TAPAs: Type Analysis for PHP Arrays

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Master's Thesis, Computer Science
June 2015
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Abstract

The PHP array data-structure has very few limits. Due to the many possibilities, array usage can obscure the intention of code, thereby making it difficult to maintain. Keeping precision about data in arrays is difficult and resource consuming. By utilizing usage patterns identified in a dynamic analysis, this thesis develops a light-weight array data abstraction for use in a classic static interprocedural data-flow analysis for a defined subset of the PHP language. The analysis is evaluated with case studies of small programs inspired by flaws found in the corpus applications. We expect the feedback provided by the analysis to enable the user to write code with a clearer intention and thus a higher maintainability.

Acknowledgements

Foremost, we want to express our gratitude to our advisor Associate Professor Anders Møller, who has provided invaluable feedback and guidance throughout our work with this thesis. Our gratitude goes towards our respective partners as well, for putting up with endless talk about the infinite stupidity possible within the language of PHP. Thanks also for being supportive in general and dragging us away from thesis work for a much needed break in the late evenings with the promise of a well-prepared meal. Thanks to the students and staff of the Programming Languages research group for providing a friendly environment and refreshing hallway talks. Lastly, we want to thank the family and friends, who worked their way through the heavy amounts of spelling mistakes, missing commas, and weird phrasing, bound to happen in a project of this scale. Without all these supportive people around us, this thesis would never have happened.

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Aarhus, June 14, 2015.

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Chapter 1

Introduction

PHP is one of the most popular languages for server-side web-development. It is powering over 80% of the web[B41], including major websites, such as Wikipedia and Facebook, and the most used content management systems: Wordpress, Joomla, Drupal, and Magento. It requires no compilation and is dynamically typed, which makes development and deployment easy.

As with other dynamically typed languages, static type reasoning is non-trivial. This task is only worsened by allowing variable-variables, variable-functions and the all-purpose array datastructure. PHP supports associative arrays with integer and/or string-typed indices (referred to as keys) mapping to values of arbitrary type, including arrays. Combined with the dynamic type system, extensive coercion, and optional error-reporting, debugging becomes difficult and time consuming. Furthermore, no official language specification exists and the language is thus defined by the reference Zend Engine interpreter.

This thesis will focus on a static type analysis of arrays. Reasoning about the structure of an array with a decent level of precision seems like an impossible task, since practically no structure is imposed on arrays. But is the imagination of the average PHP developer in practice limited? Are arrays used as other data-structures, such as maps and lists, and can these structures be identified statically? If this is the case, then these structures might be the key to an abstraction yielding a fair compromise between speed and precision for a static type analysis.

By analysing a corpus of existing frameworks dynamically, this thesis aims to identify use-patterns of arrays as other, more restrictive, data-structures. The results of the dynamic analysis are going to motivate the data-abstraction in a *static interprocedural data-flow type analysis* on a subset of the PHP language. The static analysis should serve as a tool in a development environment, facilitating error detection by identifying suspicious code.

The following example, found in the Part framework (a CMS written by one of the authors), illustrates suspicious usage of arrays. Here the `$keyArray` and `$valueArray` arrays are first used as maps in lines 4 and 5, while later, at line 9 and 10 being used as lists, with the *array append* operation. The intention of this kind of usage is unclear and not very maintainable, but since it ultimately results in the correct behavior, and yields no errors, it is not easily discovered.

The analysis should facilitate discovery of such suspicious cases by providing feedback to the user in the development environment. By bringing the user's attention to suspicious cases while developing it is possible to further the clear intention of the code thereby creating more maintainable code.

Program 1.1 Mixing array types

```
private function createInstance($string, $instance,
    callable $callback)
{
    if (!isset($this->keyArray[$string])) {
        $this->keyArray[$string] = [];
        $this->valueArray[$string] = [];
    } else if(($k = array_search($instance, $this->
    keyArray, true)) !== false){
        return $this->valueArray[$k];
    }
    $this->keyArray[] = $instance;
    return $this->valueArray[] = $callback();
}
```

1.1 Problem statement

The widely used array data structure in PHP has very few restrictions, making it difficult to reason about with program analysis. This thesis will identify possible use-patterns for arrays in PHP and how to detect them using a static analysis. An *interprocedural data-flow type-analysis* is proposed to detect suspicious cross-use of the identified patterns, and consequently evaluated on live code.

1.2 Motivation

Creating code that seemingly works is one thing, and for languages like PHP that can be done in many different ways. However creating code that conveys a clear purpose and is easily maintainable later on is a whole other world. The latter is preferable most of the time. Due to the range of possible uses of PHP arrays being very large, they are not conveying a clear purpose in and of themselves. Creators of PHP programs thus have to ensure the clarity of their use of arrays themselves.

We hypothesize that arrays are subject to a specific use-pattern during their lifetime. If the hypothesis holds, a statical analysis can be employed to detect and thereby prevent cross-use of the patterns, which in turn will lead to a more clear intention of the code and in the end higher maintainability of the program code.

Introducing feedback from the analysis directly in the integrated development environment used in daily work ensures a small overhead for the benefits gained by using feedback to develop better programs.

1.3 Structure of this thesis

Chapter 2 provides the necessary background knowledge of the PHP language and modern PHP program structure to understand, why arrays are difficult to apply existing methods to. In chapter 3, a dynamic analysis is conducted on a corpus of real PHP applications, to identify use-patterns and test the hypothesis about use-patterns of arrays. In chapter 4, use-patterns and knowledge gained in the previous chapter is utilized to define and implement a static analysis of a subset of PHP, focusing on detecting suspicious use of arrays. The static analysis implementation is evaluated in chapter 5 by studying interesting cases found in or inspired by the corpus used in the dynamic analysis. Related work is discussed in chapter 6. The last two chapters, 7 and 8, conclude our thesis and describe possible future work.

Chapter 2

Background

PHP (PHP: Hypertext Preprocessor) was created by Rasmus Lerdorf in 1995. As one of the first dedicated web development server-side languages it has become widely popular over the past 20 years. A survey[B41] shows that 82% of websites use PHP, including some major websites, such as Facebook, which consequently has created their own gradually typed dialect of the language, called Hack, and HHVM (Hip Hop Virtual Machine), in order to deal with scalability and an enormous code base. The apparent simplicity, availability of the language, and cheap hosting solutions, also enables creation of small websites relatively fast, requiring no knowledge of types, concurrency, or objects from the programmer. It is no wonder why PHP, as it is the case for many other programmers, was the first programming language learned by the authors of this thesis.

2.1 Program structure

With the introduction of an object model with PHP 5 in 2005 followed a trend to organize PHP programs in an object oriented manner.

For better organization of code, in 2009, namespaces were introduced (PHP 5.3) and the PHP Framework Interoperability Group[B25], which aims to formulate standards on different concepts in PHP, was created. Utilizing these tools and standards, many modern frameworks are managing dependencies to other frameworks and libraries through package managers such as Composer [B36]. Normally these dependencies are hosted open-source on GitHub, made available for Composer on Packagist [B39]. Composer also handles auto-loading of classes, which in practice removes the task of manually loading PHP files using the `include "file.php";` or `require "file.php";` statement.

The `include` and `require` statements allow dynamical loading of dependencies, by taking an expression as input. Resolving these statically is potentially difficult, however with auto-loading and a proper program structure (as advocated by PHP-FIG), resolving dependencies statically becomes trivial.

With increasing complexity follows a need for quality assurance and testing. PHPUnit is a framework, written in PHP and available via Composer, that facilitates unit-testing. This framework is widely used and e.g. supports testing with databases and browser output through Selenium (browser-automation) integration. PHPUnit is also used for generating coverage information for code-analysers, such as Code Climate, and is natively supported, as a metric of quality, by continuous integration tools, such as Travis continuous integration[B23].

Travis CI is an online service, which is free for open-source projects just as GitHub and Code Climate. It observes GitHub repositories and runs an advanced check on every new committed version, emulating multiple different deployment environments with respect to operating system, PHP interpreter version, web-server and more. Emulating different environments locally can be done using Vagrant, which promises to lower development environment setup time by automating the process, making it possible for developers to develop for a production environment.

2.2 Language features

PHP is an ever-changing language, with a new syntax and language features being introduced in every version. It includes features such as objects, introduced and modified throughout PHP 5, anonymous functions, introduced in PHP 5.3, variadic functions, introduced in PHP 5.6, etc. Furthermore PHP supports a large number of alias features, i.e. features which are semantically the same but have different syntax, e.g. array initialization can be written as `array(···)` or `[···]`, array access can be denoted with brackets (`$a['key']`) or curly-brackets (`$a{'key'}`), etc. In the rest of this section follows the description of some of the language features that have proven interesting when designing our analysis.

2.2.1 Arrays in PHP

The language construct `array` in PHP is an ordered map. Since *keys* of these ordered maps can be either integer, string or a combination, and *values* can be any combination of types, it is possible to use arrays as many different collection-types e.g. maps, lists, queues, stacks, trees, dictionaries and probably any other collection-like type that exists.

An array can be multidimensional, by containing other arrays, or circular, by containing a reference to itself. They do not need to be initialized explicitly, but can be created by performing an array write operation, e.g. `$a['foo'] = 42`, or an append operation, e.g. `$a[] = 42`, on an uninitialized variable or a variable containing `null`.

2.2.2 Scoping

The variable scoping of PHP is rather simple; there is a unique global variable scope, which is the scope of the statements not part of a function body, a static variable scope for each function, holding static variables, and a scope for each function invocation. Variables declared in a scope generally are not directly accessible in other scopes. For example, in order to access a variable defined in the global scope from the scope of a function body, the `global` statement can be used to create a local alias variable pointing to the global variable. Similarly the static scope can be accessed by using a `static` statement. All blocks that are not function bodies share the scope of their parent block.

The only variables directly accessible in both function and global scope, are the *superglobals*. They are variables containing arrays, including `$_POST`, `$_GET`, `$_REQUEST` and `$_COOKIE` for fetching data from HTTP POST requests, HTTP GET requests, both of the former, and cookies respectively, `$_SERVER` and `$_ENV` for accessing server settings and environment variables, and a few others. Program 2.1 shows an example of using superglobals.

Program 2.1 Global variables used in function scope

```php
session_start();
$username = "";

function setUser($ID, $name) {
    global $username;
    $_SESSION["ID"] = $ID;
    $username = $name;
}

setUser(1, "Admin");

echo "Hello $username $_SESSION['ID']";
// Result: Hello Admin 1
```

While the previous superglobals were defined by external conditions, such as requests or server settings, the variable `$GLOBALS` is an array modelling the global scope. Reading, modifying, and adding entries in this array are equivalent to reading, modifying, and initializing variables in the global scope, and thus can be used to access global variables in function scope without using the `global` keyword.

2.2.3 Almost-deep-copy and references

Many languages have a notion of pointers and provides the ability for a variable to be a pointer to some value. In PHP the concept of references can easily be confused with pointers, however references are not pointers. Names of variables and their content are treated as different things in PHP, meaning that variable names are in fact just names for a specific content. Making a reference in PHP corresponds to giving the same content an additional name. Assigning a variable which is already a reference as a reference of another variable will remove the binding of the original content and bind the variable to the new content. The PHP concept of references also means that it is not possible to change a reference by another reference as shown in program 2.2.

Knowing how PHP handles names and content as two different concepts, assignment can be seen as copying the content and assigning this new content a name. In practice, a copy-on-write strategy is employed which increases performance and decreases memory usage compared with a naive copy-on-assign strategy. In program 2.3 after line 3 both `$a`, `$b`, and `$c` point to the same array. After evaluating line 4 the array is copied, updated and `$b` now points

Program 2.2 Overwriting references

```php
$hello = "world";
$hello2 = "stupid";

function change(&$input) {
    $input = &$GLOBALS["hello2"];
    $input = "awesome";
}

change($hello);
// Result: $hello2 = "awesome" and $hello remains
    unchanged
```

to the new array. Meanwhile `$a` and `$c` are still pointing to the same array since none of them have changed from the original array. In the example only two copies of the array are ever stored, whereas a blind copy-on-assign strategy would have stored three copies, of which two would never differ.

Program 2.3 Copy-on-write strategy

```php
$a = [1,2,3];
$b = $a;
$c = $b;
$b[1] = 5;
echo $a[1] . ", " . $b[1] . ", " . $c[1];
// Result: 2, 5, 2
```

As an alternative, PHP offers an explicit way to assign and pass function parameters by reference. Using the &-operator, multiple variables can reference the same value, as shown in program 2.4

Program 2.4 Aliasing

```php
function byvalFunc($input) {
    $input["hello"] = "PHP";
}

function byrefFunc(&$input) {
    $input["hello"] = "PHP";
}

$greet = ["hello" => "world"];
byvalFunc($greet);
echo $greet["hello"]; // Result: world
byrefFunc($greet);
echo $greet["hello"]; // Result: PHP
```

PHP arrays are treated as ordinary values and are thus copied like other values when assigning variables. The copy is deep, in the way that the inner-arrays of multidimensional arrays will be copied as well. There is, however, one exception to the deep-copy of arrays, namely that array entries which are references are referencing the same content even after copying. This effect can be seen in program 2.5.

Program 2.5 Keeping references in arrays

```
$a = [1,2,3];
$c = &$a[0];
$b = $a;
$c = 5; // Result: $a = [5,2,3]; $b = [5,2,3]; $c = 5;
$b[0] = 6; // Result: $a = [6,2,3]; $b = [6,2,3]; $c =
    6;
$a[0] = 7; // Result: $a = [7,2,3]; $b = [7,2,3]; $c =
    7;
$b[1] = 8; // Result: $a = [7,2,3]; $b = [7,8,3];
```

Chapter 3

Dynamic Analysis

The PHP array data structure allows for many different kinds of uses ranging from lists over maps to trees and tables. The purpose of the dynamic analysis in this chapter is to detect patterns of array-usage in order to be able to identify some more restrictive data types contained within the way PHP arrays are used. The results of the analysis are used to choose a suitable abstraction for the static analysis in chapter 4. The first section of this chapter describes basic definitions used in the dynamic analysis to detect patterns. With the definitions in place a hypothesis for the analysis is formed in section 3.1 followed by a discussion of implementation details in section 3.2. Section 3.3 presents the results of the dynamic analysis and section 3.4 draws the conclusion of the analysis.

Definition 1. Let a be an array of size n containing values of the same type, where all integer keys from 0 to $n-1$ exists. Then a can be considered an array of type list.

An example of an array used as a list can be seen in program 3.1, where an element is appended to the list and shifted off the beginning of the list. The values of the `$numbers` array all share the same type (integers) and the keys, though never directly manipulated, range at initialization from 0 to 2. The following operations all preserve the type consensus of the values and the type of the keys.

Program 3.1 Array used as a list

```
$numbers = [1,2,3];
$numbers[] = 4; // $numbers = [1,2,3,4]
$first = array_shift($numbers); // $numbers = [2,3,4]
```

Besides the `array_shift` function and the array append operation, `$v[]`, the PHP library contains many other library functions for manipulating lists, e.g. `array_push`, `array_pop`, `sort`.

Arrays can also explicitly define keys, which can be either a string or an integer.

Definition 2. Let a be an array of size n containing values of the same type, where some integer key from 0 to $n-1$ does not exist. Then a can be considered an array of type map.

As the name suggests, maps can be used as a mapping from a string/integer to a value. In the dynamic analysis a map with only integer keys is also denoted a sparse list. In program 3.2 the `$text_to_int` array is a mapping from strings containing number names to their corresponding integer representations.

Program 3.2 Array used as a map

```
$text_to_int =
    [
        'one' => 1,
        'two' => 2,
        'three' =>  3
    ];
echo $text_to_int[$input];
$keys = array_keys($text_to_int);
    // $keys = ["one", "two", "three"]
$values = array_values($text_to_int);
    // $values = [1,2,3]
```

If given an array-map, the values or keys can be fetched using the functions `array_values` or `array_keys` respectively. These functions return an array of the list type.

Finally arrays can be treated as objects, i.e. the entries can be viewed as properties of arbitrary type. These arrays could be replaced by the `stdClass` which mainly is used for its dynamic properties, just like arrays. Some of the built-in arrays of PHP can be considered objects, including the `$_SERVER` array[B29]. This array contains server and execution environment information, which are of different types, e.g. `$_SERVER['argv']` is an array of arguments passed to the interpreter, and `$_SERVER['REQUEST_TIME']` is an integer UNIX timestamp of the start of the request.

Definition 3. Let a be an array containing values of different types. Then a can be considered as an array of type object.

3.1 Hypothesis

We hypothesize that any given array throughout its lifespan from initialization to last usage can be viewed as one and only one of the above mentioned types, i.e. either as a list, a map or an object. It is also expected that the arrays in general are acyclic and that *append*, *push*, *pop*, *shift*, and *unshift* operations are only used on arrays of the list type.

If the hypothesis holds, it should be possible to statically analyse the code to identify these types and detect errors related to misuse of the arrays, e.g. using maps as lists or vice versa. The hypothesis is tested against a corpus consisting of ten widely used open-source frameworks, by performing a dynamic analysis of the code.

The chosen frameworks all implement some kind of test suite written in PHPUnit[B20], a unit testing framework for PHP programs similar to JUnit for Java programs. By running the test suites on a modified PHP interpreter[B26], we are able to log and later analyze the structure and usage of the arrays. By using test suites instead of manually inspecting the frameworks through e.g. a browser, the aim is to gain a higher code coverage. This follows from the assumption, that the developers are using code coverage as a metric for the quality of the test-suite. The corpus consists of the following open source frameworks:

- *WordPress*: A blogging system and a content management system [B42].
- *phpMyAdmin*: An administration panel for managing MySQL databases [B38].
- *MediaWiki*: A framework for creating knowledge base sites like Wikipedia [B35].
- *Joomla*: A content management system [B32].
- *CodeIgniter*: A lightweight framework for building web applications [B24].
- *phpBB*: A forum platform [B37].
- *Symfony 2*: A framework used in many major systems, such as phpBB, Magento and Drupal [B40].
- *Magento 2*: An e-commerce platform [B19].
- *Zend Framework*: A framework for web development focused on simplicity, reusability and performance [B34].
- *Part*: A lightweight content management system developed by one of the authors of this thesis [B22].

3.2 Implementation

This section contains the implementation details of the dynamic analysis. The last part of the section discusses flaws and limitations arisen from the chosen implementation of the analysis. The analysis consists of two phases: *test suite execution* with logging of feature usage, and *analysis* of the data logged. The test suites are executed on a modified version of the official PHP interpreter to enable logging of feature usage.

3.2.1 Logging of feature usage

All usages of array reads, array writes, assignments, array library functions (`array_push()`, `array_pop()`, `array_search()`, `count()`, etc.), and every array initialization are logged while executing the test suites. These are logged in a CSV file where each line is a log entry containing information separated by the tab character. All entries begin with *line type*, which identifies the type of the entry. The possible line types are described in the list below.

- *array function*: Every call to a library array function [B27], such as `count()` or `array_push()` is logged with the function name as line type. The array functions do not include the `array()` used to initialize an array, since it is a language construct and not an actual function. Some subroutines are also logged when dealing with multiple arrays in the same function, e.g. `array_mr_part` used by the `array_merge` function.

- `array_read`: Every read from an array is logged with the array being read from and the key used, as well as the type of the value being read.

- `array_write`: All array writes of the form `$x[$key] = $y` are logged with the array being read from (`$x`) and the key (`$key`).

- `array_append`: When elements are added to the array using the append method, `$x[] = $y`, this is logged with the array being read from, `$x`.

- `assign_*`: Every assignment is logged as either `assign_var`, `assign_tmp`, `assign_const` or `assign_ref` depending on whether the value being assigned is a constant, temporary variable, variable or reference respectively. The assignment `$x = (string) $y` is an example of an assignment from a temporary variable. Here the `$y` variable is cast and saved in a temporary variable which is then assigned to `$x`. One of these lines always follow `array_write` and `array_append` and is used to determine the type of value written in those lines.

- `array_init`: When an array is initialized without the static keyword, using either the `array('key' => 'value')` construct or the corresponding bracket notation, `['key' => 'value']`, it is logged with the array being created. If the array is initialized in any other way, e.g. as a field or by array write, it is not logged with `array_init`.

- `hash_init`: Whenever a hash table, the underlying structure of arrays, is initialized, this is logged with the memory address of the table.

Arrays are logged as a tuple with four entries (t, d, s, a), where $t \in T \times C$ is the type of the array, d is the depth of the array, s is the size of the array, and a is the memory address. Here $T = \{\text{List, Map, Sparse List}\}$ and $C = \{\text{Cyclic, Acyclic}\}$. The array-type logged indicates the type of keys present in the array, see definitions 1 and 2, as well as whether it contains any self-references. Any array with a self-reference is cyclic and all other arrays are acyclic.

Objects are logged with their class name, integers and floats are logged with their value, strings are logged only as `string`, booleans as 0 if `false` otherwise 1, and the null value logged as `NULL`. Strings are generally not logged with a value, because doing so increases the file size drastically, tends to corrupt the file when containing binary data, and has not proven to be useful for the analysis.

All entries besides the `hash_init` entries contain a line number and a file path to where the action occurred.

```
hash_init       0x539
array_init      1       a.php       0       1       0       0x539
assign_tmp      1       a.php       NULL    array   1       1
        3       0x539
array_append    2       a.php       1       1       3       0x539
        long    4
```

(3.1.1) Log from running file `a.php`

```
$a = [1,2,3];
$a[] = 4;
```

(3.1.2) File: `a.php`

Figure 3.1: Example of the result from a run with the modified interpreter.

3.2.2 Identification of arrays

In order to analyse how arrays are used throughout an execution of a test suite, some method for identifying which arrays that are mentioned on a given line is needed. For instance, in the output depicted in figure 3.1.1 all lines concern the same array with memory address `0x539`. Here, identifying these arrays as the same is a matter of checking the address. Due to the size of the test suites, relying only on the address is not a sound approach. Over time addresses will be reused and false identifications will happen. This issue can be solved by depending on the `hash_init` line, which indicates that a new array is initialized at some address. If such a line occurs between two usages of an address they can not be considered representing the same array.

Since the log files are generated from running a test suite, relying on addresses for identification alone might result in a skewed analysis with an over-representation of arrays occurring in *critical* code. Determining array equality based on initialization location in the file should provide a more equal representation of arrays, not letting some arrays dominate the statistics. Locational identification would, however, identify four different arrays in example 3.1.1, which does not reflect the program 3.1.2 and thus the address is still needed to identify the same array across multiple uses on different code locations.

Definition 4. Given two lines, l_1 and l_2, from a log file R, formatted as described above, each containing an array, $x_1 \in l_1$ and $x_2 \in l_2$, where $x_1 = (t_1, d_1, s_1, a_1)$ and $x_2 = (t_2, d_2, s_2, a_2)$, the arrays are said to be positionally equal $x_1 \overset{pos}{=} x_2$, if and only if the two lines share the same line number, line type, and file or $a_1 = a_2$ and there is no

$$\texttt{hash\_init}\ a_1$$

line between l_1 and l_2.

This definition utilizes file position and addresses in order to identify arrays. The line type has been added in order to heighten precision, since multiple different operations, on different arrays, may occur on the same line.

Definition 5. Given two lines $l_1, l_2 \in R$ and two arrays, $x_1 \in l_1$ and $x_2 \in l_2$, then id is an ID-function if and only if

$$id(x_1) = id(x_2) \Leftrightarrow x_1 \overset{pos}{=} x_2$$

When iterating through a log file from top to bottom, IDs can be generated by keeping a mapping from locations to IDs and from addresses to IDs, and by *forgetting* addresses when a `hash_init` line is observed.

3.2.3 Determining type

Determining the type of every positionally distinct array is done by first determining the key type, $t \in T$, then determining the type of the values, and from this deduce the type as either list, map or object as defined in the beginning of this chapter. Since we want to test the hypothesis of whether an array-type changes, the type of the keys is a set of types. If an array is observed with different key types throughout the analysis, then the key type of the array is the set of these types. E.g, let an array be observed at one point with type list and later with type sparse list, then the type of the array is {List, Sparse List}.

Detecting the key type for each array is done by traversing the file from top to bottom inspecting each line. If a line contains an array a the type of the line is associated with the corresponding ID of the array.

Detecting the type of values is also done by traversing through the log file from top to bottom. Here the reads and writes from and to the arrays are used to determine the types of the values. This is done by associating all the types of the values read/written with the respective array.

For every array with key and value type information, it is now possible to determine whether it is a list, map, object or uncategorizable. Given an array, a, with type information, if a has multiple key types, it is considered uncategorizable. Otherwise if a contains values of a single type, it is either a map or a list, depending on the key type. If the values have multiple types, then a is an object.

When the types of the arrays are determined, we can analyse the operations used with each type of array. This is done by once again iterating through the log file and associating line types with the types of the arrays.

3.2.4 Compiling and running PHP with logging

The source code needed to compile and run the modified PHP interpreter can be found at `http://github.com/Silwing/tapas`. For the purpose of the dynamic analysis, Vagrant[B30] is used to create a clean and reproducible environment. A Vagrant initialization file is used to setup a virtual machine running a 64-bit Ubuntu 14.04, install the necessary dependencies and compile the modified PHP Interpreter. The environment for running the corpus test suites is then ready and can be accessed via SSH on the virtual machine. The folder `/vagrant/corpus` contains a Makefile which can be used to fetch dependencies and corpus frameworks as well as running all the test suites.

All modifications to the interpreter are guarded by an ini-directive[B33, Chapter 14.12] that is disabled by default when compiling and running the modified interpreter source. The logging can be enabled via `php.ini` or for single runs as seen in figure 3.2

```
$ php -d rb.enable_debug=1 -d rb.enable_debug_file=<
    path-to-log-file> <path-to-php-file>
```

(3.2.1) Enable logging for running a single PHP file.

```
rb.enable_debug=1
rb.enable_debug_file="/path/to/output/csv/file"
```

(3.2.2) Enable logging in php.ini.

Figure 3.2: How to enable logging

3.2.5 Limitations

Since the analysis is performed by a modified interpreter, some limitations are imposed on the achievable precision.

- `array_init` does not capture the type of the array at initialization. This implies that the types of arrays initialized without being assigned or manipulated afterwards are not captured by the analysis. In figure 3.3.2 line 3, the call to `print_r` does yield an `array_init` line in the log 3.3.1 but with no type, depth 1 and size 0. The size should be 3 and the type should be list.

- Detecting the type of arrays relies on the type of the values read from or written to the arrays. This implies that there is no reasoning about arrays never being read or written. Some of these arrays may fall into the uncategorizable type but remain undetected by the analysis.

- Callables can be written as anonymous functions, strings, or arrays containing either an instance or a string representing a class name together with string representing a function name. Arrays of callables should be considered lists, however this analysis will classify them as objects. Program 3.3 shows different types of callables.

- Multiple operations of the same type using different arrays lead to sharing of IDs. Following the limited information available to distinguish between operations, operations such as assign to a multidimensional array leads to sharing the ID between the array and its sub-arrays, (see figure 3.3.2 line 5). This follows from the value first being assigned to the sub-array, which is then assigned to the super-array. Combining multiple arrays may lead to uncategorizable arrays even if each array is categorizable. A possible solution would be if the interpreter kept character location information in addition to line number and file name.

Program 3.3 Callables in PHP

```
class A{

    public function f1(){
        ...
    }

}

function f(){
    ...
}

$a = new A();

$callable1 = [$a, "f1"];
$callable2 = ["A", "f1"];
$callable3 = "f";
$callable4 = function() use ($a){
    ...
};
```

	List	Map	Sparse List	Object	Object (L)	Object (SL)	Uncategorizable
CodeIgniter	39.66%	36.21%	2.59%	12.93%	2.59%	0.00%	6.03%
Joomla	30.78%	39.13%	2.17%	20.02%	3.66%	0.11%	4.12%
Magento 2	23.54%	46.51%	3.38%	17.93%	2.63%	0.70%	5.30%
MediaWiki	32.48%	32.23%	2.69%	15.60%	8.20%	0.49%	8.32%
Part	33.33%	39.10%	0.00%	12.82%	5.77%	0.00%	8.97%
phpBB	27.13%	33.33%	3.17%	25.11%	4.33%	0.14%	6.78%
PhpMyAdmin	33.24%	33.43%	2.09%	14.06%	5.89%	0.38%	10.92%
Symfony 2	34.32%	28.01%	1.99%	14.86%	8.63%	0.21%	11.99%
WordPress	35.50%	33.03%	2.02%	14.11%	6.61%	0.45%	8.29%
Zend Framework 2	30.99%	35.07%	1.08%	19.78%	6.25%	0.00%	6.82%

Table 3.1: Distribution of different array types

3.3 Results

Running the modified interpreter on the corpus created large log files, ranging from 41 MB to 13 GB in size. Most of the entries in the log files were created by the test framework or other dependencies, i.e. not by the framework in question. These entries were removed before analysing the logs, reducing the file-sizes to between 3.4 MB and 11 GB.

Figure 3.4 and table 3.1 show the distribution of array types for the frameworks. Between 4% and 12% of the arrays are uncategorizable. These include false uncategorizables originating from flaws in the array identification as discussed in section 3.2.5. One of these was regarding the imprecision w.r.t. multidimensional arrays. A quick inspection of some of the code-locations containing uncategorizable arrays did show that many of these were in fact caused by performing operations on multidimensional arrays.

Figure 3.5 shows the distribution of operations on the arrays over the different array types from figure 3.4. Write and append correspond to the language

```
hash_init        0x2A
array_init       3        b.php    0       1       0       0x2A
hash_init        0x2B
array_write      5        b.php    0       1       0       0x2B   long
             1      NULL
hash_init        0x2C
array_write      5        b.php    0       1       0       0x2C   long
             2      NULL
assign_const     5        b.php    NULL    long    3
```

(3.3.1) Log from running file `b.php`

```php
<?php

print_r([1,2,3]);

$a[1][2] = 3;
```

(3.3.2) File: `b.php`

Figure 3.3: A problematic program

features for writing to arrays:

```php
$a = [];
$a[0] = 42; // array write
$a[] = 1337; // array append
```

These are by far the most used. The library function `array_push` is equivalent to the append operation if given only a single argument. The documentation recommends the append operation in such situations for performance reasons, which aligns with the use of append over push in the figure.

Notice how the objects are divided into three categories, Object, Object (List), and Object (Sparse List). The last two are arrays with values of different types, but with keys of lists and sparse lists respectively. The distribution of array operations shows that array list operations are almost exclusively performed on lists (List, Sparse List, Object List, Object Sparse List). From this follows that if a list array-operation is performed on an array, then it is almost certain that the array is of type list. When encountering an array write operation it is not necessarily the case that the array is a list. Array write operations are used frequently on lists, arrays, and objects.

Table 3.2 shows that across the corpus less than 1% (column 5) of the arrays are detected as being cyclic. The largest percentage of cyclic arrays detected in the corpus is in phpMyAdmin with a total of 10 cyclic arrays out of 3,373 arrays identified. With such relatively few cyclic arrays found, a manual inspection of the code locations was possible. The manual inspection showed that almost all of the reported cyclic arrays are uses of the super-global `$GLOBALS` which is an array consisting of all variables defined in the global scope. This array also has a reference to itself which makes it a cyclic array. Only two of the frameworks in the corpus had cases where it was not immediately clear whether it was a use of the `$GLOBALS` array: Zend Framework 2 and Symfony 2; these are noted in column 4 as “NG Cyclic” arrays. These few cases are function input parameters reported as cyclic, which might in fact be the `$GLOBALS` array passed to the function. The fact that no creation of cyclic arrays were found supports

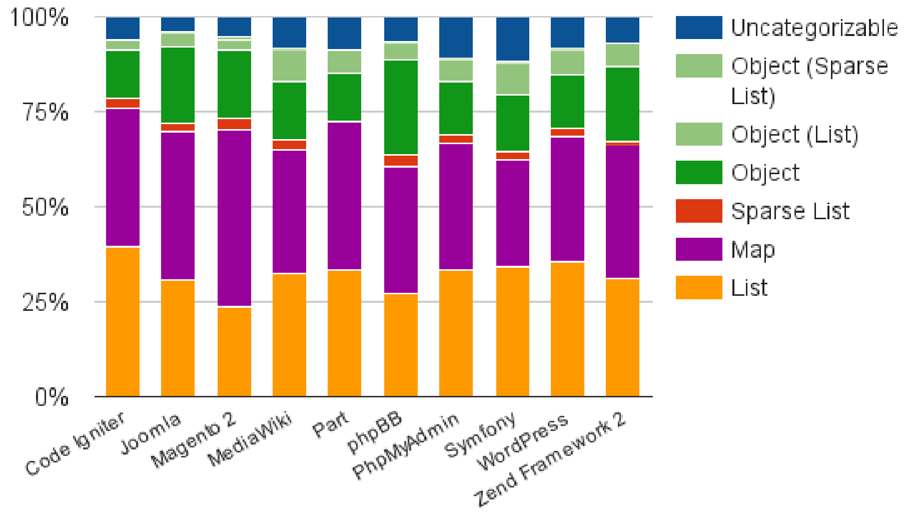


Figure 3.4: Distribution of different types of arrays

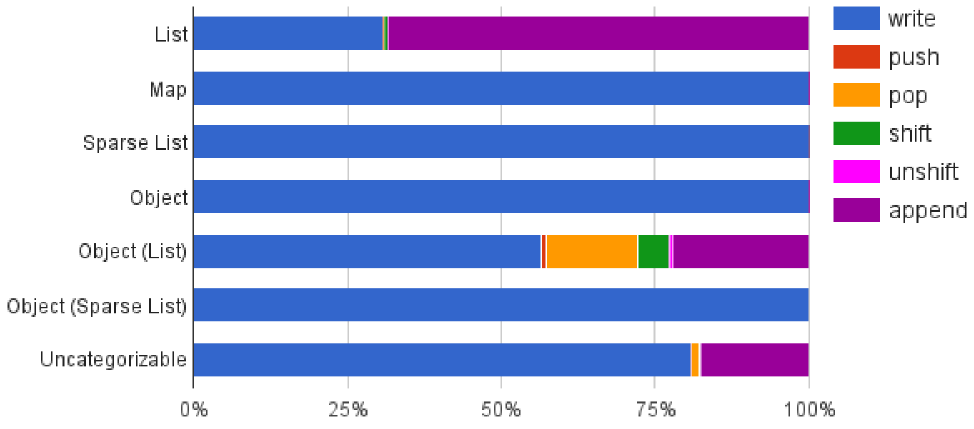


Figure 3.5: Distribution of array operations over array types

Framework	# Arrays	# Cyclic	# NG Cyclic	%
CodeIgniter	331	0	0	0.0%
Joomla	1969	2	0	0.1%
Magento2	6942	0	0	0.0%
MediaWiki	27368	1	0	<0.1%
Part	378	0	0	0.0%
phpBB	2529	1	0	<0.1%
PhpMyAdmin	3373	10	0	0.3%
Symfony	3707	6	6	0.2%
Wordpress	3054	1	0	<0.1%
Zend Framework 2	4381	3	2	0.1%

Table 3.2: Amount of cyclic arrays detected in the corpus

this theory.

Based on the results of the manual inspection, the hypothesis of arrays being acyclic is mostly true for all frameworks in the corpus. It is, however, also the case that every PHP program has at least one cyclic array in its scope, namely the `$GLOBALS` array, therefore the analysis should support handling and creation of such arrays.

3.4 Conclusion

The purpose of the dynamic analysis was to evaluate our hypothesis stating that arrays in a given program can be categorized as either list, map, or object, and once categorized, will stay in the category throughout multiple executions of that program. The results of the analysis support this hypothesis by showing that arrays generally keep the same type. Furthermore, the usage of array operations normally associated with lists, proved almost exclusive to arrays categorized as lists. This information can be used to define unexpected behaviour reported by the static analysis, e.g. reporting `array_pop` performed on a map.

The initial definitions categorized arrays as objects based on the type of the values. In the analysis however, a significant number of arrays turned out to be lists with different type values, defining them as objects. Operations on these objects were often list-operations, which indicates that categorizing based on value type might not be a meaningful strategy. It can be considered whether the object type is providing significant information in itself, or should be consumed by the definitions of maps and lists, i.e. letting maps and lists allow values of different type.

Almost every framework in the corpus contains cyclic arrays, however these are nearly exclusively uses of the superglobal `$GLOBALS`. Manipulating the global variables as a method for passing information seems suspicious and indicates poor program design, but reminds us that every PHP program has at least one cyclic array which must be handled in a sound manner. No creation of cyclic arrays has been detected in the program, which follows our hypothesis, that the developer will generally not utilize the more advanced array structures.

Chapter 4

Data Flow Analysis

Based on the findings in chapter 3, a *dataflow analysis* is designed and described in this chapter. The aim of the analysis is to introduce two new array types, array-lists and array-maps respectively, and subsequently report any suspicious behaviour on these arrays. Examples of suspicious behaviour could be appending to maps, using keys of type string to access lists and adding elements of a different type to an array.

The definitions of maps and lists from chapter 3 are redefined as:

Definition 6. Let a be an array with exclusively integer keys, then a is considered an array-list.

Definition 7. Let a be an array with non-exclusively integer keys, then a is considered an array-map.

While running the analysis on the corpus of the dynamic analysis would be ideal, limited time forces the analysis to be restricted to a subset of PHP, introduced in section 4.1. The analysis is performed using the monotone framework. Using a control-flow graph (introduced in section 4.2), a model of program states (introduced in section 4.3), and finally transfer functions for each CFG-node (introduced in section 4.4), an instance of the monotone framework is derived in section 4.7. Since PHP relies heavily on coercion, a separate section (section 4.5) covers coercion of abstract values. Section 4.6 covers abstract evaluation and in section 4.8 the implementation of the analysis is briefly introduced.

4.1 PHP language subset

To simplify the static analysis, a subset of the PHP language (P0) is used. The PHP language has no formal definition and thus the language used here can not be formally shown to be a subset of the complete PHP language. The full PHP language is defined by the reference Zend Interpreter.

To simplify the analysis and keep the focus on arrays, resource handles and objects have been completely removed from the language. Dynamic dispatch (variable function names), variable variables and dynamic loading of code (`require` and `include`) have also been omitted. It is assumed that any possible path in a function body results in a return statement and return statements are only allowed in a function body. There are no anonymous functions and a limited number of statements but the language does support all reference features, e.g. reference assigning entries in an array. Initializing an array with references is not supported directly, however this can be done by initializing an empty array and writing or appending the initial values one by one. Reading from and writing to the `$GLOBALS` array will get and set the value of the variables, respectively. Creating a new variable by adding a new entry to the array, however, does not initialize a new variable in the global scope.

The syntax can be expressed with grammar 4.1. Here $e : \langle expr \rangle$ denotes an expression, $e : \langle rexpr \rangle$ a reference expression, and $e : \langle vexpr \rangle$ a variable expression. Furthermore a program is only valid in P0 if it is also a valid PHP program. For example the syntax allows negation of arrays, however this action yields a fatal error in PHP and may be considered as an invalid program, hence also an invalid P0 program.

Notice that returning an $\langle rexpr \rangle$ with a non-reference function might result in a fatal error, e.g. when returning the result of an array-append operation, but the same operation is valid in a reference-function.

PHP supports using the array access syntax with strings to read and write individual characters of the string given. P0 does not support accessing strings with array syntax. The full PHP language defines a lot of cross-type operations, e.g. comparing a boolean with a string using <=, however P0 supports only the operations described in sections 4.5 and 4.6.

A few function-like language constructs exists. Syntactically they look like function calls, but the expressions allowed as parameters may be limited or the constructs may have special side-effects. The `unset` and `isset` language constructs are two such functions which work only with variables and array-access expressions as parameters. Together with `empty`, `exit` and `eval` these special language constructs are not supported in P0.

4.2 Control-flow graph

The control-flow graph defines the basic instructions of a program and how data flows between those instructions. Nodes correspond to instructions and edges to data flow. The graph is built recursively by defining sub graphs corresponding to grammar 4.1. Table 4.1 gives a description of sub-graphs and their respective arguments.

For each sub-graph with an argument this argument corresponds to the target argument (c_{tar}) of the last node in the sub-graph. For example, let $E =$ `1+(2+3)` then the graph of $[\![E]\!](t)$ is recursively constructed as in graph 4.1. Notice how the argument, t, of the sub-graph is the third argument of the last $bop_{+}(\_)$ node.

Definition 8. A control-flow graph is a four-tuple $G = (V, E, s, t)$, where V is a set of nodes, E is a set of node pairs representing an edge between two nodes, $s \in V$ is a start node and $t \in V$ is an exit node.

⟨*program*⟩ ::= (⟨*function-definition*⟩ | ⟨*statement*⟩)*

⟨*function-definition*⟩ ::= ‘`function`’ ‘`&`’?⟨*function-name*⟩ ‘`(`’ (‘`&`’? ⟨*var*⟩ (‘`,`’ ‘`&`’? ⟨*var*⟩)*) |
    ϵ‘`)`’ ⟨*block*⟩

⟨*statement*⟩ ::= ‘`while (`’ ⟨*expr*⟩ ‘`)`’ ⟨*statement*⟩
  | ‘`for (`’ ⟨*expr*⟩?‘`;`’⟨*expr*⟩?‘`;`’⟨*expr*⟩? ‘`)`’ ⟨*statement*⟩
  | ‘`if(`’⟨*expr*⟩‘`)`’ ⟨*statement*⟩
  | ‘`if(`’⟨*expr*⟩‘`)`’ ⟨*statement*⟩ ‘`else`’ ⟨*statement*⟩
  | ‘`;`’
  | ⟨*expr*⟩‘`;`’
  | ‘`global`’ ⟨*var*⟩ (‘`,`’ ⟨*var*⟩)*‘`;`’
  | ‘`return`’ (⟨*expr*⟩|⟨*rexpr*⟩)?‘`;`’
  | ⟨*block*⟩

⟨*expr*⟩ ::= ⟨*expr*⟩ $\oplus$ ⟨*expr*⟩
  | $\circ$ ⟨*expr*⟩
  | ‘`(`’ ⟨*expr*⟩ ‘`)`’
  | ⟨*vexpr*⟩‘`+ +`’
  | ⟨*vexpr*⟩‘`- -`’
  | ‘`+ +`’⟨*vexpr*⟩
  | ‘`- -`’⟨*vexpr*⟩
  | ⟨*var*⟩
  | ⟨*expr*⟩ ‘`[`’⟨*expr*⟩ ‘`]`’
  | ⟨*function-reference*⟩
  | ⟨*const*⟩
  | ⟨*assignment*⟩
  | ‘`[`’ (ϵ | ⟨*array-init-entry*⟩ (‘`,`’ ⟨*array-init-entry*⟩)*) ‘`]`’
  | ‘`array(`’ (ϵ | ⟨*array-init-entry*⟩ (‘`,`’ ⟨*array-init-entry*⟩)*) ‘`)`’

⟨*function-reference*⟩ ::= ⟨*function-name*⟩‘`(`’ (⟨*function-arg*⟩ (‘`,`’ ⟨*function-arg*⟩)* | ϵ) ‘`)`’

⟨*function-arg*⟩ ::= ⟨*expr*⟩
  | ⟨*rexpr*⟩

⟨*rexpr*⟩ ::= ⟨*var*⟩
  | ⟨*function-reference*⟩
  | ⟨*rexpr*⟩‘`[]`’
  | ⟨*rexpr*⟩‘`[`’ ⟨*expr*⟩ ‘`]`’

⟨*vexpr*⟩ ::= ⟨*var*⟩
  | ⟨*rexpr*⟩‘`[]`’
  | ⟨*rexpr*⟩‘`[`’ ⟨*expr*⟩ ‘`]`’

⟨*array-init-entry*⟩ ::= ⟨*expr*⟩ ‘`=>`’ ⟨*expr*⟩
  | ⟨*expr*⟩

⟨*assignment*⟩ ::= ⟨*rexpr*⟩‘`[]`’ ‘`=`’ ⟨*expr*⟩‘`;`’
  | ⟨*rexpr*⟩‘`[`’ ⟨*expr*⟩ ‘`]`’ ‘`=`’ ⟨*expr*⟩‘`;`’
  | ⟨*var*⟩ ‘`=`’ ⟨*expr*⟩
  | ⟨*rexpr*⟩‘`[]`’ ‘`=`’ ‘`&`’ ⟨*rexpr*⟩‘`;`’
  | ⟨*rexpr*⟩‘`[`’ ⟨*expr*⟩ ‘`]`’ ‘`=`’ ‘ `&`’ ⟨*rexpr*⟩‘`;`’
  | ⟨*var*⟩ ‘`=`’ ‘`&`’ ⟨*rexpr*⟩

⟨*block*⟩ ::= ‘`{`’ ⟨*statement*⟩* ‘`}`’

Grammar 4.1: P0 syntax

Symbol	Description
$t \in \text{Temps}$	A temporary variable name used to pass evaluated values between CFG nodes
$h \in \text{HeapTemps}$	A temporary heap variable name used to pass a set of heap locations between CFG nodes
$c \in \text{Temps} \bigcup \text{HeapTemps}$	Either of the above two types of variable names
$[\![E]\!](t)$	Sub graph for expression E with evaluation result stored in t
$[\![R]\!](h)$	Sub graph for reference expression R with evaluated heap-location set stored in h
$[\![V]\!](h)$	Sub graph for a variable expression V with evaluated heap-location set stored in h
$[\![T]\!](c)$	Sub graph for either an expression, a reference expression or a variable expression with c being the corresponding t or h as described above
$[\![S]\!]$	Sub graph for statement S

Table 4.1: Symbols used in the control-flow graph

When illustrated as a graph, the entry node of a control-flow graph is marked with an in-going edge with no origin and the exit node is marked with an outgoing edge with no target. In example graph 4.1, $s = \mathit{constRead}(1, t_1)$ and $t = \mathit{bop}_+(t_1, t_2, t)$.

There are seventeen different nodes, all introduced below

start: This node indicates the start of a program and is the first node of any program or function body.

$\mathit{bop}_\oplus(t_l, t_r, t_{tar})$, $\mathit{sop}_\oplus(t_l, t_r, t_{tar})$, $\mathit{uop}_\circ(t, t_{tar})$, $\mathit{inc}_\circ(h, t_{tar})$: These nodes indicate binary, short-circuit-binary, unary, and increment/decrement operations, respectively. The operations of the first three are all performed on temporary storage, while the fourth is performed on the heap. The last argument, t_{tar}, indicates where the result of performing the operation should be stored. For example `1+2` is a binary operation (*bop*) returning `3`, this value should be stored in temporary storage at t_{tar}. The arguments t_l and t_r correspond to entries in the temporary storage containing the values of the left operand and the right operand, respectively. For unary operations the t argument is where the value of the operand is stored in temporary storage and for the increment and decrement operations the h variable is the set of heap-locations storing possible operand values.

$\mathit{if}(t)$: This node has one in-going and two out-going edges, representing the choice of one branch or the other. The argument t is the entry in temporary storage where the evaluated value of the condition is stored.

$\mathit{constRead}(k, t_{tar})$: This node represents reading a constant into the temporary storage at t_{tar}. The constant k can be a string, a boolean, null or a number.

$\mathit{varRead}(\texttt{\$v}, c_{tar})$, $\mathit{varWrite}(\texttt{\$v}, c_{val}, t_{tar})$: These nodes indicate reading from and writing to a variable `$v` respectively. Depending on the context, the target of the read and value of the write can either be a temporary or temporary heap variable name.

$\mathit{arrayInit}(t_{tar})$: This node represents initializing an empty array in the temporary storage at t_{tar}.

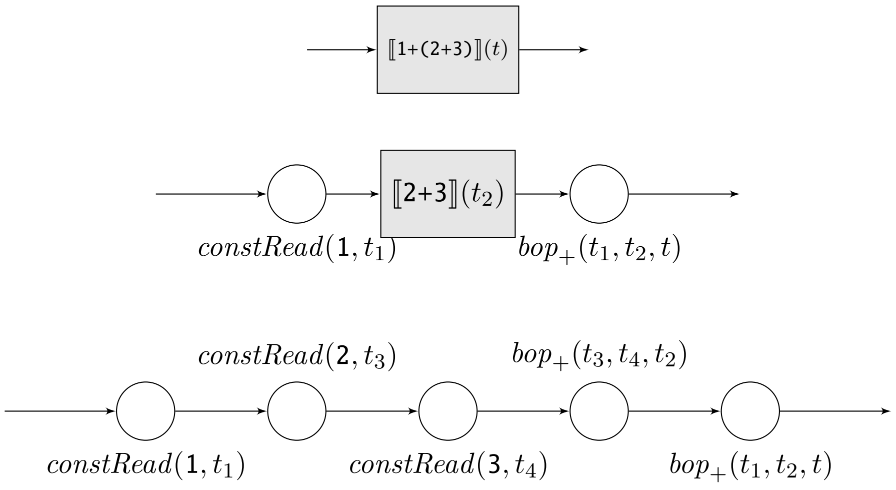
$\mathit{arrayAppend}(t_{val}, t_{arr})$, $\mathit{arrayAppend}(h_{var}, c_{val}, t_{tar})$, $\mathit{arrayAppend}(h_{var}, h_{tar})$: With three different signatures, this node represents appending to an array in temporary storage, in the heap, or in a read-context. Appending to an array in temporary storage happens when an array is initialized with values without keys, in which case the first type of append node is used. Appending to an array on the heap is an ordinary array append, where h_{var} is the possible heap locations of the array, c_{val} is either a heap temporary variable name in case of a reference append or a temporary variable name in case of a normal append. The value of c_{val} is stored in t_{tar}. Appending in a read context, i.e. without a value to be written, is usually not allowed, however there are some exceptions. For those cases the last node is used and the appended heap location is placed in temporary heap storage for later access.

$\mathit{arrayRead}(h_{arr}, t_{key}, c_{tar})$: Reading from an array on the heap (h_{arr}) with a key derived from the value at t_{key}. The result can either be a reference to the entry or the value at the given key, hence the c_{tar} variable.

$\mathit{arrayWrite}(t_{val}, t_{arr})$, $\mathit{arrayWrite}(h_{arr}, c_{val}, t_{tar})$: Writing to an array in temporary storage or in the heap respectively. The arguments to the former (t_{val} and t_{arr}) are temporary variable names for the value and the array respectively. Just as with append, the value written can be either a reference or a value, hence the c_{val} variable. The value evaluated from c_{val} is stored in temporary storage at t_{tar}.

$\mathit{call}_{\mathit{fn}}(c_1, \cdots, c_n)$, $\mathit{exit}(c_1, \cdots, c_m)$, $\mathit{result}_v(c_{tar})$: A function call is performed with the *call* node. This holds the name, *fn*, of the function being called (which can always be resolved) as well as information about function parameters $(c_1, \cdots, c_n)$. For every call node, v, there is a single result node, result_v. This restores the calling context and stores the result of the function call in c_{tar}. The node preceding the result node is an *exit* node, which is unique to the function being called and the last node of the function sub-graph. The exit arguments $c_1, \cdots, c_m$ are entries in the temporary storage which contain the evaluations of return statements in the function.

nop: This node does nothing and is only there for structural purposes. It is in the control-flow graphs denoted as a small node with no label.



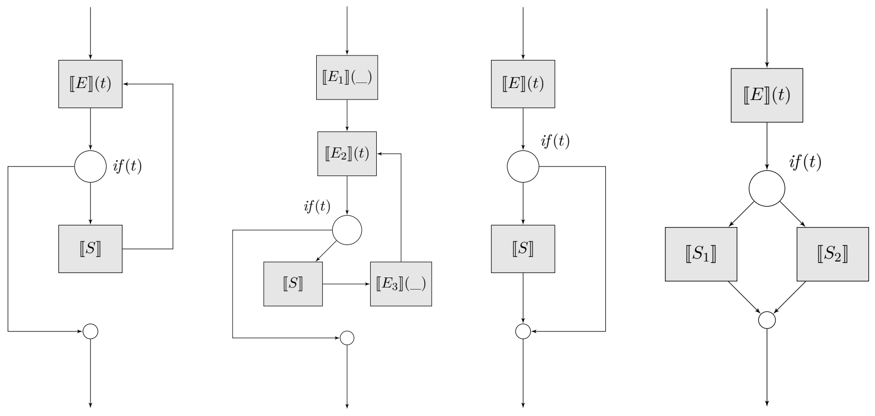
Graph 4.1: Recursively constructing graph $[\![$`1+(2+3)`$]\!](t)$

After parsing a P0 program $p : \langle program \rangle$ to an abstract syntax tree the control-flow graph, $G_p = (V_p, E_p, s_p, t_p)$, can be constructed recursively by constructing sub-graphs for statements $S_1, \cdots, S_n$ in p. The sub graphs, $G_i = (V_i, E_i, s_i, t_i)$ and $G_{i+1} = (V_{i+1}, E_{i+1}, s_{i+1}, t_{i+1})$, for statement i and $i+1$ respectively are connected by edges from t_i to s_{i+1}. A separate *start* node is created as s_p and $t_p = t_n$. For each function definition in p a separate graph, $G_f = (V_f, E_f, s_f, t_f)$, is created with $s_f = start_f$ and $t_f = exit_f$. Function calls in p create edges to the corresponding s_f and from the corresponding t_f.

4.2.1 Statements

Let $s : \langle statement \rangle$ be a statement, then there are nine different graphs, one for each case in the grammar 4.1. The first four, for $s =$ `while(`E`)` S, $s =$ `for(`E_1`;`E_2`;`E_3`)` S, $s =$ `if(`E`)` S, and $s =$ `if(`E`)` S_1 `else` S_2 statements, are depicted as graph 4.2.1, 4.2.2, 4.2.3, and 4.2.4 respectively.

Return-statements, $s =$ `return` T, have three different graphs. An empty statement, i.e. which does not contain any expressions, is equivalent to returning `null`. This case yields the graph in 4.3.1. If $T : \langle rexpr \rangle$ and the function is a reference function, i.e. the function signature has an ampersand preceding the function name (see program 4.1.2), then the references are returned (graph 4.3.2 where c : HeapTemps). If this is not the case, (see program 4.1.1), and assuming the program is a valid P0 program, then it is fair to assume that T can be parsed as an expression, since it cannot be an array-append operation. Assuming it was an array append operation, the program would not be a valid PHP program and thus not a valid P0 program (see section 4.1). Assuming $T : \langle expr \rangle$ the graphs for a return statement evaluates T and return the result.



(4.2.1) `while`-statement (4.2.2) `for`-statement (4.2.3) `if`-statement (4.2.4) `if-else`-statement

Graph 4.2: Statement graphs

This is the case in graph 4.3.2 with c : Temps. For all graphs, the exit-node is the unique exit-node of the function.

Program 4.1 Return-statement examples

```
function normRet(){
  $a++;
  return $a;
}

```

(4.1.1) Normal return-statement

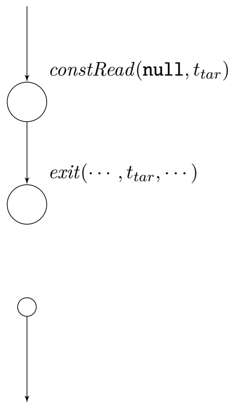
```
function &refRet(&$a){
  return $a[];
}


```

(4.1.2) Reference return-statement

The remaining four graphs are the empty graph, the graph of the expression statement, the graph of `global` statement, and the graph of the block statement, which are all straight-forward.

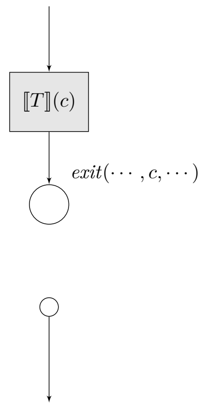
4.2.2 Expressions

Let $e : \langle expr \rangle$, then by ignoring the trivial parenthesized expression case, viewing the four increment/decrement operations as one, and the two array-initialization operations as one, the expression can be of nine different forms. For $e = E_l \oplus E_r$, the graph depends on the operation. If the operation is a short-circuit operation, logical `&&` or `||`, then the graph is as 4.4.1, since only one branch may be required to be evaluated. If the operation is not a short-circuit operation, then the graph becomes as 4.4.2, since both expressions must be evaluated. In both cases, the operations are performed on and saved in the temporary storage. The unary operation $e = \circ E$ is similar to the previous case with a graph as 4.4.3. A separate graph for unary post/pre increment/decrement operations is necessary, because of the performed update on the



$constRead(\texttt{null}, t_{tar})$
$exit(\cdots, t_{tar}, \cdots)$

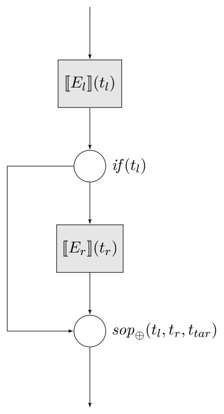
(4.3.1) `return`-statement



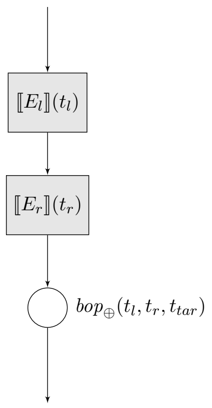
(4.3.2) `return`-expression-statement

Graph 4.3: Return-statement graphs

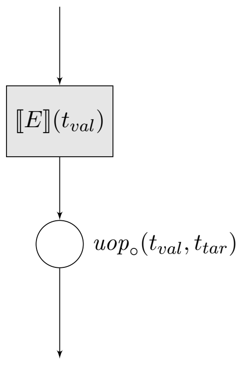
heap location. This is the reason for the operations not being performed on the temporary storage, but instead on heap-locations directly. The result of the operation is stored in the temporary storage. Figure 4.4.4 illustrates the corresponding flow graph.



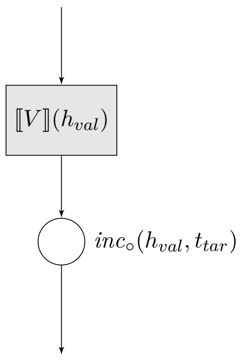
(4.4.1) Short-circuit binary operation



(4.4.2) Binary operation



(4.4.3) Unary operation

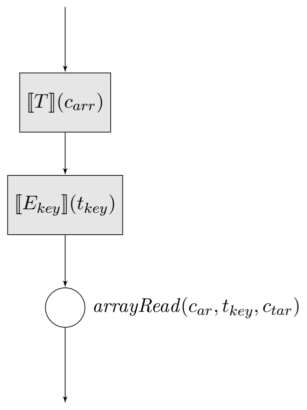


(4.4.4) Post/pre increment/decrement opreation

Graph 4.4: Operation-expression graphs

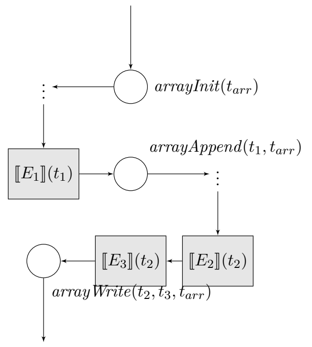
For a variable read $e = \texttt{\$v}$ (for some variable `$v`), or a constant read, e.g. $e = \texttt{"foo"}$, the graph is a single $varRead(\texttt{\$v}, t_{tar})$ or $constRead(\texttt{"foo"}, t_{tar})$ node, respectively. For an array read expression, $e = E_{arr}\texttt{[}E_{key}\texttt{]}$, the sub array expression, E_{arr}, should be evaluated before the key expression, E_{key}, and the graph then becomes like graph 4.5.1, where T is the graph corresponding to E_{arr} and c_{arr}, c_{tar} : Temps. If the expression is an array initialization, $e =$

`[`$\cdots, E_1, \cdots, E_2$`=>`E_3`]`, then an array is first initialized in temporary storage after the entries are either appended or written to the array, hence graph 4.5.2.



$[\![T]\!](c_{arr})$
$[\![E_{key}]\!](t_{key})$
$arrayRead(c_{ar}, t_{key}, c_{tar})$

(4.5.1) Array read

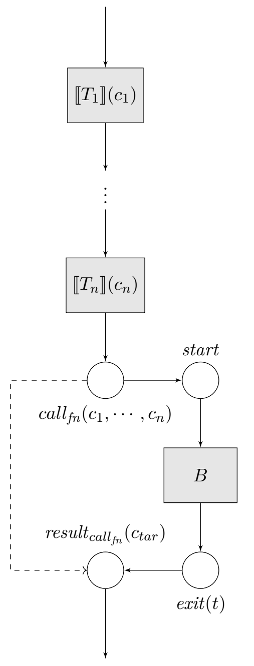


(4.5.2) Array initialize

Graph 4.5: Array-read and -initialize graphs

For function calls $e = fn$`(`$T_1, \cdots, T_n$`)`, the result variable is a temporary variable, c_{tar} : Temps, the arguments are either an expression, T_i : $\langle expr\rangle$ and c_i : Temps, or a reference expression, T_i : $\langle rexpr\rangle$ and c_i : HeapTemps, depending on the signature of *fn*. If the argument is pass-by-reference, i.e. the variable v_i is denoted with a `&` in the signature, then the expression must be a reference expression. If not, the argument is an expression. This follows from the program being a valid P0 program. The function graph will be as graph 4.6, where the start node, exit node, and function body are the unique nodes of the *fn* function, i.e. they are not copied. This ensures that the graph is finite, but multiple, say n, calls to the same function will yield a graph with n edges to the start node and from the exit node. Notice the dashed line going directly from the call node to the return node. This indicates that the call node may pass information directly to the return node, used for restoring the local context before calling *fn*.

Finally, the expression can be an assignment. There are two types of assignments, a regular value-assignment and a reference-assignment, using the `&` operator. Each assignment can be split into three categories; variable-, array-write-, and array-append-assignments, depending on the target (left-hand side of the operation). Examples of these six operations can be seen in program 4.2. Due to the distinction between temporary storage of values and heap-location-sets, these six cases must be handled individually. For value array write ($e = R$`[`E_{key}`]=`E_{val}), array append ($e = R$`[]=`E_{val}), and variable write ($e =$ `$v=`E_{val}), the graphs are as shown in graphs 4.7.1, 4.7.2, and 4.7.4, respectively, where T is the subgraph of the value expression E_{val} : $\langle expr\rangle$ and c_{val} : Temps is the temporary variable holding the result. The reference assignments $e = R$`[`e_{key}`]=&`R_{val}, $e = r$`[]=&`R_{val}, and $e =$ `$v=&`R_{val} are similar, but with T being the subgraph of the reference expression, R_{val} : $\langle rexpr\rangle$ and



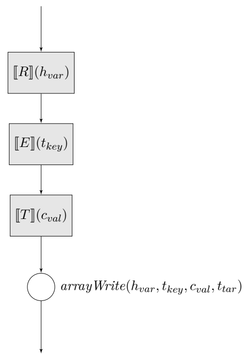
Graph 4.6: Function-call graph

c_{val} : HeapTemp the heap temporary variable holding the heap locations of the value.

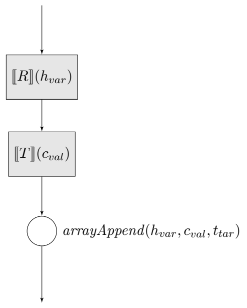
4.2.3 Reference and variable expressions

Since PHP supports nested assignments, e.g. `$a[]['foo'] = &func()[]`, deciding which location to update is performed recursively. The graph of this assignment is illustrated as graph 4.8. Here the locations of variable `$a` is stored in variable $h_{var'}$. A new location l is then appended to the array values of the locations in $h_{var'}$, and $h_{var} = \{l\}$. Now the expression of the index is resolved and stored in t_{key}, and the locations of the right-hand side are resolved and stored in h_{val}. Finally, the locations in h_{val} are written to the array at h_{var}, i.e. l, with the key of t_{key}.

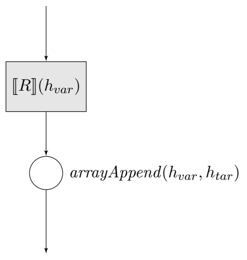
The sub-graphs which take a h : HeapTemp variable are called reference- and variable-expressions, where the only difference between the two is that reference expressions may contain function references. As seen in the previous example, they resolve heap-location sets rather than values. For $r = fn(c_1, \cdots, c_n)$ the graph corresponds to graph 4.6, with a heap-location set as the result, i.e. c_{tar} : HeapTemps. For the variable read $r =$ `$v` the graph is a single $varRead($`$v`$, h_{tar})$ node. When the expression is an array-read $r = R_{arr}[E_{key}]$ the graph corresponds to that of graph 4.5.1 with c_{arr}, c_{tar} : HeapTemps and T being the graph of R_{arr}. Finally, for the append operation $r = R_{arr}[]$ the graph corresponds to that of graph 4.7.3.



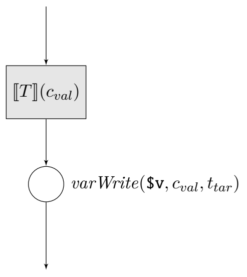
(4.7.1) Array write



(4.7.2) Array append



(4.7.3) Array append without write

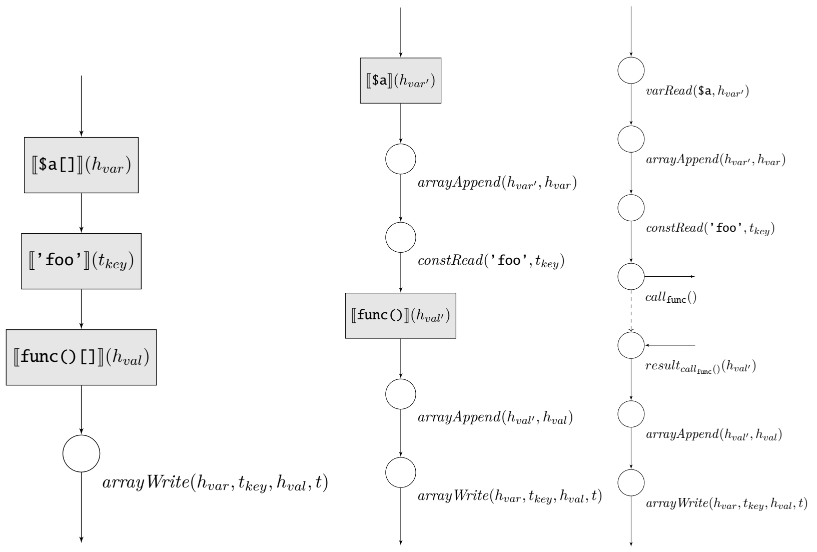


(4.7.4) Variable write

Graph 4.7: Array-append, array-write and variable-write expressions

Program 4.2 Assignments

```php
<?php

$a = []; //Value assignment
$a[] = 1; //Array append assignment
$a[1] = 2; //Array write assignment

$b = &$a; //Value reference assignment
$c[] = &$a;//Array append reference assignment
$d[1] = &$a; //Array write reference assignment
```



$[\![\texttt{\$a[]}]\!](h_{var})$
$[\![\texttt{'foo'}]\!](t_{key})$
$[\![\texttt{func()[]}]\!](h_{val})$
$arrayWrite(h_{var}, t_{key}, h_{val}, t)$
$[\![\texttt{\$a}]\!](h_{var'})$
$arrayAppend(h_{var'}, h_{var})$
$constRead(\texttt{'foo'}, t_{key})$
$[\![\texttt{func()}]\!](h_{val'})$
$arrayAppend(h_{val'}, h_{val})$
$arrayWrite(h_{var}, t_{key}, h_{val}, t)$
$varRead(\texttt{\$a}, h_{var'})$
$arrayAppend(h_{var'}, h_{var})$
$constRead(\texttt{'foo'}, t_{key})$
$call_{\texttt{func}}()$
$result_{call_{\texttt{func}}()}(h_{val'})$
$arrayAppend(h_{val'}, h_{val})$
$arrayWrite(h_{var}, t_{key}, h_{val}, t)$

Graph 4.8: Creating graph of expression $[\![$`$a[]['foo'] = &func()[]`$]\!](t)$

4.3 Lattice

The lattice is the data-structure passed around by the flow of the control-flow graph. In order to create an *inter-procedural analysis*, the analysis lattice is defined as

$$\text{AnalysisLattice} = \Delta \rightarrow \text{State} \tag{4.1}$$

This is a map-lattice from a context to an abstract state, where the context Δ consists of a list of call-sites, represented as the call nodes in the control-flow graph with length bounded by $k > 0$. The bound k must be greater than zero, since the context is used to decide between local and global scope. Definitions on the different type of lattices can be found in appendix A.

If the context was bounded by $k = 0$, this would entail that all variables would be updated in the global scope resulting in a unsound analysis. In the analysis the only strong update of the heap is performed when writing to a variable pointing to no locations, which is sound, since the variable has not been initialized and hence cannot have been referenced. By using only the global scope, performing a strong update with a not-null value will indicate that the variable cannot be `null`. This is true for the function body, but in the global scope the variable is uninitialized, i.e. `null`, hence the analysis would be unsound.

$$\Delta = \text{CallNode}_{*}^{\leq k} \tag{4.2}$$

The abstract state is a product lattice with five factors. The first two model the scope, the third models the heap, and the last two model the storage for intermediate results.

$$\text{State} = \text{Locals} \times \text{Globals} \times \text{Heap} \times \text{Temps} \times \text{HeapTemps} \tag{4.3}$$

As described in section 2.2.2, the scoping rules of PHP are very simple and can be expressed with a global and a local scope. The global scope is required, since global variables can always be accessed from a function using the `global` statement. Furthermore, the superglobals reside in the global scope but they can always be accessed directly. Two scopes are enough, because any other variables have to be passed to a function as an argument.

$$\text{Locals} = \text{Globals} = \text{Scope} = \text{Var} \rightarrow \mathcal{P}(\text{HLoc}) \tag{4.4}$$

The scopes are defined as maps from variable names in Var to power-sets of heap locations $\mathcal{P}(\text{HLoc})$. While PHP supposedly performs deep copies of values on assignments, letting the scope be a map from variable names to values would not facilitate the feature of assigning references to and from variables and array entries. This is done using the `&` operator and makes the heap abstraction necessary. The heap allows values to be used by multiple variables and arrays, which enables proper propagation of changes.

$$\text{Heap} = \text{HLoc} \rightarrow \text{Value} \tag{4.5}$$

The Temps and HeapTemps map-lattices store intermediate results. Since these results cannot be referenced, there is no need to store them in the heap. By keeping them in a separate lattice, they can be strongly updated and do not have to (and should not) be passed when switching context, since they are in every respect local to the current context. A single temporary storage mapping from temporary variables to a sum-lattice of values and power-set lattice was considered. This however would involve special handling of $\top$ and $\bot$ elements, which is avoided by this method.

$$\text{Temps} = \text{TVar} \to \text{Value} \tag{4.6}$$

$$\text{HeapTemps} = \text{THVar} \to \mathcal{P}(\text{HLoc}) \tag{4.7}$$

The necessity of the HeapTemps lattice follows from the fact that reference assignments may be nested, which requires intermediate results shared between nodes in the control-flow graph. The sets of temporary variable names, TVar and THVar, are both finite following from the control-flow graph being finite.

The heap locations are allocation site abstractions with respect to the context, node, and a natural number. The natural number allows the creation of multiple locations per node, which is necessary in *call*-nodes to support multiple arguments. Adding the natural number as a factor makes the set of allocation sites possibly infinite. However, in practice the set is finite since the number of function parameters is finite.

$$\text{HLoc} = \Delta \times \mathcal{N} \times \mathbb{N} \tag{4.8}$$

where $\mathcal{N}$ is the set of nodes in the control-flow graph.

An abstract value is defined as the product lattice of the five factors defined by the Hasse diagrams shown in figure 4.1. These lattices were chosen with the hope of better coercion between values, but others might be considered, e.g. by focusing more on coercion from strings to array indices.

$$\text{Value} = \text{Array} \times \text{String} \times \text{Number} \times \text{Boolean} \times \text{Null} \tag{4.9}$$

Following the results of the dynamic analysis in chapter 3, the array is considered either a set of locations or a map from indices to sets of types, i.e. array-lists or array-maps. The sum-lattice has been chosen, as opposed to a product-lattice, since the dynamic analysis indicated that arrays seldom change from lists to maps or vice versa. Top array elements are then predictors for suspicious behavior. Furthermore the array lattice has an element for the empty array which can become either a list or a map.

$$\text{ArrayList} = \mathcal{P}(L) \tag{4.10}$$

$$\text{ArrayMap} = \text{Index} \to \mathcal{P}(L) \tag{4.11}$$

The indices of the array-map-lattice is an infinite lattice, yielding a possibly infinite array-lattice. To ensure termination of the analysis, the lattice must be finite, so it must be argued that the lattice is finite in practice. Assuming that an infinite-sized array exists, an infinite number of writes to a map is required. This in turn requires an infinite-sized program, a recursive function, or a loop. Since an infinite-sized program is not possible, one of the two latter cases must hold. Assuming the cause is a recursive function, the array must then be finite because the number of contexts are bounded and the number of heap locations are bounded. Now, assuming that the array is caused by a loop, then the indices must be generated from previous iterations, meaning that they are generated from information stored on the heap. With a finite number of heap locations and no strong heap update, the indices must be abstracted, thus not yielding an array of infinite size.

$$\text{Index} = \text{String} + \text{Integer} \tag{4.12}$$

4.4 Transfer functions

To propagate the lattice-elements between nodes in the control-flow graph, each node type has a corresponding transfer function. Most of the transfer functions are defined on State instead of AnalysisLattice, i.e. they are defined as $f_{n,\delta}$: State $\rightarrow$ State rather than $f_{n,\delta}$: AnalysisLattice $\rightarrow$ AnalysisLattice. This eases the notation. Given a state-transfer-function $f'_{n,\delta}$ the corresponding lattice-transfer function, $f_{n,\delta}$, can be defined as

$$f_{n,\delta}(l) = l[\delta \mapsto f'_{n,\delta}(l(\delta))] \tag{4.13}$$

where $n \in \mathcal{N}$ is a node in the control-flow graph and $\delta \in \Delta$ is the current context. The transfer functions are defined in sections 4.4.1 through 4.4.5. In the definitions the 5-tuple $(s_l, s_g, s_h, s_t, s_{ht})$ is used to represent the five lattice-elements inside the State lattice-element given as input to the function.

4.4.1 Operations

Let $n = bop_{\oplus}(t_l, t_r, t_{tar})$ or $n = sop_{\oplus}(t_l, t_r, t_{tar})$. Then

$$f_{n,\delta}((s_l, s_g, s_h, s_t, s_{ht})) = (s_l, s_g, s_h, s_t[t_{tar} \mapsto s(t_l) \oplus s(t_r)], s_{ht}) \tag{4.14}$$

Let $n = uop_{\circ}(t_{val}, t_{tar})$. Then

$$f_{n,\delta}((s_l, s_g, s_h, s_t, s_{ht})) = (s_l, s_g, s_h, s_t[t_{tar} \mapsto \circ s(t_{val})], s_{ht}) \tag{4.15}$$

The soundness of the binary, unary, and short-circuit operations follow from the subsequent implementation of the abstract evaluation. This is covered in detail in section 4.6. These operations solely operate on the temporary variables,

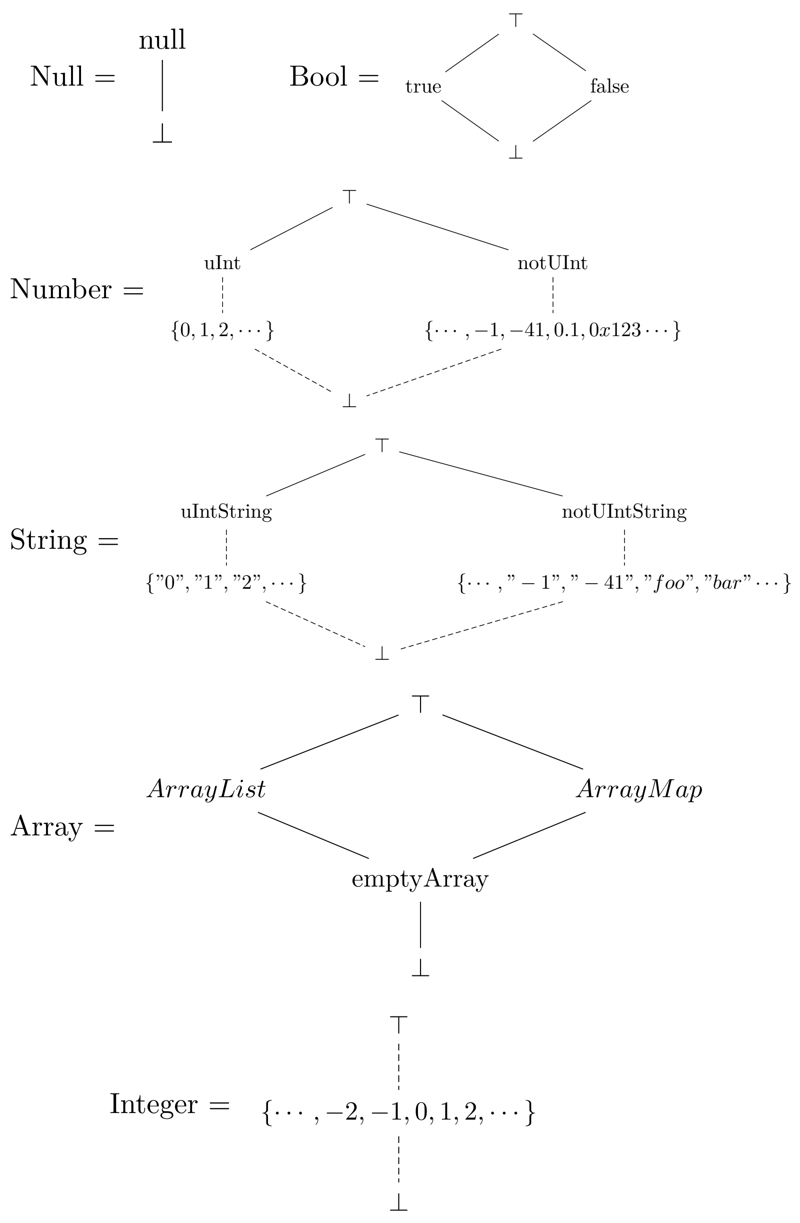


Diagram 4.1: Hasse diagrams of lattices

which act as intermediate storage for the results of computations. By not storing these in the heap every update is a strong update, which increases precision.

Since the increment and decrement operations have to read a set of possible locations and update the value of the locations, these are not performed on the temporary variables. Operations on the heap can never be performed by strong update, hence the new values must be joined with the old. The $\mathit{updateLocations} : \mathcal{P}(\text{HLoc}) \times \text{Heap} \times (\text{HLoc} \to \text{Value}) \to \text{Heap}$ function writes a value to the heap using weak updates.

$$\mathit{updateLocations}(L, h, v) = h[\forall l \in L.l \mapsto h(l) \sqcup v] \tag{4.16}$$

For $n = \mathit{inc}_{\circ}(h_{val}, t_{tar})$ the transfer function is defined as

$$\begin{aligned}
f_{n,\delta}((s_l, s_g, s_h, s_t, s_{ht})) = &\texttt{match } \circ \\
&\quad \texttt{with } \text{PreIncrement:} \\
&\quad \texttt{with } \text{PreDecrement:} \\
&\quad\quad \texttt{let} \\
&\quad\quad\quad s'_h = \mathit{updateLocations}(\\
&\quad\quad\quad\quad s_{ht}(h_{val}), s_h, l \to \circ s_h(l)) \\
&\quad\quad \texttt{in} \\
&\quad\quad (s_l, s_g, s'_h, s_t[t_{tar} \mapsto s'_h(s_{ht}(h_{val}))], s_{ht}) \\
&\quad \texttt{with } \text{PostIncrement:} \\
&\quad \texttt{with } \text{PostDecrement:} \\
&\quad\quad (s_l, s_g, \\
&\quad\quad\quad \mathit{updateLocations}(s_{ht}(h_{val}), s_h, l \to \circ s_h(l)), \\
&\quad\quad\quad s_t[t_{tar} \mapsto s_h(s_{ht}(h_{val}))], s_{ht})
\end{aligned} \tag{4.17}$$

which updates the heap and the target temporary variable t_{tar}.

4.4.2 Variables

When writing to a variable, as in the previous section, strong updates can never occur. The reason for this follows from how PHP performs deep-copy and is covered later in this chapter. The $\mathit{writeVar} : \text{Var} \times \text{Scope} \times \text{Heap} \times \text{Value} \to \text{Scope} \times \text{Heap}$ function writes to the heap while ensuring that the provided scope is updated accordingly.

$$\begin{aligned}
\mathit{writeVar}_{n,\delta}(v, s, h, v_{val}) = &\texttt{if } s(v) = \emptyset \texttt{ then} \\
&\quad (s[v \mapsto \{\text{HLoc}(n, \delta, 0)\}], h[\text{HLoc}(n, \delta, 0) \mapsto v_{val}]) \\
&\texttt{else} \\
&\quad (s, \mathit{updateLocations}(s(v), h, v_{val}))
\end{aligned} \tag{4.18}$$

With the separate Locals and Globals scopes, the current scope (with respect to a variable v) is determined by looking at the current context as well as the variable name. If the context is empty or if the variable is a super-global, then the current scope is the global scope, else it is the local scope. Deciding whether a variable is a superglobal is done by the predicate *isSuperGlobal* which is true if and only if v is either `$_GET`, `$_POST`, `$_SESSION`, `$_COOKIE`, `$_SERVER`, `$_REQUEST`, `$_FILES`, `$_ENV`, or `$GLOBALS`.

An example of how the scope is determined can be seen in program 4.3. The current scope of the variable `$a` on line 4 in a function body is the local scope. The variable `$GLOBALS` on line 5 is a superglobal and thus in the global scope. The variable `$c` is not in a function body, so it is in the global scope. The variable `$b` on line 3 is also in the local scope. This follows from the fact that the variable is only an alias for the corresponding global variable, e.g. it shares the same locations as the global value, but if a reference assignment is performed on `$b`, i.e. `$b = &$a`, it will only affect the local variable, as opposed to a reference assignment to a super-global.

Program 4.3 Scopes

```
1 <?php
2 function f($a){
3   global $b;
4   var_dump($a);
5   var_dump($GLOBALS);
6 }
7 var_dump($c);
```

For $n = \mathit{varWrite}(v, t_{val}, t_{tar})$, the transfer function is defined as

$$\begin{aligned} f_{n,\delta}((s_l, s_g, s_h, s_t, s_{ht})) = & \texttt{if } \delta = \Lambda \vee \mathit{isSuperGlobal}(v) \texttt{ then} \\ & \quad \texttt{let } (g, h) = \mathit{writeVar}_{n,\delta}(v, s_g, s_h, s_t(t_{val})) \texttt{ in} \\ & \quad (s_l, g, h, s_t[t_{tar} \mapsto s_t(t_{val})], s_{ht}) \\ & \texttt{else} \\ & \quad \texttt{let } (l, h) = \mathit{writeVar}_{n,\delta}(v, s_l, s_h, s_t(t_{val})) \texttt{ in} \\ & \quad (l, s_g, h, s_t[t_{tar} \mapsto s_t(t_{val})], s_{ht}) \end{aligned} \tag{4.19}$$

and for $n = \mathit{varWrite}(v, h_{val}, t_{tar})$, the transfer function is defined as

$$\begin{aligned} f_{n,\delta}((s_l, s_g, s_h, s_t, s_{ht})) = & \texttt{if } \delta = \Lambda \vee \mathit{isSuperGlobal}(v) \texttt{ then} \\ & \quad (s_l, s_g[v \mapsto s_{ht}(h_{val})], s_h, s_t[t_{tar} \mapsto s_h(s_{ht}(h_{val}))], s_{ht}) \\ & \texttt{else} \\ & \quad (s_l[v \mapsto s_{ht}(h_{val})], s_g, s_h, s_t[t_{tar} \mapsto s_h(s_{ht}(h_{val}))], s_{ht}) \end{aligned} \tag{4.20}$$

In the latter case the variable is always strongly updated. This is sound, since the current language subset of PHP offers no ambiguity with respect to which variable is currently being updated, specifically because the infamous variable-variable feature is not supported.

Besides resolving the scope as above, reading a variable is quite straight forward. In order to be sound, however, the transfer function needs to take uninitialized variables into account. When reading an uninitialized variable in PHP, the default value is `NULL`. Because of this, if the read is stored in a temporary variable and the variable is not set in the current scope, the result should be Value(Null(⊤)). Otherwise the result should be the joined value of the heap locations pointed to by the variable. So for $n = \mathit{varRead}(v, t_{tar})$, the transfer function is defined as

$$\begin{aligned} f_{n,\delta}((s_l, s_g, s_h, s_t, s_{ht})) = & \texttt{let } s = \\ & \quad \texttt{if } \delta = \Lambda \vee \mathit{isSuperGlobal}(v) \texttt{ then } s_g \texttt{ else } s_l \\ & \quad \texttt{in} \\ & \texttt{let } v = \\ & \quad \texttt{if } s(v) = \emptyset \texttt{ then } \text{Value}(\text{Null}(\top)) \texttt{ else } s_h(s(v)) \\ & \quad \texttt{in} \\ & (s_l, s_g, s_h, s_t[t_{tar} \mapsto v], s_{ht}) \end{aligned} \tag{4.21}$$

When reading the locations of a variable, special care has to be taken when the variable is uninitialized. Since reading the same variable twice with no intermediate modification must return the same locations, the variable has to be initialized when first read. This is done by the $\mathit{initializeVariable}_{n,\delta} : \text{Var} \times \text{Scope} \to \text{Scope}$ function, which creates a new location in the provided scope, if none exists.

$$\mathit{initializeVariable}_{n,\delta}(v, s) = \texttt{if } s(v) = \emptyset \texttt{ then } s[v \mapsto \{\text{HLoc}(n, \delta, 0)\}] \texttt{ else } s \tag{4.22}$$

For $n = \mathit{varRead}(v, h_{tar})$, the transfer function becomes

$$\begin{aligned} f_{n,\delta}((s_l, s_g, s_h, s_t, s_{ht})) = & \texttt{if } \delta = \Lambda \vee \mathit{isSuperGlobal}(v) \texttt{ then} \\ & \quad \texttt{let } s'_g = \mathit{initializeVariable}_{n,\delta}(v, s_g) \texttt{ in} \\ & \quad (s_l, s'_g, s_h, s_t, s_{ht}[h_{tar} \mapsto s'_g(v)] \\ & \texttt{else} \\ & \quad \texttt{let } s'_l = \mathit{initializeVariable}_{n,\delta}(v, s_l) \texttt{ in} \\ & \quad (s'_l, s_g, s_h, s_t, s_{ht}[h_{tar} \mapsto s'_l(v)] \end{aligned} \tag{4.23}$$

4.4.3 Arrays

There are four types of array operations; initialize, read, write, and append, with one, two, three, and four different signatures respectively. For $n = \mathit{arrayInit}(t_{tar})$ the transfer function becomes

$$f_{n,\delta}((s_l, s_g, s_h, s_t, s_{ht})) = (s_l, s_g, s_h, s_t[t_{tar} \mapsto \text{Value}(\text{emptyArray})], s_{ht}) \tag{4.24}$$

which is trivially sound, since all it does is initializing an empty array in the temporary variable given.

Array initialization

Array initialization happens when writing the expression `[···]` or `array(···)`, where the dots indicate initial content. Remember, however, that arrays do not need to be initialized explicitly. An array write or append to an uninitialized variable creates an array and writes to it. This does not yield an *arrayInit* node in the control-flow graph. The initial content is added to the array immediately after initialization by the following $\mathit{arrayAppend}(t_{val}, t_{arr})$ node and the $\mathit{arrayWrite}(t_{val}, t_{key}, t_{arr})$ node.

Array append

Appending a value stored in the temporary storage to an array likewise stored in the temporary storage is performed by first storing the value in the heap at some location l. Then the array is joined with an array-list containing only l. While this implies that an append operation on an array-map results in the $\top$-element array (thus loosing all precision) our hypothesis states that the append operation should only be performed on lists. Therefore, this loss should not occur in a *good* program. Furthermore, cases where the result is the $\top$-element array can be reported to the user as suspicious use. For $n = \mathit{arrayAppend}(t_{val}, t_{arr})$ the transfer function is defined in 4.25. The 5-tupel $(v_a, v_s, v_n, v_b, v_u)$ unfolds the Value lattice-element returned from the look-up in the temporary storage s_t.

$$\begin{aligned}
f_{n,\delta}((s_l, s_g, s_h, s_t, s_{ht})) = \texttt{let} \\
&(v_a, v_s, v_n, v_b, v_u) = s_t(t_{arr}), \\
&l = \mathrm{HLoc}(\delta, n, 0) \\
&\texttt{in} \\
&(s_l, s_g, \\
&\quad s_h[l \mapsto s_t(t_{val})], \\
&\quad s_t[t_{arr} \mapsto (v_a \sqcup \mathrm{ArrayList}(\{l\}), v_s, v_n, v_b, v_u)], \\
&\quad s_{ht})
\end{aligned} \tag{4.25}$$

As mentioned earlier, this append node only occurs immediately after array initialization as a method for inserting initial content into an array. E.g. for the expression $[1, 2, 3]$, the numbers 1, 2, and 3 are appended to the array initialized by the brackets.

Probably the most common use of array appends are in an ordinary assignment, e.g. `$a[] = 42` or `$a['someKey'][] = 42`. In this case the value, `42`, is stored in temporary storage, and the location of the array being modified is stored in the heap. The operation is then appending a value on a set of locations, which is done in the same manner as the previous node using a newly created array-list lattice-element to join with. Here however, the value being appended is also added to the temporary variable t_{tar}, since this is the evaluation of the append-expression, e.g. `echo $a[] = 42;` prints the number `42`.

For $n = \mathit{arrayAppend}(h_{var}, t_{val}, t_{tar})$, the transfer function is defined as

$$\begin{aligned} f_{n,\delta}((s_l, s_g, s_h, s_t, s_{ht})) = & \texttt{let } l' = \text{HLoc}(\delta, n, 0) \texttt{ in} \\ & \texttt{let } s'_t = s_t[t_{tar} \mapsto s_t(t_{val})] \texttt{ in} \\ & \texttt{let } s'_h = s_h[\\ & \quad l' \mapsto s_t(t_{val}), \\ & \quad \forall l \in s_{ht}(h_{var}). \\ & \quad \texttt{let } (v_a, v_s, v_n, v_b, v_u) = s_h(l) \texttt{ in} \\ & \quad l \mapsto (v_a \sqcup \text{ArrayList}(\{l'\}), v_s, v_n, v_b, v_u)] \\ & \;\texttt{in} \\ & (s_l, s_g, s'_h, s'_t, s_{ht}) \end{aligned} \tag{4.26}$$

Another type of append is in the context of a reference assignment, e.g. `$a[] = &$b`. Here the locations pointed to by `$b` should be appended to the array(s) at `$a`, i.e. appending a value, in the form of a set of locations to a set of locations. This is done like before, the only difference being that the array-list of which the existing values are joined, does not contain a single new location, rather the set of locations corresponding to the value. Again, the target variable in temporary storage must be set to the value assigned, not the location-set representing the value.

For $n = \mathit{arrayAppend}(h_{var}, h_{val}, t_{tar})$, the transfer function becomes

$$\begin{aligned} f_{n,\delta}((s_l, s_g, s_h, s_t, s_{ht})) = & \texttt{let } s'_t = s_t[t_{tar} \mapsto s_h(s_{ht}(h_{val}))] \texttt{ in} \\ & \texttt{let } s'_h = s_h[\\ & \quad \forall l \in s_{ht}(h_{var}). \\ & \quad \texttt{let } (v_a, v_s, v_n, v_b, v_u) = s_h(l) \texttt{ in} \\ & \quad l \mapsto (v_a \sqcup \text{ArrayList}(s_{ht}(h_{val})), v_s, v_n, v_b, v_u)] \\ & \;\texttt{in} \\ & (s_l, s_g, s'_h, s'_t, s_{ht}) \end{aligned} \tag{4.27}$$

The final array-append operation occurs when an array is appended and immediately thereafter accessed, e.g. `$a[]['key']` where a location is appended to the array at `$a` and immediately thereafter implicitly initialized as an array and written to. As previously mentioned an array does not have to be explicitly initialized. The location l' is created and appended in the same way as previously to all possible array locations. Since the heap lattice element initializes new locations to Value(Null($\top$)), it is important and sound to set l' to Value($\perp$), since the location will be joined with another array immediately after.

For $n = \mathit{arrayAppend}(h_{var}, h_{tar})$, the transfer function is defined as

$$
\begin{aligned}
f_{n,\delta}((s_l, s_g, s_h, s_t, s_{ht})) = & \texttt{let } l' = \mathrm{HLoc}(\delta, n, 0) \texttt{ in} \\
& \texttt{let } s'_{ht} = s_{ht}[h_{tar} \mapsto \{l'\}] \texttt{ in} \\
& \texttt{let } s'_h = s_h[\\
& \quad l' \mapsto \mathrm{Value}(\bot), \\
& \quad \forall l \in s_{ht}(h_{var}). \\
& \quad \texttt{let } (v_a, v_s, v_n, v_b, v_u) = s_h(l) \texttt{ in} \\
& \quad l \mapsto (v_a \sqcup \mathrm{ArrayList}(\{l'\}), v_s, v_n, v_b, v_u)] \\
& \ \texttt{in} \\
& (s_l, s_g, s'_h, s_t, s'_{ht})
\end{aligned}
\tag{4.28}
$$

Array read and write

When writing to or reading from an array, given a value v as key, the value must first be coerced to an array index. The easy approach would be to use the coercion function $c_{\text{Value,ArrayIndex}}(v)$ introduced in section 4.5 directly, which coerces and then joins all factors. This approach would for instance coerce the value $v = (\bot, \texttt{"foo"}, 4, \bot, \bot)$ to the index $i = c_{\text{Array,ArrayIndex}}(\bot) \sqcup \cdots \sqcup c_{\text{Null,ArrayIndex}}(\bot) = \texttt{"foo"} \sqcup 4 = \top$.

Another approach would be to consider a set of possible indices I rather than a single index, by coercing the factors individually and accessing the array with each index. For the previous example v would yield the set $I = \{\bot, \texttt{"foo"}, 4\}$. Since the value will most likely contain at least one $\bot$ factor, the set of indices will also contain the $\bot$ array index, which will become a problem. This becomes apparent when first considering how values are written to and read from array-maps. Writing index i with location set L on some array-map, a, should ideally be done by joining the location set of each entry in a with L where i is contained in the corresponding key, i.e. $a[\forall d \in \mathit{dom}(a) \wedge i \sqsubseteq d.d \mapsto a(d) \sqcup L]$. Updating a possibly infinite domain could be done lazily, but deciding containment of two lattices, where one has infinitely many changes, is not practically feasible. As a compromise the only entry updated in a is key i with the joined set $a(i) \sqcup L$. This compromise entails that when reading i' from array-map a, the set of possible keys is all $d \in \mathit{dom}(a)$ where $d \sqsubseteq i' \vee i' \sqsubseteq d$, which is practically feasible.

Returning to the problematic $\bot$ factors, since most writes would contain a at least one $\bot$ factor, most writes would, with the second approach, write to the $\bot$ index, and since $\bot$ is contained in all indices, massive loss of precision occurs. Therefore a third option is to only consider coerced factors, of the key value, that are not contained in other factors. This reduces the set of the previous example to $I = \{\texttt{"foo"}, 4\}$. These are the indices returned by the function *indices* : Value $\to$ ArrayIndex*

$$\begin{aligned}
\mathit{indices}(v) = & \texttt{let } (v_a, v_s, v_n, v_b, v_u) = v \texttt{ in} \\
& \texttt{let } I = \{c_{\text{Array,Index}}(v_a), \\
& \quad c_{\text{String,Index}}(v_s), \\
& \quad c_{\text{Number,Index}}(v_n), \\
& \quad c_{\text{Boolean,Index}}(v_b), \\
& \quad c_{\text{Null,Index}}(v_n)\} \texttt{ in} \\
& I \setminus \{j | i, j \in I \land j \sqsubseteq i \land i \neq j\}
\end{aligned} \tag{4.29}$$

Using the above function we are able to generalize reading from an array as a function *readArray* : Value $\times$ Value $\times$ Heap $\to \mathcal{P}(L)$, which given a value, key, and heap returns a set of possible value locations. Reading an index from a list returns the set of locations in the list, since no key information is kept about list indices. Reading from $\perp$ or emptyMap results in the empty set, since those contain no locations. Finally, reading from $\top$ results in all possible locations, e.g. the top element of $\mathcal{P}(L)$, since an array can potentially point to every location in the heap, including itself.

$$\begin{aligned}
\mathit{readArray}(v, k, h) = & \texttt{let } (v_a, v_s, v_n, v_b, v_u) = v \texttt{ in} \\
& \texttt{match } v_a \\
& \quad \texttt{with } \top\text{: } \mathit{dom}(h) \\
& \quad \texttt{with } \text{ArrayList}(L)\text{: } L \\
& \quad \texttt{with } \text{ArrayMap(m):} \\
& \quad \quad \bigcup_{d \in \mathit{dom}(m) \land \exists i \in \mathit{indices}(k). i \sqsubseteq d \lor d \sqsubseteq i} m(d) \\
& \quad \texttt{with } \text{emptyArray: } \emptyset \\
& \quad \texttt{with } \perp\text{: } \emptyset
\end{aligned} \tag{4.30}$$

In the same manner, the act of writing to an array can be generalized to the function *writeArray* : Value $\times$ Value $\times \mathcal{P}(L) \to$ Value. Here, writing to a $\top$ array results in a $\top$ array, writing to a map updates the keys as discussed before, and writing to anything else either returns a list or a map depending on the type of keys being used. If any of the indices are strings, then a map is returned otherwise a list is returned. The predicate *isInteger*(i) holds iff i is an integer.

```
$writeArray(v,k,L) =$ let $(v_a, v_s, v_n, v_b, v_u) = v$ in
                      let $m = \text{ArrayMap}([\forall i \in indices(k).i \mapsto L])$ in
                      (match $v_a$
                        with $\text{ArrayList}(L')$:
                          if $\exists i \in indices(k).\neg isInteger(i)$ then
                            $\text{ArrayMap}([\top \mapsto L']) \sqcup m$ else
                            $\text{ArrayList}(L \cup L')$
                        with $\text{ArrayMap}(m')$: $m' \sqcup m$
                        with emptyArray:
                          if $\exists i \in indices(k).\neg isInteger(i)$ then
                            $m$ else ArrayList(L)
                        with $\bot$:
                          if $\exists i \in indices(k). \neq isInteger(i)$ then
                            $m$ else ArrayList(L)
                        with $\top$: $\top, v_s, v_n, v_b, v_u$)                    (4.31)
```

With these functions in place, the transfer functions for the array-read and array-write nodes can be defined. For reading from an array in temporary storage, e.g. the right-hand side of the assignment `$b = $a['key']`, the node is $n = arrayRead(t_{arr}, t_{key}, t_{tar})$ where the value read from the array should be stored at t_{tar}. The query is always joined with Value(Null($\top$)) since an entry might not be set. The transfer function is defined as

```
$f_{n,\delta}((s_l, s_g, s_h, s_t, s_{ht})) =$ let $L = readArray(s_t(t_{arr}), s_t(t_{key}), s_h)$ in
                                  let $v = \text{Value}(\text{Null}(\top)) \sqcup s_h(L)$ in
                                  $(s_l, s_g, s_h, s_t[t_{tar} \mapsto v], s_{ht})$          (4.32)
```

Another array-read operation is resolving the locations of an entry corresponding to a given key, e.g. resolving entry `$a['foo']` in the assignment `$a['foo'][] = 42`. This is done by joining the locations of each possible entry, adding a new location to each entry yielding an empty location-set. Updating empty entries ensures that subsequent modifications of the returned location-set are propagated to every possible array. For this operation, the node is

$n = \mathit{arrayRead}(h_{var}, t_{key}, h_{tar})$ and the transfer function becomes

$$\begin{aligned} f_{n,\delta}((s_l, s_g, s_h, s_t, s_{ht})) = & \texttt{let } l = \text{HLoc}(\delta, n, 0) \texttt{ in} \\ & \texttt{let } s'_{ht} = s_{ht}[h_{tar} \mapsto \\ & \quad \cup_{l' \in s_{ht}(h_{var})} \mathit{cardCheck}(\\ & \quad\quad \mathit{readArray}(s_h(l'), s_t(t_{key}), s_h), l)] \\ & \; \texttt{in} \\ & \texttt{let } s'_h = \\ & \quad s_h[\forall l' \in s_{ht}(h_{var}) \\ & \quad\quad\quad \wedge \mathit{readArray}(s_h(l'), s_t(t_{key}), s_h) = \emptyset. \\ & \quad\quad l' \mapsto \mathit{writeArray}(s_h(l'), s_t(t_{key}), \{l\})] \\ & \; \texttt{in} \\ & (s_l, s_g, s'_h, s_t, s'_{ht}) \end{aligned} \tag{4.33}$$

where

$$\mathit{cardCheck}(L, l) = \texttt{if } L = \emptyset \texttt{ then } \{l\} \texttt{ else } L \tag{4.34}$$

All explicit array initializations initialize an empty array. Any initial data is added by subsequent array-appends (covered in the section about array append) and array-write operations. For example initializing an array `['a'=>1, 'b'=>2]` two array-write operations follow, one for each entry. The transfer function for the corresponding control-flow node $n = \mathit{arrayWrite}(t_{key}, t_{val}, t_{arr})$ uses the *writeArray* function. Here, the value at temporary variable t_{val} is stored in the heap at a new location, which is consequently written to the existing array. The transfer function is defined as

$$\begin{aligned} f_{n,\delta}((s_l, s_g, s_h, s_t, s_{ht})) = & \texttt{let } l' = \text{HLoc}(\delta, n, 0) \texttt{ in} \\ & \texttt{let } v' = \texttt{ in} \\ & (s_l, s_g, s_h[l' \mapsto s_t(t_{val})], \\ & \quad s_t[t_{arr} \mapsto \mathit{writeArray}(s_t(t_{arr}), s_t(t_{key}), \{l'\})], s_{ht}) \end{aligned} \tag{4.35}$$

When the array is residing in the heap rather than temporary storage, e.g. `$a['key'] = 42`, the possible locations of the array must first be resolved. Having done that, the write operation can be performed. This is expressed with the node $n = \mathit{arrayWrite}(h_{var}, t_{key}, t_{val}, t_{tar})$, where the transfer function is defined as

$$
\begin{aligned}
f_{n,\delta}((s_l, s_g, s_h, s_t, s_{ht})) = & \texttt{let } l' = \mathrm{HLoc}(\delta, n, 0) \texttt{ in} \\
& \texttt{let } s'_t = s_t[t_{tar} \mapsto s_t(t_{val})] \texttt{ in} \\
& \texttt{let } s'_h = s_h[\\
& \qquad \forall l \in s_h(h_{var}). \\
& \qquad\quad \forall l'' \in \mathit{readArray}(s_h(l), s_t(t_{key}), s_h). \\
& \qquad\qquad l'' \mapsto s_h(l'') \sqcup s_t(t_{val})] \texttt{ in} \\
& \texttt{let } s''_h = s'_h[\\
& \quad l' \mapsto s_t(t_{val}), \\
& \quad \forall l \in s_{ht}(h_{var}). \\
& \quad l \mapsto \mathit{writeArray}(s'_h(l), s_t(t_{key}), \{l'\})] \\
& \texttt{ in} \\
& (s_l, s_g, s''_h, s'_t, s_{ht})
\end{aligned} \tag{4.36}
$$

Writing a value to an array can be viewed as two cases; writing to an existing entry and writing to a new entry. The first case entails that the value stored in the heap should be updated and the other that a new location pointing to the new value should be added to the entry. In order to perform a sound write, both cases are performed.

Writing to an array in the context of a reference assignment, e.g. `$a['key'] = &$b;`, is performed by writing the set of locations pointed to by `$b` to the entry at `'key'` in array `$a`. This is expressed with the node $n = \mathit{arrayWrite}(h_{var}, t_{key}, h_{val}, t_{tar})$, where the transfer function is defined as

$$
\begin{aligned}
f_{n,\delta}((s_l, s_g, s_h, s_t, s_{ht})) = & \texttt{let } s'_t = s_t[t_{tar} \mapsto s_t(s_h(s_{ht}(h_{val})))] \texttt{ in} \\
& \texttt{let } s'_h = s_h[\\
& \quad \forall l \in s_{ht}(h_{var}). \\
& \quad l \mapsto \mathit{writeArray}(s_h(l), s_t(t_{key}), s_{ht}(h_{val}))] \\
& \texttt{ in} \\
& (s_l, s_g, s'_h, s'_t, s_{ht})
\end{aligned} \tag{4.37}
$$

Notice that this operation does not update the heap values as the previous functions. This is sound because assigning new locations are in practice overwriting old ones. If the array keys were to be exactly resolved a strong update could be performed here, just as the case with the reference assignment to variables.

The array operations might seem similar to the operations on variables just with another level of ambiguity. Viewing the scopes as array-maps from strings to location-sets is not far from how PHP implements scopes and may provide a good intuition as to how and why the variable-variables feature is implemented.

Notice that no strong updates are performed on heap values. This is in order to maintain soundness and follows from how PHP performs deep copy, which is described in section 2.2.3. By copying the references, PHP opens the possibility for the modification of a deep-copied array through another variable or array, with no reference assignment from the array. In order to be sound, the analysis has to assume that no arrays are deep copied, but instead share the internal references of the original array. From this follows that no strong updates can be performed on any location, because it might result in an update of an array which in practice never share the location of the variable. This issue is illustrated in program 4.4. If strong updates were allowed, updating `$c` in the last line would result in `$a` rightfully and `$b` wrongfully being updated to the list containing the number two (`2`) since the two arrays share the same internal locations. By only performing weak updates, the two arrays become lists of UIntNumber which is sound.

Program 4.4

```
$a = [1];
$b = $a;
$c = &$a[0];
$c = 2;
```

4.4.4 Function calls

The transfer functions for function calls (*call* and *result* nodes) differ from the other functions. For $n = call_{fn}(c_1, \ldots, c_n)$, the transfer function $f_{n,\delta}$: AnalysisLattice $\rightarrow$ AnalysisLattice sets up the local scope for the function body of *fn*. This scope is initially empty with the exception of the function arguments being set by reference or by value, depending on whether the call arguments, $c_1, \ldots, c_n$, are variable names in THVar or TVar.

If the argument is passed by reference, the corresponding argument is set in the local scope to point at the provided heap locations. If the argument is passed by value, then the argument is pointing to a newly created heap location, which in turn points to the value. The second case is one of the reasons for HLoc being defined as a product of context, node, and a natural number. Without the third factor all value-passed arguments would be written to the same heap-location. This is avoided by setting the number in the heap location to the position of the argument in question.

The global scope and heap is preserved in the new state, while the temporary maps both are *emptied*. The transfer function is defined as

```
$f_{n,\delta}(l) =$ let $\delta' = addCallNode(\delta, n)$ in
        let $(\_, s_g, s_h, s_t, \_) = l[\delta]$ in
        let $s_l = [\forall(v, i) \in args(fn).v \mapsto$
          match $c_i$
            with TVar: $\{\text{HLoc}(\delta, startNode(fn), i)\}$
            with THVar: $s_h(c_i)]$
         in
        let $s'_h = [\forall(\_, i) \in args(fn).\text{HLoc}(\delta, startNode(fn), i) \mapsto$
          match $c_i$
            with TVar: $s_t(c_i)$
            with THVar: $s_h(\text{HLoc}(\delta, startNode(fn), i))]$
         in
        $(s_l, s_g, s'_h, [], [])$                                    (4.38)
```

where the function $addCallNode : \Delta \times \text{CallNode} \to \Delta$ decides the target context from the current, the function $args : \text{FunctionNames} \to (\text{Var} \times \mathbb{N})^*$ given a function name returns a list of arguments expressed as pairs of variable names and positions, and the function $startNode : \text{FunctionNames} \to \text{StartNode}$ given a function name returns the unique *start* node of that function. The heap locations created are associated with the start node rather than the call node for higher efficiency.

After execution of a function it is the task of the transfer function of the result node to restore the old execution context. For $n = result_{call_{fn}}(\_)$, the transfer functions are defined as functions from two lattice-elements to a single lattice-element:

$$f_{n,\delta_{call},\delta_{exit}} : \text{AnalysisLattice} \times \text{AnalysisLattice} \to \text{AnalysisLattice}$$

where the first lattice-element is the element passed to the transfer function of the call node $call_{fn}$ and δ_{call} is the original context. The second lattice-element is the usual element derived from incoming flow. Depending on the argument of the *result* node, the transfer function is defined as either of 4.39

and 4.40

```
$f_{n,\delta_{call},\delta_{exit}}(l_{call}, l_{exit}) =$let  $exit(c_1, \cdots, c_n) = exitNode(fn)$  in
    let  $(s_l, \_, \_, s_t, s_{ht}) = l_{call}(\delta_{call})$  in
    let  $(\_, s_g, s_h, s'_t, s'_{ht}) = l_{exit}(\delta_{exit})$  in
    let  $v =$
        $\bigsqcup_{0<i\leq n}$ match $c_i$
            with $TVar$: $s_t(c_i)$
            with $THVar$: $s_h(s_{ht}(c_i))$
     in
    $(s_l, s_g, s_h, s_t[t_{val} \mapsto v], s_{ht})$                    (4.39)
```

let $n = result_{call_{fn}}(t_{val})$ or $n = result_{call_{fn}}(h_{val})$ as

```
$f_{n,\delta_{call},\delta_{exit}}(l_{call}, l_{exit}) =$let  $exit(c_1, \cdots, c_n) = exitNode(fn)$  in
    let  $(s_l, \_, \_, s_t, s_{ht}) = l_{call}(\delta_{call})$  in
    let  $(\_, s_g, s_h, s'_t, s'_{ht}) = l_{exit}(\delta_{exit})$  in
    let  $L =$
        $\bigcup_{0<i\leq n}$ match $c_i$
            with $TVar$: $\{\text{HLoc}(n, \delta_{call}, i)\}$
            with $THVar$: $s_{ht}(c_i)$
     in
    let  $s'_h = s_h[\forall 0 < i \leq n.\text{HLoc}(n, \delta_{call}, i) \mapsto$
      match $c_i$
        with $TVar$: $s_t(c_i)$
        with $THVar$: $s_h(\text{HLoc}(n, \delta_{call}, i))]$
     in
    $l_{call}[\delta_{call} \mapsto (s_l, s_g, s'_h, s_t, s_{ht}[h_{val} \mapsto L])]$          (4.40)
```

where the *exitNode* : FunctionName → ExitNode function given a function name returns the corresponding unique exit node. These functions will return a lattice-element containing all local values, temps and local scope from the call-context, and the global values, global scope, and heap from the exit-context. The possible result of the function-call is gathered from the exit-node and saved in either temporary- or heap-temporary-variables, depending on the function being pass-by-value or pass-by-reference respectively. In the latter case the position of the *exit-argument* is again used to decide which heap location to save the value at, if the function returns a value rather than references. Since the number of arguments in any function definition, the number of return statements in any function body, and the number of initialized arrays in the start lattice-element in practice are finite, so is the number of heap-locations.

4.4.5 Other transfer functions

Two interesting transfer functions remain. The first one is the function for $n = \mathit{constRead}(c, t_{tar})$. This function converts a constant c to a lattice using the $\mathit{value} : \mathcal{C} \to \text{Value}$ function (working as one would expect) and is defined as

$$f_{n,\delta}((s_l, s_g, s_h, s_t, s_{ht})) = (s_l, s_g, s_h, s_t[t_{tar} \mapsto \mathit{value}(c)], s_{ht}) \tag{4.41}$$

The last function is for $n = \mathit{global}(v_0, v_1, \cdots, v_{n-1})$, which creates variables in the local scope, sharing the locations of the corresponding variable in the global scope. If the variable points to no locations, a new location must be added to the global and local scope. If the current scope is empty no modifications are made to the input lattice-element. The transfer function is defined as

```
$f_{n,\delta}((s_l, s_g, s_h, s_t, s_{ht})) =$match $\delta$
    with $\Lambda$: $(s_l, s_g, s_h, s_t, s_{ht})$
    with _:
      let $s'_g = s_g[\forall 0 \leq i \leq n.v_i \mapsto$
        if $s_g[v_i] = \emptyset$ then
          $\{\text{HLoc}(n, \delta, i)\}$ else $s_g[v_i]]$
       in
      let $s'_l = s_l[\forall 0 \leq i \leq n.v_i \mapsto s'_g(v_i)]$ in
      $(s'_l, s'_g, s_h, s_t, s_{ht})$                                   (4.42)
```

All other transfer functions are the identity function: $f_{n,\delta}(l) = l$.

4.5 Coercion

In order to fully utilize the benefits of a dynamically typed language, PHP supports coercion from most types to scalars (strings, numbers and booleans). Coercion is primarily used when performing binary and unary operations, and when accessing arrays. Coercion to an array index must be treated as a separate case, since it behaves differently from string or number coercion. For example accessing an array with key `$key` (`$a[$key]`) if `$key = 42` or `$key = "42"` then the entry at integer 42 is accessed, which is similar to string-to-number coercion. The same entry is accessed with `$key = 42.1` or `$key = 4.34E1`, since keys must be either integers or strings. Accessing with `$key = "42.1"` accesses the entry with string key `"42.1"`.

Since there is no formal language specification, these coercion rules have largely been discovered by manual inspection, using different operators, e.g. number coercion has been explored by adding values of various types together, with the binary `+`-operator and string coercion with the string-concatenation `.`-operator.

Coercion on abstract values can be performed using the $c_{\alpha,\beta} : \alpha \to \beta$ function, where $\alpha \in \{\text{Value}, \text{Array}, \text{Number}, \text{String}, \text{Null}, \text{Boolean}\}$ and $\beta \in \{\text{Number}, \text{Value}, \text{String}, \text{Index}, \text{Boolean}\}$.

Coercing to and from abstract values is defined by the following functions

$$c_{\alpha,\text{Value}}(v) = \begin{cases} (v,\bot,\bot,\bot,\bot) & \text{if } \alpha = \text{Array} \\ (\bot,v,\bot,\bot,\bot) & \text{if } \alpha = \text{String} \\ (\bot,\bot,v,\bot,\bot) & \text{if } \alpha = \text{Number} \\ (\bot,\bot,\bot,v,\bot) & \text{if } \alpha = \text{Boolean} \\ (\bot,\bot,\bot,\bot,v) & \text{if } \alpha = \text{Null} \end{cases}$$

$$\begin{aligned} c_{\text{Value},\beta}((v_1,v_2,v_3,v_4,v_5)) = {} & c_{\text{Array},\beta}(v_1) \sqcup c_{\text{String},\beta}(v_2) \\ & \sqcup c_{\text{Number},\beta}(v_3) \sqcup c_{\text{Boolean},\beta}(v_4) \sqcup c_{\text{Null},\beta}(v_5) \end{aligned}$$

$$c_{\text{Array,String}}(v) = \begin{cases} \texttt{"Array"} & \text{if } v \neq \bot \\ \bot & \text{else} \end{cases} \qquad c_{\text{Null,String}}(v) = \begin{cases} \text{""} & \text{if } v = \top \\ \bot & \text{else} \end{cases}$$

$$c_{\text{Number,String}}(v) = \begin{cases} \text{uIntStr} & \text{if } v = \text{uInt} \\ \text{notUIntStr} & \text{if } v = \text{notUInt} \\ \top & \text{if } v = \top \\ \bot & \text{if } v = \bot \\ \mathit{string}(v) & \text{else} \end{cases} \qquad c_{\text{Bool,String}}(v) = \begin{cases} \texttt{""} & \text{if } v = \text{false} \\ \texttt{"1"} & \text{if } v = \text{true} \\ v & \text{else} \end{cases}$$

$$c_{\text{Array,Bool}}(v) = \begin{cases} \text{false} & \text{if } v = \text{emptyArray} \\ \bot & \text{if } v = \bot \\ \top & \text{else} \end{cases} \qquad c_{\text{Null,Bool}}(v) = \begin{cases} \text{false} & \text{if } v = \top \\ \bot & \text{else} \end{cases}$$

$$c_{\text{Number,Bool}}(v) = \begin{cases} \text{false} & \text{if } v = 0 \\ \bot & \text{if } v = \bot \\ \top & \text{if } v = \text{uInt} \vee v = \top \\ \text{true} & \text{else} \end{cases} \qquad c_{\text{String,Bool}}(v) = \begin{cases} \text{false} & \text{if } v = \texttt{""} \vee v = \texttt{"0"} \\ \bot & \text{if } v = \bot \\ \top & \text{if } v = \text{uIntString} \vee v = \top \\ \text{true} & \text{else} \end{cases}$$

$$c_{\text{Null,Number}}(v) = \begin{cases} 0 & \text{if } v = \top \\ \bot & \text{else} \end{cases} \qquad c_{\text{Array,Number}}(v) = \bot$$

$$c_{\text{Bool,Number}}(v) = \begin{cases} 1 & \text{if } v = \text{true} \\ 0 & \text{if } v = \text{false} \\ \text{uInt} & \text{if } v = \top \\ \bot & \text{if } v = \bot \end{cases} \qquad c_{\text{String,Number}}(v) = \begin{cases} \mathit{num}(v) & \text{if } \mathit{isNumber}(v) \\ \text{uInt} & \text{if } v = \text{uIntString} \\ \top & \text{if } v = \text{notUIntString} \\ \top & \text{if } v = \top \\ \bot & \text{if } v = \bot \\ 0 & \text{else} \end{cases}$$

$$c_{\text{Array,Index}}(v) = \bot \qquad c_{\text{Bool,Index}}(v) = c_{\text{Bool,Number}}(v)$$

$$c_{\text{Number,Index}}(v) = \begin{cases} \mathit{int}(v) & \text{if } \mathit{isNumber}(v) \\ \bot & \text{if } v = \bot \\ \top & \text{else} \end{cases} \qquad c_{\text{String,Index}}(v) = \begin{cases} \mathit{int}(v) & \text{if } \mathit{isInteger}(v) \\ v & \text{if } \mathit{isString}(v) \\ \top & \text{else} \end{cases}$$

$$c_{\text{Null,Index}}(v) = \begin{cases} \texttt{""} & \text{if } v = \top \\ \bot & \text{else} \end{cases} \qquad c_{\alpha,\alpha}(v) = v$$

The functions *int*, *num*, and *string* create an integer, a number, and a string, respectively, in the obvious way, e.g. $\mathit{int}(42.1) = 42$, $\mathit{string}(1337) = $ `"1337"`, and *number*(`"1337"`) $= 1337$. Furthermore the predicates *isNumber*, *isInteger* and *isString* are satisfied if and only if the value can be interpreted as a number, integer, or string respectively. For example *isNumber*(`"42.1"`) is satisfied while *isInteger*(`"42.1"`) is not.

Five interesting cases of coercion in PHP include: (i) any array coerced to a string will result in the string `"Array"`, (ii) `null` is string-coerced to the empty

Operator	Name	Signature
`x + y`	Addition	Number × Number → Number
`x - y`	Subtraction	
`x * y`	Multiplication	
`x ** y`	Exponentiation	
`x / y`	Division	Number × Number → Value
`x % y`	Modulo	
`x == y`	Equal	Value × Value → Boolean
`x != y`	Not equal	
`x === y`	Identical	
`x !== y`	Not identical	
`x < y`	Less than	
`x <= y`	Less than or equal	
`x > y`	Greater than	
`x >= y`	Greater than or equal	
`x && y`	Logical and	Boolean × Boolean → Boolean
`x AND y`		
`x || y`	Logical or	
`x OR y`		
`x XOR y`	Exclusive or	
`x . y`	String concatenation	String × String → String

Table 4.2: Binary operators

string, (iii) both the empty string and the string literal `"0"` are boolean-coerced to boolean `false`, (iv) boolean `false` is string-coerced to the empty string, and (v) an empty array is boolean-coerced to boolean `false`.

4.6 Abstract evaluation

The PHP language syntax contains a set of binary and unary operators. These operators evaluate one or two operand values to a result value. Working with abstract values introduces the need for an abstract evaluation of these operators. Being dynamically typed, PHP allows for many cross-type operations to be performed, some of which simply coerce the operands to sensible types. However some exceptions exist, e.g. performing the increment operation on strings. P0 does not support these exceptions. The operations are supported on the types on which they are defined, and cross-type operations are supported by using the coercion functions defined in the previous section.

In order to maintain some precision when evaluating binary and unary operators, a table is created for each operation defining the result of evaluating a given input abstractly. These tables are available in appendix B with some interesting cases presented below.

The binary and unary operators supported are listed in table 4.2 and 4.3 respectively. Associated with them is their signature, indicating for which values they are defined. The operators are generalized to values by using the coercion

Operator	Name	Signature
`! x`	Negation	Boolean $\rightarrow$ Boolean
`- - x`	Pre-decrement	Number $\rightarrow$ Number
`x - -`	Post-decrement	
`+ + x`	Pre-increment	
`x + +`	Post-increment	
`- x`	Unary Minus	

Table 4.3: Unary operators

function from the previous section. E.g. given values x and y

$$x \oplus y = c_{\beta,\text{Value}}(c_{\text{Value},\alpha}(x) \oplus c_{\text{Value},\alpha}(y))$$

where $\oplus : \alpha \times \alpha \rightarrow \beta$. Likewise the unary operations can be generalized to values

$$\circ x = c_{\alpha,\text{Value}}(\circ(c_{\text{Value},\alpha}(x)))$$

where $\circ : \alpha \rightarrow \alpha$. For example performing addition `41 + true` coerces the right-hand side to `1` yielding `42` as result of the addition.

In table 4.2 logical `AND` and `OR` operators have two different notations. This is due to PHP specifying different precedence for the two notations. The textual operators bind weaker than assignments, whereas the symbol operators bind stronger than assignments. Since the abstract syntax tree for the analysis is provided, this difference has no direct impact on the analysis implementation.

For numeric operators the variables x, y, a, and b are used. The variables x and y denote an integer larger than zero ($x, y \in \mathbb{Z} \wedge x, y > 0$) and the variables a, b denotes a double smaller than zero or not an integer, $a, b \in \mathbb{R} \wedge (a, b < 0 \vee a, b \notin \mathbb{Z})$. Rephrased; x and y are uInt numbers and a and b are notUInt numbers, e.g. with this notation the addition $x + a$ would be an addition of a uInt number (x) and a notUInt number (a).

Table 4.4 defines abstract subtraction. Numbers in uInt are split into 0 and all other numbers, while numbers in notUInt are split into negative and positive numbers. These splits are made to improve the precision of the operator. The right-identity of subtraction is 0 which is used in the 0-column of table 4.4 to get uInt instead of $\top$. Subtracting negative numbers correspond to adding the absolute value of the number, e.g. $5 - (-3) = 5 + 3$. For uInt this means that adding negative integers results in uInt instead of $\top$.

For division and modulo operators, an error can occur trying to divide by 0. PHP handles division by 0 by returning the boolean `false` value instead of a number. For this reason, division and modulo operators are functions from numbers to a value as opposed to the rest of the numeric operators. The shorthand f is used instead of the boolean `false` value to keep the table smaller. Only the uInt part of the number lattice can contain 0 which restricts the amount of possible `false` returns for division. However as seen in table 4.5 the amount of possible `false` values is high for the modulus operator. This is

$-$	$\bot$	0	y	uInt	$b \in \mathbb{Z}$	b	notUInt	$\top$
$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$
0	$\bot$	0	y	$\top$	$-b$	$-b$	$\top$	$\top$
x	$\bot$	x	$x-y$	$\top$	$x-b$	$x-b$	$\top$	$\top$
uInt	$\bot$	uInt	$\top$	$\top$	uInt	notUInt	$\top$	$\top$
$a \in \mathbb{Z}$	$\bot$	a	$a-y$	notUInt	$a-b$	$a-b$	$\top$	$\top$
a	$\bot$	a	$a-y$	notUInt	$a-b$	$a-b$	$\top$	$\top$
notUInt	$\bot$	notUInt	notUInt	notUInt	$\top$	$\top$	$\top$	$\top$
$\top$	$\bot$	$\top$	$\top$	$\top$	$\top$	$\top$	$\top$	$\top$

Table 4.4: Abstract subtraction

because PHP handles modulus for decimal numbers by truncating the decimal part, which means $-0.5 \Rightarrow 0$ and $0.8 \Rightarrow 0$. The result of the modulus operator is always an integer and the sign is dictated by the sign of the left-hand operand, which can be seen in the table by the $\top$-element column not consisting solely of $\top$-element results.

%	$\bot$	0	y	uInt	$1 > b > -1$	b	notUInt	$\top$
$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$
0	$\bot$	f	0	$0 \sqcup f$	$0 \sqcup f$	0	$0 \sqcup f$	$0 \sqcup f$
x	$\bot$	f	$x\%y$	uInt $\sqcup f$	$x\%b$	$x\%b$	uInt $\sqcup f$	uInt $\sqcup f$
uInt	$\bot$	f	uInt	uInt $\sqcup f$	uInt $\sqcup f$	uInt	uInt $\sqcup f$	uInt $\sqcup f$
$1 > a > -1$	$\bot$	f	$a\%y$	uInt $\sqcup f$	$a\%b$	$a\%b$	uInt $\sqcup f$	uInt $\sqcup f$
a	$\bot$	f	$a\%y$	notUInt $\sqcup f$	$a\%b$	$a\%b$	notUInt $\sqcup f$	notUInt $\sqcup f$
notUInt	$\bot$	f	$\top$	$\top \sqcup f$	$\top \sqcup f$	$\top$	$\top \sqcup f$	$\top \sqcup f$
$\top$	$\bot$	f	$\top$	$\top \sqcup f$	$\top \sqcup f$	$\top$	$\top \sqcup f$	$\top \sqcup f$

Table 4.5: Abstract modulus

Comparison operators are defined directly on values, since different types can be compared with each other courtesy of type translation. PHP has a non-complete ordered definition of how values are compared depending on their type, which can be seen in table 4.6. Any combination of operators not present in the table is considered unspecified and yields a boolean $\top$ value.

For performance reasons, the analysis does not try to compare all different combinations of possible types when performing abstract comparison operators. If either value has multiple possible types the result is the boolean $\top$-element. Otherwise the comparison operators follow the order of table 4.6 for coercion of values and comparison of specific types are specified in the tables in appendix B.

Arrays are first of all compared by size. Equal sized arrays with different keys are incomparable, while arrays of equal size are compared by their values. Since the array lattice has no notion of size it is not possible to reason about the results of array comparisons. The only possible sound result is the boolean $\top$-element.

Type of left operand	Type of right operand	Result
null or string	string	null is coerced to string
bool or null	anything	operands are coerced to bool
string or number	string or number	strings are coerced to numbers
array	anything	arrays are always greater

Table 4.6: Comparison with various types based on [A3]

4.7 The Monotone Framework

In order to perform a data flow analysis on a P0 program, the Embellished Monotone Framework, as introduced by Nielson, Nielson and Hanikin in [A13], is used. This section describes how the concepts of the previous sections fit into the framework. A *monotone data-flow analysis* is a tuple $(L, \mathcal{F})$ where L is a lattice and $\mathcal{F}$ is a monotone function space on L.

Given a program, a corresponding instance of the data-flow analysis can be expressed as a six-tuple $(L, \mathcal{F}, F, E', \iota, f)$. Here L and $\mathcal{F}$ are the lattice and function space of the analysis, F is a set of tuples expressing the flow between labels, E' is the set of external labels, ι is the initial lattice element of the external labels, and f is a mapping from labels to functions in $\mathcal{F}$. Labels are in this analysis defined as the product of nodes and context, $\mathcal{L} = \mathcal{N} \times \Delta$. From an instance, the data-flow equations $A = \mathcal{L} \to L$ are defined as

$$A_\bullet((n,\delta)) = \begin{cases} f_{(n,\delta,(\delta,c))}(A_\circ((c,\delta)), A_\circ((n,\delta))) & \text{if } n = \mathit{return}_c(\_) \\ f_{(n,\delta)}(A_\circ((n,\delta))) & \text{else} \end{cases} \tag{4.43}$$

where

$$A_\circ(l) = \bigsqcup\{A_\bullet(l') | (l', l) \in F\} \sqcup \iota^l_{E'} \tag{4.44}$$

and

$$\iota^l_{E'} = \begin{cases} \iota & \text{if } l \in E' \\ \bot & \text{else} \end{cases} \tag{4.45}$$

Intuitively, $A_\bullet$ expresses the abstract state immediately after performing the given label and $A_\circ$ the state just before. Solving these equations performs the data-flow analysis.

Given a control-flow graph $G = (V, E, s, t)$, an instance of the analysis can be derived, where L = AnalysisLattice and $\mathcal{F}$ is the function space of the transfer functions. The mapping f is defined throughout section 4.4 mapping nodes to transfer functions. $F : \mathcal{L} \times \mathcal{L}$ is defined as

$$\begin{aligned} F = \{&((n,\delta),(n',\delta')) | (n,n') \in E \wedge \delta \in \Delta \\ &\wedge \mathit{validSuccessor}(n,n') \\ &\wedge \delta' = \mathit{nextC}(n,\delta)\} \end{aligned} \tag{4.46}$$

where

$$nextC(n,\delta) = \begin{cases} \delta' & \text{if } n = \mathit{exit}(\_) \text{ and } \delta = (\delta', c) \\ (\delta, n) & \text{if } n = \mathit{call}(\_) \\ \delta & \text{else} \end{cases} \tag{4.47}$$

The predicate *validSuccessor* is defined by definition 9, and it is necessary because of the ambiguity associated with potentially multiple outgoing edges of the *exit* node, which indicates that the flow may go from an exit node to an arbitrary result node. This is naturally not the case. A successor w to a node v is valid if and only if v is an exit node and w is the return node corresponding to the call node of the current function-call, or if v is not an exit node.

Definition 9. The predicate *validSuccessor* : $\mathcal{L} \times \mathcal{L}$, is defined as

$$\begin{aligned} \mathit{validSuccessor}(n,\delta,n',\delta') \Leftrightarrow & (n = \mathit{exit}(\_) \wedge n' = \mathit{result}_c(\_) \wedge \delta = (\delta' c)) \\ & \vee n \neq \mathit{exit}(\_) \end{aligned} \tag{4.48}$$

The set of external nodes can be defined as $E' = \{s\}$. The initial lattice-element, ι, is the element where the empty context, Λ, maps to the state, $s_\iota = (\bot, g_\iota, h_\iota, \bot, \bot)$. Here the global scope g_ι models the superglobals as

$$\begin{aligned} g_\iota = [&\texttt{\$GLOBALS} \mapsto \{\text{HLoc}(\Lambda, s, 0)\}, \\ &\texttt{\$\_SERVER} \mapsto \{\text{HLoc}(\Lambda, s, 1)\}, \\ &\texttt{\$\_SESSION} \mapsto \{\text{HLoc}(\Lambda, s, 2)\}, \\ &\texttt{\$\_ENV} \mapsto \{\text{HLoc}(\Lambda, s, 3)\}, \\ &\texttt{\$\_COOKIE} \mapsto \{\text{HLoc}(\Lambda, s, 4)\}, \\ &\texttt{\$\_POST} \mapsto \{\text{HLoc}(\Lambda, s, 5)\}, \\ &\texttt{\$\_GET} \mapsto \{\text{HLoc}(\Lambda, s, 6)\}, \\ &\texttt{\$\_REQUEST} \mapsto \{\text{HLoc}(\Lambda, s, 7)\}, \\ &\texttt{\$\_FILES} \mapsto \{\text{HLoc}(\Lambda, s, 8)\}] \end{aligned}$$

and the heap, h_ι is

$$\begin{aligned}
h_\iota = [&\mathrm{HLoc}(\Lambda, s, i \in [0,2]) \mapsto \mathrm{Value}(\mathrm{Array}(\top)),\\
&\mathrm{HLoc}(\Lambda, s, 3) \mapsto \mathrm{Value}(\mathrm{ArrayMap}([\mathrm{Index}(\top) \mapsto \mathrm{HLoc}(\Lambda, s, 9)])),\\
&\mathrm{HLoc}(\Lambda, s, 4) \mapsto \mathrm{Value}(\mathrm{ArrayMap}([\mathrm{Index}(\top) \mapsto \mathrm{HLoc}(\Lambda, s, 10)])),\\
&\mathrm{HLoc}(\Lambda, s, 5) \mapsto \mathrm{Value}(\mathrm{ArrayMap}([\mathrm{Index}(\top) \mapsto \mathrm{HLoc}(\Lambda, s, 11)])),\\
&\mathrm{HLoc}(\Lambda, s, 6) \mapsto \mathrm{Value}(\mathrm{ArrayMap}([\mathrm{Index}(\top) \mapsto \mathrm{HLoc}(\Lambda, s, 12)])),\\
&\mathrm{HLoc}(\Lambda, s, 7) \mapsto \mathrm{Value}(\mathrm{ArrayMap}([\mathrm{Index}(\top) \mapsto \mathrm{HLoc}(\Lambda, s, 13)])),\\
&\mathrm{HLoc}(\Lambda, s, 8) \mapsto \mathrm{Value}(\mathrm{ArrayMap}([\mathrm{Index}(\top) \mapsto \mathrm{HLoc}(\Lambda, s, 14)])),\\
&\mathrm{HLoc}(\Lambda, s, i \in [9,10]) \mapsto \mathrm{Value}(\mathrm{String}(\top)),\\
&\mathrm{HLoc}(\Lambda, s, i \in [11,13]) \mapsto \mathrm{Value}(\mathrm{Array}(\top), \mathrm{String}(\top)),\\
&\mathrm{HLoc}(\Lambda, s, 14) \mapsto \mathrm{Value}(\mathrm{ArrayMap}([\mathrm{Index}(\top) \mapsto \mathrm{HLoc}(\Lambda, s, 15)])),\\
&\mathrm{HLoc}(\Lambda, s, 15) \mapsto \mathrm{Value}(\mathrm{Number}(\top), \mathrm{String}(\top)),\\
&\mathrm{HLoc}(\Lambda, s, 16) \mapsto \mathrm{Value}(\top)\\
&\_ \mapsto \mathrm{Value}(\mathrm{Null}(\top))]
\end{aligned}$$

The last entry maps all other locations to the null value.

The initial values of the superglobals are based on inspections of the structure of each individual variable. Take the `$_FILES` array as an example. The structure is a map from form-element names to maps of information about the file such as name, size, and type. In the initial lattice-element this structure is expressed by a map of maps containing strings and numbers. Location 16 is not used directly in the global scope. The location is created to ensure any initial values of the superglobals are covered when reading from a $\top$-element array. For example reading from the `$_SERVER` superglobal may result in any value defined by the server, which is expressed by the $\top$-element value in the heap.

By modifying the initial lattice-element it is possible to introduce assumptions about the superglobals into the analysis. By introducing such assumptions it is possible to analyse how different user input and environment will affect a program. The element chosen here is chosen to be sound for all possible values of the superglobals.

4.8 Implementation

In order to solve the data-flow equations of the monotone framework, the above lattice, control-flow graph, and transfer functions have been implemented in approximately 8100 lines of Java code as a plug-in for the IntelliJ IDEA (Ultimate edition) development environment by JetBrains[B31]. This IDE supports multiple languages, such as Java, Python, C, C++, C#, Ruby, and PHP with tools such as re-factoring and type-checking, and a vast library of plug-ins, developed by JetBrains or the JetBrains community. The full source code of the implementation can be found at `http://github.com/Silwing/tapas`.

When running a plug-in on a given program, an AST and type-information is available from the environment, expressed as `PSIElements` (Program-Structure-

Interface elements). The control-flow graph is created in a single pass of these elements, where each node keeps a reference to the element from which it was created. This allows for easy error reporting when performing the analysis.

The lattices are defined by interfaces and the elements are implemented as immutable data structures of these interfaces. In the name of efficiency the domain of map-lattice elements (`MapLatticeElement`) are defined as the indices of modified entries, not including the values defaulted to Value(Null($\top$)) in the initial array. Comparing two map elements is then done by comparing the values corresponding to the joint domain of the elements, which in turn allows comparisons to be done in finite time. This shortcut also ensures that, when updating the entry of a $\top$-array only the variables initialized are effected, which is sound and yields a more precise model.

The transfer functions are implemented notoriously as introduced in section 4.4 with added statements for reporting of suspicious behaviour to the IDE through `Annotation`s. Reporting does not affect the outcome of the analysis and is made possible by the references to the `PSIElements` in the nodes of the control-flow graph. The feedback given to the user is in the form of either an error or a warning. An error indicates code that is definitely using an array in a suspicious way. A warning indicates code that might be suspicious, meaning that the analysis has lost some precision. Table 4.7 lists the warnings and errors currently implemented. Chapter 5 contains screenshots of how the warnings and errors are presented to the user in IntelliJ IDEA. Solving the data-flow equations of the monotone framework is performed by an implementation of the worklist algorithm (Algorithm 1). Notice that, since $\iota \not\sqsubseteq \bot$, any reachable node is bound to be analysed at least once.

Algorithm 1 Worklist algorithm

```
Require: Control-flow graph, $G = (V, E, s, t)$
 1: $I = [\forall \delta \in \Delta, n \in \mathcal{N}.(n, \delta) \mapsto \bot]$
 2: $I[(s, \Lambda) \mapsto \iota]$
 3: $W = [f \in F | f = ((s, \Lambda), \_)]$
 4: while $W \neq \emptyset$ do
 5:     $(l_1, l_2) = W.takeFirst()$
 6:     if $f_{l_1}(l_1) \not\sqsubseteq I[l_2]$ then
 7:         $I[l_2 \mapsto f_{l_1}(l_1)]$
 8:         $W.append([f \in F | f = (l_2, \_)])$
 9:     end if
10: end while
```

Condition	Type	Message
Appending on locations all pointing to maps.	E	Appending on map
Appending on locations where one or more are pointing to maps.	W	Possible appending on map
Merging a list with a map in `array_merge`.	E	Merging a list with a map
Merging a map with a list in `array_merge`.	E	Merging a map with a list
Writing to a list with a key that is definitely a string.	E	Array write is with string index on list
Writing to a list with a key that is not an integer.	W	Array write may be with string index on list
Array assigning to a location that might be a boolean, string, or number.	W	Target of write might be non-array
Array assigning a new scalar/array-type value to an array.	W	Assigning value to array of different type
Popping an element of a map.	E	array_pop on map

Table 4.7: Supported errors (E) and warnings (W)

4.8.1 Library functions

Until now, it has been assumed that any function called should be implemented in the same program. PHP however comes with a large number of internal functions, which are essential to any program. In order to support these, a `LibraryFunction` interface has been created. Implementing a class of this interface and registering it in the `PSIParser` allows modelling of a function by expressing in the signature, whether arguments and return values are passed by reference or value, and specifying a transfer function for the result node. Let *lib* be the name of a library function. Then the transfer function of the $call_{lib}(\_)$ node becomes the identity function, the flow graph is the graph containing a *start* node followed by an *exit* node, and the transfer function of the $result_{call_{lib(\_)}}$ is the specified transfer function.

For the library function $fn =$ `array_merge`[B28] the arguments and return value are all passed by value. The transfer function for the result node, $n = result_c(c_{tar})$, where $c = call_{fn}(t_1, \cdots, t_n)$, is defined as

```
$f_{n,\delta_{call},\delta_{exit}}(l_{call}, l_{exit}) =$let $(s_l, s_g, s_h, s_t, s_{ht}) = l_{call}[\delta_{call}]$ in
    let $V = \{v_i | v_i = s_t[t_i] \wedge i \in [1;n]\}$ in
    let $(v_a, v_s, v_n, v_b, v_u) = \bigsqcup V$ in
    let $w =$
      if $\perp \in V \vee v_s \neq \perp \vee v_n \neq \perp$
          $\vee v_b \neq \perp \vee v_u \neq \perp$ then
         $\text{Value}(\text{Null}(\top))$ else $\perp$
     in
    let $v = w \sqcup \text{Value}(v_a)$ in
    let $(s'_t, s'_{ht}, s'_h) =$ match $c_{tar}$
      with Temp: $(s_t[c_{tar} \mapsto v], s_{ht}, s_h)$
      with HeapTemp:
         $(s_t,$
            $s_{ht}[c_{tar} \mapsto \text{HLoc}(\delta_{call}, n, 0)],$
            $s_h[\text{HLoc}(\delta_{call}, n, 0) \mapsto v])$
     in
    $l_{call}[\delta_{call} \mapsto (s_l, s_g, s'_h, s'_t, s'_{ht})]$
```

This transfer function simply joins the arrays of each input value, taking invalid arguments yielding `null` into account. The joined value is then stored in the heap or temporary storage, depending on the result argument.

The implementation has been tested against 48 small scripts. While these are not representative of actual PHP programs, neither in size nor feature usage, they do aim to cover as many feature cases as possible.

Library functions have been implemented on a by-need basis for the functional tests and case studies presented in chapter 5. Some of the implemented library functions, which do not contain reference-parameters or reference-return, have been naively implemented by returning the $\top$-element value, since the precision was not required for the test in question.

4.9 Summary

In this chapter a subset of PHP (P0) has been defined. This language focuses on arrays by supporting native array operations, such as array append, write, and initialization as well as references. References are used to create more advanced arrays, e.g. cyclic arrays, and have proven to be a source of precision loss, since they disable deep-copy of arrays and thereby strong updates on the heap.

An interprocedural data-flow analysis has been designed in the monotone framework, yielding a method for creating control-flow graphs, a lattice expressing abstract state, and a set of transfer-functions. By relying on the monotone framework, the analysis has been performed using a straight-forward implementation of the worklist-algorithm as a plug-in in the development environment IntelliJ IDEA.

For the monotone framework to work all transfer-functions must be monotone. Monotonicity has not been proven formally. For abstract evaluation appendix B contains a full set of tables defining the abstract operators which have all been inspected for monotonicity.

The analysis aims to be sound for the features supported by P0, however the lack of a formal language specification for PHP makes soundness a difficult topic. All behavior-assumptions are based on the PHP documentation and subsequent inspection of the behavior for small test cases.

Chapter 5

Case Study

In this chapter, the analysis from chapter 4 is evaluated on six small programs. The first program, evaluated in 5.1, is a constructed example illustrating how the analysis handles the two array types introduced. The remaining five programs, evaluated in section 5.2 to 5.6, have been found by manually inspecting the results from the dynamic analysis in chapter 3, looking for uncategorizable arrays and misuse of list-operations, e.g. `array_pop` on a map.

When found, the programs were minimized (i.e. unnecessary logic was removed), rewritten to P0, and necessary library functions implemented. Running the analysis was performed with a context bound by length two ($k = 2$). This bound only imposes a practical restriction on the recursive directory content program (section 5.3), since the maximum possible depth of function calls for all other examples is two.

Execution statistics (such as running time and memory consumption) have been omitted, since an implementation of a fast and resource efficient analysis is not a goal of this thesis. Instead, this chapter will investigate whether the analysis provides useful error-messages, which are of the right kind and if the problem can be resolved without raising new errors.

5.1 Month names and numbers

Program 5.1 first defines an array-list of month names, `$monthNames`, and uses a loop to create a new array-map, `$monthMap`, where the month names are keys and the corresponding month numbers are values, e.g. given `$monthNames = ["January", ... , "December"]` after running the program the map becomes `$monthMap=["January"=>1, ... , "December" => 12]`. The constructed array-map is then used to print a string containing month number of a given input, e.g. the input `"August"` yields the string `"August is month number 8"` and input `"Duck"` yields `"Duck is month number "`. The input is provided by the super-global `$_GET`, which contains the data of the query string (as defined in [B21]), as field `"monthName"`.

The array creation at line 3 is performed by initializing an empty array and immediately thereafter appending the month names. Since the only operations performed on the array are appends, the analysis will represent the array as a list

Program 5.1 Month name and number example

```
 1 <?php
 2
 3 $monthNames = ["January", "February", "March", "April",
        "May", "June", "July", "August", "September", "
      October", "November", "December"];

 4 $monthMap = [];
 5
 6 for($i = 1; $i <= 12; $i++) {
 7   $monthMap[array_pop($monthNames)] = $i;
 8 }
 9 $input = $_GET["monthName"];
10
11 echo $input . " is month number " . $monthMap[$input];
```

of strings. At line 4, the **`$monthMap`** variable is initialized to an empty array. The analysis will represent this as emptyArray, since no operations are yet performed on the array. Notice how this explicit initialization is not necessary since any subsequent array operation will implicitly initialize the array. The month array-map is first modified at line 7 by an array-write operation with keys from the month-names array. Since the function **`array_pop`** is used to generate the key, which may return **`null`** if the given array is empty, **`$monthMap`** will be represented as an array-map with NotUIntString mapping to UInt.

The analysis yields no error or warning, following from the arrays being treated properly, i.e. when first represented as either lists or maps only the *right* operations are performed on them, e.g. writes with string keys on maps and **`array_pop`** on list.

5.2 Array pivot

The function **`pivot`** in program 5.2, was found in the Joomla content management system in a class containing functions for manipulating arrays. It uses the library functions **`count`**, which returns the size of a given array, and **`array_key_exists`** which given an array and a key checks if the key is set in the array.

The **`pivot`** function accepts an array as its only argument and returns an array with the unique values of the input array as keys and their position in the original array as value. For example executing **`pivot([1,2,3,4,5,4,3,2,1])`** yields the map

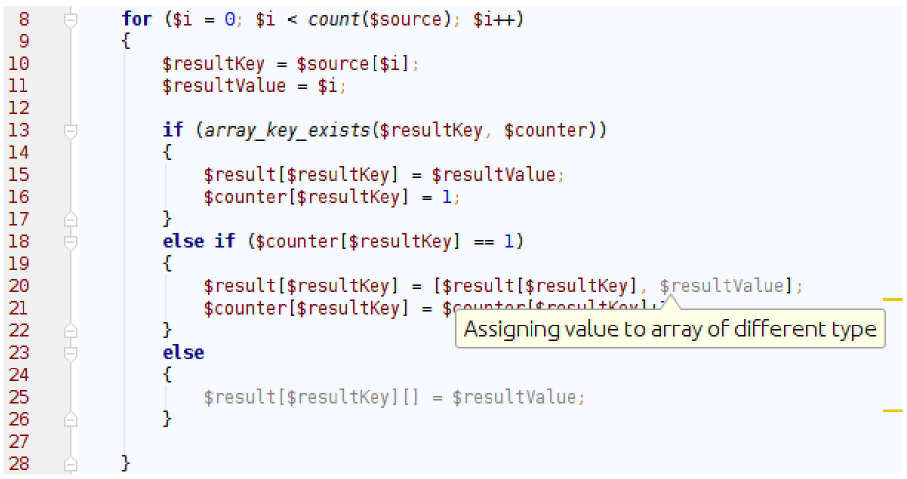
```
[
  1 => [0,8],   //1 is at key 0 and 8
  2 => [1,7],   //2 is at key 1 and 7
  3 => [2,6],   //3 is at key 2 and 6
  4 => [3,5],   //4 is at key 3 and 5
  5 => 4        //5 is at key 4
]
```

Notice how the type of the values in the resulting array above alternates. If a value only occurs once in the input array, that single position is returned in the output array, otherwise if there are more than one, an array of possible positions is returned. While PHP supports coercion between many of the simple types,

Program 5.2 Pivot example

```php
<?php

function pivot($source)
{
    $result = array();
    $counter = array();

    for ($i = 0; $i < count($source); $i++)
    {
        $resultKey = $source[$i];
        $resultValue = $i;

        if (array_key_exists($resultKey, $counter))
        {
            $result[$resultKey] = $resultValue;
            $counter[$resultKey] = 1;
        }
        else if ($counter[$resultKey] == 1)
        {
            $result[$resultKey] = [$result[$resultKey],
     $resultValue];
            $counter[$resultKey] = $counter[$resultKey
    ]+1;
        }
        else
        {
            $result[$resultKey][] = $resultValue;
        }

    }

    return $result;
}

$simpleArr =
    [1,2,3,4,5,6,7,8,1,5,3,7,9,0,4,2,5,8,4,3,8,9];
$result = pivot($simpleArr);
```

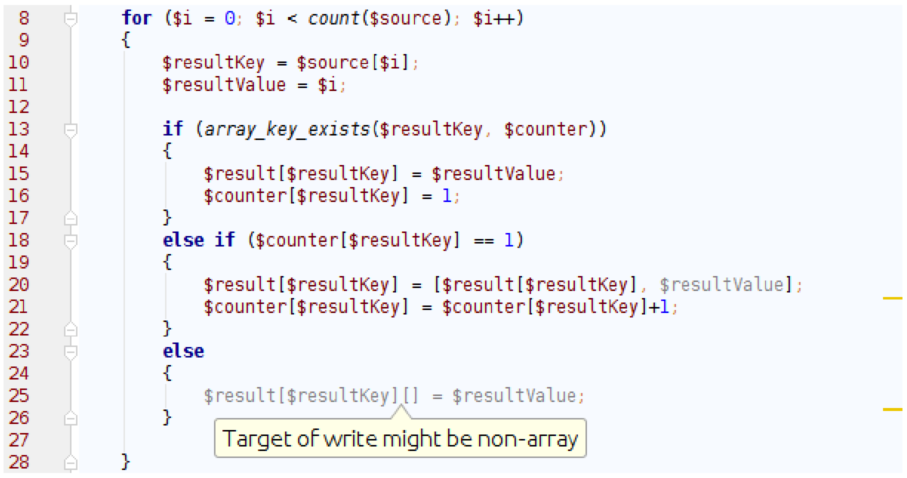
there is no such thing as array coercion. The mix of arrays and scalar values in the resulting array would ultimately require a check of the data type before using the values, which could have been avoided if the function consistently returned an array containing arrays of integers. The need for data type checks strongly suggest bad design choices and the analysis provides warnings about suspicious use of arrays as seen in figure 5.1. Both warnings are based on the fact that values of the array associated with “result” might be arrays or number values. The first happens when an integer is appended to an array already containing an array or integer (figure 5.1.1) and the second when an



```
8   for ($i = 0; $i < count($source); $i++)
9   {
10      $resultKey = $source[$i];
11      $resultValue = $i;
12
13      if (array_key_exists($resultKey, $counter))
14      {
15          $result[$resultKey] = $resultValue;
16          $counter[$resultKey] = 1;
17      }
18      else if ($counter[$resultKey] == 1)
19      {
20          $result[$resultKey] = [$result[$resultKey], $resultValue];
21          $counter[$resultKey] = $counter[$resultKey]+1;
22      }
23      else
24      {
25          $result[$resultKey][] = $resultValue;
26      }
27
28  }
```

Assigning value to array of different type

(5.1.1) Array write with different values



```
8   for ($i = 0; $i < count($source); $i++)
9   {
10      $resultKey = $source[$i];
11      $resultValue = $i;
12
13      if (array_key_exists($resultKey, $counter))
14      {
15          $result[$resultKey] = $resultValue;
16          $counter[$resultKey] = 1;
17      }
18      else if ($counter[$resultKey] == 1)
19      {
20          $result[$resultKey] = [$result[$resultKey], $resultValue];
21          $counter[$resultKey] = $counter[$resultKey]+1;
22      }
23      else
24      {
25          $result[$resultKey][] = $resultValue;
26      }
27
28  }
```

Target of write might be non-array

(5.1.2) Array append on non-array

Figure 5.1: Running the analysis on `pivot`

array append operation is performed on something that might be a number (figure 5.1.2).

Both warnings occur as side-effects of the real problem, namely the type of the content. In practice, the sub-array always contains integers (not arrays and integers) and the append operation is always performed on a number. The real problem, however, is not captured by the analysis. This happens when the branches of the if-statement meet. Here, the analysis performs a join of the analysis lattice element, hence a join of the lattice element representing the abstract value of `$result` array. For the first iteration of the for-loop, the first branch of the `if`-statement on line 13 would express the array as a list of integers, while the second branch would express it as a list of lists containing integers. A warning on a join of these opposing representations could be implemented, but is currently not supported by the analysis.

By rewriting the program to always return a list of lists (see program 5.3) the specification must be changed, however the warnings will disappear. The program is nine lines shorter and definitely easier to understand due to a lower number of branches and variables, i.e. an `if`-statement and the use of the `$counter` array has been removed.

Program 5.3 Fixed pivot example

```php
<?php

function pivot($source)
{
    $result = array();

    for ($i = 0; $i < count($source); $i++)
    {
        $resultKey = $source[$i];
        $resultValue = $i;

        if (!array_key_exists($resultKey, $resultKey))
        {
            $result[$resultKey] = [$resultValue];
        } else {
            $result[$resultKey][] = $resultValue;
        }

    }

    return $result;
}

$simpleArr =
    [1,2,3,4,5,6,7,8,1,5,3,7,9,0,4,2,5,8,4,3,8,9];
$result = pivot($simpleArr);
```

5.3 Directory content

Found in the CodeIgniter framework, program 5.4 demonstrates mixing the map and list type arrays. This program uses four library functions for traversing the file-system; *i*) `opendir` which creates a file-pointer for a given directory, *ii*) `readdir` which reads the name of the next file/directory in the given directory using the file-pointer, *iii*) `is_dir` which as the name suggests checks if a path is a directory, and *iv*) `closedir` which *closes* the file-pointer. Since P0 does not support file pointers, these are modelled as numbers in the analysis.

The `directory_map` function takes a directory name and a depth as input and returns the structure of the given directory recursively bound by the provided length. The resulting structure is a mix of a list of file names and a map from sub directory name to the structure of that sub directory. Mixing an array-list and an array-map, as done in program 5.4, provides no obvious way of using the output of the function. Furthermore the program seems to assume that directories cannot have integers as names. If a directory has integer i as a name and more than i files have been seen, then adding the new folder will

Program 5.4 Directory content example

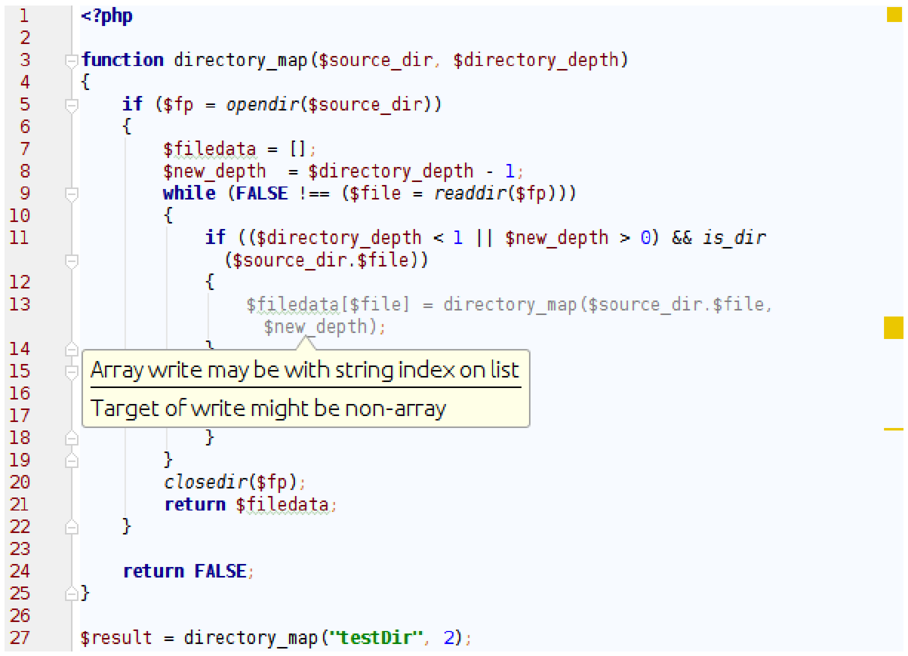
```php
<?php

function directory_map($source_dir, $directory_depth)
{
    if ($fp = opendir($source_dir))
    {
        $filedata = [];
        $new_depth  = $directory_depth - 1;
        while (FALSE !== ($file = readdir($fp)))
        {
            if (($directory_depth < 1 || $new_depth >
    0) && is_dir($source_dir.$file))
            {
                $filedata[$file] = directory_map(
    $source_dir.$file, $new_depth);

            }
            else
            {
                $filedata[] = $file;
            }
        }
        closedir($fp);
        return $filedata;
    }

    return FALSE;
}

$result = directory_map("testDir", 2);
```

override a file already added to the list. For example let a directory contain a file named `file1` and an empty sub directory named `0`. If `readdir` first returns the name of the file and then the folder, the result will be `[[]]` (a list containing an empty list). If the order is reversed, the result will be `["file1", []]`. This subtle assumption (or bug) is a result of `readdir` not specifying an order for the read operation, thus the user of the function cannot rely on a specific ordering of the files and directories being read.

This is a good example of how arrays in PHP serve as the go-to data-structure even when other alternatives might be better suited to handle the problem. In this case, representing the files and directories as objects would solve the problem.

The analysis raises three warnings on two code locations (see figure 5.2). Just as in the previous case, these warnings seem to have been raised as side-effects of the real problem, which is caused by the `$filedata` array being represented as a map at line 13, a list at line 17, and joined at the end of the `if`-statement. This join yields the $\top$ array, which is the source of the last warning at both code-locations: *"Target of write might be non-array"*, since it causes all heap locations to be updated when writing to `$filedata`. Yielding a warning when a join results in a $\top$ array might be a better indicator of the *real* problem.

As mentioned above, the files and folders could be represented as objects in order to solve the problem. However, since P0 does not support objects, these can be *emulated* with arrays. In program 5.5 the result is a map from file-names to maps representing files and folders. The file- and folder-array has key `"type"` pointing to `"file"` and `"dir"` respectively. If the `$directory_depth` is not exceeded, the folder-array also has key `"content"` pointing to a list representing the content of the folder, or `FALSE` if the folder could not be opened. This solution will successfully represent a given folder independently of the order in which the folder content is read in by `readdir`.

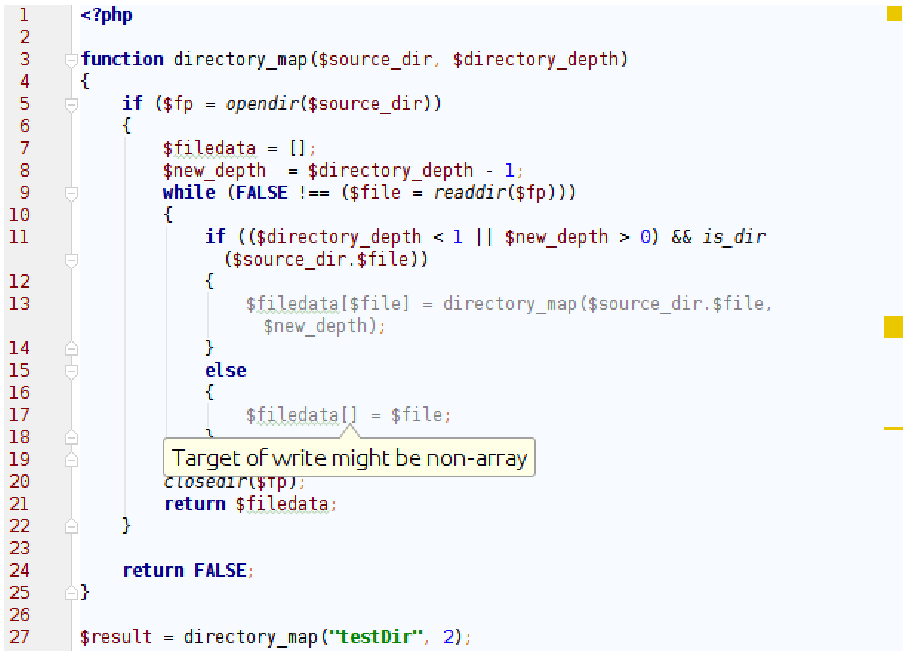


```
<?php

function directory_map($source_dir, $directory_depth)
{
    if ($fp = opendir($source_dir))
    {
        $filedata = [];
        $new_depth  = $directory_depth - 1;
        while (FALSE !== ($file = readdir($fp)))
        {
            if (($directory_depth < 1 || $new_depth > 0) && is_dir
              ($source_dir.$file))
            {
                $filedata[$file] = directory_map($source_dir.$file,
                  $new_depth);
```

```
Array write may be with string index on list
Target of write might be non-array
```

```
            }
        }
        closedir($fp);
        return $filedata;
    }

    return FALSE;
}

$result = directory_map("testDir", 2);
```

(5.2.1) Writing with string on list and type mismatch



```
<?php

function directory_map($source_dir, $directory_depth)
{
    if ($fp = opendir($source_dir))
    {
        $filedata = [];
        $new_depth  = $directory_depth - 1;
        while (FALSE !== ($file = readdir($fp)))
        {
            if (($directory_depth < 1 || $new_depth > 0) && is_dir
              ($source_dir.$file))
            {
                $filedata[$file] = directory_map($source_dir.$file,
                  $new_depth);
            }
            else
            {
                $filedata[] = $file;
```

```
Target of write might be non-array
```

```
        closedir($fp);
        return $filedata;
    }

    return FALSE;
}

$result = directory_map("testDir", 2);
```

(5.2.2) Appending a string and type mismatch

Figure 5.2: Running analysis on `directory_map`

Program 5.5 Fixed directory content example

```php
<?php

function directory_map($source_dir, $directory_depth)
{
    if ($fp = opendir($source_dir))
    {
        $filedata = [];
        $new_depth  = $directory_depth - 1;
        while (FALSE !== ($file = readdir($fp)))
        {
            if (is_dir($source_dir.$file))
            {
                $dir = ['type'=>'dir'];
                if($directory_depth < 1 || $new_depth >
 0){
                    $dir['content'] = directory_map(
    $source_dir.$file, $new_depth);
                }
                $filedata[$file] = $dir;
            }
            else
            {
                $filedata[$file] = ['type'=>'file'];
            }
        }
        closedir($fp);
        return $filedata;
    }

    return FALSE;
}

$result = directory_map("testDir", 2);
```

5.4 Date validation

Program 5.6 is from the e-commerce platform Magento 2, where the original functions were located in two different files. The `isValidDate` function takes three arguments expressing a date and returns a map being either empty or containing an error message at the `"invalidDate"` key. The `isMinimumDay` similarly checks the validity of a date using the previous function. Here however, the output is a list which leads to a merge of a list and a map at line 17.

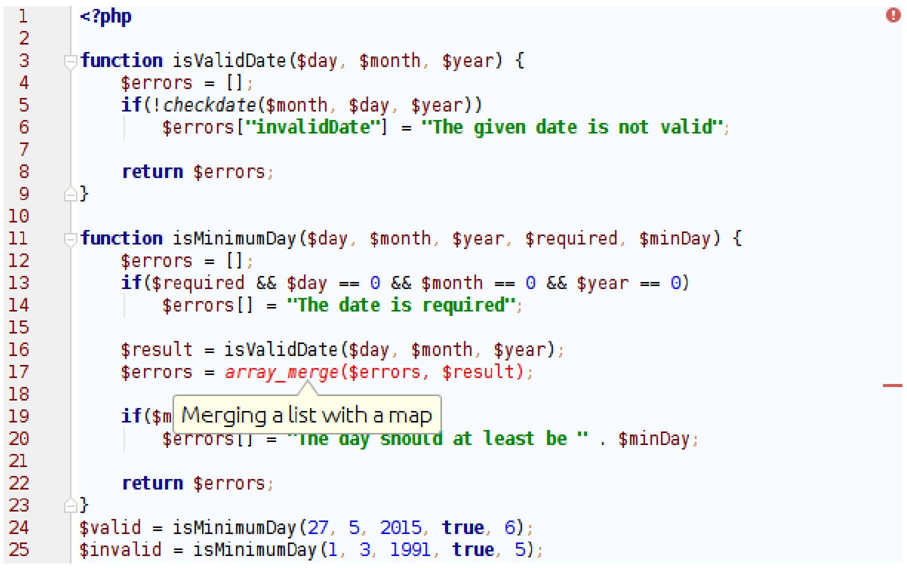
Program 5.6 Date validation example

```
 1 <?php
 2 
 3 function isValidDate($day, $month, $year) {
 4     $errors = [];
 5     if(!checkdate($month, $day, $year))
 6         $errors["invalidDate"] = "The given date is not
      valid";
 7 
 8     return $errors;
 9 }
10 
11 function isMinimumDay($day, $month, $year, $required,
     $minDay) {
12     $errors = [];
13     if($required && $day == 0 && $month == 0 && $year
     == 0)
14         $errors[] = "The date is required";
15 
16     $result = isValidDate($day, $month, $year);
17     $errors = array_merge($errors, $result);
18 
19     if($minDay > $day)
20         $errors[] = "The day should at least be " .
     $minDay;
21 
22     return $errors;
23 }
24 $valid = isMinimumDay(27, 5, 2015, true, 6);
25 $invalid = isMinimumDay(1, 3, 1991, true, 5);
```

The program uses two library functions; `checkdate`, modelled as a function returning boolean $\top$, and `array_merge`, as described in section 4.8.1.

Running the analysis on the program yields a single error, as illustrated in figure 5.3. As opposed to the previous cases, this error reflects the main problem, namely the merge of a list and a map. It is not clear whether the issue is caused by a misunderstanding of the specification of the `isValidDate` function or is as designed.

Assuming the error occurs due to incorrect assumptions regarding the return value of `isValidDate`, the problem can be resolved by converting the map to a list. This is done in program 5.7 using the `array_values` library function. Running the analysis on this program raises no errors or warnings.



```php
<?php

function isValidDate($day, $month, $year) {
    $errors = [];
    if(!checkdate($month, $day, $year))
        $errors["invalidDate"] = "The given date is not valid";

    return $errors;
}

function isMinimumDay($day, $month, $year, $required, $minDay) {
    $errors = [];
    if($required && $day == 0 && $month == 0 && $year == 0)
        $errors[] = "The date is required";

    $result = isValidDate($day, $month, $year);
    $errors = array_merge($errors, $result);

    if($m
        $errors[] = "The day should at least be " . $minDay;

    return $errors;
}
$valid = isMinimumDay(27, 5, 2015, true, 6);
$invalid = isMinimumDay(1, 3, 1991, true, 5);
```

Figure 5.3: Running the analysis on date validation example

Program 5.7 Date validation example

```php
<?php

function isValidDate($day, $month, $year) {
    $errors = [];
    if(!checkdate($month, $day, $year))
        $errors["invalidDate"] = "The given date is not
 valid";

    return $errors;
}

function isMinimumDay($day, $month, $year, $required,
    $minDay) {
    $errors = [];
    if($required && $day == 0 && $month == 0 && $year
    == 0)
        $errors[] = "The date is required";

    $result = isValidDate($day, $month, $year);
    $errors = array_merge($errors, array_values($result
    ));

    if($minDay > $day)
        $errors[] = "The day should at least be " .
    $minDay;

    return $errors;
}
$valid = isMinimumDay(27, 5, 2015, true, 6);
$invalid = isMinimumDay(1, 3, 1991, true, 5);
```

5.5 Caching instances

Program 5.8 was found in the CMS framework Part, which is created by one of the authors. The program is supposed to work as a map of maps from `$instance`s to `$value`s with caching of values and no type-restriction of the instances. For example calling `createInstance("key1", "instance1", "value1"` should return `"value1"`. Then calling `createInstance("key1", "instance1", "value2")` should also return `"value1"`, since the value is cached.

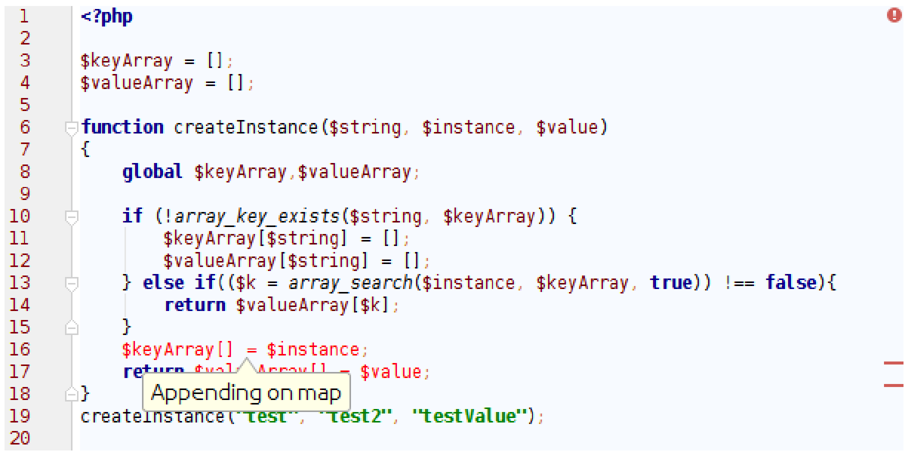
Program 5.8 Caching instances example

```
 1 <?php
 2 
 3 $keyArray = [];
 4 $valueArray = [];
 5 
 6 function createInstance($string, $instance, $value)
 7 {
 8     global $keyArray,$valueArray;
 9 
10     if (!array_key_exists($string, $keyArray)) {
11         $keyArray[$string] = [];
12         $valueArray[$string] = [];
13     } else if(($k = array_search($instance, $keyArray,
       true)) !== false){
14         return $valueArray[$k];
15     }
16     $keyArray[] = $instance;
17     return $valueArray[] = $value;
18 }
19 createInstance("test", "test2", "testValue");
```

Program 5.9 illustrates how the program should have been implemented by keeping two maps of lists containing instances or values, respectively. Two maps are used, as opposed to a single multidimensional map, since it might not be possible to coerce the instances to array indices. The actual implementation is wrong however, in that it does not use the multidimensionality of the `$keyArray` or `$valueArray`. Instead, instances are appended and lists written to the array, i.e. the two maps are used as lists and maps simultaneously.

When running the analysis on program (5.8), two errors are raised as illustrated in figure 5.4. Both errors are of the same type, but on the `$keyArray` (line 16) and `$valueArray` (line 17) respectively. They occur when an append operation is performed on arrays that previously were considered maps, and represent the main problem of the program quite well. They would not occur in the corrected version (program 5.9), where the append operations would be performed on lists. No problems are found in the corrected version.

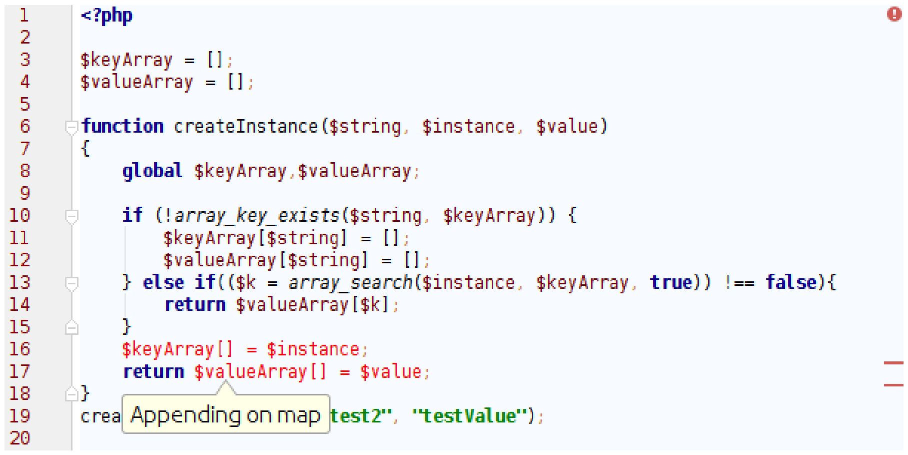
Two library functions are used in the program; `array_key_exists`, modelled as a function returning boolean $\top$, and `array_search`, modelled as a function returning array indices from the given array and boolean false. These are used for checking if a key is set in an array and finding the key of a given value in an array, respectively.



```php
<?php

$keyArray = [];
$valueArray = [];

function createInstance($string, $instance, $value)
{
    global $keyArray,$valueArray;

    if (!array_key_exists($string, $keyArray)) {
        $keyArray[$string] = [];
        $valueArray[$string] = [];
    } else if(($k = array_search($instance, $keyArray, true)) !== false){
        return $valueArray[$k];
    }
    $keyArray[] = $instance;
    return $valueArray[] = $value;
}
createInstance("test", "test2", "testValue");
```

Appending on map

(5.4.1) Appending on map: `$keyArray`



```php
<?php

$keyArray = [];
$valueArray = [];

function createInstance($string, $instance, $value)
{
    global $keyArray,$valueArray;

    if (!array_key_exists($string, $keyArray)) {
        $keyArray[$string] = [];
        $valueArray[$string] = [];
    } else if(($k = array_search($instance, $keyArray, true)) !== false){
        return $valueArray[$k];
    }
    $keyArray[] = $instance;
    return $valueArray[] = $value;
}
crea test2", "testValue");
```

Appending on map

(5.4.2) Appending on map: `$valueArray`

Figure 5.4: Running analysis on `createInstance`

Program 5.9 Caching instances corrected example

```php
<?php

$keyArray = [];
$valueArray = [];

function createInstance($string, $instance, $value)
{
    global $keyArray,$valueArray;

    if (!array_key_exists($string, $keyArray)) {
        $keyArray[$string] = [];
        $valueArray[$string] = [];
    } else if(($k = array_search($instance, $keyArray[
    $string], true)) !== false){
        return $valueArray[$string][$k];
    }
    $keyArray[$string][] = $instance;
    return $valueArray[$string][] = $value;
}
createInstance("test", "test2", "testValue");
```

5.6 Joining array values

Inspired by code found in Zend Framework 2, program 5.10 takes lists of strings, `$people` and `$animals`, both of size n, and constructs an array with values from the first array as keys pointing to values from the second array. Additionally, integer keys, 0 to $n-1$, point to the strings `", "`. The array `$animalMap` then serves as a map from `$people` to `$animal` and as the `$animal` array with comma separators. For example finding the *animal* corresponding to `"John"` can be found by reading `$animalMap["John"]`, i.e. the animal string `"Dog"`. A comma-separated string of animals can be created using `implode`, as shown in line 13. Note that the creation of a comma-separated list utilizes how arrays are ordered, i.e. in the order added to the array rather than e.g. lexicographical order.

While the `$arrayMap` might seem suspicious, it can be considered a map and is correctly classified as such by the analysis. An error occurs when the `array_pop` function is executed on the map (see figure 5.5). Just as with array append operations, this function (as considered by the analysis) should only be performed on lists.

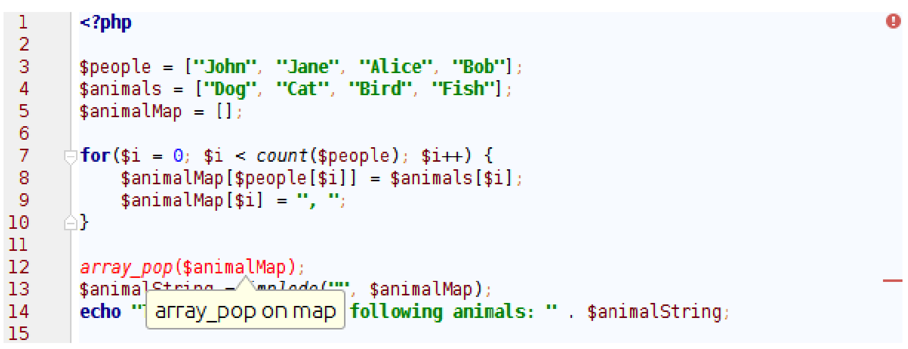
The error could be resolved by not adding the `", "` strings to `$animalMap`, and imploding with `", "` instead of the empty string in line 13. This would also prevent dependence on the iteration-order of the array. The corrected program is illustrated as program 5.11.

Program 5.10 Joining array values example

```php
<?php

$people = ["John", "Jane", "Alice", "Bob"];
$animals = ["Dog", "Cat", "Bird", "Fish"];
$animalMap = [];

for($i = 0; $i < count($people); $i++) {
    $animalMap[$people[$i]] = $animals[$i];
    $animalMap[$i] = ", ";
}

array_pop($animalMap);
$animalString = implode("", $animalMap);
echo "The people have the following animals: " .
    $animalString;
```

Program 5.11 Joining array values corrected example

```php
<?php

$people = ["John", "Jane", "Alice", "Bob"];
$animals = ["Dog", "Cat", "Bird", "Fish"];
$animalMap = [];

for($i = 0; $i < count($people); $i++) {
    $animalMap[$people[$i]] = $animals[$i];
}

$animalString = implode(", ", $animalMap);
echo "The people have the following animals: " .
    $animalString;
```



```php
<?php

$people = ["John", "Jane", "Alice", "Bob"];
$animals = ["Dog", "Cat", "Bird", "Fish"];
$animalMap = [];

for($i = 0; $i < count($people); $i++) {
    $animalMap[$people[$i]] = $animals[$i];
    $animalMap[$i] = ", ";
}

array_pop($animalMap);
$animalString = implode("", $animalMap);
echo "                   following animals: " . $animalString;

```

Figure 5.5: Running the analysis on the joining array values example

$$\text{Array} = \begin{tikzcd} & \top \arrow[d, dash] & \\ & \mathcal{P}(\text{HLoc}) \arrow[dl, dash] \arrow[dr, dash] & \\ ArrayList \arrow[dr, dash] & & ArrayMap \arrow[dl, dash] \\ & \text{emptyArray} \arrow[d, dash] & \\ & \perp & \end{tikzcd}$$

Figure 5.6: Proposed modified array lattice

5.7 Conclusion

The implementation of the analysis successfully indicated errors when a program contained suspicious arrays and operations. Subsequently, these errors were all resolved by rewriting the programs, without creating new errors.

It would, however, seem beneficial to add a warning when two paths meet, e.g. after an `if`-statement, as was indicated by the second and third case. The inaccuracy of the $\top$ array also became apparent, where updating a top array would update most of the heap. It should be considered to modify the Array-lattice, by adding an element of heap locations between the ArrayMap and ArrayList elements and the $\top$ element (see figure 5.6). This would intuitively represent arrays that are not known to be lists or maps, but are assured to contain some locations, thus allowing for more precision than the $\top$ array.

Since this thesis does not focus on efficiency with respect to memory consumption or run-time, no such information is associated with this case study. It should be noted however, that execution was reasonably fast (performed in seconds rather than minutes) in spite of the current analysis being performed after running the static analysis of the IDE. The observed memory consumption was rather high, which possibly follows from the implemented caching strategy of the lattice elements.

Chapter 6

Related Work

As it might have become evident throughout this thesis, PHP supports many dynamic features, most of which has been omitted in this analysis, due the focus being on arrays. Just as an analysis of popular PHP frameworks has been performed in this thesis, with focus on arrays, [A8] and [A7] analyse which dynamic features are commonly used. In [A14], a similar dynamic analysis is used to determine the behavior of JavaScript programs. The approach taken is different from our approach in that they record "meaningful" interactions with corpus websites, whereas our dynamic analysis relies on test suites provided by the corpus applications

WeVerca, presented in [A5], is a framework for designing static analysis of PHP. This provides the control-flow, the heap shape, and dynamic data access directly to the designer, which in turn allows the designer to implement a static analysis independently of these features. WeVerca uses the Phalanger parser, which currently supports up to PHP 5.4. With the aim of designing an analysis supporting PHP 5.6, using WeVerca was discarded as an option early on.

In [A6], variable variables are supported by treating the global scope of PHP as an array with keys corresponding to the names of variables. Accessing variable variables is then a simple matter of how array access is handled in general.

Dynamically loading PHP files, e.g. using the `require` and `include` statements, is considered by [A9], which provides a technique for statically resolving includes in PHP. This is done by first using a file-centered context-less algorithm to find possible file matches and then refining the results with a context sensitive program-centered algorithm.

The concept of references in PHP complicates reasoning about PHP programs. In [A15], the copy-on-write practice exhibited by the official PHP interpreter is investigated and compared to the stated copy-on-assignment semantics of the PHP documentation. In [A6], references are treated by implementing a data-flow analysis using a concept of aliases.

JavaScript is similar to PHP in many ways. The static analysis provided by this thesis is inspired by TAJS [A10], a type analysis for JavaScript. As opposed to PHP, JavaScript does not deep-copy arrays. TAJS makes use of pointers in its Value-lattice for arrays and objects whereas the analysis in this thesis includes arrays directly in the Value-lattice.

Pixy [A11] is a static analysis tool aimed at detecting security vulnerabilities. The tool is limited to PHP 4, which is a long out-dated version of PHP, neither developed nor supported anymore. The analysis developed in this thesis aims to support PHP 5.6, which is the newest version as of the time of writing.

Blended analysis is a different approach to utilizing dynamic analysis. In [A18], a dynamic analysis is used to prune unused and impossible paths, effectively speeding up the performance of a subsequent static taint analysis. Furthermore, the pruned paths have the possibility of removing false positives from the static analysis result. However, as stated by [A2], utilizing dynamic analysis this way requires some kind of restriction on possible inputs for the programs, as each input has to be run by the dynamic analysis.

Each program analysis of course has its own specific purposes. It is, however, possible to place the common purposes of program analysis into a few broader categories. Many analyses like [A1] and [A12], are concerned with finding security flaws or other types of bugs. It is also possible to use program analysis to prove conformity to a specification. The findings of our analysis is not per se bugs, since the program in question may work to specification despite our analysis generating errors or warnings. Instead our analysis concerns clarity of intention and maintainability. In the end, these properties also lead to code in which bugs are easier to find. The following works relate to this thesis in the sense that our analysis complements those analyses well.

The analysis in [A1] employs a strategy of dynamic test generation and explicit-state model checking to be able to find bugs resulting in execution errors or malformed HTML output. By dynamically creating path constraints the analysis covers possible execution paths and is then able to report possible malformed output.

Another approach to finding malformed HTML output is taken by [A12]. Using an analysis that generates a context-free grammar describing the possible output of a program, it is possible to check this output against a regular language describing valid HTML strings with a bounded tag-nesting.

Detection of cross-site scripting vulnerabilities is a popular topic for analyses of PHP. In [A12], it is proposed to detect occurrences of the `<script>`-tag and report these as cross-site scripting vulnerabilities. In [A17], the detection of these vulnerabilities is taken a step further, trying to compensate for browsers allowing malformed HTML which may lead to finding vulnerabilities undetected by other approaches.

Chapter 7

Conclusion

In this thesis, a corpus consisting of some of the most popular PHP frameworks have been run and subsequently dynamically analysed, revealing that almost all PHP arrays can mostly be categorized into two types: lists and maps, both acyclic. Cases outside those categories have been shown to benefit from being rewritten to fit the categories, with a clearer intention and higher maintainability as the result. Furthermore, it was shown that operations normally associated with lists, e.g. `array_pop`, `array_push`, `array_shift`, are used almost exclusively on array-lists. Running these programs relies on the test-suites defined by the designers of the respective frameworks, which reduces the task of analysing the corpus to adding a logging feature to the interpreter and inspecting the output. While this strategy relies on the quality of the test-suites, the size of the log-files generated (41 MB to 13 GB) and the popularity of the programs, assure us that the coverage achieved is better than anything we could have designed in a reasonable amount of time. The categories and operation-usage identified agrees with the initial hypothesis, that PHP arrays are subject to specific use-patterns.

The results of the dynamic analysis motivated the design of a classic inter-procedural data-flow analysis using the monotone framework. In this respect, the main contributions are the definition of a subset language of PHP, a method for generating control-flow graphs, a context sensitive lattice expressing abstract states, and a set of transfer functions aiming to be sound. This analysis has been integrated into one of the most popular IDEs for PHP programming, utilizing the AST generated by the environment and allowing instantaneous annotation of code.

Due to the lack of specification and large number of features, the analysis is neither proven sound, optimized for fast execution, nor executed on large programs. It has however successfully annotated suspicious cross-use of the array patterns on code discovered in the corpus in a reasonable amount of time. These cases were chosen by inspecting arrays that according the dynamic analysis either were uncategorizable (i.e. neither lists or maps) or maps on which list operations were performed. Some modifications have been proposed as a result of the case study described in chapter 5, i.e. a new array lattice and more precise error-reporting. It is expected that further evaluation will lead to more of such improvements.

This analysis serves as a stepping stone to the construction of a full-fledged static analysis of programs written in the obscure language that is PHP. By building this analysis on basic static analysis principles, other techniques for achieving e.g. dynamic dispatch should be relatively easy to apply. The analysis should serve as a tool for PHP developers, integrated in their development environment, allowing them to discover errors before the programs are published.

Chapter 8

Future Work

It is evident from the evaluation of the analysis developed in this thesis that several parts of the analysis can be improved and further developed. The evaluation consists of small and simple case studies adapted to the supported language P0. Even these small cases strain the resource usage and P0 lacks many commonly used features of PHP, e.g. objects, variable variables, etc.

In this chapter, the limitations, possible improvements, and further development of the analysis are discussed, the main goal being to enable analysis of large PHP programs, e.g. as large as the programs of the corpus presented in chapter 3. This is done by focusing on three obvious subjects: Supporting all features of the full PHP language, improvements in the precision of the analysis, and improving the performance of the analysis implementation, in section 8.1, 8.2, and 8.3, respectively.

8.1 Supporting the full PHP language

The static analysis developed in this thesis supports a subset of PHP (P0), as defined in chapter 4. Section 4.1 defines the restricted syntax and semantics of P0, omitting most dynamic features of PHP and non-obvious usage of operators.

8.1.1 Operators

Since variables are not restricted to a single type throughout a PHP program and there are no static types, a lot of cross-type operations are allowed, e.g. comparing a boolean with a string using <=. P0 removes support for some of these cross-type operations, since they are not defined in an intuitive way. As an example, the unary increment and decrement operators can be applied to strings. Program 8.1 demonstrates how different strings are incremented. If the last character is a letter from a to y (always keeping the current case), that letter will be turned into the following letter in the alphabetical order. If the last letter is a z it will turn into an a, as well as recursively applying the increment operation to the previous letter. If no previous letter exists, an a will be prepended to the string. Any character that is not a letter from a to z will stop the increment operation and stay unchanged. While this definition seems somewhat sensible, intuitively the decrement operator should then do the opposite of increment, however that is not the case. Applying the decrement operator to a string never changes the initial string.

Program 8.1 Increment operator used with strings

```
$a = "a";
$b = "Bob";
$c = "Z";
$d = "Hello World!";
$a++; // Result: "b"
$b++; // Result: "Boc"
$c++; // Result: "AA"
$d++; // Result: "Hello World!"
// Decrementing does nothing
```

To be able to support all these operations in a sound manner, the official PHP interpreter has to be studied to create an overview of how each operation is implemented and thus defined. The interpreter is the only definition of the PHP language yet, even though the work on an official definition is in progress [A4]. Until the official definition of the language is available, inspecting the interpreter source code is the only way to get a full overview of how operators are implemented and to use that overview to create a full set of abstract operators from Value-lattice-element to Value-lattice-element.

8.1.2 Dynamic features

The language subset P0 does not support variable variables, variable functions, or dynamic loading of code. One way of supporting variable variables is to change the definition of the local and global scope lattices. Instead of mapping from variable names, they could be maps from strings to heap-locations, allowing an abstract operation for look-up in the global and local variable scopes. Supporting variable variables will impact precision in cases containing many writes to variable variables with names that cannot be reasoned about statically. Any write to a $\top$-element string has to be joined when reading from all variables, which lowers the precision of all variable reads.

Supporting variable variables will also introduce some of the problems encountered when implementing the array-map. For example, a reference assignment to a variable is currently updated strongly, just as a reference assignment to an array. This would, however, not always be sound with variable variables.

In order for the analysis to support the whole language, resolving functions dynamically must also be supported. This follows from the special functions `call_user_func` and `call_user_func_array` and the so-called *callables*, which are strings, arrays, or anonymous functions that represent a function. For example, let function `f()` be defined. Then calling the string `"f"` is equivalent to calling the function directly. Resolving functions dynamically could possibly be implemented using existing methods for supporting dynamic dispatch on e.g. objects.

As mentioned in section 2.1, dynamically loading code with the `include` or `require` statements should not practically impose a problem, since modern PHP programs tend to use the auto-loading features of dependency managers. Another method for dynamically loading code is the `eval` function, which evaluates the PHP code in a given string. Adding support for this feature should be done inspired by existing work for the JavaScript `eval` function.

8.1.3 Objects and resources

This thesis has disregarded a large part of PHP, namely the object model. To be able to handle real PHP applications, objects must be supported, since almost every PHP application is at least partly object oriented. When adding support for objects, existing techniques for making a type analysis object-sensitive should be investigated.

Special care should be taken when implementing properties, since properties can be added and removed at run time. To keep soundness of the analysis, object properties can be modelled as an array-map. This approach suffers from the same weakness as variable variables, that write-operations to $\top$-element property names lessens the precision of all other properties. Another approach would involve researching usage of these dynamic features by logging and analysing object property creation and removal. If the occurrence of these operations proves rare, an unsound disregard of property creations and removals can be applied in the analysis, which will in turn improve the precision of the analysis.

The resource type is not supported by this thesis. It is a special type used for handling references to external resources like files or database connections, which are used by most real applications. To support the resource type, an abstraction in the form of a lattice must be created and added as another factor in the Value-lattice. Furthermore operators and coercion must be expanded to the resource type as well.

8.1.4 Library functions

The huge library of functions packaged with PHP by default is essential to any real application. To be able to handle real applications, all of these functions must be supported with at least a naive and imprecise transfer function. Functions without any side-effects, i.e. without reference-parameters, can be naively supported by resulting in the $\top$-element value. Functions with possible side-effects furthermore have to join the heap location values of the reference parameters with the $\top$-element value. By adding these naive transfer-functions for library functions, the analysis will keep soundness for any use of library functions at the cost of possibly losing a lot of precision.

The soundness argument here is based on an assumption that library functions do not have side-effects except for possible manipulation of reference-parameters. Since library functions are implemented using an API provided by the interpreter they may have side-effects. We have, however, not observed any functions with such side-effects, except the `eval` function which requires special attention in itself.

A more precise model of the library functions would require manual inspection of the source code, which is time-consuming, to say the least.

8.1.5 Special language constructs

Function-like language constructs are not supported in P0. However, most real programs rely on at least some of these constructs.

In program 8.2, the `isset`, `unset`, `empty`, and `exit` constructs are demonstrated. The most straight-forward construct is `empty`, since it takes ordinary expressions as input, just like any function. A transfer function must be specified like for library functions to support `empty`. The constructs `isset` and `unset` accept variables or array-reads only as parameters.

Program 8.2 Function-like language constructs

```
$a = 0;
$b = 42;
empty($a); // true
empty($b); // false
empty($c); // true
isset($a); // true
isset($b); // true
isset($c); // false
unset($b);
isset($b); // false
```

(8.2.1) Isset, unset, and empty

```
$a = 1;
$b = 2;
exit();
$c = 3; // unreachable
```

(8.2.2) Exit

Unsetting can be abstracted by joining with the `null`-value, since that is the value of unset variables and unset array entries. Implementing `isset` naively is simple. However, to get more precision, the implementation of `unset` has to be taken into account, since unsetting a variable will result in `isset` for that variable returning boolean true.

8.1.6 Other unsupported features

The previous mentioned features are some of the most frequently used features, but as mentioned in chapter 2, PHP is an ever-changing language with new language features added with every new version. Other features not supported by the analysis in this thesis include: casting to scalars, e.g. casting to boolean `(bool) $a` or null `(unset) $a`, array access on strings, accessing arrays with curly brackets. In order to support the whole language, a notorious analysis of the source-code and documentation is required.

An alternative approach would be to only support a subset of the language as done in this thesis, but on a much larger scale. The subset could be decided based on an analysis of existing PHP frameworks, which hopefully excludes some of the more obscure features.

8.2 Precision

The abstraction of a static analysis based on the monotone framework is done in two places; in the lattice used to represent the state of the analysis and the transfer functions or abstract operations used to transition between different lattice elements to represent changes of the program state. These abstractions are where precision is traded for other properties of the analysis, like performance and ease of implementation. In this section, some improvements to the lattice and transfer functions are discussed. All improvements should be subject to evaluation on *real* programs which, as previously stated would require a larger range of language features to be supported by the analysis.

Each element of the lattice represents either a certain value or a predicate restricting possible values, e.g. the string `"foo"` can be represented as a concrete value (notUIntString: `"foo"`), as uIntString, or as $\top$-string. The analysis developed in this thesis is path-insensitive, which is why we have chosen an analysis lattice which represent only a single predicate, i.e. whether strings, numbers, and array indices are positive integers or not. Otherwise, exact values are kept where possible.

Currently, the Integer-lattice, which is part of the Index-lattice, has no predicates, besides the $\top$-integer. By mimicking the separation between unsigned integer and not unsigned integer from the Number and String lattices, differentiation between maps and lists might become more precise, since writes with non-negative integer keys would produce lists, and otherwise a map will be produced. Alternatively, the predicates of numbers and strings could be redesigned to express integer and not-integer strings and numbers, keeping in alignment with the current definitions of array-lists and -maps (definition 6 and 7 respectively).

Another immediate improvement of the lattice would be to introduce a new parent to ArrayList and ArrayMap in the Array lattice, as proposed in section 5.7. By keeping track of the locations of an array, even when it is not a list nor map, would most likely provide enormous precision. Notice that this would also remove many of the errors raised from performing operations on the $\top$-array element observed throughout the cases presented in chapter 5 and thus another method for alerting precision loss should be implemented.

Because of PHP keeping references when copying arrays, the analysis can not soundly perform strong updates on the heap. Assigning references from arrays may however be one of the less used features of PHP. A hypothesis about the use of references in arrays can be tested by expanding the dynamic analysis in chapter 3. If references in arrays turn out to be rarely used, strong updates could be reintroduced, thus sacrificing soundness. Alternatively the heap could have an associated entry expressing whether any given location has been referenced. This would model the implementation of the interpreter more precisely and should allow strong updates on some locations.

8.3 Performance

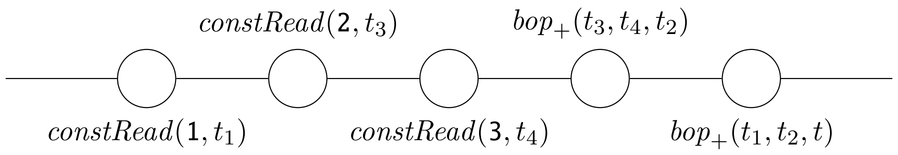
Performance has not been a primary concern of this thesis, and as such only few thoughts have been put into optimization of the performance. The analysis in practice has high memory consumption and while it might terminate within a few seconds, even that might be too long for it to be used as a tool in a development environment where the changes are frequent.

When optimizing for performance, two approaches can be considered; optimizing theoretical performance and optimizing practical performance. The former is the performance of the specified analysis, whereas the latter is optimization in the implementation, while still conforming to the specification of the analysis.

8.3.1 Analysis performance

The analysis lattice is the primary data-structure used and thus a major factor in performance regarding memory usage. To obtain context sensitivity the State-lattice is stored multiple times in the analysis lattice and because of this minimizing the size of the State-lattice potentially results in multiple times the performance gain.

The two lattice-parts Temps and HeapTemps are used to pass information between control-flow nodes and are specified as complete maps from temporary variable names and temporary heap variable names, respectively. Consider $\perp$-values smaller to store than other values as this is the default value. The current analysis never resets entries from the map, which implies that it will keep growing in size with programs of larger size, as more temporary storage entries are set to values different than $\perp$. Due to the nature of how these maps are used, each entry can be seen as having a provider and potentially also a consumer control-flow node. The provider node sets the entry which is later used by the consumer node. To keep the maps small in size, even with large programs, the consumer nodes can reset the entries they consume to $\perp$. Graph 8.1 shows a simple control-flow graph to demonstrate the effect of letting the consumer node reset consumed entries.



Graph 8.1: Example graph $[\![$1+(2+3)$]\!](t)$

In the program below, the first line shows the entries which would be set, i.e. not $\perp$, in the Temps lattice-element associated with the last node without any optimizations. The second line shows the set entries with the optimization.

```
temps → [t1, t2, t3, t4, t] // without optimization
temps → [t] // with optimization
```

8.3.2 Implementation performance

The implemented analysis cache results and performs joins lazily, which should in theory limit the computation necessary. There is however much more to be done, and it is expected that existing techniques could be used for identifying possible optimizations. For example, it could be considered how running the analysis on the whole program even for the smallest change could be avoided by reusing abstract states from unchanged code.

8.4 Summary

In this chapter we have proposed different ways to continue the work done in this thesis. To be able to use the analysis developed in chapter 4 in any real context, the full PHP language has to be supported and performance has to be improved. For the former we have proposed ways to handle dynamic features, the remaining operations, objects, resources, and library functions. For the latter we have proposed a method to keep the lattice-parts concerned with temporary variables small in size regardless of the size of the program. Furthermore, we have proposed possible precision improvements, which could be adopted, some at the cost of soundness.

Appendix A

Lattice theory

Definition 10. A partial order, $S = (A, \sqsubseteq)$ is a set of elements, A, and a binary relation, $\sqsubseteq: A \times A$, where $\sqsubseteq$ is

- Reflexive: $\forall a \in A: \; a \sqsubseteq a$
- Anti-symmetric: $\forall a, b \in A: \; a \sqsubseteq b \wedge b \sqsubseteq a \Rightarrow a = b$
- Transitive: $\forall a, b, c \in A: \; a \sqsubseteq b \wedge b \sqsubseteq c \Rightarrow a \sqsubseteq c$

Definition 11. A lattice $L = (E, \sqsubseteq)$ is a partial order where each subset $S \subseteq E$ has a least upper bound and a greatest lower bound $\sqcup S$ and $\sqcap S$, respectively

Definition 12. The sum of two lattices, $L_1 = (E_1, \sqsubseteq_1)$ and $L_2 = (E_2, \sqsubseteq_2)$ where $\{\top, \bot\} \subseteq E_1 \cap E_2$, is defined as

$$L_{Sum} = L_1 + L_2 = (E_{Sum}, \sqsubseteq_{Sum}) \tag{A.1}$$

Where

$$E_{Sum} = \{(i, x) | x \in L_i \setminus \{\top, \bot\}\} \cup \{\top, \bot\} \tag{A.2}$$

and for every $e_1, e_2 \in E_{Sum}$

$$e_1 \sqsubseteq_{Sum} e_2 \Leftrightarrow (x \sqsubseteq_i y \wedge e_1 = (x, i) \wedge e_2 = (y, i)) \vee e_2 = \top \vee e_1 = \bot \tag{A.3}$$

Definition 13. The product of two lattices, $L_1 = (E_1, \sqsubseteq_1)$ and $L_2 = (E_2, \sqsubseteq_2)$, is defined as

$$L_{Prod} = L_1 \times L_2 = (E_{Prod}, \sqsubseteq_{Prod}) \tag{A.4}$$

Where

$$E_{Prod} = \{(e_1, e_2) | e_1 \in L_1, e_2 \in L_2\} \tag{A.5}$$

and for every $(x_1, x_2), (y_1, y_2) \in E_{Prod}$

$$e_1 \sqsubseteq e_2 \Leftrightarrow x_1 \sqsubseteq_1 y_1 \wedge x_2 \sqsubseteq_2 y_2 \tag{A.6}$$

Definition 14. Given a set, $A = \{a_1, \cdots, a_n\}$, and a lattice $L = \{E, \sqsubseteq\}$, a map lattice is defined as

$$L_{Map} = A \mapsto L = (E_{Map}, \sqsubseteq_{Map}) \tag{A.7}$$

Where

$$E_{Map} = \{([a_1 \mapsto x_1, \cdots, a_n \mapsto x_n] | x_i \in E\} \tag{A.8}$$

and for two elements $e_1, e_2 \in E_{Map}$,

$$e_1 \sqsubseteq_{Map} e_2 \Leftrightarrow \forall a \in A: \; e_1(a) \sqsubseteq e_2(a) \tag{A.9}$$

Definition 15. Given a set A, the powerset is defined as

$$P(A) = (E_P, \sqsubseteq_P) \tag{A.10}$$

Where

$$E_P = \{S | S \subseteq E\} \tag{A.11}$$

and for two elements $e_1, e_2 \in E_P$

$$e_1 \sqsubseteq_P e_2 \Leftrightarrow e_1 \subseteq e_2 \tag{A.12}$$

Appendix B

Abstract operators

The following definitions are used for all tables in this appendix.

$$x, y \in \mathbb{Z} \land x, y > 0$$
$$a, b \in \mathbb{R} \land (a, b < 0 \lor a, b \notin \mathbb{Z})$$

Furthermore the shorthand f is used for the boolean `false` value.

$+$	$\bot$	0	y	uInt	b	notUInt	$\top$
$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$
0	$\bot$	0	y	uInt	b	notUInt	$\top$
x	$\bot$	x	$x+y$	uInt	$x+b$	$\top$	$\top$
uInt	$\bot$	uInt	uInt	uInt	$\top$	$\top$	$\top$
a	$\bot$	a	$a+y$	$\top$	$a+b$	$\top$	$\top$
notUInt	$\bot$	notUInt	$\top$	$\top$	$\top$	$\top$	$\top$
$\top$	$\bot$	$\top$	$\top$	$\top$	$\top$	$\top$	$\top$

Table B.1: Abstract addition

$-$	$\bot$	0	y	uInt	$b < 0 \land b \in \mathbb{Z}$	b	notUInt	$\top$
$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$
0	$\bot$	0	y	$\top$	$-b$	$-b$	$\top$	$\top$
x	$\bot$	x	$x-y$	$\top$	$x-b$	$x-b$	$\top$	$\top$
uInt	$\bot$	uInt	$\top$	$\top$	uInt	notUInt	$\top$	$\top$
$a < 0 \land a \in \mathbb{Z}$	$\bot$	a	$a-y$	notUInt	$a-b$	$a-b$	$\top$	$\top$
a	$\bot$	a	$a-y$	notUInt	$a-b$	$a-b$	$\top$	$\top$
notUInt	$\bot$	notUInt	notUInt	notUInt	$\top$	$\top$	$\top$	$\top$
$\top$	$\bot$	$\top$	$\top$	$\top$	$\top$	$\top$	$\top$	$\top$

Table B.2: Abstract subtraction

$\cdot$	$\bot$	0	y	uInt	$b<0$	b	notUInt	$\top$
$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$
0	$\bot$	0	0	0	0	0	0	0
x	$\bot$	0	$x \cdot y$	uInt	$x \cdot b$	$x \cdot b$	$\top$	$\top$
uInt	$\bot$	0	uInt	uInt	notUInt	$\top$	$\top$	$\top$
$a<0$	$\bot$	0	$a \cdot y$	notUInt	$\top$	$a \cdot b$	$\top$	$\top$
a	$\bot$	0	$a \cdot y$	$\top$	$a \cdot b$	$a \cdot b$	$\top$	$\top$
notUInt	$\bot$	0	$\top$	$\top$	$\top$	$\top$	$\top$	$\top$
$\top$	$\bot$	0	$\top$	$\top$	$\top$	$\top$	$\top$	$\top$

Table B.3: Abstract multiplication

$/$	$\bot$	0	y	uInt	$b<0$	b	notUInt	$\top$
$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$
0	$\bot$	f	0	$0 \sqcup f$	0	0	0	$0 \sqcup f$
x	$\bot$	f	$\frac{x}{y}$	$\top \sqcup f$	$\frac{x}{b}$	$\frac{x}{b}$	$\top$	$\top \sqcup f$
uInt	$\bot$	f	$\top$	$\top \sqcup f$	notUInt	$\top$	$\top$	$\top \sqcup f$
$a<0$	$\bot$	f	$\frac{a}{y}$	notUInt $\sqcup f$	$\frac{a}{b}$	$\frac{a}{b}$	$\top$	$\top \sqcup f$
a	$\bot$	f	$\frac{a}{y}$	$\top \sqcup f$	$\frac{a}{b}$	$\frac{a}{b}$	$\top$	$\top \sqcup f$
notUInt	$\bot$	f	$\top$	$\top \sqcup f$	$\top$	$\top$	$\top$	$\top \sqcup f$
$\top$	$\bot$	f	$\top \sqcup f$	$\top \sqcup f$	$\top$	$\top$	$\top$	$\top \sqcup f$

Table B.4: Abstract division

$\%$	$\bot$	0	y	uInt	$b>-1$	b	notUInt	$\top$
$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$
0	$\bot$	f	0	$0 \sqcup f$	$0 \sqcup f$	0	$0 \sqcup f$	$0 \sqcup f$
x	$\bot$	f	$x\%y$	uInt $\sqcup f$	$x\%b$	$x\%b$	uInt $\sqcup f$	uInt $\sqcup f$
uInt	$\bot$	f	uInt	uInt $\sqcup f$	uInt $\sqcup f$	uInt	uInt $\sqcup f$	uInt $\sqcup f$
$a>-1$	$\bot$	f	$a\%y$	uInt $\sqcup f$	$a\%b$	$a\%b$	uInt $\sqcup f$	uInt $\sqcup f$
a	$\bot$	f	$a\%y$	notUInt $\sqcup f$	$a\%b$	$a\%b$	notUInt $\sqcup f$	notUInt $\sqcup f$
notUInt	$\bot$	f	$\top$	$\top \sqcup f$	$\top \sqcup f$	$\top$	$\top \sqcup f$	$\top \sqcup f$
$\top$	$\bot$	f	$\top$	$\top \sqcup f$	$\top \sqcup f$	$\top$	$\top \sqcup f$	$\top \sqcup f$

Table B.5: Abstract modulus

$**$	$\bot$	0	y	uInt	b	notUInt	$\top$
$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$
0	$\bot$	1	0	uInt	0	0	uInt
x	$\bot$	1	x^y	uInt	$\top$	$\top$	$\top$
uInt	$\bot$	1	uInt	uInt	$\top$	$\top$	$\top$
a	$\bot$	1	a^y	$\top$	a^b	$\top$	$\top$
notUInt	$\bot$	1	$\top$	$\top$	$\top$	$\top$	$\top$
$\top$	$\bot$	1	$\top$	$\top$	$\top$	$\top$	$\top$

Table B.6: Abstract exponentiation

==	⊥	t	f	⊤
⊥	⊥	⊥	⊥	⊥
t	⊥	t	f	⊤
f	⊥	f	t	⊤
⊤	⊥	⊤	⊤	⊤

(a) Equality

! =	⊥	t	f	⊤
⊥	⊥	⊥	⊥	⊥
t	⊥	f	t	⊤
f	⊥	t	f	⊤
⊤	⊥	⊤	⊤	⊤

(b) Not equality

<	⊥	t	f	⊤
⊥	⊥	⊥	⊥	⊥
t	⊥	f	f	f
f	⊥	t	f	⊤
⊤	⊥	⊤	f	⊤

(c) Less than

<=	⊥	t	f	⊤
⊥	⊥	⊥	⊥	⊥
t	⊥	t	f	⊤
f	⊥	t	t	t
⊤	⊥	t	⊤	⊤

(d) Less than/equal

>	⊥	t	f	⊤
⊥	⊥	⊥	⊥	⊥
t	⊥	f	t	⊤
f	⊥	f	f	f
⊤	⊥	f	⊤	⊤

(e) Greater than

>=	⊥	t	f	⊤
⊥	⊥	⊥	⊥	⊥
t	⊥	t	t	t
f	⊥	f	t	⊤
⊤	⊥	⊤	t	⊤

(f) Greater than/equal

Table B.7: Abstract comparison operators for booleans

==	⊥	y	uIntString	s	notUIntString	⊤
⊥	⊥	⊥	⊥	⊥	⊥	⊥
x	⊥	x==y	⊤	f	f	⊤
uIntString	⊥	⊤	⊤	f	f	⊤
r	⊥	f	f	r==s	⊤	⊤
notUIntString	⊥	f	f	⊤	⊤	⊤
⊤	⊥	⊤	⊤	⊤	⊤	⊤

Table B.8: Abstract equal for strings

! =	⊥	y	uIntString	s	notUIntString	⊤
⊥	⊥	⊥	⊥	⊥	⊥	⊥
x	⊥	x!=y	⊤	t	t	⊤
uIntString	⊥	⊤	⊤	t	t	⊤
r	⊥	t	t	r!=s	⊤	⊤
notUIntString	⊥	t	t	⊤	⊤	⊤
⊤	⊥	⊤	⊤	⊤	⊤	⊤

Table B.9: Abstract not equal for strings

$\oplus \in \{<, >, \leq, \geq\}$	$\perp$	y	uIntString	s	notUIntString	$\top$
$\perp$	$\perp$	$\perp$	$\perp$	$\perp$	$\perp$	$\perp$
x	$\perp$	$x \oplus y$	$\top$	$x \oplus s$	$\top$	$\top$
uIntString	$\perp$	$\top$	$\top$	$\top$	$\top$	$\top$
r	$\perp$	$r \oplus y$	$\top$	$r \oplus s$	$\top$	$\top$
notUIntString	$\perp$	$\top$	$\top$	$\top$	$\top$	$\top$
$\top$	$\perp$	$\top$	$\top$	$\top$	$\top$	$\top$

Table B.10: Abstract less than (or equal) and greater than (or equal) for strings.

==	$\perp$	y	uInt	b	notUInt	$\top$
$\perp$	$\perp$	$\perp$	$\perp$	$\perp$	$\perp$	$\perp$
x	$\perp$	$x == y$	$\top$	f	f	$\top$
uInt	$\perp$	$\top$	$\top$	f	f	$\top$
a	$\perp$	f	f	$a == b$	$\top$	$\top$
notUInt	$\perp$	f	f	$\top$	$\top$	$\top$
$\top$	$\perp$	$\top$	$\top$	$\top$	$\top$	$\top$

Table B.11: Abstract equal on numbers

! =	$\perp$	y	uInt	b	notUInt	$\top$
$\perp$	$\perp$	$\perp$	$\perp$	$\perp$	$\perp$	$\perp$
x	$\perp$	x!=y	$\top$	t	t	$\top$
uInt	$\perp$	$\top$	$\top$	t	t	$\top$
a	$\perp$	t	t	a!=b	$\top$	$\top$
notUInt	$\perp$	t	t	$\top$	$\top$	$\top$
$\top$	$\perp$	$\top$	$\top$	$\top$	$\top$	$\top$

Table B.12: Abstract not equal on numbers

$\oplus \in \{<, \leq\}$	$\perp$	y	uInt	b < 0	b	notUInt	$\top$
$\perp$	$\perp$	$\perp$	$\perp$	$\perp$	$\perp$	$\perp$	$\perp$
x	$\perp$	x $\oplus$ y	$\top$	f	x $\oplus$ b	$\top$	$\top$
uInt	$\perp$	$\top$	$\top$	f	$\top$	$\top$	$\top$
a < 0	$\perp$	t	t	a $\oplus$ b	a $\oplus$ b	$\top$	$\top$
a	$\perp$	a $\oplus$ y	$\top$	a $\oplus$ b	a $\oplus$ b	$\top$	$\top$
notUInt	$\perp$	$\top$	$\top$	$\top$	$\top$	$\top$	$\top$
$\top$	$\perp$	$\top$	$\top$	$\top$	$\top$	$\top$	$\top$

Table B.13: Abstract less than (or equal) on numbers

$\oplus \in \{>, \geq\}$	$\bot$	y	uInt	b < 0	b	notUInt	$\top$
$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$	$\bot$
x	$\bot$	$x \oplus y$	$\top$	t	$x \oplus b$	$\top$	$\top$
uInt	$\bot$	$\top$	$\top$	t	$\top$	$\top$	$\top$
a < 0	$\bot$	f	f	$a \oplus b$	$a \oplus b$	$\top$	$\top$
a	$\bot$	$a \oplus y$	$\top$	$a \oplus b$	$a \oplus b$	$\top$	$\top$
notUInt	$\bot$	$\top$	$\top$	$\top$	$\top$	$\top$	$\top$
$\top$	$\bot$	$\top$	$\top$	$\top$	$\top$	$\top$	$\top$

Table B.14: Abstract greater than (or equal) on numbers

`&&`	$\bot$	t	f	$\top$
$\bot$	$\bot$	$\bot$	$\bot$	$\bot$
t	$\bot$	t	f	$\top$
f	$\bot$	f	f	f
$\top$	$\bot$	$\top$	f	$\top$

(a) `AND`

`||`	$\bot$	t	f	$\top$
$\bot$	$\bot$	$\bot$	$\bot$	$\bot$
t	$\bot$	t	t	t
f	$\bot$	t	f	$\top$
$\top$	$\bot$	t	$\top$	$\top$

(b) `OR`

`XOR`	$\bot$	t	f	$\top$
$\bot$	$\bot$	$\bot$	$\bot$	$\bot$
t	$\bot$	f	t	$\top$
f	$\bot$	t	f	$\top$
$\top$	$\bot$	$\top$	$\top$	$\top$

(c) `XOR`

Table B.15: Abstract logical binary boolean operators

`++`	$\bot$	n	uInt	notUInt	$\top$
	$\bot$	$n+1$	uInt	$\top$	$\top$

(a) Abstract pre- and post-increment

`- -`	$\bot$	n	uInt	notUInt	$\top$
	$\bot$	$n-1$	$\top$	notUInt	$\top$

(b) Abstract pre- and post-decrement

`-`	$\bot$	n	uInt	notUInt	$\top$
	$\bot$	$-n$	notUInt	$\top$	$\top$

(c) Unary minus

`!`	$\bot$	true	false	$\top$
	$\bot$	false	true	$\top$

(d) Boolean negate

Table B.16: Abstract unary operators

Primary Bibliography

[A1] Shay Artzi, Adam Kieżun, Julian Dolby, Frank Tip, Danny Dig, Amit Paradkar, and Michael D. Ernst. Finding bugs in web applications using dynamic test generation and explicit state model checking. *IEEE Transactions on Software Engineering*, 36(4):474–494, July/August 2010.

[A2] Bruno Dufour, Barbara G. Ryder, and Gary Sevitsky. Blended analysis for performance understanding of framework-based applications. In *Proceedings of the 2007 International Symposium on Software Testing and Analysis*, ISSTA '07, pages 118–128, New York, NY, USA, 2007. ACM.

[A3] The PHP Group. Php: Comparison operators - manual. `http://php.net/manual/en/language.operators.comparison.php`, 2015. Accessed: 2015-05-12.

[A4] The PHP Group. Php language specifications. `https://github.com/php/php-langspec`, 2015. Accessed: 2015-11-06.

[A5] David Hauzar and Jan Kofron. WeVerca: Web applications verification for PHP. In *Proc. Software Engineering and Formal Methods - 12th International Conference, SEFM '14*, pages 296–301, 2014.

[A6] David Hauzar, Jan Kofroň, and Pavel Baštecký. Data-flow analysis of programs with associative arrays. In Jun Pang and Yang Liu, editors, Proceedings Third International Workshop on *Engineering Safety and Security Systems,* Singapore, Singapore, 13 May 2014, volume 150 of *Electronic Proceedings in Theoretical Computer Science*, pages 56–70. Open Publishing Association, 2014.

[A7] Mark Hills. Evolution of dynamic feature usage in php. In *Proc. 22nd International Conference on Software Analysis, Evolution, and Reengineering, SANER '15*, March 2015.

[A8] Mark Hills, Paul Klint, and Jurgen Vinju. An empirical study of php feature usage: A static analysis perspective. In *Proceedings of the 2013 International Symposium on Software Testing and Analysis*, ISSTA 2013, pages 325–335, New York, NY, USA, 2013. ACM.

[A9] Mark Hills, Paul Klint, and Jurgen J. Vinju. Static, lightweight includes resolution for PHP. In *ACM/IEEE International Conference on Automated Software Engineering, ASE '14, Vasteras, Sweden - September 15 - 19, 2014*, pages 503–514, 2014.

[A10] Simon Holm Jensen, Anders Møller, and Peter Thiemann. Type analysis for JavaScript. In *Proc. 16th International Static Analysis Symposium, SAS '09*, volume 5673 of *LNCS*. Springer-Verlag, August 2009.

[A11] Nenad Jovanovic, Christopher Kruegel, and Engin Kirda. Pixy: A static analysis tool for detecting web application vulnerabilities (short paper). In *IN 2006 IEEE SYMPOSIUM ON SECURITY AND PRIVACY*, pages 258–263, 2006.

[A12] Yasuhiko Minamide. Static approximation of dynamically generated web pages. In *Proceedings of the 14th International Conference on World Wide Web*, WWW '05, pages 432–441, New York, NY, USA, 2005. ACM.

[A13] Flemming Nielson, Hanne Riis Nielson, and Chris Hankin. *Principles of Program Analysis*. Springer, 1999.

[A14] Gregor Richards, Sylvain Lebresne, Brian Burg, and Jan Vitek. An analysis of the dynamic behavior of javascript programs. *SIGPLAN Not.*, 45(6):1–12, June 2010.

[A15] Akihiko Tozawa, Michiaki Tatsubori, Tamiya Onodera, and Yasuhiko Minamide. Copy-on-write in the php language. *SIGPLAN Not.*, 44(1):200–212, January 2009.

[A16] W3Techs. Usage statistics and market share of server-side programming languages for websites, june 2015. `http://w3techs.com/technologies/overview/programming_language/all`, 2015. Accessed: 2015-06-10.

[A17] G. Wassermann and Zhendong Su. Static detection of cross-site scripting vulnerabilities. In *Software Engineering, 2008. ICSE '08. ACM/IEEE 30th International Conference on*, pages 171–180, May 2008.

[A18] Shiyi Wei and Barbara G. Ryder. Practical blended taint analysis for javascript. In *Proceedings of the 2013 International Symposium on Software Testing and Analysis*, ISSTA 2013, pages 336–346, New York, NY, USA, 2013. ACM.

Secondary Bibliography

[B19] Magento 2. Magento 2 developers hub. https://magento.com/developers/magento2, 2015. Accessed: 2015-04-06.

[B20] Sebastian Bergmann. Phpunit - the php testing framework. https://phpunit.de, 2015. Accessed: 2015-06-10.

[B21] T. Berners-Lee, R. Fielding, and L. Masinter. Uniform Resource Identifier (URI): Generic Syntax. RFC 3986 (INTERNET STANDARD), January 2005. Updated by RFCs 6874, 7320.

[B22] Christian Budde Christensen. Part. https://github.com/budde377/Part, 2015. Accessed: 2015-04-06.

[B23] Travis CI. Travis ci - test and deploy your code with confidence. https://travis-ci.org/, 2015. Accessed: 2015-06-10.

[B24] CodeIgniter. Codeigniter web framework. http://www.codeigniter.com/, 2015. Accessed: 2015-04-06.

[B25] PHP FIG. Php framework interop group. http://www.php-fig.org/, 2015. Accessed: 2015-06-10.

[B26] The PHP Group. Modified php interpreter. https://github.com/Silwing/php-src, 2015. Accessed: 2015-06-10.

[B27] The PHP Group. Php: Array functions - manual. http://php.net/manual/en/ref.array.php, 2015. Accessed: 2015-06-10.

[B28] The PHP Group. Php: array_merge - manual. http://php.net/manual/en/function.array-merge.php, 2015. Accessed: 2015-06-10.

[B29] The PHP Group. Php: $_server - manual. http://php.net/manual/en/reserved.variables.server.php, 2015. Accessed: 2015-06-10.

[B30] HashiCorp. Vagrant. http://vagrantup.com, 2015. Accessed: 2015-06-10.

[B31] JetBrains. Jetbrains. http://jetbrains.com, 2015. Accessed: 2015-06-10.

[B32] Joomla. Joomla! the cms trusted by millions for their websites. http://www.joomla.org/, 2015. Accessed: 2015-04-06.

[B33] Rasmus Lerdorf, Kevin Tatroe with Bob Kaehms, and Ric McGredy. *Programming PHP*. O'Reilly, 2002.

[B34] Zend Technologies Ltd. Zend framework. `http://framework.zend.com/`, 2015. Accessed: 2015-04-06.

[B35] MediaWiki. Mediawiki. `https://www.mediawiki.org/`, 2015. Accessed: 2015-04-06.

[B36] Jordi Boggiano Nils Adermann and many community contributions. Composer. `https://getcomposer.org/`, 2015. Accessed: 2015-06-10.

[B37] phpBB. phpbb • free and open source forum software. `https://www.phpbb.com/`, 2015. Accessed: 2015-04-06.

[B38] phpMyAdmin. phpmyadmin. `http://www.phpmyadmin.net/`, 2015. Accessed: 2015-04-06.

[B39] Toran Proxy. Packagist. `https://packagist.org/`, 2015. Accessed: 2015-06-13.

[B40] SensioLabs. Symfony, high performance php framework for web development. `http://symfony.com/`, 2015. Accessed: 2015-04-06.

[B41] W3Techs. Usage statistics and market share of server-side programming languages for websites, june 2015. `http://w3techs.com/technologies/overview/programming_language/all`, 2015. Accessed: 2015-06-10.

[B42] Wordpress. Wordpress › blog tool, publishing platform, and cms. `https://wordpress.org/`, 2015. Accessed: 2015-04-06.