Applied Static Analysis

Why Static Analysis?

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Questions that we may ask about a program:

- Will the variable `x` always contain the same value?
- Which objects can variable `x` points to?
- What is a lower/upper bound on the value of the integer variable `x`?
- Which methods are called by a method invocation?
- How much memory is required to execute the program?
- Will it throw a `NullPointerException`?
- Will it leak sensitive data? Will data from component `a` flow to component `b`?

Buggy C-Program:

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
int main(int argc, const char * argv[]) {
    char *p, *q;
    p = NULL;
    printf("%s",p);
    q = (char *)malloc(100);
    p = q;
    free(q);
    *p = 'x';
    free(p);
    p = (char *)malloc(100);
    q = (char *)malloc(100);
    q = p;
    strcat(p,q);
}
```

Line 7: The behavior of printf is undefined in the string referred to by %s is NULL. (Actually, the behavior of the program may even change depending on the optimizations done by the compiler!)

Line 11: We have a use after free (detected by some modern compilers).

Line 14 in combination with line 15: Resource leakage; the memory area is not freed.

Line 16: q and p overlap - this will lead to a segmentation fault.

What is Static Analysis?

A static analysis of a program is a ***sound***, *finite*, and ***approximate*** calculation of the program's execution semantics which helps us to solve practical problems.

Sound means that the analysis is consistent with the actual concrete execution semantics and that the result models all possible executions of the analyzed program.

An analysis is **conservative** if all errors lean to the same side. For example, if we want to remove useless synchronization primitives, then an analysis should always only identify those primitives as useless that are definitively not required. In case of doubt, it should return that the synchronization primitive is required.

Sound static analyses are generally *overapproximations* which describe a superset of the program's possible/observable executions. However, the analyses should still be precise enough to be practically useable. For example, an analysis that would list all methods as being possible targets for a method invocation would be impractical.

Sometimes, analyses are deliberately not sound and compute only *underapproximations*; i.e., the analysis does not describe all observable executions. This is, e.g., done to improve an analysis' scalability and/or to improve an analyses precision. For practical analyses it may be more important to produce fewer so called *false positives* then to report more *potential issues*.

A static analysis is finite in the sense that it will terminate for any given program. The analysis will not execute the program.

Purposes of Code Analyses

- Finding code smells.
- Quality assessments.
- Improving the quality of the code.
- Support debugging of code.
- Optimizing the code.

> Not every analysis which does not execute the code is a *static analysis*!

Code smells range from simple issues such as useless computations, which have no lasting effect on the program state, over bugs which will potentially lead to dead locks and race conditions up to security vulnerabilities which enable attackers to steal sensitive data. *Here, we use the term code smells to refer to those issues in the code that a developer (typically) did not add deliberately.*

Analyses which, e.g., identify code duplicates or which compute metrics are frequently used to perform quality assessments; however, these analyses are not static analyses.

Refactorings (e.g., extract method) often required (sound) static analyses to ensure that the refactoring does not break the code.

Debugging is supported, e.g., by computing slices which encompass all statements in a program that affect a given statement.

Classical code optimizations are, e.g., removing dead code, hoisting loop invariants, removing useless synchronization, avoiding runtime checks to detect `null-pointer` accesses, allocating objects on the stack, or avoiding `array index out of bounds` checks.

Finding Programming Bugs

> JavaDoc of java.lang.BigDecimal.setScale:
> [...] Note that since BigDecimal objects are immutable, calls of this method do not result in the original object being modified, contrary to the usual convention of having methods named setX mutate field X. Instead, setScale returns an object with the proper scale; the returned object may or may not be newly allocated.

```
class X {
    private long scale;
    X(long scale) { this.scale = scale; }
    void adapt(BigDecimal d){
        d.setScale(this.scale);
    }
}
```

In this case the bug is that the `setScale` method is side-effect free (though the name `setScale` suggests something different) and therefore the call `d.setScale(...)` is useless. Hence, this code smells.

There is typically more than one way to find certain bugs and not all require (sophisticated) static analyses!

Finding Bugs Using Bug Patterns

Code smells such as useless calls to `setScale` can easily be described and found using *bug patterns*. A bug pattern is an abstract description of a problem that occurs over and over again and which can be used to identify concrete instances of the problem.

A complete implementation of an analysis in the OPAL static analysis framework which analyzes a Java project's bytecode is shown next:

```
import org.opalj.br._
import org.opalj.br.instructions.{INVOKEVIRTUAL,POP}
import org.opalj.bytecode.JRELibraryFolder
val p = analyses.Project(JRELibraryFolder) // <= analyze the code of the JRE
p.allMethodsWithBody.foreach{m =>
  m.body.get.collectPair{
    case (
        i @ INVOKEVIRTUAL(ObjectType("java/math/BigDecimal"),"setScale",_),
        POP
    ) => i
  }
  .foreach(i => println(m.toJava(i.toString)))
}
```

The above static analysis uses Scala's pattern matching (line 8 and 9) to find the sequence of instructions that calls the `setScale` method (`INVOKEVIRTUAL`) and then immediately throws the returned result away (`POP`).

Even the analysis is so trivial it already finds a real instance in Java 8u191:
`com.sun.rowset.CachedRowSetImpl.updateObject(int,java.lang.Object,int)`

Finding Bugs Using Bug Patterns (Assessment)

- Advantages:
  - very fast and scale well to very large programs
  - (usually) simple to implement
- Disadvantages:
  - typically highly specialized to specific language constructs and APIs
  - requires some understanding how the issue typically manifests itself in the (binary) code
  - small variations in the code may escape the anaylsis
  - to cover a broader range of similar issues huge efforts are necessary

Finding bugs using bug patterns is supported by, e.g., FindBugs/SpotBugs.

Finding Bugs Using Machine Learning

The core idea is to use code that is known to be buggy and code that is expected to be correct to train a machine learning model. The resulting classifier is then used to find buggy code in new code. Buggy code can, e.g., be extracted from public repositories by analyzing the commit history and looking for issues. An alternative is to inject code that will most likely result in buggy code.

An interesting approach which is able to find bugs which could not be found with others approaches is described by Michael Pradel et al.[1]. The idea is to find contradicting code snippets.

Finding Bugs Using Machine Learning

Guess the problem of the following JavaScript code snippet:

```
function setPoint(x, y) { ... }
var x_dim = 23;
var y_dim = 5;
setPoint(y_dim, x_dim);
```

In this example, the order of the parameters was confused. The idea to find such issues is based on checking the names of the variables passed to the method in relation to the names of the parameters. This is generally non-trivial, because the names of the parameters and the passed values generally don't match!

Finding Bugs Using Machine Learning (Assessment)

- Finds bugs that are practically impossible to find using other approaches; hence, often complementary to classic static analyses and also bug pattern based analyses.
- Requires the analysis of a huge code base; it may be hard to find enough code examples for less frequently used APIs.

Today, a lot of code can be found on open source code repositories such as BitBucket, GitHub and SourceForge; even for niche languages. This generally facilitates all kinds of *big code* based analyses.

Finding Bugs by Mining Usage Patterns (Idea)

Is the following code buggy?

```
Iterator<?> it = ...
it.next();
while (it.hasNext()) {
    it.next();
    ...
}
```

The core idea is to first extract usage patterns from existing code. E.g., that calling `close` on a stream should be the last operation or that an Iterator's `next` method should always be called after a `hasNext` method. After extracting the usage patterns from a given code base, a corresponding algorithm is applied to new code to extract its usage patterns and to check for deviations. However, as shown recently, all existing approaches are far away from being practically useable [2].

An alternative (manual) approach would be to let developers explicitly specify the valid usage patterns (e.g., using state machines) and then to check for deviations between the implementations and the explicit specification. However, so far this approach is too expensive.

Finding Bugs Using Generic Static Code Analysis

```
class com.sun.imageio.plugins.png.PNGMetadata{
    void mergeStandardTree(org.w3c.dom.Node) {
        [...]
        if (maxBits > 4 || maxBits < 8) {
            maxBits = 8;
        }
        if (maxBits > 8) {
            maxBits = 16;
        }
        [...]
    }
}
```

The condition of the first `if` (line 4) will always be true. Every possible int value will either be larger than four or smaller than eight. Hence, line 5 will **always** be executed and therefore the condition of the second `if` will never be `true`; `maxBits` will never be 16.

This bug can be found using a very generic analysis that just tries to be very precise (e.g., by computing the interval of the values stored in an int variable) and which then looks for dead code. [3]

Finding Bugs Using Generic Static Code Analysis

```
class sun.font.StandardGlyphVector {
    public int getGlyphCharIndex(int ix) {
        if (ix < 0 && ix >= glyphs.length) {
            throw new IndexOutOfBoundsException("" + ix);
        }
    }
}
```

The condition (line 3) will never be `true`; `glyphs.length` will either be a value equal or larger than `0` or will throw a `NullPointerException`. Hence, there is no effective validation of the parameter `ix`.

This bug can be found by the same (type of) analysis as the previous issue.

Finding Bugs Using Generic Static Code Analysis

```
class sun.tracing.MultiplexProviderFactory {
    public void uncheckedTrigger(Object[] args) {
        […]
        Method m = Probe.class.getMethod(
            "trigger",
            Class.forName("[java.lang.Object")
        );
        m.invoke(p, args);
    }
}
```

The `m.invoke` statement will never be executed, because the string passed to `Class.forName` is invalid.

This bug can be found by the same (type of) analysis as the previous issue (but requires – at least rudimentarily – handling of reflection.)

Finding Bugs Using Generic Static Code Analysis

```
class com.sun.corba.se.impl.naming.pcosnaming.NamingContextImpl {
    public static String nameToString(NameComponent[] name)
        [...]
        if (name != null || name.length > 0) {
            [...]
        }
        […]
    }
}
```

If `name` is `null` the test `name.length > 0` (line 4) will be executed and will result in a `NullPointerException`. In this case, we have confused logical operators. The developer most likely wanted to use `&&`.

This bug can be found by the same (type of) analysis as the previous issues (but requires – at least rudimentarily – handling of null values.)

Finding Bugs Using Static Code Analysis ?

Found in `javax.crypto.CryptoPolicyParser` (Java 8u25):

```
private boolean ...isConsistent(
        String alg,
        String exemptionMechanism,
        Hashtable<String, Vector<String>> processedPermissions) {
    String thisExemptionMechanism = exemptionMechanism == null ? "none" : exemptionMec
hanism;
    if (processedPermissions == null) {
        processedPermissions = new Hashtable<String, Vector<String>>();
        Vector<String> exemptionMechanisms = new Vector<>(1);
        exemptionMechanisms.addElement(thisExemptionMechanism);
        processedPermissions.put(alg, exemptionMechanisms);
        return true;
    }
    […]
}
```

The code shown in line 7 to 11 has no sideeffect; however, identifying this situation in a generic manner requires sophisticated analyses.

Finding Bugs Using (Highly) Specialized Static Analyses

Do you see the security issue?

```
Cipher c = Cipher.getInstance("DES/CBC/PKCS5PADDING")
```

In this case an insecure algorithm (DES) is used.

Security bugs related to the Java Cryptographic API can be found using [4]. CogniCrypt's underlying analysis performs an in-depth data-flow analysis to ensure that the number of false positives is very low. (In this case, false negatives are not acceptable and therefore the analyses issues a warning if the analysis is not conclusive.)

(True|False) (Positives|Negatives)

- a **true positive** is the correct finding (of something relevant)
- a **false positive** is a finding that is incorrect (i.e., which can't be observed at runtime)
- a **true negative** is the correct finding of no issue.
- a **false negative** refers to those issues that are not reported.

Typically the goal of every static analysis is to only report true positives and to avoid as many false positives as possible. Often an analysis is considered useable if 80% of all findings are true positives. False positives are typically caused by imprecisions of the analysis. False negatives are usually not a (major) concern of static analyses; however, they are a primary concern of formal approaches.

Unguarded Access - True Positive ?

```
void printIt(String args[]) {
    if (args != null) {
        System.out.println("number of elements: " + args.length);
    }
    for (String arg : args) {
        System.out.println(arg);
    }
}
```

In this case, the first access of `args` (`args.length` in line 3) is guarded by an explicit null check. However, the second access (line 5) isn't! Hence, we could detect such code smells (here, lack of inner consistency) using a basic analysis that detects object accesses (e.g., `args.length`) that appear in a guarded context (`if (o != null)`) and also outside of an explicitly guarded context.

Implicitly Guarded Access

```
void printReverse(String args[]) {
    int argscount = 0;
    if (args != null) {
        argscount = args.length;
    }
    for (int i = argscount - 1; i >= 0; i--) {
        System.out.println(args[i]);
    }
}
```

This code is correct, but the analysis sketched previously would return a false positive in this case; the guard is implicitly established: `argscount` is only larger than 0 if `args` is definitively not null.

Irrelevant True Positives

Better static analyses can sometimes prove assertions to always hold; which are then useless.

Let's assume that the following function is only called with `non-null` parameters.

In that case the `assert` statement is useless, but adding an assert statement (even in such cases) is a common best practice!

```
private boolean isSmallEnough(Object i) {
    assert(i != null);
    Object o = " "+i;
    return o.length < 10;
}
```

> Don't use assert for validating parameters of non-private methods, i.e., if you don't have full control of the calling context.

Complex True Positives

The cast in line 5 will fail:

```
GeneralPath result = new GeneralPath(GeneralPath.WIND_NON_ZERO);
[…]
if (dx != 0 || dy != 0) {
    AffineTransform tx = AffineTransform.getTranslateInstance(dx, dy);
    result = (GeneralPath)tx.createTransformedShape(result);
}
```

Given the available code, it is non-obvious that the cast fails: an affine transformation of a `GeneralPath` is performed. An investigation of `createTransformedShape` would reveal that the actual type that is returned is a `Path2D.Double`. This still suggests that a cast to `GeneralPath` is reasonable! However, when you then study the class hierarchy, you'll realize that Path2d.Double is not a subtype of `GeneralPath`.

Complex True Positives - Assessment

The sad reality:

> [...] the general trend holds; a not-understood bug report is commonly labeled a false positive, rather than spurring the programmer to delve deeper. The result? We have completely abandoned some analyses that might generate difficult to understand reports. [5]

Soundiness

> [...] in practice, soundness is commonly eschewed: we [the authors] are not aware of a single realistic whole-programa analysis tool [...] that does not purposely make unsound choices.
> [...]
> Soundness is not even necessary for most modern analysis applications, however, as many clients can tolerate unsoundness. [6]

Reasons for soundiness: engineering effort or (likely) costs w.r.t. the precision and scalability of the resulting analysis.

Most practical analysis have a sound core w.r.t. some language features and APIs. In particular the most relevant language features and APIs are typically soundly supported. Such analyses are called **soundy**; i.e., the analyses are concerned with soundness, but do not support *a well identified set of features*. Unfortunately, often the set of features that is unsoundly handled is not at all well identified as often suggested.

Soundiness - Java

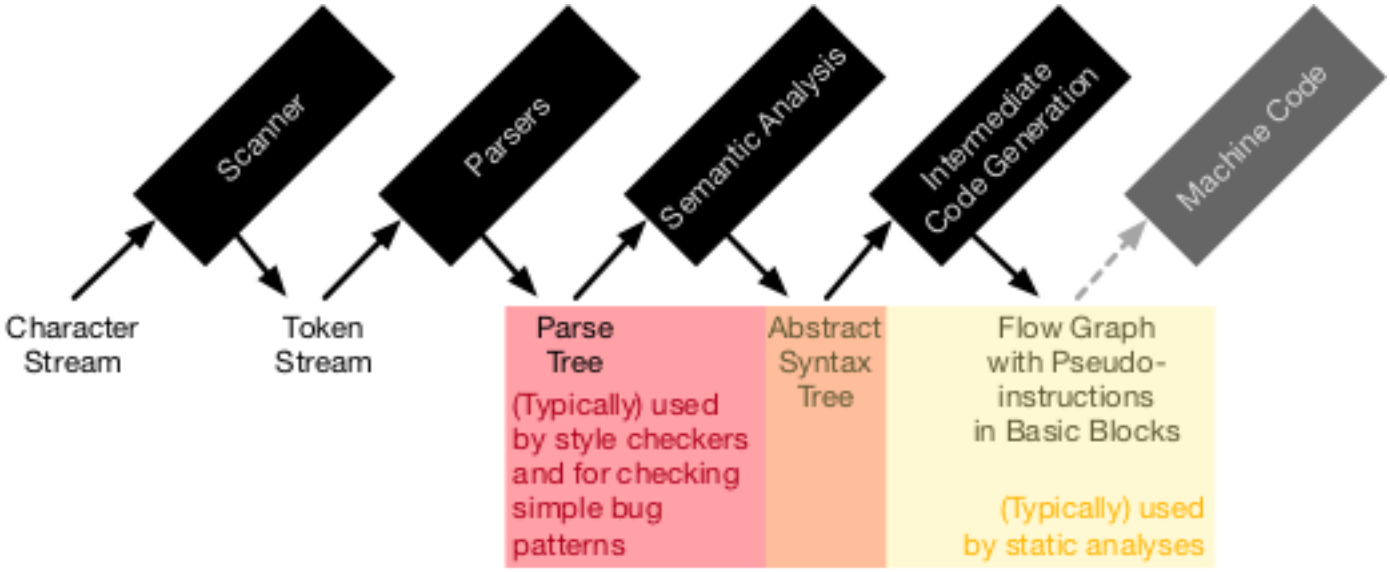
Common features that are often not soundly handled in Java:

- Reflection (*often mentioned in research papers*)
- Native methods (*often mentioned in research papers*)
- Dynamic Class Loading / Class Loaders (*sometimes mentioned in research papers*
- (De)Serialization (*often not considered at all*)
- Special System Hooks (e.g., `shutdownHooks`)

Examples in C/C++ are `setJmp` / `longJmp` or pointer arithmetic.
Examples in Javascript are `eval` if the code is not *trivially* known or data-flow through the DOM.

Compilers and Static Analyses

Usually (static) code analyses are built on top of the the results of the first phases of compilers.



Compilers and Static Analyses

Source Code:
`i = j + 1;`

Tokens:
`Ident(i) WS Assign WS Ident(j) WS Operator(+) WS Const(1) Semicolon`

AST with annotations:

```
AssignmentStatement(
    target     = Var(name=i,type=Int),
    expression = AddExpression(
                     type  = Int,
                     left  = Var(name=j,type=Int),
                     right = Const(1)))
```

In the (later) intermediate representations, nested Control-flow and complex expressions are unraveled. Intermediate values are given explicit names. The instruction set is usually limited. All of that facilitates static analysis (but renders syntax oriented code analyses impossible).

References

1. Pradel, M., & Sen, K.; DeepBugs: a learning approach to name-based bug detection. Proceedings of the ACM - OOPSLA, 2018, doi↩

2. Sven Amann, Hoan Anh Nguyen, Sarah Nadi, Tien N. Nguyen, and Mira Mezin; A Systematic Evaluation of Static API-Misuse Detectors; IEEE TRANSACTIONS ON SOFTWARE ENGINEERING, 2018↩

3. Eichberg, M., Hermann, B., Mezini, M., & Glanz, L.; Hidden truths in dead software paths; ACM, 2015, doi↩

4. Krüger, S., Nadi, S., Reif, M., Ali, K., Mezini, M., Bodden, E., et al.; CogniCrypt: supporting developers in using cryptography; IEEE Press., 2017↩

5. Bessey, A., Block, K., Chelf, B.; A few billion lines of code later: using static analysis to find bugs in the real world; Communications of the ACM, 2010, vol. 53, No. 2↩

6. Livshits, B., Sridharan, M., Smaragdakis, Y., Amaral, J. N., Møller, A., Lhoták, O., et al.; In Defense of Soundiness: A Manifesto; Communications of the ACM, 2015 , 58(2). ↩