



To what extent is C# being used as a functional programming language?

An evaluation of functional purity in C#

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Abstract

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This thesis develops a method of statically determining the level of purity in a given C# program. It investigates problems with determining purity in object oriented languages, with a focus on C#. A function is defined to be pure if it side-effect free and deterministic.

TODO

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Sammanfattning

TODO

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1 Introduction

Functional programming is on the rise and becoming more mainstream [6]. Object oriented (OO) programming has been the industry norm for quite some time now, and for a long time functional programming was considered by developers to only be applicable in academic domains. However it is now becoming popular in the IT industry as well. Many mainstream languages like Java, C# and C++ have adopted first-class functions from the functional paradigm [6]. Moreover, functional programming can be used for building web applications and mobile apps [25].

Functional programs have many benefits over purely object oriented ones. Perhaps one of the most useful features of functional programming that the object oriented world of programming could adopt is *functional purity*. Programs with pure functions are generally easier to reason about impure ones because they have no *side-effects* [2]. A side-effect is anything that a function does besides producing a return value and that is visible from the function's caller's point of view [18]. Pure functions are also easier to test since all we need to look at are functions' inputs and outputs, which also, for instance, facilitates property-based testing [2]. Moreover, research has shown that pure programs are easier to debug and maintain [18]. For this reason it is useful in software engineering to evaluate the level of functional purity in programs [18].

C# is among the top five most popular programming languages [24]. To its core, it is an object-oriented programming language. However, it has features that allow for functional programming [17]. But to what extent is C# being used as a functional programming language by developers? This paper will attempt to answer this by evaluating to what degree functional purity is used in C# programs today.

In this thesis the term *method* and *function* will be used interchangeably.

2 Background

2.1 Definitions

Functional programming and object oriented programming are two different programming paradigms. There is no universal definition of either of them. Following is how they have been chosen to be defined in this thesis.

2.1.1 Functional programming

1. All functions are *functionally pure*, meaning that they do not have any side-effects, and their output depends only on the input [4]. The latter is what Finifter et al. call *determinism* [5]. Not all definitions of functional purity include determinism, and the choice of definition used in this thesis is discussed in [subsection 5.8](#).
2. Functions are first-class and can be higher-order, meaning that functions can be passed to functions as parameters, and can be returned by functions [25].
3. Variables are immutable, meaning that their value does not change after being initiated [25].

2.1.2 Object oriented programming

1. Computations are done via *methods* belonging to *objects*, whose structure suits the goal of whatever computation we're doing [4].
2. Objects are based on *classes*, and objects belonging to a class have a shared set of properties [4].
3. Classes can *inherit* from other superclasses, such that a class is also an instance of its superclass [4].

2.1.3 Definition of functional purity

As mentioned in [subsubsection 2.1.1](#), the definition of functional programming consists of three parts. *Purity*, functions being *first-class* and *higher-order*, and variables being *immutable*. To delimit the scope of this thesis it will only focus on purity, mainly because it seems like the most useful one out of the three for object oriented programming.

As seen in [section 5](#) a lot of related work defines purity only as being synonymous with side-effect free. This definition therefore doesn't require functions' output to depend purely on their input – what Finifter et al. call *determinism*, as mentioned in [subsection 5.8](#) – but allows them to read from variables defined outside of their scope. This definition is less functional. The definition of purity used in this thesis will therefore require pure functions to not only be side-effect free but also to be deterministic. This is the definition of purity that is used by Finifter et al. [5], Pitidis et al. [20] and Alexander [2], the first two who's work is mentioned in [subsection 5.1](#) and [subsection 5.8](#),

respectively. Moreover, requiring pure functions to be both side-effect free *and* deterministic does in a way also simplify the analysis because it means that any symbol used in a function F but defined outside F would make F impure. If we allowed pure functions to be non-deterministic, that would mean that we would have to check each symbol used in F to see if it is being written to or if it is only being read before concluding if F is pure.

Thus, a function is pure if it is side-effect free and deterministic.

TODO: Add a description of the following

- Side-effects and referential transparency, which implies purity [18]
- .NET Core/C#
- Compilers
- Abstract syntax trees (ASTs)
- .NET ASTs [1]
- Objects: fields and properties

TODO: Things to consider

- Abstract syntax trees
- Input/output
- Recursion
- Monads
- Call-by-value vs. call-by-reference:
- Control flow analysis
- Sometimes we call compiled methods, i.e. methods that we don't have the code for, e.g. the .NET framework base class library (BCL)
- [Delegates](#) and [anonymous functions](#).
- Implicit and explicit variable declarations (C# handles both)

- **Identifiers** are the names of types, members variables or namespaces used in source code. They reference **symbols**, representing a declared namespace, type, method, field, variable, etc. The compiler's process of associating identifiers with symbols is called *binding* [12].
- Closures and how objects can be considered closures (if fields are `readonly`?), and whether or not they should be considered pure.
- **Exceptions**.

2.2 What makes a C# method pure?

Figure 1 and Figure 2 illustrate two very simple examples of pure and impure code, respectively. In Figure 1 the function `addOne()` is impure because it is writing to the variable `number` which was defined outside `addOne()`'s scope, which is a side-effect. Figure 2 illustrates how `addOne()` can be rewritten to a pure function while preserving the program's semantics.

```
public class Program {  
    static int number = 42;  
  
    public static void addOne() {  
        number += 1; // this is a side-effect  
    }  
  
    public static void Main() {  
        addOne();  
        Console.WriteLine(number); // outputs 43  
    }  
}
```

Figure 1: A simple example of *impure* code due to a side-effect.

```

public class Program {
    public static int addOne(int number) { //this method is now pure
        return number + 1;
    }

    public static void Main() {
        int number = 42;
        number = addOne(number);
        Console.WriteLine(number); // outputs 43
    }
}

```

Figure 2: This is how `addOne()` from the example in Figure 1 can be rewritten and used as a *pure* function.

Function parameters preceded with the `in` keyword are passed by reference and read-only inside the function [15]. This means that input parameters marked with `in` cannot be re-assigned inside the function, which may suggest functional purity. Consider the example in Figure 3, where the parameter `number` is preceded by the `in` keyword. Because of this, modifying it inside the function will raise an error.

```

int globalValue = 42;
addOne(globalValue);
Console.WriteLine(globalValue); // value is still 42

void addOne(in int number) // note the 'in' keyword
{
    number += 1; // illegal assignment will raise error CS8332
}

```

Figure 3: Assignment to the parameter `number` which is preceded with `in` raises an error [15].

However, `in` is not a purity guarantee. Consider the example in Figure 4. The `in` keyword before the argument `list` ensures that `list` is readonly. This prevents `list` from being re-assigned after instantiation, but it doesn't prevent the data structure which `list` refers to from being modified [3]. In C# there are two kinds of types: *value types* and *reference types* [16]. Value types directly contain their data, while reference types – also known as objects – are simply pointers that refer to the location of their data. Even though strings are of the reference type they are immutable, meaning that they cannot be modified after being created [14]. Therefore, value types and strings are passed to methods by value, which means that a method that modifies a value type parameter only modifies it locally, which doesn't affect its purity.

```

List<int> globalValue = new List<int>{42};
addOne(globalValue);
globalValue.ForEach(Console.WriteLine); // list is now {42, 1}

void addOne(in List<int> list) // note the 'in' keyword
{
    list.Add(1); // this will _not_ raise an error even though
                // Add(1) modifies the list
}

```

Figure 4: The expression `list.Add(1)` which writes a value to `list` is allowed, even though `list` is read-only due to its preceding `in` keyword.

Since the `in` keyword does not entirely prevent methods modifying their input parameters of reference type, and mutations to parameters of value type are not visible outside of methods regardless of the `in` keyword, it does not help us to determine the purity of a method.

2.3 The .NET Abstract Syntax Tree and the CodeAnalysis library

Abstract syntax trees (ASTs) are the primary data structure used when analysing source code [10]. It encapsulates every piece of information held in the source code [10]. A syntax tree generated by a parser can be re-built into the exact same text that was originally parsed [10].

The abstract syntax tree (AST) generated by the `Microsoft.CodeAnalysis` library represents the lexical and syntactic structure of a .NET program [10]. The tree consists primarily of *syntax nodes* which represent syntactic constructs including declarations, statements, clauses and expressions [10]. Each node is derived from the `SyntaxNode` class [10]. Every node is non-terminal, meaning that they always have children - either other nodes or *tokens* [10]. Tokens are the smallest syntactic pieces of the program, consisting of keywords identifiers, literals and punctuation [10].

2.3.1 Microsoft Syntax Analysis API CodeAnalysis

`Microsoft.CodeAnalysis` is a Syntax API developed by Microsoft which allows programmers to convert a C# program to an abstract syntax tree and traverse it [13].

AST nodes

- The `ClassDeclarationSyntax` node represents the declaration of a class.
- The `MethodDeclarationSyntax` node represents the declaration of a method. Each `MethodDeclarationSyntax` node has a `ParameterListSyntax` - a list of `ParameterSyntax` nodes represents, each representing a method parameter.
- The `LocalFunctionStatementSyntax` node represents a function declared inside a method. Just like the `MethodDeclarationSyntax` it has a `ParameterListSyntax` representing the local function's parameters.
- The `ReturnStatementSyntax` node represents the return token.
- The `VariableDeclarationSyntax` node represents declarations of new variables.
- The `LocalDeclarationStatementSyntax` node represents declarations of new local variables. This node contains a `VariableDeclarationSyntax` node.
- The `AssignmentExpressionSyntax` node represents assignments to already instantiated variables.
- The `IdentifierNameSyntax` node represents symbols used in the code, including variable names and method names.

2.4 C# Events

Events are a way for classes or object to notify other classes or objects when something happens [8]. The class raising the event is called the *publisher* and the class handling the event is called the *subscriber* (there can be more than one subscriber) [8]. When an event is raised the subscriber's handler method is executed. Since events clearly are side-effects, a method that raises events or handles events is not considered pure

2.5 Impure built-in C# methods

The following methods that are built into C# and are non-deterministic [27]:

- `Console.Read`, `Console.ReadLine`, `Console.ReadKey`, `DateTime.Now` and `DateTimeOffset.Now` depend on the outside world.

- `Random.Next`, `Guid.NewGuid` and `System.IO.Path.GetRandomFileName` give random output.

The following methods that are built into C# and have side-effects [27]:

- `System.Threading.Thread.Start` and `Thread.Abort` mutate states.
- `Console.Read`, `Console.ReadLine`, `Console.ReadKey`, `Console.Write` and `Console.WriteLine` produce console I/O.
- `System.IO.Directory.Create`, `Directory.Move`, `Directory.Delete`, `File.Create`, `File.Move`, `File.Delete`, `File.ReadAllBytes` and `File.WriteAllBytes` produce file system I/O.
- `System.Net.Http.HttpClient.GetAsync`, `HttpClient.PostAsync`, `HttpClient.PutAsync` and `HttpClient.DeleteAsync` produce network I/O.
- `IDisposable.Dispose` interacts with the program's environment.

The fact that previously mentioned methods are non-deterministic or have side-effects means that we know for sure that they are impure, which means that any function that uses them is also impure.

2.6 Problems with determining purity in object oriented languages

2.6.1 Inheritance and method overriding

When calling an object parameter's method, because of inheritance and method overriding we can never be sure of which method implementation will be called. Consider the following example [19]:

```
void f(List<string> x) {
    x.Add("Hello");
}
```

Figure 5: Since `x` can be of any subclass of `List` we can never be sure of `x.Add()`'s implementation.

Because the parameter x can be of any subclass of `List` we can not for sure know the implementation of `x.Add()`, nor therefore can we be certain of `x.Add()`'s purity. Thus, we can not determine $f()$'s purity.

One solution to this that David J. Pearce suggests is to demand that pure methods only are overridden by methods that are also pure [19]. Therefore, if a method m is overridden by at least one impure method, m is assumed to be impure.

This means that in the example in Figure 5, the function $f()$ is pure iff all methods that override `List.Add()` are pure.

2.6.2 Modifying a fresh object

If an object o is allocated inside the analysed method m , the object o is said to be *fresh* [19]. To modify o 's state we might call a method that looks impure (since that method would have the side-effect of modifying o). However, this method should not make m impure since o is fresh, which means that the modification of o is not a side-effect of m .

Consider the following example:

```
public List<String> Foo() {
    List<String> list = new List<String>();
    list.Add("hello"); // this changes list's state
    return list;
}
```

Figure 6: `List.Add()` has a side-effect because it modifies the list `list`. However, since `list` is fresh `Foo()`'s purity is not affected.

Because `list.Add()` in Figure 6 modifies the state of `list`, which is a side-effect of `Add()`, `Add()` cannot be a pure method. Does that mean that the function `Foo()` calling `list.Add()` is also impure, because it calls a non-pure method? In general functions that invoke impure functions are themselves impure. However, this is not the case for `Foo()`. Recall the definition of purity in subsection 2.1.3:

A function is pure if it is side-effect free and deterministic.

Because the function `Foo()` only modifies an object exclusively visible inside the function, `Foo()` does not have any side-effect. Nor is the function non-deterministic since it does not read any value outside of the function besides its parameters, which it in this

case doesn't have. This means that `Foo()` is pure.

To solve this we introduce the purity level *locally impure*. Any method that is pure except for reading or modifying its object's fields is locally impure. This includes methods that return `this` or pass `this` as an argument to a function. Consider the following example:

```
public A Foo() { // pure
    A a = new A();
    a.Increment();
    return a;
}

public class A {
    public int value = 0;

    public void Increment() { // locally impure
        value++;
    }
}
```

Figure 7: Since `Foo()` modifies a fresh object with a locally impure method `Increment()` it is still pure.

The method `Increment()` in Figure 7 is locally impure because it modifies its object's field `value` but doesn't have any other side-effects. A function that calls a fresh object's locally impure method `m` is not contaminated by `m`'s local impurity.

There is however one more way to modify a fresh object: to pass it as an argument to a method that alters its state. Consider the following example:

```

public A Foo() { // pure
    A a = new A();
    A.Increment(a);
    return a;
}

public class A {
    public int value = 0;

    public static void Increment(A a) { // parametrically impure
        a.value++;
    }
}

```

Figure 8: Since `Foo()` modifies a fresh object with a parametrically impure method `Increment()`, `Foo()` is still pure.

Because the method `Increment()` in Figure 8 modifies its input parameter object it cannot be considered truly pure. However, since `Foo()` uses `Increment()` to modify a fresh object `Foo()` is still pure. I have chosen to categorize methods that are pure except for modifying the state of its input as *parametrically impure*. There are two ways for a method to modify its input parameters: either by mutating a value belonging to a reference type input parameter, i.e. an object’s field or property, or the cell of an array; or by calling a locally impure method belonging to a parameter object.

The key thing in both the example where a method m calls locally or parametrically impure methods is that they modify a fresh object, which therefore doesn’t affect m ’s purity level. So as long as the analyzed method m or any of its called methods don’t perform any truly impure action like I/O operations or throw exceptions, m is pure.

What if an object’s method is both locally and parametrically impure? Just like in the previous cases, as long as the object is fresh the purity of the caller is not affected.

2.6.3 Iterators

As Pearce suggests, an iterator may at first glance look pure [19]. However, consider the following ([link](#)):


```
bool ListHas(List<int> items, int item) {  
    foreach(int i in items) if(i == item) return true;  
    return false;  
}
```

Figure 9: ListHas () may at first glance look pure, TODO

TODO: explain that this doesn't affect us because our definition of purity includes determinism, or because of the C# compiler's implementation

2.6.4 Non-static property pointing to a static field

Properties in C# are special `get` and `set` methods for reading, computing or writing to values of object fields [9]. Properties can, just like other fields or methods be set to `static`, which means that they are assigned to the class rather than any instantiated object. If a method reads from or modifies a static property, that method would be considered to be non-deterministic or to have a side-effect, i.e. it would be impure, because static fields are accessible anywhere in a program.

However, properties can also be non-static but still read or modify static fields. Consider the following:

```

public class Foo {
    public Swede gert = new Swede();

    public void Bar() {
        Swede stina = new Swede();
        stina.Nationality = "Norway"; // assignment to non-static field

        Console.WriteLine(gert.Nationality); // prints "Norway"
    }

    public class Swede {
        static string nationality = "Sweden"; // This field is static

        public string Nationality { // This property is non-static
            get { return nationality; }
            set { nationality = value; }
        }
    }
}

```

Figure 10: What looks like a non-static assignment to an object property does in fact mutate a static field, which is a clear side-effect of `Bar()`.

In the example in [Figure 10](#), the method `Bar()` assigns to the field `Nationality` of the fresh object `stina`. Because the property `Nationality` is non-static it, it might look like a pure action at a first glance. But since the property writes method `get` itself modifies a static field, the `Bar()`'s assignment to `Nationality` is in fact a side-effect, which alters all `Swede` objects' `Nationality`. Therefore, it is not enough to check if a property is static in order to determine whether a read or write is pure, but the property's `get` and `set` have to be checked as well.

Perhaps ignore cases like this for simplicity?

2.7 The analysis

There are five kinds of functional purity levels for: *pure*, *locally impure*, *parametrically impure*, *impure*, and *unknown*.

Traverse the Abstract Syntax Tree (AST) and build the *dependency set* for each function, i.e. the set of calls inside a function. If during the traversal a call or reference to a compiled method or a field is found, mark the caller function's purity as *unknown*.

Because of the problem with inheritance and method overriding discussed in [subsubsection 2.6.1](#), when going through the AST and building the dependency set, if any object

parameter's method is overridden by any of its subclasses, add all the overridden methods to the calling function's dependency set. Each function together with its dependency set is stored in a lookup table where the key is the function identifier f and the values are f 's dependency set D_f as well as f 's purity level p . The purity of each function is initialized to *pure*, except those that were explicitly marked *unknown*.

Let the *working set* W be the set of all functions with empty dependency sets. Whenever a function's dependency set becomes empty, that function is added to W . Calculate the purity level for each function in W as described below. Then, for each function f in the working set, propagate the impurity of those with purity level *impure* or *unknown* to the functions dependant on f , "contaminating" them. Remove f from the dependency sets of all functions that depend on f , as well as from the working set W . Add functions that now have empty dependency sets to W . Repeat this process until there are no more changes to the lookup table, in which case the analysis is complete. Each function in the lookup table will now have been marked with its corresponding purity level. Because the purity level of each function was initialized to *pure*, any function who's purity level was unaffected by the analysis will be marked *pure* at the end of the analysis.

A method can have multiple impurity levels. The following is how to determine the purity level p for the currently analyzed method m .

- If any object field or property of the currently analyzed method m 's object is read from or modified, mark m as *locally impure*.
- If m calls a locally impure method belonging to m 's object (i.e. `this`) m is marked *locally impure*.
- If the method m reads or modifies a static field of an object, m is marked *impure*. This is because reading a static field of an object is a non-deterministic action, and modifying a static field of an object is a side-effect since it mutates the field for all instantiations of that object's class.
- If the currently analyzed method m calls an input parameter's method m_p and m_p is overridden by any locally impure and/or parametrically impure method, m_p is temporarily marked with the impurities of all the overriding methods in the context of the analysis of the current method m . If m_p is overridden by any impure method, m is permanently marked as impure.
- If the analyzed method m modifies an input parameter of reference type, mark m as *parametrically impure*. This could be done in a couple of ways:
 - By calling an object type parameter's method that has been marked as *locally impure*.

- By passing an object type parameter as an argument to a method that has been marked as *parametrically impure*.
- By directly mutating a parameter object's field or property, or the cell of a parameter array.

If m does at least one of the above, mark it as *parametrically impure*.

- If a method returns `this` or passes it as an argument to a function it marked *locally impure* since it is dependent on the state of its object, making it non-deterministic.
- Any method that raises an event or an exception is marked as *impure*, as well as any method mentioned in the two lists of impure built-in C# methods in [subsection 2.5](#).

We do not have to explicitly handle the case mentioned in [subsubsection 2.6.2](#) where fresh objects are modified with their own locally impure methods due to the fact that our definition of local purity includes determinism. Because if a non-fresh object o is modified with its locally impure method, then we must have read the pointer to o from a field outside the method, meaning that m is non-deterministic and therefore locally impure. This is why we only propagate the purity level of *impure* functions to their callers, and not *local impurity* or *parametrical impurity*. There are however two exceptions to this, which are covered by previously mentioned checks in our analysis:

- The case of o being a static field of an instantiated object has to be checked.
- The case of o being a parameter to m has to be checked because this is parametrical impurity.

TODO: add example which follows the analysis step by step

```

public class LinkedList
{
    private Node head;
    private Node tail;

    // Returns length of list
    public static int Length(LinkedList list)
    {
        Node current = list.head;
        int length = 0;

        while (current != null)
        {
            length++;
            current = current.next;
        }
        return length;
    }

    // Appends data to the list
    public void Add(Object data)
    {
        if (LinkedList.Length(this) == 0)
        {
            head = new Node(data);
            tail = head;
        }
        else
        {
            Node addedNode = new Node(data);
            tail.next = addedNode;
            tail = addedNode;
        }
    }

    // ... code continues in next column

    // Removes item at index from list.
    // Assumes that list is non-empty and
    // that index is non-negative and less
    // than list's length
    static public void Remove(int index,
                               LinkedList list)
    {
        if (index == 0) {
            list.head = list.head.next;
        }
        else {
            Node pre = list.head;

            for (int i = 0; i < index - 1; i++)
            {
                pre = pre.next;
            }
            pre.next = pre.next.next;
        }
    }

    public static void PrintListLength(
        LinkedList list)
    {
        Console.WriteLine(Length(list));
    }

    public void PrintLength()
    {
        PrintListLength(this);
    }

    private class Node
    {
        public Node next;
        public Object data;

        public Node() { }

        public Node(Object data)
        {
            this.data = data;
        }
    }
}

```

Figure 11: Simple implementation of a linked list. For the sake of this example, it contains some odd design choices.

2.8 Code base

Mostly pure code

- `ImmutableHashMap.cs` - has many methods marked with `[pure]`

- [NodaTime](#) has many pure methods. NodaTime's [AnnualDate.cs](#) for instance has many pure methods not marked with `[pure]`

Mostly impure code

- [ImageSharp](#)
- [sharpDox](#)

TODO

3 Implementation of the analysis tool

Because there was a clear goal for the software and its requirements, test driven development was used.

Because .NET has many libraries with functions of unknown purity, the purity level "unknown" has to be added.

The code analysis tool is built in .NET core and C#. It can be compiled, run and tested from the command line using the command `dotnet`, followed by `run`, `build` or `test`, respectively.

To find the declaration/definition of symbols (in the form of `IdentifierNameSyntax`) the method `SemanticModel.GetSymbolInfo()` is used, which uses the semantic model of the program.

TODO

4 Results

The analysis works backwards through the analyzed program's function dependencies and for each function visited its functional purity level is calculated. The purity levels *impure* and *unknown* also get propagated from callee to caller.

Due to the choice of including determinism in the definition of functional purity, which is not included in some definitions, the analysis could be somewhat simplified. The main advantage of including determinism is that we don't have to explicitly check if

objects read from or modified by a function f are fresh or not in order to determine f 's purity.

The analysis does not handle recursion, which could cause it finish before all functions' purities have been calculated, because no more functions are added to the working set. Support for recursive functions can be added by searching for independent strongly connected components [20].

The analysis uses a blacklist of built-in impure C# functions, in order to spot functions that handle impure actions such as randomness and I/O. There may be other impure built-in similar functions that are not in the blacklist.

TODO

5 Related work

5.1 Purity in Erlang

In their paper *Purity in Erlang* Mihalis Pitidis and Konstantinos Sagonas develop a tool that automatically and statically analyses the purity of Erlang functions [20]. It classifies functions into being functionally pure, or one of three levels of functional impurity [20]. The three levels of functional impurity they defined are: containing side-effects; containing no side-effects but being dependent on the environment; and containing no side-effects, having no dependencies on the environment but raising exceptions [20].

Their definition of purity uses *referential transparency*, as it implies purity [20]. Referential transparency means that an expression always produces the same value when transparency [20]. This means that a referentially transparent function could always be replaced with its output without altering the program's behaviour in any way [20].

They store all analysis information in a *lookup table* where the keys are the function identifiers f and the values are the purity level p_f of each f as well as f 's *dependency set* D_f [20]. The dependency set is the set of functions being called by f and is constructed by parsing the program's Abstract Syntax Tree [20].

Their analysis starts with Erlang's so called built in-functions (BIFs), which are functions native to the Erlang's virtual machine and are written in C [20]. Impure actions in Erlang can only be done through BIFs, including performing I/O actions or writing to global variables [22]. Because BIFs are written in C they cannot be analysed by their analysis tool, and their purity is assumed to be already known in beforehand by the

analysis tool [20]. The analysis propagates the impurity of BIFs to each function which directly or indirectly depends on them.

In short terms, their analysis algorithm works like this: Initialize the purity of all functions in the lookup table to be analyzed to "pure" [20]. Define the *working set* to always equal the set of functions whose purity level is fully determined, i.e. the functions with empty dependency sets [20]. For each function f in the working set, propagate its purity level to functions depending on it and "contaminate" them with f 's purity level [20]. Then remove f from the dependency set of each function depending on it [20]. If f has the highest impurity level, remove the entire dependency set of each function depending on f [20]. If the working set gets empty, find a set of functions that are dependent on each other and no other functions, and set their purity level to the purity of the impurest function [20]. Simplify their dependency sets by removing their dependency on each other from their dependency set [20]. Repeat this process until there are no more changes to the lookup table [20].

TODO

5.2 JPure: A Modular Purity System for Java

David J. Pearce built a purity system and analyzer for Java in his paper JPure: a modular purity system for Java [19]. The system uses the properties *freshness* and *locality* to increase the system's ability to classify methods as pure [19]. An object is fresh if it is newly allocated inside a method [19]. An object's locality is its local state [19]. Their definition of a pure method is one that does not assign (directly or indirectly) to any field that existed before the method was called [19].

The system uses annotations `@Pure`, `@Local`, `@Fresh`. `@Pure` indicates that a method is pure. `@Local` indicates that a method only modifies an object's locality. `@Fresh` indicates that a method only returns fresh objects. These three annotations are modularly checkable, i.e. one method's purity annotations to be checked in isolation from all other methods.

The system consists of two parts, *purity inference* and *purity checker* [19]. Purity inference adds `@Pure` annotations (and any auxiliary annotations required) to the code and is intended to be run once because it is more costly. The purity checker checks the correctness of all annotations at compile-time, and is intended to be used continuously to maintain the code's purity.

TODO

5.3 Purity and Side Effect Analysis for Java Programs

Similarly, Sălcianu and Rinard presented a method for analysing purity in Java programs, but their definition of purity also only includes side-effects and does not look at the input or output [23]. Their pointer analysis is based on tracking object creation and updates, as well as updates to local variables, and defines methods that mutate memory locations that existed before a method call as impure [23]. Moreover, their analysis can recognize purity-related properties for impure methods, including *read-only* and *safe* parameters [23].

The analysis method presented looks at each program point in each method m , and computes a points-to graph modelling the parts of the heap that method m points to, represented by nodes in the graph [23]. There are three kinds of nodes: *Inside nodes* which model objects created by m , *parameter nodes* which model objects passed to m as arguments, and *load nodes* modelling objects read from outside m [23]. Edges in the points-to graph model heap references [23]. There are two types of edges: *inside edges* which model heap references created by m , and *outside edges* modelling heap references read by m from outside of it (this includes m 's parameters) [23].

The analysis also keeps track of *globally escaped nodes*, which are nodes that may be accessed by unknown code, i.e. passed as argument to a native methods or pointed to static fields [23]. Since globally escaped nodes may be mutated by unknown code, the analysis has to handle them conservatively [23].

To check if a method m is pure, the analysis computes the set A consisting of nodes reachable from parameter nodes along outside edges [23]. In other words, A represents all objects existing before executing m [23]. m is pure if and only if no node in A escapes globally (i.e. is accessed by unknown code) and no fields in any node in A is modified [23]. There is one exception to the purity constraint: constructors are allowed to mutate fields of the `this` object [23]. Therefore all mutated abstract fields of `this` are ignored by the analysis [23].

TODO

5.4 Detecting function purity in JavaScript

Nicolay et al. developed a method of detecting function purity in JavaScript using something called *pushdown analysis* [18]. Their definition of functional purity, however, includes only side-effects and does not require functions' output to depend purely on their input [18].

5.5 Writing Pure Code in C#

In his article *Writing Pure Code in C#* Massad defines three levels of pure methods [7]:

1. Pure methods, i.e. methods that do not read or write to instance state variables, or call impure methods.
2. Methods that are pure, and that *read* the state of their containing object, or the state of objects that are passed as parameters or created in the current method.
3. Methods that are pure, and that *read* or *write* to the state of their containing objects, or to the state of objects created in the current method.

5.6 .NET Code Contracts

.NET code contracts are used to define pre- and postconditions, as well invariants for pieces of code – some which can be checked statically and some at runtime [11]. One available code contract is the `[pure]` attribute, which indicates that the method is pure [11]. However, current analysis tools do not enforce that methods marked with `[pure]` actually are pure, and so the attribute does not guarantee functional purity. Microsoft defines pure methods as methods that don't modify an pre-existing state, i.e. methods can only modify objects that were created *after* the method was called. The following code elements are assumed by the code contract tools to be pure [11]:

- Methods or types marked with `[pure]` (for types marked with `[pure]` this should apply to all the type's methods).
- Property get accessors.
- Operators.
- Any method with a fully qualified name starting with `System.Diagnostics.Contracts.Contract`, `System.String`, `System.IO.Path`, or `System.Type`.
- Any called delegate with the `[pure]` attribute. Delegates are basically function pointers.

5.7 Evolution of Degree of Purity in Programming Languages

Rajasekhara Babu et al. [21].

5.8 Verifiable Functional Purity in Java

In their definition of functional purity Finifter et al. require pure functions to be both side-effect free and *deterministic* [5]. A function is deterministic if any two evaluations of it have the same result [5]. This means that a deterministic function is one that relies purely on its arguments [5]. A function is side-effect free if it only modifies objects that were created during its execution [5].

The language that their analyzer handles is a subset of Java, in which they can prove functional purity [5]. They make the point that if all of method's parameters are immutable, including the implicit `this`, then the method is pure [5]. If its class is immutable it means that a method's global scope has a constant state, and so the only varying state is the one observable through its arguments [5].

Their verifier has a white list of fields and methods from Java libraries that do not expose the ability to observe a global mutable state, or provide access to nondeterminism, and it will reject any reference to a field or method that is not on the list [5].

5.9 Dynamic Purity Analysis For Java Programs

[26] TODO

6 Conclusion and Future Work

6.1 Conclusion

Functional purity is perhaps the most useful concept from functional programming that object oriented programmers can learn from. The definition of a pure program used in this paper is one that is side-effect free and deterministic. There are many benefits of using functionally pure methods in object oriented programming. Pure methods are generally easier to reason about due to their lack of side effects. Moreover, pure methods are easier to test, debug and maintain. The ability to automatically determine the level of purity in a given C# program can help programmers to write less impure code, and thereby reap previously mentioned benefits.

6.2 Future work

- Tool can point out exact position of impurity and suggest improvements to increase the purity. Because purity is determined by passing the purity level of impure functions to their callers, this could be implemented by also passing the identifier of the impure function to the caller.

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