when the developer has more information about the program that is too complex to explain in terms of the typing constraints. To that end, the constraints of a type system can be relaxed to permit more programs to be valid at the expense of causing more errors at run-time. There are essentially two mechanisms that relax the typing constraints: *Unsafe Intrinsics* and *Casting*.

Unsafe Intrinsics. Unsafe intrinsics is the ability to perform certain operations *without* being checked by the compiler. They are *unsafe* because any misuse made by the programmer can compromise the entire system, *e.g.*, corrupting data structures without notice, or crashing the run-time system. Unsafe intrinsics can be seen in safe languages, *e.g.*, JAVA, C#, RUST, or HASKELL. Foreign Function Interface (*FFI*), *i.e.*, calling native code from within a safe environment is unsafe. It is so because the run-time system cannot guarantee that the native code will not compromise the entire system. In addition to FFI, some safe languages offer so-called *unsafe* blocks, *i.e.*, making unsafe operations within the language itself, *e.g.*, C#[1] and RUST[2] . Other languages provide an API to perform unsafe operations, *e.g.*, HASKELL[3] and JAVA. But in the case of JAVA, the API to make unsafe operations, sun.misc.Unsafe,

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[1] https://docs.microsoft.com/en-us/dotnet/csharp/language-reference/language-specification/unsafe-code

[2] https://doc.rust-lang.org/book/second-edition/ch19-01-unsafe-rust.html

[3] http://hackage.haskell.org/package/base-4.11.1.0/docs/System-IO-Unsafe.html

is unsupported[4] and undocumented. It was originally intended for internal use within the JDK, but as we shall see later on, it is used outside the JDK as well.

Casting. Programming languages with subtyping such as JAVA or C++ provide a mechanism to *view* an expression as a different type as it was defined. This mechanism is often called *casting* and takes the form (T)t. Casting can be in two directions: *upcast* and *downcast*. An upcast conversion happens when converting from a reference type S to a reference type T, provided that T is a *supertype* of S. An upcast does not require any explicit casting operation nor compiler check. However, as we shall see later on, there are situations where an upcast requires an explicit casting operation. On the other hand, a downcast happens when converting from a reference type S to a reference type T, provided that T is a *subtype* of S. Unlike upcasts, downcasts require a run-time check to verify that the conversion is indeed valid. This implies that downcasts provide the means to bypass the static type system. By avoiding the type system, downcasts can pose potential threats, because it is like the developer saying to the compiler: *"Trust me here, I know what I'm doing"*. Being a escape-hatch to the type system, a cast is often seen as a design flaw or code smell Tufano et al. [2015] in an object-oriented system.

If static type systems aim to prevent causing certain kind of errors at run-time, yet they provide the means to circumvent their constraints, why exactly does one need to do so? Are these mechanisms actually used in real-world code? This triggers our **research question**:

> Why developers need to circumvent the static type system's constraints?

To answer it, we plan to empirically study how the two aforementioned mechanisms — unsafe intrinsics and casting — are used by developers. Since any kind of language study must be language-specific, our plan is to focus on JAVA given its wide usage and relevance for both research and industry. We focus on the JAVA Unsafe API to study unsafe intrinsics. The Java Native Interface already has been studied in Tan et al. [2006]; Tan and Croft [2008]; Kondoh and Onodera [2008]; Sun and Tan [2014]; Li and Tan [2009].

We want to understand to what degree JAVA's type system is useful. To that end, we have devised (for the Unsafe API) and we plan to devise (for casting) usage patterns. We believe that having usage patterns can help us to better categorize use cases and thus understanding how those features are used. These patterns can provide an insight on how the language is being used by developers in real-world applications. We have confidence that this knowledge can be: a) useful to make informed decisions for current & future language designers, not only JAVA, b) a reference for tool builders, *e.g.*, by providing more precise or new refactoring analyses, c) a guide for researchers to test new language features or to carry out controlled programming experiments, and d) a guide for developers for best or better practices.

The rest of this proposal is organized as follows: Chapter 2 reviews the literature in the *state-of-the-art* of the different aspects related to our goal. Chapter 3 summarizes the study we already made on the Unsafe API in JAVA Mastrangelo et al. [2015]. Finally, Chapter 4 presents our proposal plan for the *casting* study, showing the results we have so far.

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[4]http://www.oracle.com/technetwork/java/faq-sun-packages-142232.html

Chapter 2

Literature Review

Understanding how language features and APIs are being used is a broad topic. There is plenty of research in computer science literature about empirical studies of programs; which involves several directions directly or indirectly related to our topic. Along the last decades, researchers always has been interested in understanding what kind of programs developers write. The motivation behind these studies is quite broad and — together with the evolution of computer science itself — has shifted to the needs of researchers.

For instance, already Knuth [1971] started to study FORTRAN programs. By knowing what kind of programs arise in practice, a compiler optimizer can focus in those cases, and therefore can be more effective. Alternatively, to measure the advantages between compilation and interpretation in BASIC, Hammond [1977] has studied a representative dataset of programs. Adding to Knuth's work, Shen et al. [1990] made an empirical study for parallelizing compilers. Similar works have been done for COBOL Salvadori et al. [1975]; Chevance and Heidet [1978], PASCAL Cook and Lee [1982], and APL Saal and Weiss [1975, 1977] programs.

The organization of the rest of this chapter is as follows: How benchmarks and corpora relate to this kind of studies is presented in §2.1. In §2.2 we give an overview of other large-scale studies either in JAVA or in other languages. Code Patterns discovery is presented in §2.3. An overview of what tools are available to extract information from software repositories is given in §2.4, while §2.5 shows how to select good candidates projects from a large-base software repository. Finally in §2.6 and §2.7 we present the related work more specific to the Unsafe API and Casting respectively.

2.1 Benchmarks and Corpora

Benchmarks are crucial to properly evaluate and measure product development. This is key for both research and industry. One popular benchmark suite for JAVA is DaCapo Blackburn et al. [2006]. This suite has been already cited in more than thousand publications, showing how important is to have reliable benchmark suites.

Another suite has been developed by Tempero et al. [2010]. They provide a corpus of curated open source systems to facilitate empirical studies on source code. On top of Qualitas Corpus, Dietrich et al. [2017b] provide an executable corpus of JAVA programs. This allows any researcher to experiment with both static and dynamic analysis.

For any benchmark or corpus to be useful and reliable, it must faithfully represent real world code. Along these lines, Allamanis and Sutton [2013] go one step further and provide a large-scale (14,807) curated corpus of open source JAVA projects.

2.2   Large-scale Codebase Empirical Studies

In the same direction to our plan, Callaú et al. [2013] performed an empirical study to assess how much the dynamic and reflective features of SMALLTALK are actually used in practice. Analogously, Richards et al. [2010, 2011] made a similar study, but in this case targeting JAVASCRIPT's dynamic behavior and in particular the eval function. Also for JAVASCRIPT, Madsen and Andreasen [2014] analyzed how fields are accessed via strings, while Jang et al. [2010] analyzed privacy violations. Similar empirical studies were done for PHP Hills et al. [2013]; Dahse and Holz [2015]; Doyle and Walden [2011] and SWIFT Rebouças et al. [2016].

Going one step forward, Ray et al. [2017] studied the correlation between programming languages and defects. One important note is that they choose relevant project by popularity, measured *stars* in *GitHub*. We argue that it is more important to analyse projects that are *representative*, not *popular*. Gorla et al. [2014] mined a large set of Android applications, clustering applications by their description topics and identifying outliers in each cluster with respect to their API usage. Grechanik et. al. Grechanik et al. [2010] also mined large scale software repositories to obtain several statistics on how source code is actually written.

For JAVA, Dietrich et al. [2017a] made a study about how programmers use contracts in *Maven Central*[1]. Landman et al. [2017] have analyzed the relevance of static analysis tools with respect to reflection. They made an empirical study to check how often the reflection API is used in real-world code. They argue that controlled experiments on subjects need to be correlated with real-world use cases, *e.g.*, *GitHub* or *Maven Central*. Dietrich et al. [2014] have studied how changes in API library impact in JAVA programs. Notice that they have used the Qualitas Corpus Tempero et al. [2010] mentioned above for their study.

Exceptions

Kery et al. [2016]; Asaduzzaman et al. [2016] focus on exceptions. They made empirical studies on how programmers handle exceptions in JAVA code. The work done by Nakshatri et al. [2016] categorized them in patterns. Whether Coelho et al. [2015] used a more dynamic approach by analysing stack traces and code issues in *GitHub*.

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[1] http://central.sonatype.org/

Kechagia and Spinellis [2014] analyzed how undocumented and unchecked exceptions cause most of the exceptions in Android applications.

Functional Programming Features

Programming language design has been always a hot topic in computer science literature. It has been extensively studied in the past decades. For instance, there is a trend in incorporating functional programming features into mainstream object-oriented languages, *e.g.*, lambdas in JAVA 8[2], C++11[3] and C# 3.0[4]; or parametric polymorphism — *i.e.*, generics — in JAVA 5[5,6].

Mazinanian et al. [2017] and Uesbeck et al. [2016] studied how developers use lambdas in JAVA and C++ respectively. The inclusion of generics in JAVA is closely related to collections. Parnin et al. [2011, 2013] studied how generics were adopted by JAVA developers. They found that the use of generics do not significantly reduce the number of type casts.

Costa et al. [2017] have mined *GitHub* corpus to study the use and performance of collections, and how these usages can be improved. They have found out that in most cases there is an alternative usage that improves performance.

This kind of studies give an insight of the adoption of lambdas and generics; which can drive future direction for language designers and tool builders, while providing developers with best practices.

2.3   Code Patterns Discovery

Posnett et al. [2010] have extended ASM Bruneton et al. [2002]; Kuleshov [2007] to implement symbolic execution and recognize call sites. However, this is only a meta-pattern detector, and not a pattern discovery. Hu and Sartipi [2008] used both dynamic and static analysis to discover design patterns, while Arcelli et al. [2008] used only dynamic.

Trying to unify analysis and transformation tools Vinju and Cordy [2006], Klint et al. [2009] built *Rascal,* a DSL that aims to bring them together.

As mentioned above, Dietrich et al. [2017a] made a study about how programmers use contracts in *Maven Central*. For their analysis[7], they have use JavaParser[8]. The main issue with JavaParser is the lack to do symbol resolution integrated with the project dependencies.

Urma and Mycroft [2012] evaluates seven source code query languages[9]: *Java Tools Language* Cohen and Maman, *Browse-By-Query* [10], *SOUL* De Roover et al. [2011], *JQuery*

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[2]https://docs.oracle.com/javase/specs/jls/se8/html/jls-15.html#jls-15.27
[3]http://www.open-std.org/jtc1/sc22/wg21/docs/papers/2006/n1968.pdf
[4]https://msdn.microsoft.com/en-us/library/bb308966.aspx#csharp3.0overview_topic7
[5]https://docs.oracle.com/javase/1.5.0/docs/guide/language/generics.html
[6]http://www.oracle.com/technetwork/java/javase/generics-tutorial-159168.pdf
[7]https://bitbucket.org/jensdietrich/contractstudy
[8]http://javaparser.org/
[9]https://wiki.openjdk.java.net/display/Compiler/Java+Corpus+Tools
[10]http://browsebyquery.sourceforge.net/

Volder [2006], *.QL* d Moor et al. [2007], *Jackpot* [11], and *PMD* [12]. They have implemented — whenever possible — four use cases using the tools mentioned above. They concluded that only *SOUL* and *.QL* have the minimal features to implement all their use cases.

2.4   Tools for Mining Software Repositories

When talking about mining software repositories, we refer to extracting any kind of information from large-scale codebase repositories. Usually doing so requires several engineering but challenging tasks. The most common being downloading, storing, parsing, analyzing and properly extracting different kinds of artifacts. In this scenario, there are several tools that allows a researcher or developer to query information about software repositories.

Dyer et al. [2013a,b] built *Boa*, both a domain-specific language and an online platform[13]. It is used to query software repositories on two popular hosting services, *GitHub*[14] and *SourceForge*[15]. The same authors of *Boa* made a study on how new features in JAVA were adopted by developers Dyer et al. [2014] over time. This study is based *SourceForge* data. The current problem with *SourceForge* is that is outdated.

To this end, Gousios [2013] provides an offline mirror of *GitHub* that allows researchers to query any kind of that data. Later on, Gousios et al. [2014] published the dataset construction process of *GitHub*.

Similar to *Boa*, *lgtm*[16] is a platform to query software projects properties. It works by querying repositories from *GitHub*. But it does not work at a large-scale, *i.e.*, *lgtm* allows the user to query just a few projects. Unlike *Boa*, *lgtm* is based on QL — before named *.QL* as mentioned in §2.3 —, an object-oriented domain-specific language to query recursive data structures Avgustinov et al. [2016].

On top of *Boa*, Tiwari et al. [2017] built *Candoia*[17]. Although it is not a mining software repository *per se*, it eases the creation of mining applications.

Another tool to analyze large software repositories is presented in Brandauer and Wrigstad [2017]. In this case, the analysis is dynamic, based on program traces. At the time of this writing, the service[18] was unavailable for testing.

Bajracharya et al. [2009] provide a tool to query large code bases by extracting the source code into a relational model.

sourcegraph[19] is a tool that allows regular expression and diff searches. It integrates with source repositories.

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[11]http://wiki.netbeans.org/Jackpot
[12]https://pmd.github.io/
[13]http://boa.cs.iastate.edu/
[14]https://github.com/
[15]https://sourceforge.net/
[16]https://lgtm.com/
[17]http://candoia.github.io/
[18]http://www.spencer-t.racing/datasets
[19]https://sourcegraph.com

2.5   Selecting Good Representatives

Another dimension to consider when analyzing large codebases, is how relevant the repositories are. Lopes et al. [2017] made a study to measure code duplication in *GitHub*. They found out that much of the code there is actually duplicated. This raises a flag when consider which projects analyze when doing mining software repositories.

Nagappan et al. [2013] have developed the Software Projects Sampling (SPS) tool. SPS tries to find a maximal set of projects based on representativeness and diversity. Diversity dimensions considered include total lines of code, project age, activity, and of the last 12 months, number of contributors, total code churn, and number of commits.

2.6   Unsafe API

Oracle software engineer Paul Sandoz performed some informal analysis of Maven artifacts and usages in Grepcode Sandoz [2015] and conducted a survey to study how *Unsafe* is used Sandoz [2014]. The survey consists of 7 questions[20] that help to understand what pieces of sun.misc.Unsafe should be mainstreamed. We go beyond Sandoz' work by performing a comprehensive study of the *Maven Central* software repository to analyze how and why sun.misc.Unsafe is being used.

Oracle provides the sun.misc.Unsafe class for low-level programming, e.g, synchronization primitives, direct memory access methods, array manipulation and memory usage. Although the sun.misc.Unsafe class is not officially documented, there is literature based on it.

Korland et al. [2010] presented a Java STM framework, intended as a development platform for scalable concurrent applications and as a research tool for designing STM algorithms. They chose to use sun.misc.Unsafe to implement fast reflection, as it proved to be vastly more efficient than the standard Java reflection mechanisms. Pukall et al. introduced a runtime update approach based on Java that offers flexible dynamic software updates with minimal performance overhead. They used the allocateInstance method, because it eases the creation of instances even if the class has no default constructor. Gligoric et al. [2011] proposed a new approach to serialization/deserialization via code generation, using sun.misc.Unsafe to allocate instances and to set the fields. The Jikes RVM Alpern et al. [2005] is a Java Virtual Machine targeting researchers in runtime systems. It is a Java-in-Java virtual machine because is itself built in Java, a style of implementation termed meta-circular. The Jikes RVM provides an implementation of sun.misc.Unsafe with the *magic* framework. Frampton et al. [2009] proposed org.vmmagic to provide an escape hatch to low-level alternatives needed to build virtual machines; however, they require compiler support.

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[20]http://www.infoq.com/news/2014/02/Unsafe-Survey

2.7 Casting

Winther [2011] has implemented a path sensitive analysis that allows the developer to avoid casting once a guarded `instanceof` is provided. He proposes four cast categorizations according to their run-time type safety: *Guarded Casts*, *Semi-Guarded Casts*, *Unguarded Casts*, and *Safe Casts*. We propose (in Chapter 4) to refine this categorization, according to semantic patterns.

Livshits [2006]; Livshits et al. [2005] "describes an approach to call graph construction for JAVA programs in the presence of reflection." He has devised some (seven) common usage patterns for reflection. Most of the patterns use casts. We plan to categorize all cast usages, not only where reflection is used.

Controlled Experiments on Subjects

There is an extensive literature *per se* in controlled experiments on subjects to understand several aspects in programming, and programming languages. For instance, Soloway and Ehrlich [1984] tried to understand the how expert programmers face problem solving. Budd et al. [1980] made a empirical study on how effective is mutation testing. Prechelt [2000] compared how a given — fixed — task was implemented in several programming languages.

LaToza and Myers [2010] realize that, in essence, programmers need to answer reachability questions to understand large codebases.

Several authors Stuchlik and Hanenberg [2011]; Mayer et al. [2012]; Harlin et al. [2017] measure whether using a static-type system improves programmers productivity. They compare how a static and a dynamic type system impact on productivity. The common setting for these studies is to have a set of programming problems. Then, let a group of developers solve them in both a static and dynamic languages.

For these kind of studies to reflect reality, the problems to be solved need to be representative of the real-world code. Having artificial problems may lead to invalid conclusions. The work by Wu and Chen [2017]; Wu et al. [2017] goes towards this direction. They have examined programs written by students to understand real debugging conditions. Their focus is on ill-typed programs written in HASKELL. Unfortunately, these dataset does not correspond to real-world code.

Therefore, it is important to study how casts are used in real-world code. This can led to informed decisions when designing these kind of experiments.

Chapter 3

The JAVA Unsafe API in the Wild

We have analyzed 74*GB* of compiled JAVA code, spread over 86,479 JAVA archives, to determine how JAVA's unsafe capabilities are used in real-world libraries and applications. We found that 25% of JAVA bytecode archives depend on unsafe third-party JAVA code, and thus JAVA's safety guarantees cannot be trusted. We identify 14 different usage patterns of JAVA's unsafe capabilities, and we provide supporting evidence for why real-world code needs these capabilities. Our long-term goal is to provide a foundation for the design of new language features to regain safety in JAVA.

We already have published our work on how developers use the `sun.misc.Unsafe` API. For a detailed description of the methodology used to find patterns and the patterns we found please refer to Mastrangelo et al. [2015]. In this proposal we present the overview of our study (§3.1), followed by how the patterns we found could be implemented in a safer way (§3.2).

3.1   Overview of Our Study

We need to determine whether and how Unsafe is actually used in real-world third-party JAVA libraries, and to what degree real-world applications directly and indirectly depend on such unsafe libraries. To achieve our goal, several elements are needed.

Code Repository. As a code base representative of the "real world", we have chosen the Maven Central software repository. The rationale behind this decision is that a large number of well-known JAVA projects deploy to Maven Central using Apache Maven. Besides code written in JAVA, projects written in SCALA are also deployed to Maven Central using the Scala Build Tool (sbt). Moreover, Maven Central is the largest Java repository[1] , and it contains projects from the most popular source code management repositories, like *GitHub* and *SourceForge*.

Artifacts. In Maven terminology, an artifact is the output of the build procedure of a project. An artifact can be any type of file, ranging from a *.pdf* to a *.zip* file. However,

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[1]`http://www.modulecounts.com/`

artifacts are usually *.jar* files, which archive compiled JAVA bytecode stored in *.class* files.

Bytecode Analysis. We examine these kinds of artifacts to analyze how they use `sun.misc.-Unsafe`. We use a bytecode analysis library to search for method call sites and field accesses of the `sun.misc.Unsafe` class.

Dependency Analysis. We define the impact of an artifact as how many artifacts depend on it, either directly or indirectly. This helps us to define the impact of artifacts that use `sun.misc.Unsafe`, and thus the impact `sun.misc.Unsafe` has on real-world code overall.

Usage Pattern Detection. After all call sites and field accesses are found, we analyze this information to discover usage patterns. It is common that an artifact exhibits more than one pattern. Our list of patterns is not exhaustive. We have manually investigated the source code of the 100 highest-impact artifacts using `sun.misc.Unsafe` to understand why and how they are using it.

3.2   Discussion

Many of the patterns we found indicate that *Unsafe* is used to achieve better performance or to implement functionality not otherwise available in the Java language or standard library.

However, many of the patterns described can be implemented using APIs already provided in the Java standard library. In addition, there are several existing proposals to improve the situation with *Unsafe* already under development within the Java community. Oracle software engineer Paul Sandoz Sandoz [2014] performed a survey on the OpenJDK mailing list to study how Unsafe is used[2] and describes several of these proposals.

A summary of the patterns with existing and proposed alternatives to *Unsafe* is shown in Table 3.1. The table consists of the following columns: The **Pattern** column indicates the name of the pattern. The next three columns indicate whether the pattern could be implemented either as a language feature (**Lang**), virtual machine extension (**VM**), or library extension (**Lib**). The **Ref** column indicates that the pattern can be implemented using reflection. A bullet (•) indicates that an alternative exists in the Java language or API. A check mark (✓) indicates that there is a proposed alternative for Java.

Many Java APIs already exist that provide functionality similar to *Unsafe*. Indeed, these APIs are often implemented using *Unsafe* under the hood, but they are designed to be used safely. They maintain invariants or perform runtime checks to ensure that their use of *Unsafe* is safe. Because of this overhead, using *Unsafe* directly should in principle provide better performance at the cost of safety.

For example, the *java.util.concurrent* package provides classes for safely performing atomic operations on fields and array elements, as well as several synchronizer classes. These classes can be used instead of *Unsafe* to implement atomic operations or strongly consistent shared variables. The standard library class *java.util.concurrent.locks.LockSupport* provides *park* and *unpark* methods to be used for implementing locks. These methods are just thin wrappers

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[2]`http://www.infoq.com/news/2014/02/Unsafe-Survey`

Table 3.1: Patterns and their alternatives. A bullet (•) indicates that an alternative exists in the Java language or API. A check mark (✓) indicates that there is a proposed alternative for Java.

#	Pattern	Lang	VM	Lib	Ref
1	Allocate an Object without Invoking a Constructor	✓			
2	Process Byte Arrays in Block		✓		
3	Atomic Operations			•	
4	Strongly Consistent Shared Variables			✓	
5	Park/Unpark Threads			•	
6	Update Final Fields				•
7	Non-Lexically-Scoped Monitors	✓			
8	Serialization/Deserialization	✓		•	•
9	Foreign Data Access and Object Marshaling	✓		•	
10	Throw Checked Exceptions without Being Declared	✓			
11	Get the Size of an Object or an Array	✓		✓	
12	Large Arrays and Off-Heap Data Structures	✓		✓	
13	Get Memory Page Size	✓		✓	
14	Load Class without Security Checks	✓		✓	

around the sun.misc.Unsafe methods of the same name and could be used to implement the park pattern. Java already supports serialization of objects using the *java.lang.Serializable* and *java.io.ObjectOutputStream* API. The now-deleted JEP 187 Serialization 2.0 proposal[3] [4] addresses some of the issues with Java serialization.

Because volatile variable accesses compile to code that issues memory fences, strongly consistent variables can be implemented by accessing volatile variables. However, the fences generated for volatile variables may be stronger (and therefore less performant) than are needed for a given application. Indeed, the *Unsafe Put Ordered* and *Fence* methods were likely introduced to improve performance versus volatile variables. There is currently a proposal for enhanced volatile support in the JVM (JEP 193 Enhanced Volatiles Lea [2014]). This proposal introduces *variable handles*, which allow atomic operations on fields and array elements.

Many of the patterns can be implemented using the reflection API, albeit with lower performance than with *Unsafe* Korland et al. [2010]. For example, reflection can be used for accessing object fields to implement serialization. Similarly, reflection can be used in combination with *java.nio.ByteBuffer* and related classes for data marshaling. The reflection API can also be used to write to final fields. However, this feature of the reflection API makes sense only during deserialization or during object construction and may have unpredictable behavior in other cases.

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[3]http://mail.openjdk.java.net/pipermail/core-libs-dev/2014-January/024589.html
[4]http://web.archive.org/web/20140702193924/http://openjdk.java.net/jeps/187

Writing a final field through reflection may not ensure the write becomes visible to other threads that might have cached the final field, and it may not work correctly at all if the VM performs compiler optimizations such as constant propagation on final fields.

Many patterns use *Unsafe* to use memory more efficiently. Using structs or packed objects can reduce memory overhead by eliminating object headers and other per-object overhead. Java has no native support for structs, but they can be implemented with byte buffers or with JNI.[5]

The Arrays 2.0 proposal Rose [2012] and the value types proposal Rose et al. [2014] address the large arrays pattern. Project Sumatra OpenJDK [2013] proposes features for accessing GPUs and other accelerators, one of the use cases for foreign data access. Related proposals include JEP 191 Nutter [2014], which proposes a new foreign function interface for Java, and Project Panama Rose [2014], which supports native data access from the JVM.

A *sizeof* feature could be introduced into the language or into the standard library. A use case for this feature includes cache management implementations. A higher level alternative might be to provide an API for memory usage tracking in the JVM. A page size method could be added to the standard library, perhaps in the *java.nio* package, which already includes *MappedByteBuffer* to access memory-mapped storage.

Other patterns may require Java language changes. For instance, the language could be changed to not require methods to declare the exceptions they throw, obviating the need for *Unsafe* in this case. Indeed, there is a long-running debate[6] about the software-engineering benefits of checked exceptions. C#, for instance, does not require that exceptions be declared in method signatures at all. One alternative not requiring a language change, proposed in a Stack Overflowdiscussion, is to use Java generics instead.[7] Because of type erasure, a checked exception can be coerced unsafely into an unchecked exception and thrown.

Changing the language to support allocation without constructors or non-lexically-scoped monitors is feasible. However, implementation of these features must be done carefully to ensure object invariants are properly maintained. In particular, supporting arbitrary unconstructed objects can require type system changes to prevent usage of the object before initialization Qi and Myers [2009]. Limiting the scope of this feature to support deserialization only may be a good compromise and has been suggested in the JEP 187 Serialization 2.0 proposal.

Since *Unsafe* is often used simply for performance reasons, virtual machine optimizations can reduce the need for *Unsafe*. For example, the JVM's runtime compiler can be extended with optimizations for vectorizing byte array accesses, eliminating the motivation to use *Unsafe* to process byte arrays. Many patterns use *Unsafe* to use memory more efficiently. This could be ameliorated with lower GC overhead. There are proposals for this, for instance JEP 189 Shenandoah: Low Pause GC Christine H. Flood [2014].

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[5]http://www.oracle.com/technetwork/java/jvmls2013sciam-2013525.pdf

[6]http://www.ibm.com/developerworks/library/j-jtp05254/

[7]http://stackoverflow.com/questions/11410042

Chapter 4

Casting Operations in the Wild

A simple search for commits[1] and issues[2] including the term `ClassCastException` on *GitHub* returns *circa* 150*K* and 72*K* results respectively. This indicates that casts represents a source of errors for developers. We have included here a few source code results. This illustrates the sort of problems developers have when applying casting conversions. To easily spot what the developer has changed to fix the `ClassCastException`, we present each source code excerpt using the Git commit *diff* as reported by *GitHub*.

Forgotten Guard. The following listing[3] shows a cast that throws `ClassCastException` because the developer forgot to include a guard. In this case, the developer fixed the error by introducing a guard on the cast with `instanceof`.

```
1 @@ -41,6 +41,8 @@ public SCMTypeColumn() {
2     }
3         public String getScmType(@SuppressWarnings("rawtypes") Job job) {
4 +         if(!(job instanceof AbstractProject<?, ?>))
5 +             return "";
6         AbstractProject<?, ?> project = (AbstractProject<?, ?>) job;
7         return project.getScm().getDescriptor().getDisplayName();
8     }
```

Wrong Cast Target. In the next example[4] the `CustomFileFilter` is an inner static class inside `JCustomFileFilter`. Notice the cast happens inside an `equals` method, where this idiom is well known. But the developer has used the outer — wrong — class to cast to.

```
1 @@ -156,7 +156,7 @@ public boolean equals(Object obj) {
2   if (getClass() != obj.getClass()) {
3       return false;
4   }
5 - final JCustomFileChooser other = (JCustomFileChooser) obj;
6 + final CustomFileFilter other = (CustomFileFilter) obj;
7   if (!Objects.equals(this.extensions, other.extensions)) {
8       return false;
9   }
```

---

[1]https://github.com/search?l=Java&q=ClassCastException&type=Commits
[2]https://github.com/search?l=Java&q=ClassCastException&type=Issues
[3]https://github.com/jenkinsci/extra-columns-plugin/commit/02d10bd1fcbb2e656da9b1b4ec54208b0cc1cbb2
[4]https://github.com/GoldenGnu/jeveassets/commit/5f4750bc8cfa7eed8ad01efd8add2cd2cc9bd831

Generic Type Inference Mismatch. In the following listing[5] the getProperty method obtains a dynamic property. If it founds a value, returns it. Otherwise, returns the default value (second argument). In this case, the property "peer.p2p.pingInterval" has type int. But the return type of getProperty is a generic type inferred by the type of the default value, long. That is why the developer has only changed the type of the literal: from long to int.

```
1 @@ -281,7 +281,7 @@ private void startTimers() {
2         } catch (Throwable t) {
3             logger.error("Unhandled exception", t);
4         }
5 -   }, 2, config.getProperty("peer.p2p.pingInterval", 5L), TimeUnit.SECONDS);
6 +   }, 2, config.getProperty("peer.p2p.pingInterval", 5), TimeUnit.SECONDS);
7 }
```

Compiler Bug One issue[6] shows bad things happen when abusing the type system. A bug in the *javac* compiler[7] was causing checkcast[8] instructions to be skipped. This bug was fixed in JDK 9, breaking Mockito answer strategies.

We present here our partial results for the cast study. First we give an overview of the study in §4.1, while §4.2 gives an estimation of how often a cast operator is used. Finally, §4.3 introduces the methodology we plan to use to discover cast usage patterns.

4.1   Overview of our Study

Our study tries to answer the following question: *Why developers need to escape the type system?* The cast operator in JAVA provides the means to view a reference as a different type as it was defined. Upcasts conversions are done automatically by the compiler. Nevertheless, if some situations a developer is forced to insert upcasts. In the case of downcasts, a check is inserted at run-time to verify that the conversion is sound, thus escaping the type system. *Why is so?* Therefore, we believe we should care about how the casting operations are used in the wild. Specifically, we want to answer the following research questions:

RQ1 : **Is casting used in common application code?** We want to understand to what extent application code actually uses casting operations.

RQ2 : **How and why casts are used?** If casts are actually used in application code, we want to know how and why developers need to escape the type system.

RQ3 : **How recurrent are the reasons for which casts are used?** In addition to understand how and why casts are used, we want to measure how often developers need to resort to certain idioms to solve a particular problem.

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[5]https://github.com/ethereum/ethereumj/commit/224e65b9b4ddcb46198a6f8faf69edc65d34d382
[6]https://github.com/mockito/mockito/issues/357
[7]https://bugs.openjdk.java.net/browse/JDK-8058199
[8]https://docs.oracle.com/javase/specs/jvms/se8/html/jvms-6.html#jvms-6.5.checkcast

To answer the above questions, we need to determine whether and how casting operations are actually used in real-world third-party JAVA applications. To achieve our goal, several elements are needed.

Source Code Analysis. We have implemented our study using the QL query language: "a declarative, object-oriented logic programming language for querying complex, potentially recursive data structures encoded in a relational data model" Avgustinov et al. [2016]. QL allows us to analyze programs at the source code level by abstracting the code sources into a relational data model. Besides providing structural data for programs, *i.e.*, ASTs, QL has the ability to query static types and data-flow analysis. To run our QL queries, we have used the service provided by Semmle.[9]

Projects. As a code base representative of the "real world", we have chosen open-source projects hosted in the most popular source code management repositories, *i.e.*, *GitHub*[10], *GitLab*[11], *Bitbucket*[12]. We have analyzed 24 JAVA projects hosted in *lgtm*.

Usage Pattern Detection. After all cast instances are found, we analyze this information to discover usage patterns. QL allows us to automatically categorize cast use cases into patterns. This methodology is described in section 4.3.

It is common that a project exhibits more than one pattern. Our list of patterns is not exhaustive. Due to the nature of the cast operator, some casts were uncategorized as they would need a whole program analysis, *e.g.*, including libraries in the analysis.

4.2   Is the Cast Operator used?

To answer *RQ*1 we want to know how many cast instances are used in a given project. To this end, we gather the following statistics using QL. We show them here to give an estimation of the size of the code base being analized.

Description	Value
Number of Projects	24
Number of LOC	1,439,913
Number of Methods	121,665
Number of Methods w/Cast	6,091
Number of Exprs	4,324,652
Number of Casts	8,627

The *Number of Methods* and *Number of Methods w/Cast* values includes only methods with a body, *i.e.*, not abstract, nor native. The *Number of Exprs* value show how many expressions there are in the ASTs of all source code analyzed. Finally, the *Number of Casts* value indicates how many cast expressions (subtype of Expr as defined by QL) were found.

---

[9]https://lgtm.com/

[10]https://github.com/

[11]https://gitlab.com/

[12]https://bitbucket.org/

For our study, we are interested in both upcasts and downcasts. This is why we want to exclude any primitive conversion in our study. The *Number of Casts* value shown above include only reference conversions. Primitive conversions are always safe (in terms of throwing `ClassCastException`. A primitive conversion happens when both the type of the expression to be casted to and the type to cast to are primitive types. Note that with this definition, we include in our study *boxed* types. Since boxed types are reference types (and therefore not necessarily safe) we want to include them for our analysis.

We want to know how many cast instances there are across projects. Thus, we have computed the ratio between methods containing at least a cast over total number of methods — with implementation — in a given project. The following chart shows this ratio for all analyzed projects:
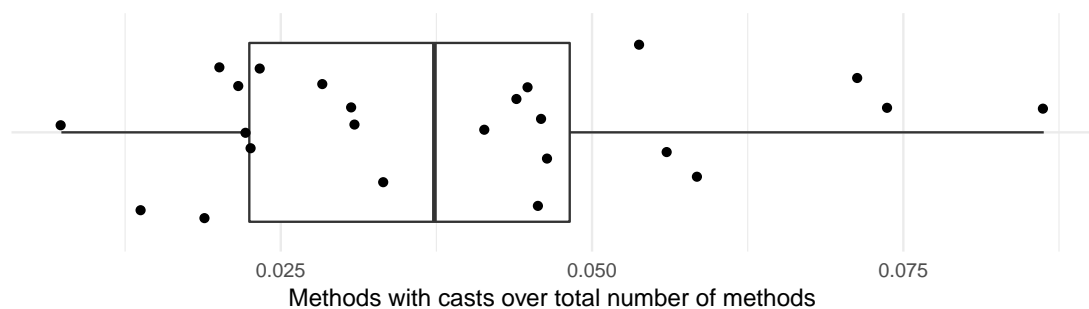
All projects have less than 10% of methods with at least a cast. Overall, around a 3.92% of methods contain at least one cast operation. This means there is a low density of casts. Given the fact that generics were introduced JAVA 5, this can explain this low density.

Nevertheless, casts are still used. We want to understand why there are casts instances (*RQ*2) and how often the use cases that leads to casts are used (*RQ*3). The following sections give an answer to these questions.

The query to gather this statistics is available online.[13] The R script to further analyze the query results is available online as well.[14]

4.3   Finding Casts Usage Patterns

To answer both research questions *RQ*2 and *RQ*3 we have used the QL query language within the *lgtm* service to look for cast instances. As mentioned in section **??**, QL treats primitive conversions as casts. Thus, a preliminary step is to exclude them as cast instances. The following QL query shows how to retrieve all relevant cast expressions:

```
1 import java
2 from CastExpr ce where not (
3 ce.getExpr().getType() instanceof PrimitiveType and
4 ce.getTypeExpr().getType() instanceof PrimitiveType
```

---

[13]https://gitlab.com/acuarica/java-cast-queries/blob/master/stats.ql

[14]https://gitlab.com/acuarica/java-cast-queries/blob/master/stats.r

```
5 ) select ce
```

Listing 4.1: QL query to retrieve all relevant cast expressions.

Figure 4.1 depicts our methodology. We have used this initial result as a starting point for our analysis. Afterwards, we select a random sample for manual inspection. We manually inspected the mentioned casts trying to understand why and how they were used.

By manually inspecting several casts instances, we observe that certain characteristics appear often, *e.g.*, a cast in a overridden method, or a cast guarded by an instanceof. We then *tag* cast instances based on these observations. We implement a QL predicate that detects them and proceed to refine our query with this new tag predicate. After a new tag is added, the query is run again to iterate over the new results.

Whenever we observe that those tags do not appear randomly, we further inspect the source code to check that is indeed a pattern. We have formalize the structure of each pattern as a QL predicate based on those tags. Similarly with tags, after a new pattern is added, the query is run again to inspect the casts without pattern. To sum it up, our methodology iterates over the results until no patterns can be detected. The final QL query is available online.[15]
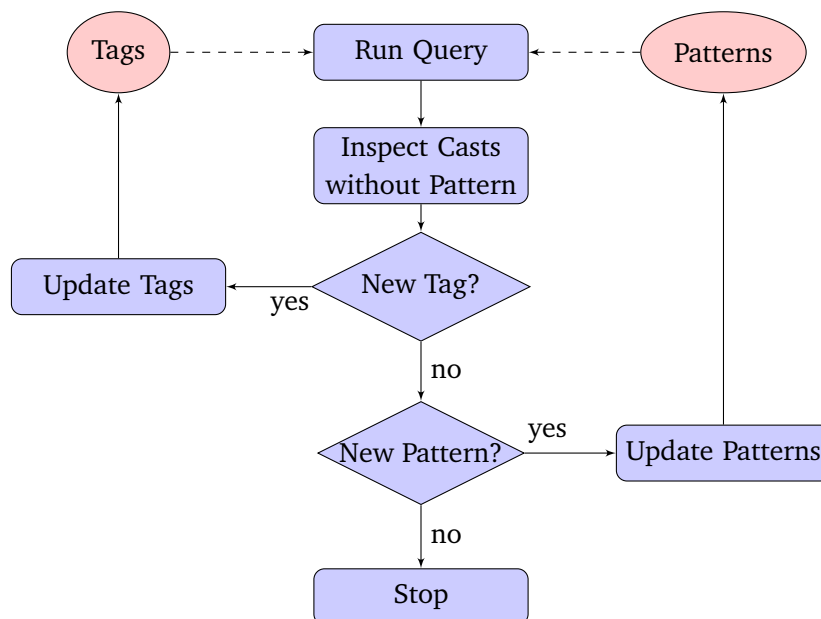

Figure 4.1: Process to discover cast tags and patterns

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[15]https://gitlab.com/acuarica/java-cast-queries/blob/master/casts.ql

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