Type inference for PHP

The value of annotations in a dynamic language

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Abstract

Dynamic language are generally hard to statically analyse because of run-time dependencies. Without running the program there are many things unknown. Because dynamic languages like PHP are widely used, the need for decent analysis tool grows. This research examines the value of adding annotations to PHP code to improve the analysability. In the results we see that annotations improve the analysability of software code (this is a guess). Here I should state something about the correctness of the annotations. And end with a general conclusion.

Chapter 1

Introduction

1.1 PHP

PHP[1]is a server-side programming language created by Rasmus Lerdorf in 1995. The original name 'Personal Home Page' changed to 'PHP: Hypertext Preprocessor' in 1998. PHP source files are executed using the PHP Interpreter. The language is dynamically typed, the types of variables are examined during run-time. PHP supports duck-typing, which allows variables to change types during execution.

Evolution The programming language PHP evolved since its creation in 1995. In the year 2000 Object-Oriented (OO) language structures were added to the langue with the release of PHP 4.0. The 5th version of PHP was released in 2004 and provided an improved OO structure. Namespace were added in PHP 5.3 in 2009, to be able to resolve class naming conflicts between library and create better readable class names. Namespaces are comparable to packages in Java. OPcache extension is added was added in PHP 5.5 and speeds up the performance of including files on run-time by storing precompiled script byte-code in shared memory. The latest 5.x version is 5.6 and includes more internal performance optimisations and introduces a new debugger. The most recent stable version is 7, which is not taken into this research.

Popularity According to the Tiobe Index[2]of December 2014, PHP is the 6th most popular language of all programming languages. The language has been in the top 10 since it's introduction in the Tiobe Index in 2001. More than 80 precent of the websites have a php backend[3]. The majority of these websites use PHP version 5, rather than version 4 or older versions. It is therefor wise to focus on PHP version from 5 and discard the older unused versions.

Analysability Although the popularity for more than a decade, there is still a lack of good PHP code analysis tools. These tools can help to reveal security vulnerabilities or find vulnerabilities or bugs in source code. The tools can also provide code completions or do automatic transformations which can be used to execute refactoring patterns. Source code analysis is performed statically or dynamically or a combination of the two.

1.2 Position

In this research we investigate how we can improve the analysability of PHP programs. We will show that the use of annotated source code can help to improve the analysability. The correctness of the annotations can also be examined by checking the implementation of the code.
These annotations can help to improve the analysis. The results can be used to find security issues, and if they are highly reliable we can even make compiler optimisations.

[1]http://php.net
[2]http://www.tiobe.com/index.php/content/paperinfo/tpci/index.html, December 2014
[3]http://w3techs.com/technologies/details/pl-php/all/all, December 2014

1.3 Contribution

This research contains contributions to the static analysis research field. It contribues by:

- creation of M^3 model for PHP programs
- constraint based type inference

The *extension of the M^3 model*, a generic model which holds facts of a program, to support PHP programs can help researchers to compare PHP programs with programs written in other languages. Until now only Java was supported. More information about M^3 can be found in section 5.1.

This paper also presents a *constrained based type inference* algorithm. These type inference results can help IDE tools and programmers by providing helpful tools. The algorithm can be found in section 5.3.

1.4 Plan

The rest of this thesis is as follows: chapter 2 contains background and related work. Background exists of important language constructs, information about annotations in PHP, introduction to M^3 and type systems. The last section of this chapter shows similar research and their relation to this research. Chapter 3, research context, describes the research approach and context. Chapter 4 describes the performed actions of this research. The analysis is presented in chapter **??**, with the results in chapter **??**. This thesis ends with the conclusions in chapter 7.

Chapter 2

Background and Related Work

Chapter 2 provides relevant background information. The first section, section 2.1, describes seven important language constructs which the reader needs to understand in order to understand the difficulties of analysing PHP. The second section, section 2.2, introduces the syntax and usage of annotations in PHP. Section 2.3 explains Rascal, the programming language used for the analysis. In this section we will explain M^3, a programming language independent meta model which holds various facts about programs, in more details. Section 2.4 provides information about type systems and how type systems relate to this research. The last section of this chapter, section 2.5, describes the related work and how these researches relate to this thesis.

2.1 PHP Language Constructs

PHP has various language constructs which complicate statical analysis. This section presents language constructs and why these constructs are important for this research. Explanations of these constructs help you to understand the performed analysis. The discussed parts are scope, file includes, conditional classes and functions, dynamic features, late static binding, magic methods and dynamic class properties.

Scope In PHP, all classes and functions are globally accessible once they are declared. All classes and functions are implicitly public, inner classes are not allowed, and conditional functions (see paragraph about conditional classes and functions) will be available in the global scope. If a class or function is declared inside a namespace, their name is prefixed with the name of the namespace.
Variables have three scope levels: global-, function-, and method-scope. Under normal circumstances when a variable is declared inside a function or method, their scope is limited to this function or method. Variables declared outside function or methods are available in the global scope, but not in the method or function scope. There is an exception for some predefined global variables which are available everywhere. Examples are `$GLOBALS`, `$_POST`, and `$_GET`. Variables inside a function or method can be aliased to a global variable by adding the keyword `GLOBAL` in front of the variable name. The variable are then linked to the global variable in the symbol table[1].
Closures (anonymous functions in PHP) have the same scoping rules as variables, but they can inherit variables from outside their scope by providing them in the use statement.

Includes PHP allows files to include other PHP-files during program execution. The content of these files will be loaded inline. This means that if you use an include in the middle of a file, the source code of this included file will be virtually inserted at that position.
File includes are mainly used for loading classes and for including templates to render output. PHP5 allows automated class loading based on the namespace, which is called autoloading classes. With autoloading classes there is no need for including files manually for each class. According to the php coding standard[2], function- and class-name classes should not appear when using namespaces and autoloading.

[1]http://php.net/manual/en/language.variables.scope.php, July 2014
[2]http://www.php-fig.org/psr/psr-0/, July 2014

Research by Mark Hills et al.[HKV14] has shown that most includes can be resolved with statical analysis. In this research we do not run such an analysis, we will assume that all files in the project are included during execution.

Conditional classes and functions Once a file is included in the execution, al the classes and functions in the top scope are declared. All class and function declarations within condition statements or within a method or function scope are only declared when the code is executed.
An example of an conditional statement can be found in listing 2.1. If the class `Foo` or function `bar` do not exist before the statements are executed, then the class and function will not yet be declared. When you try to use the class or function before the code is executed, the script will exit with an fatal error.

```
if (!class_exists("Foo"))
  class Foo { /* ... */ }

if (!function_exists("bar"))
  function bar() { /* ... */ }
```

Listing 2.1: Conditional class and function definitions

More examples of dynamic function and class loading is displayed in listing 2.2. If the first call is `g()` as you can see in `line 8`, the script will result in a fatal error because `function g()` will only be declared after `function f()` is executed. The `class C` will be declared once `function g()` is executed. As soon as the functions and classes are declared, they are available in the top scope, possibly prefixed with the name of the namespace they are declared within.

```
 1  function f() {
 2    function g() {
 3      class C {}
 4    }
 5  }
 6
 7  // Execution examples:
 8  g();                  // will fail because ‘g();’ is not declared yet
 9  f(); g();             // will work because ‘g();’ is declared when calling ‘f();’
10  f(); new C();         // will fail because ‘g();’ needs to be called first
11  f(); g(); new C();    // will work because ‘g();’ is called and has declared ‘f();’
```

Listing 2.2: Conditional function declaration

Dynamic features PHP comes with dynamic features like: include dynamic variables, dynamic class instantiations, dynamic function calls, dynamic function creation, reflection, and eval. New functions and classes can be declared on the fly. Method calls, or even whole pieces of code, can be executed based on variable strings.
A previous study by Mark Hills[HKV13] has shown that most real applications make use of dynamic features. Dynamic features are powerful, but can complicate the statical analysis. Additional analysis like constant propagation is needed to resolve most of these dynamic features. This is not in scope for this research.

Late static binding Late static binding[3]is implemented in PHP since version 5.3 by adding the keyword `static` to the language. It's usage is similar to the keyword `self`, which refers to the current class. The main difference is that `self` refers to the class where the code is located, while `static` refers to the actual instantiated class. The keyword `self` can be easily resolved while `static` can only be resolved on runtime. For the keyword `self` we will have to refer to the class it's declared in, plus all its descended classes.

[3]http://php.net/manual/en/language.oop5.late-static-bindings.php, July 2014

Magic methods PHP allows calls and property access on methods and fields that don't exist on a class. Normally a call to a non-existing method or property would result in a fatal error, but with the use of magic methods you can specify the wanted behavior. Listing 2.3 shows an example of the `__call` method. This method is triggered when a non-accessible or non-existing method is called. In this example the code will try to return the value of a private property based on the provided name. The full list of magic methods is `__construct`, `__destruct`, `__call`, `__callStatic`, `__get`, `__set`, `__isset`, `__unset`, `__wakeup`, `__toString`, `__invoke`, `__set_state`, `__clone`, and `__debugInfo`.

```php
class Car {
    private $maxSpeed = 210;
    function __get($name) { return $this->$name; }
}
var_dump((new Car)->maxSpeed); // 210
var_dump((new Car)->numberOfWheels); // NULL
```

Listing 2.3: Magic methods in PHP

Dynamic class properties Although it is a good practice to define your class properties, it is not required to do so in PHP. After instantiating a class it is possible to add properties the objects, even without the implementation of magic methods. In listing 2.4 you can see a code sample of adding a property to an object. The access of the non-existing property `nonExistingProperty` will result in a warning, but code execution will continue and will just return `NULL`. The code on `line 4` is where the property is written. The object `$c` will have the `nonExistingProperty` publicly available now. But in a new class instantiation, like you can see on `line 6`, will not have the property there.

```php
1 class C {}
2 $c = new C();
3 var_dump($c->nonExistingProperty); // NULL
4 $c->nonExistingProperty = "property now exists";
5 var_dump($c->nonExistingProperty); // string(19) "property now exists"
6 var_dump((new C)->nonExistingProperty); // NULL
```

Listing 2.4: Dynamic class property

2.2 Annotations

Annotations are pieces of meta data, defined on class, method, function, or statement level. Despite the proposal[4]for official support of annotations, PHP has still no native support for them. But PHP has a `getDocComment`[5]method in the `ReflectionClass` since version 5.1 in 2005. The `getDocComment` method returns the complete doc block of a certain element as a string. A doc block in php has the format `/**...*/`. Listing 2.5 shows an example of two doc blocks in PHP. The first doc block is defined above the class and contains information about the class. The second doc block is related to the method `getSomething`. The block contains a short description of the method, provides type hints for the parameter and the return type, and provides information which possible exceptions can be thrown by the method.

```php
namespace Thesis;

/**
 * Class Example
 * @package Thesis
 */
class Example
{
    /**
```

[4]https://wiki.php.net/rfc/annotations-in-docblock
[5]http://php.net/manual/en/reflectionclass.getdoccomment.php

```
     * This is a description of the method getSomething
     *
     * @param SomeTypeHint $someObject
     * @return string
     * @throws NoNameException
     */
    public function getSomething(SomeTypeHint $someObject)
    {
        if (null === $someObject->getName()) {
            throw new NoNameException();
        }

        return $someObject->getName();
    }
}
```

Listing 2.5: Examples of PHP DocBlocks

Annotations are mainly used for type hinting, documentation, and code execution. Software analysis tools and IDE's can use the type hints to aid understanding code and in finding bugs and security issues. Available tools can generate documentation based on the doc blocks. Programs like Symfony2, ZEND Framework, and Doctrine ORM use annotations for controller routing, templating information, ORM mappings, filters, and validation configuration.
This research focuses on the first type of annotations which can help developers and IDE's to better understand how code behaves within a program. For example a programmer can see what kind of input and output is expected for a method. Doc blocks with annotations can be placed on top of classes, methods, functions, and variables.
A standard on using annotations is not in the PHP Standard Recommendations (PSR) yet, but there is a proposal[6]. For this research we will only focus on the `@param`, `@return`, `@var`, and `@inheritDoc` annotations. The annotations `@return` and `@param` are only useful for functions, class methods, and closures. Type hints are described with `@var` and can be used on all structures, but mainly occur on variables and class fields.
There is no official standard for the use of annotations, but most projects follow the phpDocumentor[7] syntax. For this research the following annotations are considered:

$$\texttt{@return} = \begin{cases} \texttt{@return}\ \mathit{type}, & \text{unconditionally read } \texttt{@return}\ \mathit{type}. \end{cases} \tag{2.1}$$

$$\texttt{@param} = \begin{cases} \texttt{@param}\ \mathit{type}\ \$\mathit{var}, & \text{if `}\texttt{@param}\ \mathit{type}\ \$\text{var' occurs at least once.} \\ \texttt{@param}\ \$\mathit{var}\ \mathit{type}, & \text{else if `}\texttt{@param}\ \$\text{var}\ \mathit{type}\text{' occurs at least once.} \\ \texttt{@param}\ \mathit{type}, & \text{otherwise try to match `}\texttt{@param}\ \mathit{type}\text{'.} \end{cases} \tag{2.2}$$

$$\texttt{@var} = \begin{cases} \texttt{@var}\ \mathit{type}\ \$\mathit{var}, & \text{if `}\texttt{@var}\ \mathit{type}\ \$\text{var' occurs at least once.} \\ \texttt{@var}\ \$\mathit{var}\ \mathit{type}, & \text{else if `}\texttt{@var}\ \$\text{var}\ \mathit{type}\text{' occurs at least once.} \\ \texttt{@var}\ \mathit{type}, & \text{otherwise try to match `}\texttt{@var}\ \mathit{type}\text{'.} \end{cases} \tag{2.3}$$

$$\mathit{type} = \begin{cases} \mathit{type}|\mathit{type}, & \text{if `|' in } \mathit{type}. \\ \mathit{type}, & \text{otherwise} \end{cases} \tag{2.4}$$

[6]https://github.com/php-fig/fig-standards/pull/169/files, July 2014
[7]http://www.phpdoc.org/

2.3 Rascal

Rascal[KSV09] is a meta programming language developed by Centrum Wiskunde & Informatica (CWI). Rascal is designed to analyse, transform and visualise source code. The language is build on top of Java and implements various concepts of existing programming languages. In this research, Rascal is the main programming language. Rascal is used for gathering facts about the program and to solve constraints. The facts are gathered by visiting AST tree representing the program and hold semantic information about the program. Constraints are generated based on the collected facts and these constraints are solved with an in Rascal created constraint solver. The only part that does not use Rascal is the PHP parser. Although this could be easily implemented in Rascal, there was an existing library written in PHP available.

M^3[Izm+13; Bas+15] is a model which holds various information of source code and is implemented in Rascal. This model is created to gain insights in the quality of open-source projects. For our research we use the M^3-model to store facts about the program in a structured way, so we can easily use it at a later stage.

The core element of the M^3-model contains `containment`, `declarations`, `documentation`, `modifiers`, `names`, `types`, `uses`, `messages`. The `declarations` relation contains class, method, variable- information with their logical name and their real location. The type of the relation are `locations` and represent the logical name of the declaration and will be used in the rest of the M^3. The `containment` relation has information on what declarations are contained in each other. For example a package can contain a class; a class can contain fields and methods or an inner class; a method can contain variables. The `documentation` relation contains all comments from the source code and its source location. The `modifiers` relation has information on the modifiers of declarations. Modifiers are abstract, final, public, protected, or private. The `names` relation contains a simplified name of the full declarations. The `types` relation has information about the type of the source code elements. The `uses` relation describes what references use an object. For instance when a field of a class is used in some expression, the `uses` relation links the field in the expression to the declaration of the field in the class. And lastly, `messages` contains errors, warnings, and info statements.

2.4 Type systems

A **Type** is a set of possible values and a set of operations that can be performed on them. PHP is a dynamically typed language, which means that the type of expressions cannot be resolved at compile time. The time ... because the language allows expressions to change to a different type during run-time. This thesis describes a way to over-approximate the run-time types, using static analysis.

Type systems define how a set of rules are applied to types in their context. The type system validates the type usage with **type checking**. In order to perform type checking the types of the expressions needs to be known. The process of resolving the types of the expression is called **type inference**. Both type checking and type inference are explained in more details below.

Type checking Type checking is a mechanism which validates and/or enforces the constraints of a type in their specific context. There is a difference between static type checking and dynamic type checking. **Static type checking** is a process of checking the types based on the source code. The static type checker will ensure that a program is type safe before executing the program, which means that there will occur no type errors during runtime. **Dynamic type checking** performs the type checking during runtime. This means that the program needs to run to gain feedback on the usage of types. PHP is a dynamically typed language, which means that there are no types checked before actually running the program. There are languages, like JAVA, which have use a combination of static and dynamic type checking. The advantage of static type checking is that type errors can be caught early in the development process and allows for compiler optimisations. Dynamic type checking systems have more flexibility and allow dynamic loading of new code.

Type inference Type inference is the process of resolving types of variables and expressions. The inference process is a prerequisite to be able to perform type checking. Being able to infer the type before running the program enables you to optimise code execution by applying compiler optimisations. These optimisation allow performance improvements or can optimise memory usage. In dynamic languages like PHP it can be difficult to resolve the type of a variable or expression without running the program. In statically typed languages, type inference happens at compile time. In the next paragraph we will briefly explain some type inference systems.

The **Hindley-Milner**[Hin69] (HM) type system was found in 1969 by Roger J. Hinldey and almost 10 years later rediscovered[Mil78] by Robin Milner. The first implementation was created four years later by pHd student Luis Damas. Damas proved the soundness and completeness of the HM type system with **Algorithm W**[DM82] in the context of the programming language `ML`. The HM type system deduces the types of the variables to their most abstract type, based on their usage. Type declarations and hints are not necessarily to perform type inference. The type system is used for various functional languages. `Haskell` for example uses the Hinley-Milner type system as a foundation for the `Haskell` type system.

Control Flow Analysis[NNH99] (CFA) is concerned with resolving sound approximate run-time values at compile time. CFA is build on top of data flow analysis[ASU86] and tries to resolve the control-flow problem for high order programming languages. The control-flow problem deals with resolving which caller can call which callee in a program. One of the earlier CFA algorithms was Shivers' 0CFA algorithm[Shi88], a flow-sensitive constraint based algorithm. Shiver then defined k-CFA[Shi91], where the precision of the analysis is increased by taking the context of the expressions into account. The k-CFA algorithms compute an conservative over-approximations of run-time values during compile type.

The **Cartesian Product Algorithm**[Age95] (CPA) is a type inference algorithm created by Ole Agesen in 1995. Agesens work was based on Palsberg and Schwartzbach' **basic type inference algorithm**[PS91]. This basic type inference algorithm derives a set of constraints based on *trace graphs* and solves the constraints using a fix-point algorithm. Agesen extended the basic algorithm with *templates*. These templates are based on control flow and have start and end nodes with their possible in- and outputs. The CPA calculates the possibles output types for each template by taking the cartesian product (the set of all possible ordered pairs) of the input types.

2.5 Related work

Due to the big growth of the internet in the last couple of years, with a big market share of PHP programs, there are numerous people who have analysed PHP programs. We will briefly describe a few of them.

Similar work has been presented by Patrick Camphuijsen[Cam07; CHH09]. He created a constraint-based type inference analysis for his master thesis. The inference algorithm combines possible results of the constraints and takes the union to define the types. To guarantee termination the algorithm uses widening, by replacing the current result with the result of the union, to make sure that there will be a fixed-point. Further work improved the implementation by adding support for objects[VH15].

Paul Biggar created an Ahead-Of-Time (AOT) compiler for PHP[Big10]. The main goal of this compiler is to improve the performance of PHP programs. The AOT compiler starts by parsing a PHP program into an AST. This AST is transformed into an High-level Intermediate Representation (HIR) to remove all redundant constructs and then transformed into a Medium-level Intermediate Representation (MIR). Using dataflow analysis, alias analysis, static single assignment (SSA), and type analysis the compiler performs optimisations on the MIR. After the optimisations, the compiler generates C code, which then can be executed to run the program.

`PHANTM`[KSK10a; KSK10b] (PHp ANalyzer for Type Mismatch) is an open source PHP analyser written in Scala. Because of PHP's dynamic nature, without compiler or interpreter type checking, it is easy to make typing errors that result in unexpected behaviour or in fatal errors. `PHANTM` performs a hybrid flow-sensitive analysis to find type errors in PHP5. The hybrid analysis combines static and dynamic analysis. A program can be annotated to start a static analysis at a specific point. The analyser collects run-time type information while running the program and then starts the static analysis. `PHANTM` uses data-flow analysis to infer types. Although `PHANTM` has proven to be able to find a decent number of type errors on scalar usages in three different programs, there is a lack of finding errors in object oriented structures.

Facebook improved the performance of PHP programs with a static compiler, called HipHop Virtual Machine[Zha+12] (HHVM). This static compiler extracts the program into an AST, traverses this AST to collect information, performs pre-optimisations, performs type inference, preforms post-optimisations, and lastly generates C++ code. During the pre-optimisations the compiler removes unneeded actions, for example constant inlining, logical-expression simplifications, and dead-code elimination. The type inference process is based on the Hindley-Milner constraint based algorithm[DM82], to infer types of constants, variables, functions parameters, and return types. These new inferred types are then used in the post-optimisation. In the last step the AST is traversed to generate C++ code. Although the compiler does not cover all functions of PHP, it does covers most of the features. The performance benefits on the other hand are significantly better, showing on average 5.5x more efficiency.

PHPLint[8]extends the PHP syntax with type hints where PHP lacks support for it, using custom inline comment blocks to add extra typing information. These doc blocks with type information can be used in the analysis, allowing more strict type checking. The used syntax for the type hints are `/*.  .*/`, for example: `/*.  string .*/ $s = $var;` which means that the variable `$s` is of type `string`. PHPLint solves the lack of type hint support on scalar and array types. PHPLint can generate type hints based on information retrieved from simple type inference. Despite the good intentions, PHP7 will support scalar type hints as provided by this tool.

John Aycock states in Aggressive Type Inference[Ayc00] that dynamically typed languages are also used as statically typed languages. This means that you can use dynamic languages without using the magical parts. This claim is supported by a small analysis on the usage of `eval`, `execfile`, and `import`. Due to this statement he advocated for type consistency within a scope for variables, because the usage of the magic methods is limited. His analysis is flow insensitive, which means that it ignored specific paths within a scope.

[8]http://www.icosaedro.it/phplint, July 2015

Chapter 3

Research Context

This chapter describes our type system of PHP the research context. In section 3.1 we will explain more about the types we have defined. The relation between the types are described in 3.2. Section 3 explains in which context the research is executed.

3.1 Types

The basis types in PHP are integers, floats, booleans, strings, arrays, resources and null. PHP has a similar class inheritance structure and interface implementation as Java. The main difference is that in PHP all class are `public` and that inner classes are not allowed in PHP.
Because PHP has no explicit type system, we have defined our own type system for PHP. In the Rascal code below you can see our defined types, with a brief description below.

Rascal 1 M^3 core definitions in Rascal

```
module lang::php::m3::TypeSymbol

data TypeSymbol
  = \any()1                         // unknown, can be any of the types below
  | arrayType(TypeSymbol arrayType) // array of a type, can be nested
  | booleanType()                   // boolean values
  | classType(loc decl)             // a specific class
  | floatType()                     // float, double or real
  | integerType()                   // integer numbers
  | interfaceType(loc decl)         // a specific interface
  | numberType()                    // a float or integer
  | nullType()                      // empty or undefined value
  | objectType()                    // any class type
  | resourceType()                  // a build-in type
  | scalarType()                    // any number, string, resource or
  | stringType()                    // text values
  ;
```

any As you can see in the comments in the code above, 1, `any()` represents the combination of all possible types. This type will be used for mixed and unknown types, for example when variables are used, but are never defined.

arrayType The type `arrayType(TypeSymbol arrayType)` is a recursive declaration. The argument of the type is the type of the array. For example, an array of strings is declared as `arrayType(stringType())`

and for an unknown array the type is `arrayType(\any())`.

booleanType The type `booleanType()` is the type for boolean values. Just like any other language the boolean values are `true` and `false`.

classType The type `classType(loc decl)` represents a specific class, or the generic type. The argument is the declaration, which represents the logical name of the class. An example of the `Exception` class is `classType(|php+class:///exception|)`.

floatType Floating point numbers, also known as floats, reals, and doubles are defined by the `floatType()`. Example are `1.234`, `1.2e3`, and `7E-10`.

integerType Integers are whole numbers in decimal, hexadecimal, octal or binary notation. The `integerType` values can be positive or negative.

interfaceType The `interfaceType()` represents a specific interface, or the parent interface. Interfaces can be provided as type hints.

numberType The type `numberType()` covers the `integerType` and `floatType`. Because of coercion, these types can be easily mixed.

nullType The type `nullType()` is used for the value `null`.

objectType The type `objectType()` is the parent type for all class types. This type represent the object type and could also been written as `classType(|php+class:///object|)`.

resourceType The type `resourceType()` represents the build-in PHP resource type. Various function return the resourceType from build-in PHP functions.

scalarType The type `scalarType()` is the generic type for `resourceType`, `booleanType`, `numberType`, and `stringType`.

stringType The type `stringType` represents strings, a sequence of characters.

3.2 Type hierarchie

The relation between the types is shown in figure 3.1. In this diagram the `-Type` postfix is omitted to save space. We speak of **subtypes** when the types are descendant of the given type. The subtypes of the root node `any` are `scalarType`, `arrayType`, and `objectType`.

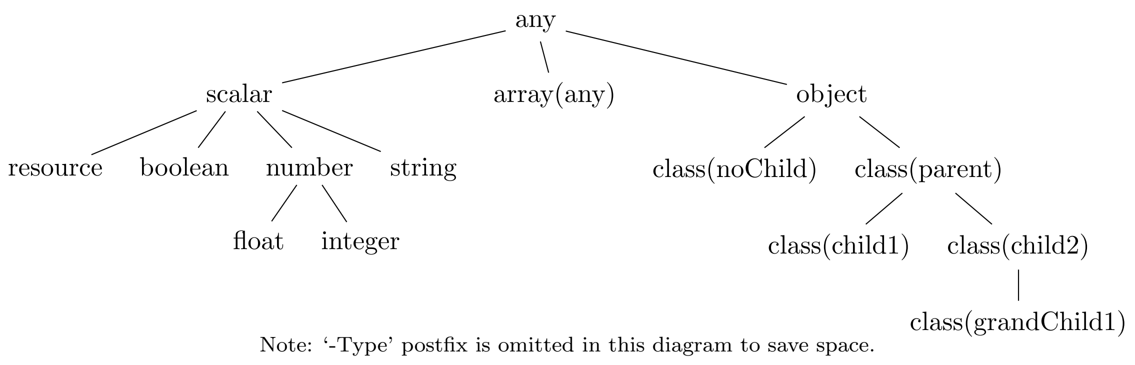
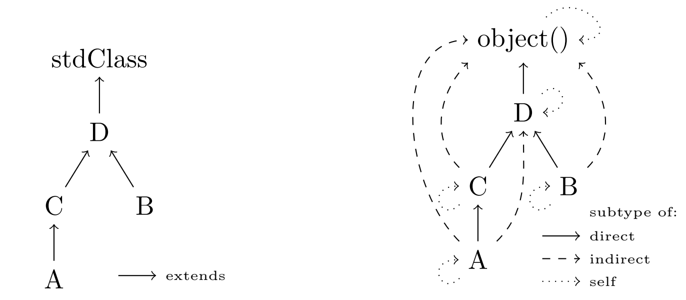


Figure 3.1: Type hierarchy

The *scalar type* is the super type for the non-complex types `resourceType`, `booleanType`, `numberTypes`, and `stringType`. These types can in practise be combined because of coercion. If they are used together, they will be classified as scalar types.

The *array type* in the subtype diagram is the most generic type of array, the array of any type. We have omitted the other array types because we of the scope in our research on arrays. In theory, this array type is a recursive type and can go to infinite depth. But in practise the generic array type is sufficient.



```
class A extends C {}
class B extends D {}
class C extends D {}
class D {}
```

(a) Inheritance relation (b) Subtype relation (c) Inheritance in PHP

Figure 3.2: Relation of subtypes among classes

The *object type* is the most generic object type, which represents the `stdClass` in PHP. The class inheritance relation in PHP is a reflexive transitive closure relation. A class extension of `class A` on `class C` will define `class A` as a subtype of `class C` in our analysis, as you can see in figure 3.2. If a class does not extend another class, it will implicitly extend the stdClass class. You can see that this happens with `class D` in the example. The `stdClass` is represented as the type `object()` in our analysis.

3.3 Research context

In order to let our research take place, we need to make sure that some environment variables are constant.

Program correctness In order to be able to execute this research we assume that the programs are correct and works as intended. This is needed to be able to say something about the programs we analyse.

File includes In this research we will assume that all file are included during runtime. When a PHP system is constructed of classes with namespaces, the files will be logically loaded using PHP's autoloader. Because most recent systems use namespaces, we will assume that all files are included. For legacy systems, this can influence the results of this research.

Register globals Register globals allows variables to be magically be created from GET and POST values. Since it is discouraged to use this setting, we will assume that all software products have this setting disabled.

PHP warnings For this research we will ignore all warnings. Warnings do not alter the behaviour of the program. In a most production environment these warnings are suppressed and will not change the behaviour of the program.

Flow insensitive Our analysis is intra-procedural flow insensitive, which means that we don't take the order of statements into account within a function or method scope. We do assume type consistency within a scope.

Chapter 4

Design of PHP type inference

Todo check/add introduction

4.1 Constraint extraction

In this section we present the constraint definitions and how they are extracted.

4.1.1 Constraint definitions

The constraint definitions we use are based on the definition of Palsberg and Schwartzbach[PS94]. We have extended the definition to conform to the PHP language. A legend with all symbols is displayed in table 4.1, followed by the constraint definitions for PHP.

symbol		description	symbol		description
$\equiv$	=	equivalent expression	$=$	=	equivalent type
$:=$	=	assignment	C	=	a class
$<:$	=	(lhs) is subTypeOf (rhs)	$\to c$	=	a class constant
E_k	=	an expression	$\to p$	=	a class property
$[\![E_k]\!]$	=	typeset of an expression	$\to m$	=	a class method
f	=	a function	$[\![m]\!]$	=	(return) type of a method call
$[\![f]\!]$	=	(return) type of a function	(A_n)	=	the n'th actual argument
$::c$	=	static property fetch	(P_n)	=	the n'th formal parameter
$::m$	=	static method call	th	=	type hint
$::p$	=	static property fetch	v	=	default value
Mfs	=	modifiers	$\in$	=	is defined in
$\{\}$	=	set of types	`instanceof`	=	instance of class in parse tree
$\wedge$	=	conjunction	$\vee$	=	disjunction

Table 4.1: Constraint definition legend

We write the definitions in the following form:

$$\frac{\text{premiss 1} \qquad \text{premiss 2}}{\begin{array}{c}\text{constraint 1,}\\ \text{constraint 2}\end{array}}$$

Above the horizontal line we write the premisses. In our case premisses are PHP expressions which are true or false depending on the context. If the premiss is true for a PHP statement or expression we can define the constraints below the horizontal line.

4.1.2 Scalars

Extracting constraints from the scalar types is straight forward. The PHP parser defines the string, integer, and float types in the AST. Booleans and null values can also be easily found in the AST.

Strings Strings in PHP can be written with single or double quotes. In the AST these are represented by the string type.

$$\frac{E \texttt{ instanceof } \text{string}}{[\![E]\!] = \{\ \mathit{stringType}()\ \}}$$

Code sample:

```
"Str"; // stringType()
'abc'; // stringType()
```

Listing 4.1: Strings

Integers In the example below you can see integers with different bases. All of these are parsed into an integer type in the Rascal AST.

$$\frac{E \texttt{ instanceof } \text{integer}}{[\![E]\!] = \{\ \mathit{integerType}()\ \}}$$

Code sample:

```
1234;       // integerType() (decimal number)
-123;       // integerType() (negative number)
0123;       // integerType() (octal number)
0x1A;       // integerType() (hexadecimal number)
0b11111111; // integerType() (binary number)
```

Listing 4.2: Integers

Floats Floats can have different forms in PHP code, but are all parsed to float objects in the Rascal AST.

$$\frac{E \texttt{ instanceof } \text{float}}{[\![E]\!] = \{\ \mathit{floatType}()\ \}}$$

Code sample:

```
1.4;   // floatType()
1.2e3; // floatType()
7E-10; // floatType()
```

Listing 4.3: Floats

Boolean values Boolean values in PHP are case sensitive, as you can see in the examples. True and false are reserved keywords in PHP. In the premiss we've only provided the lower case values.

$$\frac{E \equiv (\text{true}|\text{false})}{[\![E]\!] = \{\ \mathit{booleanType}()\ \}}$$

Code sample:

```
true;  // booleanType()
false; // booleanType()
TRUE;  // booleanType()
FALSE; // booleanType()
```

Listing 4.4: Boolean values

Null values Null is a reserved keyword in PHP. When we encounter null in the source code we can add the nullType type constraint.

$$\frac{E \equiv \text{null}}{[\![E]\!] = \{\ \mathit{nullType}()\ \}}$$

Code sample:

```
null;  // nullType()
NULL;  // nullType()
```

Listing 4.5: Null values

4.1.3 Assignments

Assign statements transfer values from one expression or variable into another. PHP uses the $=$ symbol as assignment syntax. In the premiss we use $:=$ for assigns.

Assignment When an assignment is used, we can extract the following constraint: the right hand side (E_2) of the assignment is a subtype of the left hand side (E_1). This relation is a subtype relation, not an is equal relation, because of the subclass relations of inheritance. The whole expression (E) is equal to the newly assigned value.

$$\frac{E \equiv (E_1 := E_2)}{\begin{array}{c}[\![E_2]\!] <: [\![E_1]\!],\\ [\![E_1]\!] = [\![E]\!]\end{array}}$$

Code sample:

```
$a = $b;       // [$b] <: [$a]
               // [$a] = [$a = $b]

$c = $d = $e; // [$e] <: [$d]
               // [$d] <: [$c],
               // [$d] = [$d = $e]
               // [$c] = [$c = $d = $e]
```

Listing 4.6: Assignment

Ternary operator The *ternary* operator is a conditional assignment. If the expression E_1 is evaluated as `true`, the left hand side (E_2) is the value of the whole ternary expression (i). If E_1 is evaluated as `false`, the right hand side (E_3) is the value. The constraint we can extract from the ternary expression is that the type of the whole expression should be the type of E_2 or E_3.
The ternary operator without a left hand side value (ii), also known as the elvis operator, returns the value of E_1 when E_1 is evaluated as `true`. Here the type of the expression should be either the type of E_1 or E_3.

$$\frac{E \equiv (E_1 \ ?\ E_2 : E_3)}{[\![E]\!] = [\![E_2]\!] \vee [\![E_3]\!]}\ \text{(i)} \qquad \frac{E \equiv (E_1 \ ?:E_3)}{[\![E]\!] = [\![E_1]\!] \vee [\![E_3]\!]}\ \text{(ii)}$$

Code sample:

```
$a ? $b : $c; // [$a ? $b : $c] = ([$b] || [$c])
$a ?: $c;     // [$a ?: $c]     = ([$a] || [$c])
```

Listing 4.7: Ternary operator

Assignments resulting in integers PHP provides several assignment statements combined with operators. The type of the left hand side (E_1) is in the cases of *bitwise and* (i), *bitwise inclusive or* (ii), *bitwise exclusive or* (iii), *bitwise shift left* (iv), *bitwise shift right* (v), and *modulus* (vi) always of *integer* type.

$$\frac{E_1 \ \&= E_2}{[\![E_1]\!] = \{\ integerType()\ \}}\ \text{(i)} \qquad \frac{E_1 \ |= E_2}{[\![E_1]\!] = \{\ integerType()\ \}}\ \text{(ii)} \qquad \frac{E_1 \ \hat{}= E_2}{[\![E_1]\!] = \{\ integerType()\ \}}\ \text{(iii)}$$

$$\frac{E_1 \ <<= E_2}{[\![E_1]\!] = \{\ integerType()\ \}}\ \text{(iv)} \qquad \frac{E_1 \ >>= E_2}{[\![E_1]\!] = \{\ integerType()\ \}}\ \text{(v)} \qquad \frac{E_1 \ \%= E_2}{[\![E_1]\!] = \{\ integerType()\ \}}\ \text{(vi)}$$

Code sample:

```
$a  &= $b; // [$a] = integerType()
$a  |= $b; // [$a] = integerType()
$a  ^= $b; // [$a] = integerType()
$a <<= $b; // [$a] = integerType()
$a >>= $b; // [$a] = integerType()
$a  %= $b; // [$a] = integerType()
```

Listing 4.8: Assignments resulting in integers

Assignment with string concat When the *string concat* operator is used, in combination with the assignment operator (i), the type of the left hand side (E_1) is always a string.
About the right hand side (E_2) we can say that **if** the type of E_2 is a subtype of object, then this object should have the method *__toString*() (ii).

$$\frac{E_1 \ .= E_2}{[\![E_1]\!] = \{\ stringType()\ \}}\ \text{(i)} \qquad \frac{(E_1 \ .= E_2) \qquad ([\![E_1]\!] <: \{\ objectType()\ \})}{[\![E_2]\!]\ \texttt{hasMethod}\ "\_\_tostring"}\ \text{(ii)}$$

Code sample:

```
$a .= $b;  // [$a] = stringType()
// An error occurs when $b is of type object() and
// __toString is not defined or does not return a string
```

Listing 4.9: Assignment with string concat

Assignments with division or subtraction operator *Division* (i) and *subtraction* (ii) assignment in PHP will always result in an integer type. This is the case for all values, except for array's. A fatal error will occur when the right hand side value is of type array.

$$\frac{E_1 \;/= E_2}{[\![E_1]\!] = \{\, integerType() \,\},\; [\![E_2]\!] \neq \{\, array(\_) \,\}}\;\text{(i)} \qquad \frac{E_1 -= E_2}{[\![E_1]\!] = \{\, integerType() \,\},\; [\![E_2]\!] \neq \{\, array(\_) \,\}}\;\text{(ii)}$$

Code sample:

```
$a /= $b;  // $a = integer()
$a -= $b;  // $a = integer()
// An error occurs when $b is of type array() for /= and -=
// Fatal error: Unsupported operand types
```

Listing 4.10: Assignments with division or subtraction operator

Assignments resulting in numbers The result of an *multiplication* (i) and *addition* (ii) assignment is either a float or an integer. When the type of the right hand side (E_2) is either booleanType, integerType, or nullType, the result of the assignment (E_1) will be of integerType. If E_2 is of any other type, E_1 will be of type floatType. Float and integer are both subtypes of integers, so we can use the subtype relation for numberType for this.

$$\frac{E_1 \;*= E_2}{[\![E_1]\!] <: \{\, numberType() \,\}}\;\text{(i)} \qquad \frac{E_1 \;+= E_2}{[\![E_1]\!] <: \{\, numberType() \,\}}\;\text{(ii)}$$

Code sample:

```
$a *= $b; // [$a] <: numberType()
$a += $b; // [$a] <: numberType()
```

Listing 4.11: Assignments resulting in numbers

4.1.4 Unary operators

Unary operators in PHP consist of positive and negative numbers, negation operators, and increase and decrease operators.

Positive and negative numbers When a *plus* (i) or *minus* (ii) sign is used in PHP in front of a variable, the type of the whole expression must be of numberType. The type of the variable cannot be of any arrayType.

$$\frac{E \equiv (+E_1)}{[\![E]\!] <: \{\, numberType() \,\},\; [\![E_1]\!] \neq \{\, arrayType(\_) \,\}}\;\text{(i)} \qquad \frac{E \equiv (-E_1)}{[\![E]\!] <: \{\, numberType() \,\},\; [\![E_1]\!] \neq \{\, arrayType(\_) \,\}}\;\text{(ii)}$$

Code sample:

```
+$a; // [$a] <: numberType();
     // [$a] =/= arrayType();
-$a; // [$a] <: numberType();
     // [$a] =/= arrayType();
```

Listing 4.12: Positive and negative numbers

Negation operators The PHP language holds two types of negation operators. The type of the whole expression for *normal negation* operator (i) is boolean. For the *bitwise negation* operator (ii) the type of attached variable is either a number or a string. The type of the whole expression is an integer or string.

$$\frac{E \equiv \;(!E_1)}{[\![E]\!] = \{\; booleanType() \;\}}\;(i) \qquad \frac{E \equiv \;(\sim E_1)}{\begin{array}{c}[\![E_1]\!] = \{\; numberType(),\; stringType() \;\},\\ [\![E]\!] = \{\; integerType(),\; stringType() \;\}\end{array}}\;(ii)$$

Code sample:

```
!$a // [!$a] = booleanType()
~$a // [$a] = numberType() or stringType()
    // [~$a] = integerType() or stringType()
```

Listing 4.13: Negation operators

Post increment operators From post increment and decrement operators we can only extract conditional constraints.
If the type of E_1 is of any `array` type, the result of the expression is also of any `array` type (i).
If the type of E_1 is of `boolean` type, the result of the expression is also of `boolean` type (ii).
If the type of E_1 is of `float` type, the result of the expression is also of `float` type (iii).
If the type of E_1 is of `integer` type, the result of the expression is also of `integer` type (iv).
If the type of E_1 is of `null` type, the result of the expression is either of `integer` or `boolean` type (v).
If the type of E_1 is of any `object` type, the result of the expression is also of any `object` type (vi).
If the type of E_1 is of `resource` type, the result of the expression is also of any `resource` type (vii).
If the type of E_1 is of `string` type, the result of the expression is either of `number` or `string` type (vii).
The rules below are only written for the post increment, but also apply on the post decrement.

$$\frac{(E \equiv (E_1 + +)) \qquad ([\![E_1]\!] <: \{\; arrayType(\_) \;\})}{[\![E]\!] <: \{\; arrayType(\_) \;\}}\;(i)$$

$$\frac{(E \equiv (E_1 + +)) \qquad ([\![E_1]\!] = \{\; booleanType() \;\})}{[\![E]\!] = \{\; booleanType() \;\}}\;(ii)$$

$$\frac{(E \equiv (E_1 + +)) \qquad ([\![E_1]\!] = \{\; floatType() \;\})}{[\![E]\!] = \{\; floatType() \;\}}\;(iii)$$

$$\frac{(E \equiv (E_1 + +)) \qquad ([\![E_1]\!] = \{\; integerType() \;\})}{[\![E]\!] = \{\; integerType() \;\}}\;(iv)$$

$$\frac{(E \equiv (E_1 + +)) \qquad ([\![E_1]\!] = \{\; nullType() \;\})}{[\![E]\!] = \{\; integerType(),\; nullType() \;\}}\;(v)$$

$$\frac{(E \equiv (E_1 ++)) \qquad (\llbracket E_1 \rrbracket <: \{\ objectType()\ \})}{\llbracket E \rrbracket <: \{\ objectType()\ \}} \text{(vi)}$$

$$\frac{(E \equiv (E_1 ++)) \qquad (\llbracket E_1 \rrbracket = \{\ resourceType()\ \})}{\llbracket E \rrbracket = \{\ resourceType()\ \}} \text{(vii)}$$

$$\frac{(E \equiv (E_1 ++)) \qquad (\llbracket E_1 \rrbracket = \{\ stringType()\ \})}{\llbracket E \rrbracket <: \{\ numberType(),\ stringType()\ \}} \text{(viii)}$$

Code sample:

```
$a++ // (post increase)
     // if ([$a] <: arrayType())    => [$a++] <: arrayType()
     // if ([$a]  = booleanType())  => [$a++]  = booleanType()
     // if ([$a]  = floatType())    => [$a++]  = floatType()
     // if ([$a]  = integerType())  => [$a++]  = integerType()
     // if ([$a]  = nullType())     => [$a++]  = integerType() or nullType()
     // if ([$a] <: objectType())   => [$a++] <: objectType()
     // if ([$a]  = resourceType()) => [$a++]  = resourceTYpe()
     // if ([$a]  = stringType())   => [$a++] <: numberType() or stringType()
$a-- // (post decrease)
     // same rules as above apply for $a--
```

Listing 4.14: Post increment operators

Pre increment operators From pre increment and decrement operators we can also only extract conditional constraints. The rules are similar to the rules for the post increment, except for the `nullType()`. If the type of E_1 is of `null` type, the result of the expression is either of `null` type (v).

$$\frac{(E \equiv (++ E_1)) \qquad (\llbracket E_1 \rrbracket <: \{\ arrayType(\_)\ \})}{\llbracket E \rrbracket <: \{\ arrayType(\_)\ \}} \text{(i)}$$

$$\frac{(E \equiv (++ E_1)) \qquad (\llbracket E_1 \rrbracket = \{\ booleanType()\ \})}{\llbracket E \rrbracket = \{\ booleanType()\ \}} \text{(ii)}$$

$$\frac{(E \equiv (++ E_1)) \qquad (\llbracket E_1 \rrbracket = \{\ floatType()\ \})}{\llbracket E \rrbracket = \{\ floatType()\ \}} \text{(iii)}$$

$$\frac{(E \equiv (++ E_1)) \qquad (\llbracket E_1 \rrbracket = \{\ integerType()\ \})}{\llbracket E \rrbracket = \{\ integerType()\ \}} \text{(iv)}$$

$$\frac{(E \equiv (++ E_1)) \qquad (\llbracket E_1 \rrbracket = \{\ nullType()\ \})}{\llbracket E \rrbracket = \{\ nullType()\ \}} \text{(v)}$$

$$\frac{(E \equiv (++ E_1)) \qquad (\llbracket E_1 \rrbracket <: \{\ objectType()\ \})}{\llbracket E \rrbracket <: \{\ objectType()\ \}} \text{(vi)}$$

$$\frac{(E \equiv (++ E_1)) \qquad (\llbracket E_1 \rrbracket = \{\ resourceType()\ \})}{\llbracket E \rrbracket = \{\ resourceType()\ \}} \text{(vii)}$$

$$\frac{(E \equiv (++ E_1)) \qquad (\llbracket E_1 \rrbracket = \{\ stringType()\ \})}{\llbracket E \rrbracket <: \{\ numberType(),\ stringType()\ \}} \text{(viii)}$$

Code sample:

```
++$a // (pre increase)
     // if ([$a] <: arrayType())    => [++$a] <: arrayType()
     // if ([$a]  = booleanType())  => [++$a]  = booleanType()
     // if ([$a]  = floatType())    => [++$a]  = floatType()
     // if ([$a]  = integerType())  => [++$a]  = integerType()
     // if ([$a]  = nullType())     => [++$a]  = nullType()
     // if ([$a] <: objectType())   => [++$a] <: objectType()
     // if ([$a]  = resourceType()) => [++$a]  = resourceTYpe()
     // if ([$a]  = stringType())   => [++$a] <: numberType() or stringType()
--$a // (pre decrease)
     // same rules as above apply for --$a
```

Listing 4.15: Pre increment operators

4.1.5 Binary operators

Addition-, subtraction-, multiplication-, division-, modulus-, bitwise-, comparison-, and logical operators are in PHP binary operators.

Addition operator The result of an addition operator will always be a number or an array (i). If the left and right hand side are both arrays, the return type will be array (ii). In this case two arrays are merged. In all other cases the result of this operation is a number (iii).

$$\frac{E \equiv (E_1 + E_2)}{[\![E]\!] <: \{\ arrayType(\_),\ numberType()\ \}}\ \text{(i)}$$

$$\frac{E \equiv (E_1 + E_2) \qquad [\![E_1]\!] <: \{\ arrayType(\_)\ \} \wedge [\![E_2]\!] <: \{\ arrayType(\_)\ \}}{[\![E]\!] <: \{\ arrayType(\_)\ \}}\ \text{(ii)}$$

$$\frac{E \equiv (E_1 + E_2) \qquad [\![E_1]\!]\ !<: \{\ arrayType(\_)\ \} \vee [\![E_2]\!]\ !<: \{\ arrayType(\_)\ \}}{[\![E]\!] <: \{\ numberType()\ \}}\ \text{(iii)}$$

Code sample:

```
$a + $b // (addition)
        // [$a + $b] <: arrayType() or numberType()
        // if (([$a] and [$b])  <: arrayType(_)) => [$a + $b] <: arrayType(_)
        // if (([$a] or  [$b]) !<: arrayType(_)) => [$a + $b] <: numberType()
```

Listing 4.16: Addition operator

Subtraction multiplication division operators The *subtraction* (i), *multiplication* (ii), and *division* (iii) operators are merged together in this paragraph because they have identical behaviour. The result of these operations is always of `number` type. The operations cannot be used if one of the sides is of type `array`. Therefore we can says that the left and right hand side cannot be of `array` type.

$$\frac{E \equiv (E_1 - E_2)}{\begin{array}{c}[\![E]\!] <: \{\ numberType()\ \},\\ [\![E_1]\!]\ !<: \{\ arrayType(\_)\ \},\\ [\![E_2]\!]\ !<: \{\ arrayType(\_)\ \}\end{array}}\ \text{(i)} \qquad \frac{E \equiv (E_1 * E_2)}{\begin{array}{c}[\![E]\!] <: \{\ numberType()\ \},\\ [\![E_1]\!]\ !<: \{\ arrayType(\_)\ \},\\ [\![E_2]\!]\ !<: \{\ arrayType(\_)\ \}\end{array}}\ \text{(ii)}$$

$$\frac{E \equiv (E_1 / E_2)}{[\![E]\!] <: \{\ numberType()\ \},} \text{(iii)}$$
$$[\![E_1]\!]\ !<: \{\ arrayType(\_)\ \},$$
$$[\![E_2]\!]\ !<: \{\ arrayType(\_)\ \}$$

Code sample:

```
$a - $b // (subtraction)
$a * $b // (mulitiplication)
$a / $b // (division)
        // [$a - $b] <: numberType()
        // [$a * $b] <: numberType()
        // [$a / $b] <: numberType()
        // [$a] !<: array(_)
        // [$b] !<: array(_)
```

Listing 4.17: Subtraction multiplication division operators

Modulus and bitwise shift operators The merge of *modulus* (i) and *bitwise shift* (ii, iii) operators seems not so obvious at first, but they have the same behaviour. The results of these operations is of integer type.

$$\frac{E \equiv (E_1\ \%\ E_2)}{[\![E]\!] = \{\ integerType()\ \}} \text{(i)} \qquad \frac{E \equiv (E_1 << E_2)}{[\![E]\!] = \{\ integerType()\ \}} \text{(ii)} \qquad \frac{E \equiv (E_1 >> E_2)}{[\![E]\!] = \{\ integerType()\ \}} \text{(iii)}$$

Code sample:

```
$a % $b  // [$a % $b]  = integerType()  // (modulus)
$a << $b // [$a << $b] = integerType()  // (bitwise shift left)
$a >> $b // [$a >> $b] = integerType()  // (bitwise shift right)
```

Listing 4.18: Modulus and bitwise shift operators

Bitwise operators The results of the bitwise operators *and* (i, ii, iii), *or*, and *xor* is always of `integer` or `string` type. When the left and right hand side are both strings, the result of the operation is also of type `string`. In all other cases the result of this operation is a number.

$$\frac{E \equiv (E_1\ \&\ E_2)}{[\![E]\!] = \{\ stringType(),\ integerType()\ \}} \text{(i)}$$

$$\frac{E \equiv (E_1\ \&\ E_2) \qquad [\![E_1]\!] = \{\ stringType()\ \} \wedge [\![E_2]\!] = \{\ stringType()\ \}}{[\![E]\!] = \{\ stringType()\ \}} \text{(ii)}$$

$$\frac{E \equiv (E_1\ \&\ E_2) \qquad [\![E_1]\!] \neq \{\ stringType()\ \} \vee [\![E_2]\!] \neq \{\ stringType()\ \}}{[\![E]\!] = \{\ integerType()\ \}} \text{(iii)}$$

Code sample:

```
$a & $b // (bitwise And)
        // [$a & $b] = stringType() or integerType()
        // if (($a and $b) = stringType()) => [$a & $b] = stringType()
        // if (($a or $b) != stringType()) => [$a & $b] = integerType()
$a | $b // (bitwise Or)
        // [$a | $b] = stringType() or integerType()
        // if (($a and $b) = stringType()) => [$a | $b] = stringType()
        // if (($a or $b) != stringType()) => [$a | $b] = integerType()
$a ^ $b // (bitwise Xor)
        // [$a ^ $b] = stringType() or integerType()
        // if (($a and $b) = stringType()) => [$a ^ $b] = stringType()
        // if (($a or $b) != stringType()) => [$a ^ $b] = integerType()
```

Listing 4.19: Bitwise operators

Comparison operators The result of the comparison operators is always of boolean type. The comparison operators are *equals* (i), *identical* (ii), *not equal* (iii), *not equal* (iv), *not identical* (v), *less than* (vi), *greater than* (vii), *less than or equal to* (viii), and *greater than or equal to* (ix) operators.

$$\frac{E \equiv (E_1 == E_2)}{[\![E]\!] = \{\ booleanType()\ \}}\ \text{(i)} \qquad \frac{E \equiv (E_1 === E_2)}{[\![E]\!] = \{\ booleanType()\ \}}\ \text{(ii)} \qquad \frac{E \equiv (E_1\ != E_2)}{[\![E]\!] = \{\ booleanType()\ \}}\ \text{(iii)}$$

$$\frac{E \equiv (E_1 <> E_2)}{[\![E]\!] = \{\ booleanType()\ \}}\ \text{(iv)} \qquad \frac{E \equiv (E_1\ !== E_2)}{[\![E]\!] = \{\ booleanType()\ \}}\ \text{(v)} \qquad \frac{E \equiv (E_1 < E_2)}{[\![E]\!] = \{\ booleanType()\ \}}\ \text{(vi)}$$

$$\frac{E \equiv (E_1 > E_2)}{[\![E]\!] = \{\ booleanType()\ \}}\ \text{(vii)} \qquad \frac{E \equiv (E_1 <= E_2)}{[\![E]\!] = \{\ booleanType()\ \}}\ \text{(viii)} \qquad \frac{E \equiv (E_1 >= E_2)}{[\![E]\!] = \{\ booleanType()\ \}}\ \text{(ix)}$$

Code sample:

```
$a == $b  // [$a == $b]  = booleanType()
$a === $b // [$a === $b] = booleanType()
$a != $b  // [$a != $b]  = booleanType()
$a <> $b  // [$a <> $b]  = booleanType()
$a !== $b // [$a !== $b] = booleanType()
$a < $b   // [$a < $b]   = booleanType()
$a > $b   // [$a > $b]   = booleanType()
$a <= $b  // [$a <= $b]  = booleanType()
$a >= $b  // [$a >= $b]  = booleanType()
```

Listing 4.20: Comparison operators

Logical operators Just like the comparison operators, the result of the logical operators is always of boolean type. The logical operators are *and* (i), *or* (ii), *xor* (iii), *and* (iv), and *or* (v).

$$\frac{E \equiv (E_1\ and\ E_2)}{[E] = \{\ booleanType()\ \}}\ \text{(i)} \qquad \frac{E \equiv (E_1\ or\ E_2)}{[E] = \{\ booleanType()\ \}}\ \text{(ii)} \qquad \frac{E \equiv (E_1\ xor\ E_2)}{[E] = \{\ booleanType()\ \}}\ \text{(iii)}$$

$$\frac{E \equiv (E_1\ \&\&\ E_2)}{[E] = \{\ booleanType()\ \}}\ \text{(iv)} \qquad \frac{E \equiv (E_1\ ||\ E_2)}{[E] = \{\ booleanType()\ \}}\ \text{(v)}$$

Code sample:

```
$a and $b // [$a and $b] = booleanType()
$a or $b  // [$a or $b]  = booleanType()
$a xor $b // [$a xor $b] = booleanType()
```

```
$a && $b   // [$a && $b]  = booleanType()
$a || $b   // [$a || $b]  = booleanType()
```

Listing 4.21: Logical operators

4.1.6 Array

From the PHP parser we get array declaration and array access nodes.

Array declaration From the array declarations (`array()` or `[]`) we can extract the constraint that they should be of any `array` type.

$$\frac{E \texttt{ instanceof } \mathsf{array}}{[\![E]\!] <: \{\ \mathit{arrayType}(\_)\ \}}$$

Code sample:

```
array(/*..*/); // [array(/*..*/)] <: arrayType(any())
[/*..*/];      // [[(/*..*/)]]    <: arrayType(any())
```

Listing 4.22: Array declaration

Array access From the usage of array access syntax you cannot tell what the type of the expression is. The same syntax is used to access strings. We can extract that the type of the base expression should not be of object type (i). If we know that the base type is of `string` type, we know that the result of the expression will also be a string (ii). When the base type is an array, the result type is the type of the elements in there array (iii). For all other cases, when the base type is not an string or array, the result of the expression will be of `null` type (iv).

$$\frac{E_1[E_2] \qquad E_1 \texttt{ instanceof } \mathsf{arrayAccess}}{[\![E_1]\!] \neq \{\ \mathit{objectType}()\ \}}\ \text{(i)}$$

$$\frac{E \equiv (E_1[E_2]) \qquad E_1 \texttt{ instanceof } \mathsf{arrayAccess} \qquad [\![E_1]\!] = \{\ \mathit{stringType}()\ \}}{[\![E]\!] = \{\ \mathit{stringType}()\ \}}\ \text{(ii)}$$

$$\frac{E \equiv (E_1[E_2]) \qquad E_1 \texttt{ instanceof } \mathsf{arrayAccess} \qquad [\![E_1]\!] = \{\ \mathit{arrayType}(E_2)\ \}}{[\![E]\!] = [\![E_2]\!]}\ \text{(iii)}$$

$$\frac{E \equiv (E_1[E_2]) \qquad E_1 \texttt{ instanceof } \mathsf{arrayAccess} \qquad [\![E_1]\!] \neq \{\ \mathit{stringType}()\ \} \qquad [\![E_1]\!]\ !<: \{\ \mathit{arrayType}(\_)\ \}}{[\![E]\!] = \{\ \mathit{nullType}()\ \}}\ \text{(iv)}$$

Code sample:

```
$a[$b];
// [$a] != objectType()
// if ([$a] == stringType())      => [$a[$b]] = stringType()
// if ([$a] == arrayType(x)       => [$a[$b]] = [x]
// if ([$a] != (string or array) => [$a[$b]] = nullType()
```

Listing 4.23: Array access

4.1.7 Casts

Casts PHP contains syntax to arrays, booleans, integers, floats, objects, strings, and to unset variables. The result of a cast to array is of any `array` type (i). For casting to boolean there are two keywords, *bool* (ii) and *boolean* (iii), and the result will always be of `boolean` type. There are three keywords to cast to floats, *float* (iv), *double* (v), and *real* (vi). Casts to integer integer type, you can use *integer* (vii) or *int* (viii) keywords. Any cast to *object* (ix) will result in any `object` type. A cast to *string* will always result in a `string` type. String casts (x) will always result in a `string` type. If we know that the expression (E_1) is an object, we know that this method needs to have an *__toString*() method (xi). The last cast, *unset*, results in a `null` type.

$$\frac{E \equiv (array)E_1}{[\![E]\!] <: \{\ arrayType(\_)\ \}}\ \text{(i)} \qquad \frac{E \equiv (boolean)E_1}{[\![E]\!] = \{\ booleanType()\ \}}\ \text{(ii)} \qquad \frac{E \equiv (bool)E_1}{[\![E]\!] = \{\ booleanType()\ \}}\ \text{(iii)}$$

$$\frac{E \equiv (float)E_1}{[\![E]\!] = \{\ floatType()\ \}}\ \text{(iv)} \qquad \frac{E \equiv (double)E_1}{[\![E]\!] = \{\ floatType()\ \}}\ \text{(v)} \qquad \frac{E \equiv (real)E_1}{[\![E]\!] = \{\ floatType()\ \}}\ \text{(vi)}$$

$$\frac{E \equiv (integer)E_1}{[\![E]\!] = \{\ integerType()\ \}}\ \text{(vii)} \qquad \frac{E \equiv (int)E_1}{[\![E]\!] = \{\ integerType()\ \}}\ \text{(viii)} \qquad \frac{E \equiv (object)E_1}{[\![E]\!] <: \{\ objectType()\ \}}\ \text{(ix)}$$

$$\frac{E \equiv (string)E_1}{[\![E_1]\!] = \{\ stringType()\ \}}\ \text{(x)} \qquad \frac{E \equiv (string)E_1 \qquad (E_1 <: \{\ \ \text{objectType()}\ \ \})}{[\![E_1]\!]\ \texttt{hasMethod}\ ''\_\_tostring''}\ \text{(xi)}$$

$$\frac{E \equiv (unset)E_1}{[\![E]\!] = \{\ nullType()\ \}}\ \text{(xii)}$$

Code sample:

```
(array)$a  // [(array)$a]  <: arrayType(_)
(bool)$a   // [(bool)$a]   = booleanType()
(float)$a  // [(float)$a]  = floatType()
(int)$a    // [(int)$a]    = integerType()
(object)$a // [(object)$a] = objectType()
(string)$a // [(string)$a] = stringType()
           // if ($a <: objectType()) => [$a] has method "__toString()"
(unset)$a  // [(unset)$a]  = nullType()
```

Listing 4.24: Casts

4.1.8 Clone

Clone From the PHP function *clone* we can extract the constraint that the type of the given expression and the result must be of any `object` type. We also know that the type will not change, and so the type of the expression will be the same as

$$\frac{E \equiv clone(E_1)}{\begin{array}{c}[\![E]\!] <: \{\ objectType()\ \} \\ [\![E_1]\!] <: \{\ objectType()\ \} \\ [\![E]\!] = [\![E_1]\!]\end{array}}$$

Code sample:

```
clone($a) // [$a]         <: object
          // [clone($a)] <: object
          // [$a]         =  [clone($a)]
```

Listing 4.25: Clone

4.1.9 Class

This section contains fact extraction rules from object syntax. Class instantiation, special keywords, method calls, parameters, and class constants.

Class instantiation Classes can be instantiated with the name of the class. The type of the whole expression is then of the specific `class` type (i). When a class is dynamically instantiated, we only know that it should be of some `object` type, and that the type of the expression should be any `object` or `string` type (ii).

$$\frac{E \equiv new\ C_1()}{[\![E]\!] = \text{classType(C.decl)}}\ \text{(i)} \qquad \frac{E \equiv new\ E_1}{\begin{array}{c}[\![E]\!] <: objectType(),\\ [\![E_1]\!] <: objectType() \vee [\![E_1]\!] = stringType()\end{array}}\ \text{(ii)}$$

Code sample:

```
new C;     // [new C] = classType(C)

$c = "C";
new $c;    // [new $c] <: objectType()
           // [$c]     <: ( objectType() or stringType() )
```

Listing 4.26: Class instantiation

Special keywords PHP contains a few class related reserved keywords with special behaviour. These keywords can be used inside a class scope ($\in C$). From the usage of the keyword *self* we know that the type of the expression should be the same `class` type as which the keyword is defined in (i). The constraint we can extract from *self* is that the type should be any `object` type and it should be either the contained class or one of the parent classes. The behaviour of *$this* (ii) and *static* (iii) differs, but the constraints we can extract are equal to the *self* keyword. The *parent* (iv) keyword differs because it must be a super type of the class they keyword is defined in.

$$\frac{(E \equiv \text{self}) \in C}{\begin{array}{c}[\![E]\!] <: \text{objectType}(),\\ [\![E]\!] = \text{classType(C)} \vee [\![E]\!] :> \text{classType(C)}\end{array}}\ \text{(i)}$$

$$\frac{(E \equiv static) \in C}{\begin{array}{c}[\![E]\!] <: \text{objectType}(),\\ [\![E]\!] = \text{classType(C)} \vee [\![E]\!] :> \text{classType(C)}\end{array}}\ \text{(ii)}$$

$$\frac{(E \equiv \$this) \in C}{\begin{array}{c}[\![E]\!] <: \text{objectType}(),\\ [\![E]\!] = \text{classType(C)} \vee [\![E]\!] :> \text{classType(C)}\end{array}}\ \text{(iii)}$$

$$\frac{(E \equiv parent) \in C}{\begin{array}{c}[\![E]\!] <: \text{objectType}(),\\ [\![E]\!] :> \text{classType(C)}\end{array}}\ \text{(iv)}$$

Code sample:

```
self   // in class C -> [self]   = classType(C)
parent // in class C -> [parent] = parentOf(classType(C))
static // in class C -> [static] = classType(C) or <: classType(C)
$this  // in class C -> [$this]  = classType(C) or <: classType(C)
```

Listing 4.27: Special keywords

Method calls From the usage of a method call (*expression* -> *expression*) we can extract the constraint that the type of the left hand side should be an object (i and ii). If the right hand side (E_2) is a name of a method, we can extract the constraint that the left hand side (E_1) must implement this method (ii).

$$\frac{E_1 \to E_2 \in C \qquad E_2 \texttt{ instanceof } \text{expression}}{[\![E_1]\!] <: \text{objectType}()} \text{(i)}$$

$$\frac{E_1 \to E_2 \in C \qquad E_2 \texttt{ instanceof } \text{name}}{\begin{array}{c}[\![E_1]\!] <: \text{objectType}(), \\ [\![E_1]\!] = C.\text{hasMethod}(E_2.\text{name}, \text{static} \notin \text{Mfs})\end{array}} \text{(ii)}$$

Code sample:

```
$a->$b() // [$a] <: objectType()
$a->b()  // [$a] <: objectType()
         // [$a] has a method (possible inherited) with the name 'b'
```

Listing 4.28: Method calls

4.1.10 Scope

In order to define the type of a variable within a scope, we have conducted the following constraints.

Variables The type of a certain variable is defined by adding an equal constraint on the logical name and the location. The scope of these variables is contained in the logical name. The logical name contains the name of the scope, which is optionally a namespace and the name of a class, method or function, and the name of the variable. An example of a logical name for the variable `$a` in the function `f` in the global namespace is `|php+functionVar:///f/a`.

$$\frac{E \qquad E \text{ instanceof variable}}{[\![E_{definition}]\!] = [\![E_{loction}]\!]}$$

Code sample:

```
function f() {
  $a = 1;   // [|php+functionVar:///f/a|] = [|file:///file.php|(17,2,<2,0>,<2,0>))]
  $a = "s"; // [|php+functionVar:///f/a|] = [|file:///file.php|(27,2,<3,0>,<3,0>]
}
```

Listing 4.29: Variables

Return types The type of a function or method is defined by the return statements it contains. When there are no return statements declared in a function or method (i), we can extract the constraint that the function will always return `nullType`. The type of a function is also `nullType` when there is a return statement without an expression (ii), like `return;`. When there are multiple return statements, the return type of the function or method is the concatenation of the types of the expressions (iii).

$$\frac{\text{E } \texttt{instanceof} \text{ return} \not\subseteq f}{[\![f]\!] = \mathit{nullType}()}\ \text{(i)} \qquad \frac{\texttt{instanceof} \text{ return E} \subseteq \text{f} \qquad \text{E } \texttt{instanceof} \text{ noExpr}}{[\![f]\!] = \mathit{nullType}()}\ \text{(ii)}$$

$$\frac{(\text{return } E_1) \vee \cdots \vee (\text{return } E_k) \subseteq f \qquad E_{1\ldots k} \texttt{ instanceof} \text{ someExpr}}{[\![f]\!] <: [\![E_1]\!] \vee \cdots \vee [\![E_k]\!]}\ \text{(iii)}$$

Code sample:

```
function f() {}           // [f] = nullType()
function f() { return; } // [f] = nullType()

function f() {             // [f] = [$a] or [$b]
  return mt_rand(0,1) ? $a : $b;
}
```

Listing 4.30: Return types

Chapter 5

Implementation of PHP type inference

The type inference is executed in 3 main steps. The first step creates an M^3 model for a PHP program which contains various facts about the program. The creation of an M^3 for PHP is explained in more details in section 5.1. Once the M^3 model is constructed, the second step is to extract constraints from the program using the M^3 model. In the third step, in section 5.3, the constraints are solved and resolve the types of variables used in the program. The final section 5.4 of this chapter explains how annotations can be included in the process to gain more precise results.

5.1 M^3 for PHP

As explained in section 2.3, M^3 is a language independent meta model which holds facts about programs. The model can be extended with language specific elements and will be used to query the system for facts about the system. An overview how an M^3 for PHP is build is shown in figure 5.1. Independent M^3 models are build each PHP file in the program.

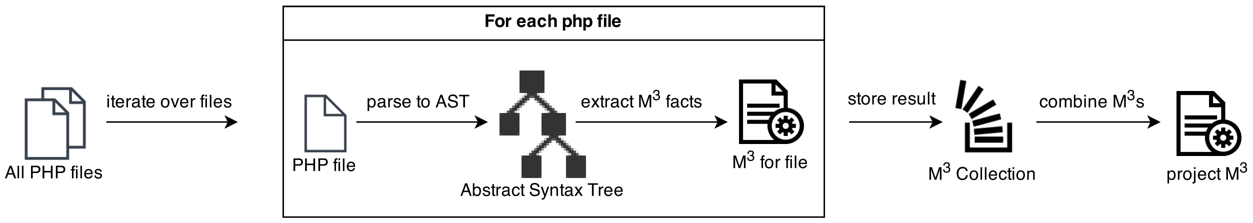


Figure 5.1: M^3 Creation

All these individual M^3's are in the end combined to collect all the facts about a program. This results in one M^3 for the whole program. M^3's are first created for each file is because it is not defined what the dependencies of a individual file are. There is no main file, and all files can load each other. In this research we assume that all files in a program are loaded when needed using autoloaders or manual includes.

5.1.1 Core elements

The M^3 model has the following core elements: `declarations`, `containment`, `modifiers`, `uses`, `names`, and `documentation`. The rascal code is displayed in Rascal 2. The characteristics of the elements are described in the paragraphs below.

Declarations `Declarations` defines the declarations of namespaces, classes, interfaces, traits, methods, functions, and variables and holds the relation between the logical name (which is used to refer to the declaration) and the actual file location (which is the physical place in the file system. For example the

Rascal 2 M^3 core definitions in Rascal

```
anno rel[loc name, loc src] M3@declarations; // maps declarations to file location.
anno rel[loc from, loc to] M3@containment; // what is logically contained in what else
anno rel[loc definition, Modifier modifier] M3@modifiers; // associated modifiers
anno rel[loc src, loc name] M3@uses; // maps src locations of usages to the declarations
anno rel[str simpleName, loc qualifiedName] M3@names; // end-user readable names
anno rel[loc definition, loc comments] M3@documentation; // comments and doc-blocks
```

logical name of a class can be |`php+class://SomeNameSpace/ClassX`| while the actual location might be |`file:///project/SomeNameSpace/ClassX.php`|.

Containment `Containment` holds information about what elements logically contain other elements. For example, a property or method is contained in a class and a class is contained in a package. When a function is declared in another function, they are both logically contained in the global namespace (the highest level) because all functions are declared as first class citizens in PHP.

Modifiers `Modifiers` element contains information about the modifiers of classes, fields, and methods. Classes can only be `abstract`, fields can be `public`, `private`, or `protected`, and methods can be all of them. Abstract methods can only be declared in abstract classes. Classes are implicitly public.

Uses `Uses` relation holds information about the usages of certain elements. It is the relation between the usage and the declaration. For example when you instantiate a class, in that case you 'use' that specific class.

Names `Names` contains the declaration and a simplified version of the name. The declared name can be long and unreadable. `names` contains human readable name which can be used for presenting the element in a GUI.

Documentation `Documentation` contains the link to the documentation related to the source code element. The link is mapped to a declaration.

5.1.2 PHP specific elements

Because every programming language differs in syntax and semantics, the M^3 model is extensible to provide language specific elements. The following php specific items are added: `extends`, `implements`, `traitUses`, `parameters`, `constructors`, `aliases`, and `annotations`. These PHP specific elements are described in more detail in the paragraphs below.

Rascal 3 PHP specific M^3 element

```
anno rel[loc from, loc to] M3@extends;    // which class extends which class
anno rel[loc from, loc to] M3@implements; // interface usages
anno rel[loc from, loc to] M3@traitUses;  // trait usages
anno rel[loc decl, PhpParams params] M3@parameters; // formal functions/methods parameters
anno rel[loc decl, loc to] M3@constructors; // constructor usages
anno rel[loc from, loc to] M3@aliases;      // class name aliases (new name -> old name)
anno rel[loc pos, Annotation annotation] M3@annotations; // annotations from doc blocks
```

Extends `Extends` contains information about what classes and interface extend other classes or interfaces. Please note that we do not hold information about which class implements which interface, because that information is contained in the `implements` relation. Interface extensions work just like class extensions.

Implements `Implements` holds information on which class implements which interfaces. One class can implement no, one, or multiple interfaces. Because the information is a relation between the class and the interface, we can easily add multiple interfaces to one class in the model.

TraitUses `TraitUses` lists which traits are used by which class or trait. A traits is a collection of reusable functions, defined in the namespace scope. One class can have multiple trait usages. All the methods of a trait are on runtime imported in the class.

Parameters `Parameters` keeps track of the parameters of a method or function. `PhpParams` is a list relation and contains the optional typehint, if the parameter is required and if it is passed as reference. This information is stored to make it easier to resolve the call to a method or function.

Constructors `Constructors` lists the constructors for classes. This information is needed because it is not always clear what constructor is used, due to legacy PHP4 way of using class constructors. In PHP4 the constructor was defined as a method with the same name as the class. Since PHP5 the language is provided with a magic method `__construct()`, which results in two ways to have constructors, but only one constructor will be called. The PHP4 constructors will be removed in PHP7.

Aliases `Aliases` has a relation between aliases and the actual implementation. For instance the function `class_alias` defines a new name for the same class. This relation is also used to keep track of references.

Annotations `Annotations` contain a relation between a declaration and the annotations that are known. Annotations are defined in the raw doc blocks and are parsed using regular expressions (regex). Regex was in this case easier then parsing because there is no official grammar or standard defined. For this research we only use `@param`, `@var`, `@returns`.

5.1.3 The algorithm

In order to get a better understanding of the creation of an M^3 for PHP, the algorithm is provided in Algorithm 1.

Algorithm 1: PHP program to M^3

```
Input: PHP files of a program
Output: $M^3$ for the PHP program
1  m3Collection = [];
2  forall the file $\in$ program do
3      ast = parseUsingPhpParserAndReturnRascalAST(file);
4      m3 = createEmptyM3(ast);
5      m3 = addDeclarations(m3, ast);
6      ast = addScopeInformation(m3, ast);
7      m3 = addContainment(m3, ast);
8      m3 = addExtendsAndImplements(m3, ast);
9      m3 = addModifiers(m3, ast);
10     m3 = addRawDocBlocksAndAnnotations(m3, ast);
11     m3 = calculateUsesFlowInsensitive(m3, ast);
12     m3Collection += m3;
13 end
14 return projectM3 = composePhpM3(m3Collection);
```

The input of the algorithm is all `PHP files of a program`, which are all files ending on `.php` within a program. **The output** is an M^3-model with facts about the provided program. The algorithm starts with initialising an empty M^3 collection in line 1 which with be filled with the result of each individual files. In the big loop on line 2 to 13 we iterate over all the PHP files of the program. The first thing that needs to be done is to create an Abstract Syntax Tree (AST) of the program using an external PHP parser[1] which returns an Rascal AST in `parseUsingPhpParserAndReturnRascalAST` on line 3. From this AST we create an empty M^3 in `createEmptyM3` on line 4. In order to be able to refer to any source code element, we need to have the declarations of the elements. These elements are extracted in `addDeclarations` on line 5 can be `namespace`, `class`, `interface`, `trait`, `method`, `function`, `variable`, `field`, or `constant`. For all `functions` we need to add scope information in case functions are declared inside another function or method. In line 6 we add the scope information to all nodes to the AST by visiting the AST. This is needed in order to extract the right facts about the logical containment which is done in line 7. The next three lines (8-10) extract facts about class inheritance and the interface implementations, modifiers, PHP doc blocks, and annotations. Once all the basic information is collected, `calculateUsesFlowInsensitive` on line 11 tries to find the declarations of the used objects, methods, functions and variables. This is flow and context insensitive and only tries to resolve non-dynamic language constructs. The last step of the iterator is to add the constructed M^3 to the M^3 collection. Finally when an M^3 is constructed for all files, all facts of the individual M^3's are merged into one M^3 model in line 14.

5.1.4 Rascal implementation

The constraints are implemented in Rascal with the `TypeOf` and `Constraint` definitions, which are shown in Rascal 4.

The `TypeOf` definition represents a literal type or the type of an expression. To define a literal type, we use the `typeSymbol` which takes a `TypeSymbol` as argument. TypeSymbols are defined in Rascal 1. We use the `typeOf` definition, which takes a Rascal location (loc) as argument, when we define the type of an expression or statement. The location represents the physical location of the expression in the source code.

The `Constraint` definition consists of recursive and non-recursive definitions. `eq` states that the type of the left hand side should be equal to the type of the right hand side. `subtyp` states that the type of the left hand side should be a sub type of the right hand size. This sub type relation is self inclusive, which means that the type can also be the same. `supertyp` is the opposite of `subtyp`, and so the type of the left hand side should be a super type of the right hand size and cannot be the same type. `isMethodOfClass` takes as arguments an two expressions and a string. The two expressions represent the possible types for the left and right hand side of the expression. The string contains the name of the called method.

The recursive definitions allow support for negation, conjunction, disjunction. The `negation` is added to make it easy invert complex constraints, for example when you can say that the type of an expression can be anything but a string. `conjunction` and `disjunction` are used for `and` and `or` relations.

[1]https://github.com/ruudvanderweijde/PHP-Parser

Rascal 4 TypeOf and Constraint definitions

```
data TypeOf
    = typeSymbol(TypeSymbol ts)
    | typeOf(loc ident)
    ;

data Constraint
    = eq(TypeOf lhs, TypeOf rhs)
    | subtyp(TypeOf lhs, TypeOf rhs)
    | supertyp(TypeOf lhs, TypeOf rhs)
    | isMethodOfClass(TypeOf expr, TypeOf classVariable, str name)

    | disjunction(set[Constraint] constraints)
    | conjunction(set[Constraint] constraints)
    | negation(Constraint constraint)
    ;
```

5.2 Constraint extraction

In section 4.1 we've defined the constraint extraction rules. These constraint rules are implemented in Rascal with the help of visiting[2] and pattern matching[3]. Visiting is a concept implemented in the core of Rascal and is based on the visitor design pattern. This makes it very easy to traverse trees like AST's, without coupling the design pattern to your code. During the visiting of the AST we use pattern matching on function arguments to find to correct functions to handle the constraint extraction.

5.2.1 Code snippet

A snippet of the constraint extraction implementation[4] is shown in Rascal 5. In this snippet we show a small subset of the code used in the constraint extraction process.

The code starts with a local declaration of `constraints`, an empty set. This set of constraints will be filled in the rest of the functions on this Rascal module.

You can get all the constraints of a program by calling the only public function `getConstraints` with a `System` and `M3` as parameters. `System` represents a collection of all AST's of a program. The provided `M3` is the M^3-model of the whole program, containing facts about the program. In this function we loop over all `Scripts` of a system and call `addConstraints` for each script.

Using argument pattern matching the function `addConstraints(Script script, M3 m3)` is triggered. The first thing this function executes is `addConstraintsOnAllVarsForScript`, where we add the constraints that the types of a variable should be of one type within a scope. Next we loop over all the statements of the body of a `script`.

Because of pattern matching, the function `private void addConstraints(Stmt statement, M3 m3)` will be called for each statement. In this function we execute a *top-down-break visit*. *Top-down* means that the visit will start at the root node and then moves down towards the leaves. *Break* means that the in dept visit will stop as soon as there is a pattern match. We need to include *break* in this visit because for some nodes we need context. For example if a variable names `$this` would match, we need to know in which class this item was declared. In the code snippet we've only included `exprstmt`, a match with a PHP expression.

The last function of the snippet, `private void addConstraints(Expr e, M3 m3)`, handles expressions like assign with operator, a string scalar, and PHP variables that has a name. With this small code snippet we can show the constraint extraction with a tiny example.

[2]http://tutor.rascal-mpl.org/Rascal/Concepts/Visiting/Visiting.html
[3]http://tutor.rascal-mpl.org/Rascal/Concepts/PatternMatching/PatternMatching.html
[4]The complete source code can be found in https://github.com/ruudvanderweijde/php-analysis

Tiny example With this part of the code, we could extract constraints for the file with the content: `<?php $a += '1';`. When we extract the constraints from this file we would come to the following constraints:

- the type of `$a` is a subtype of `numberType()`
- the type of `$a` is a subtype of `any()`
- the type of `'1'` is equal to `stringType()`

See section 4.1 to see the full list of constraints that we extract from the source. The full implementation can be found on github.

Rascal 5 Constraint extraction snippet

```
private set[Constraint] constraints = {};

public set[Constraint] getConstraints(System system, M3 m3) {
  for (s <- system)
    addConstraints(system[s], m3);
  return constraints;
}

private void addConstraints(Script script, M3 m3) {
  addConstraintsOnAllVarsForScript(script, m3);
  for (stmt <- script.body)
    addConstraints(stmt, m3);
}

private void addConstraints(Stmt statement, M3 m3) {
  top-down-break visit (statement)
    case exprstmt(Expr expr):  addConstraints(expr, m3);
}

private void addConstraints(Expr e, M3 m3) {
  top-down-break visit (e) {
    case a:assignWOp(Expr assignTo, Expr assignExpr, Op operation):  {
      addConstraints(assignTo, m3);
      addConstraints(assignExpr, m3);

      switch(operation)
        case plus():  constraints += {subtyp(typeOf(assignTo@at), numberType())};
    }
    case v:var(name(name(name))):
      constraints += {subtyp(typeOf(v@at), \any())});

    case s:scalar(Scalar scalarVal):
      switch(scalarVal)
        case string(_):  constraints += {eq(typeOf(s@at), stringType())};
  }
}
```

5.3 Constraint solving

When all constraints are extracted from the source code, we will solve the constraints until we can no longer solve any constraints. The result will be a list of possible types for each class, method, fields, functions, variable and expression.
The first step is to initialise all type-able objects. In this initial phase the types of each object is of type any, except for the literal types which can be resolved already. When we solve the constraints step by step, we will be able to limit the number of possible types for a certain object. We do this by taking the intersection of the constraint result and the possible types we have. This way there should be less and less possible types for each variable.
When we take the intersection of none overlapping types, we have a type error. There is no possible type for this object, resulting in an empty set of possible types.

5.3.1 The algorithm

In algorithm 2 we show the algorithm to solve the constraints.

Algorithm 2: Constraint solving algorithm

```
Input: set[Constraint] constraints
Output: map[TypeOf expression, set[Type] possibleTypes] solutions
1 map[TypeOf, set[Type]] solutions = init(constraints);
2 while changes in constraints or solutions do
3     constraints = constraints + deriveMore(constraints, solutions);
4     solutions = propagateSolutions(constraints, solutions);
5 end
6 return solutions;
```

The algorithm input is a set of constraints and the output is a map of solutions. The set of constraints are the constraints defined in constraint extracting section, and the map of results is the location of all type-able objects with their possible solutions. The init function on line 1 adds all type-able objects to the set of possible solutions. The initial possible types of the objects will be the collection of all possible types, called $Universe()$. Only the literal types can be resolved already, like strings, numbers and boolean constants.
Line starts a loop until a fixed point is reached. In Rascal this method is called `Solve()` and will loop until there are no more changes in the given data. The methods of line 3-4 may alter the values of constraints or solutions.
The first function of the loop on line 3, `deiveMore`, visits all constraints and checks if there can be new constraints extracted based on the latest constraints and solutions. Example of these new constraints are conditional constraints, which could only be added if more information of the conditional was available.
Function `propagateSolutions` on line 4 propagates resolved estimates. Here we take the intersection of the known solutions with the given constraints.

5.4 Annotations

After we gathers all the facts from the source code, we will add additional information which we read from the annotations. For this we use a regular expression to match `@return type` and `@param type var` for methods and functions. We read `@var type` for variables and class attributes. In our first analysis we do not include the facts we gathered from the annotations. In the second analysis we do include the facts. This way we can compare the end results.

```php
<?php

class NumberValidator
{
    /** @var int */
    private $number;

    /** @var string */
    private $message;

    /** @return int */
    public function getNumber() { return $this->number; }

    /** @return string */
    public function getMessage() { return $this->message; }
}
```

Listing 5.1: Motivating example of annotations

In listing 5.1 we show a motivating example for the usage of annotations. The types of the methods `getNumber` and `getMessage` can be guessed by a human, but for static analysis we actually need to know how these values are used to know what type they are. Annotations can help analysis tools to discover the types of these methods. In the case where the type is less likely to be guessed by humans, the annotation can help the developers to see the types.

Chapter 6

Evaluation

In this chapter we evaluate the steps we took in this research. We first describe the setup of the experiment in section 6.1. Next we present the results in section 6.2. In section 6.3 we analyse the measured results. We end this chapter with the threats to validity in section ??.

6.1 Experiment setup

In order to validate the this research we have tested the type inference on a selection of the 30 most popular packages of Packagist[1]. Due to performance reasons we are only able to analyse the smaller projects. Packagist is a repository for Composer[2]projects. Composer is a dependency manager for PHP projects. All projects have between 2 and 6 million downloads, so they should be representative for our research because they are frequently used in live applications. The selection of projects, sorted on total lines of code, is listed in table 6.1. The statistics are generated using phploc[3].

Product			Files		Objects			Lines of code		
Vendor	Project*	Version	D[1]	F[2]	C[3]	I[4]	T[5]	Total ↑	Logical	
doctrine	lexer	v1.0	2	7	3	0	0	733	128	(17.46%)
phpunit	php-timer	1.0.5	5	11	5	0	0	740	117	(15.81%)
phpunit	php-text-template	1.2.2	5	11	5	0	0	768	125	(16.28%)
doctrine	inflector	v1.0	2	7	3	0	0	853	130	(15.24%)
psr-fig	log	1.0.0	3	15	8	2	2	1 039	155	(14.92%)
phpunit	php-file-iterator	1.3.4	5	13	7	0	0	1 071	176	(16.43%)

*Selection of the 30 most popular packagist packages ordered by LOC, in July 2014.
[1] = Directories, [2] = Files, [3] = Classes, [4] = Interfaces, [5] = Traits

Table 6.1: Statictics of most populair composer projects

Type inference In this research we are interested in resolving types for expressions. As explained in section 5.3, the result of the constraint solving is a set of types for each expression. We group these results in two groups, resolved and unresolved types. Resolved type means that we can deduce the resultset to one type. All other types are unresolved. In unresolved we add empty typesets (type errors) and multiple types that cannot be reduced to one unique type for an expression.

Annotations We will first run the type inference without reading annotations from PHPDocs. As described in section 5.4

Built-ins After running the analysis with PHPDocs

Compare results

[1]https://packagist.org/explore/popular, July 2014
[2]https://getcomposer.org/, July 2014
[3]https://github.com/sebastianbergmann/phploc, July 2014

6.2 Results

Introduce the result section, explain what we see here.

		Unresolved types			Resolved types		
Project	Total	w/o	w/	Δ	w/o	w/	Δ
lexer	460	33.7%	21.7%	(-71.2%)	66.3%	78.3%	(30.7%)
php-timer	43	95.7%	58.2%	(-78.4%)	4.3%	41.9%	(179.5%)
php-text-template	52	87.6%	63.4%	(-55.3%)	12.5%	36.5%	(131.5%)
inflector	195	25.7%	21.0%	(-36.6%)	74.3%	79.0%	(11.9%)
log	103	86.2%	59.3%	(-62.4%)	13.8%	40.8%	(132.4%)
php-file-iterator	92	86.3%	69.6%	(-38.7%)	13.6%	30.4%	(110.5%)

Table 6.2: Results of type usage, with and without reading annotation from docblocks

		Unresolved types			Resolved types		
Project	Total	w/o	w/	Δ	w/o	w/	Δ
lexer	460	21.7%	28.2%	(46.1%)	78.3%	71.9%	(-16.3%)
php-timer	81	58.2%	23.5%	(-119.2%)	41.9%	76.5%	(90.5%)
php-text-template	90	63.4%	30.0%	(-105.4%)	36.5%	70.0%	(95.7%)
inflector	195	21.0%	23.5%	(21.3%)	79.0%	76.5%	(-6.3%)
log	141	59.3%	39.0%	(-68.5%)	40.8%	61.0%	(66.2%)
php-file-iterator	130	69.6%	45.4%	(-69.5%)	30.4%	54.6%	(88.6%)

Table 6.3: Results of type usage, with and without analysing php built-ins

6.3 Analysis

Analyse: hoe verklaar je wat we zien in de tabellen en klopt het met de theorie?

Chapter 7

Conclusion

Summary of the whole work, with conclusions. T.B.A.

7.1 Conclusion

7.2 Future work

These items will not be covered by the analysis (maybe add this to threats/future work)

- Analysis is flow insensitive
- Closure
- References
- Variable constructs (variable -variable, -method/function calls, -class instantiation, eval) :: todo: explain WHY not.
- Yields

Explain something about combining this analysis to other analysis (like dead code elimination, constant folding/propagation resolve, alias analysis, array analysis) to gain more precise results.

Something about performance optimisations... Explain what is already done to boost the performance and what still can be done.

Use a bigger corpus to gains better results of the analysis by doing analysis on more programs.

7.3 Threats to validity

Because we perform an over approximation of run time values at compile time, the results of this research are not 100% accurate. Although we strive to be as accurate as possible, we cannot guarantee the correctness of the results.

Law of small numbers Because our sample size is small, we cannot generalise these results. In order to gain general conclusions we should increase our sample size. We can achieve this by running analysis on more software projects.

Object references One thing we do not take into account are the side effects that can be caused by the passing arguments as reference. When an referenced argument is modified, the referenced variable is also modified. This could theoretically lead to type changes.

PHPDoc correctness In this research we also assume that the provided type annotations in the PHPDoc's are correct. These annotations are ignored during program execution and therefore could be incorrect without noticing.

Glossary

AST

An abstract representation of the structure of the source code. .

PSR

PHP Standard Recommendation (PSR) is project which provides rules for commonalities between PHP projects. Autoloading, coding style guide, logging, and HTTP Message interface are the first few accepted standards. The PHPDoc standard describes how and what to use in doc blocks and is currently in draft phase. See http://www.php-fig.org/ for more information. .

Rascal

Rascal is a meta-programming language developed by SWAT (Software analyse and transformation) team at CWI in the Netherlands. See http://www.rascal-mpl.org/ for more information.

reflexive transitive closure

A relation is transitive if $\langle a, b\rangle \in R$ then $\langle b, a\rangle \in R$.
A relation is reflexive if $\langle a, b\rangle \in R$ and $\langle b, c\rangle \in R$ then $\langle a, c\rangle \in R$.
A reflexive transitive closure can be established by creating direct paths for all indirect paths and adding self references, until a fixed point is reached.

stdClass

A predefined class in the PHP library. The class is the root of the class hierarchy. It is comparable to the Object class in Java.

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