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Measuring functional purity in C#

Developing and implementing a methodology for measuring functional purity in C#, and evaluating it using the `[Pure]` attribute

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Abstract

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Developing and implementing a methodology for measuring functional purity in C#, and evaluating it using the `[Pure]` attribute

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

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 [28].

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 [21]. 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 [21]. For this reason it is useful in software engineering to evaluate the level of functional purity in programs [21].

C# is among the top five most popular programming languages [26]. To its core, it is an object-oriented programming language. However, it has features that allow for functional programming [20]. But to what extent is C# being used as a functional programming language? In order to answer this we need a methodology for measuring a C# program's functional purity level. We also need a way of evaluating that methodology in order to assess its level of accuracy. The purpose of this thesis is thus to develop an analysis methodology for measuring the functional purity level of a given program.

2 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 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. Each object has a unique *object identity* which distinguishes it from all other objects [7].
3. Objects are based on *classes*, and objects belonging to a class have a shared set of properties [4].
4. Classes can *inherit* from other superclasses, such that an object of a class is also an object of its superclass [4].

2.2 Functional programming

1. All functions are *functionally pure*. Functional purity is defined below in [subsection 2.3](#).
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 [28].
3. Variables are immutable, meaning that their value does not change after being initiated [28].

To delimit the scope of this thesis it will only focus on functional purity, mainly because it seems like the most useful one out of the three for object oriented programming.

2.3 Definition of functional purity

Following is the definition of functional purity that will be used in this thesis:

Definition 1 (Functional purity). *A function is functionally pure if it is side-effect free and deterministic.*

Side-effect and *determinism* are defined as follows:

Definition 2 (Side-effect). *A side-effect is any action performed by a function that is visible from the function's caller's point of view [21].*

Definition 3 (Determinism). *A function is deterministic if its output depends purely on its input parameters, i.e. the method must return the same value for the same input regardless of the state of the program [5].*

As seen in [section 8](#) some related work define functional purity only as being synonymous with "side-effect free". This definition omits determinism and allows functions to read from variables defined outside of their scope, which 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. [23] and Alexander [2]. 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.

3 The C# language and .NET

C# is a type safe object oriented programming language developed by Microsoft [1]. C# is syntactically quite similar to C, C++ and Java, and includes features like nullable types, enumerations, higher-order functions, and direct memory access [13]. While C# historically has primarily been used for writing code for Windows platforms only, C# has recently spread to most other platforms, including mobile, due to its increased cross-platform support [1].

C# applications run in the .NET ecosystem [13]. There are multiple implementations of .NET, including .NET Core and the .NET Framework [13]. .NET includes a virtual execution environment called the common language runtime (CLR) on which C# programs run, as well as a common set of class libraries [1]. Before execution C# source code is compiled to the so called intermediate language (IL) and stored on disk [13]. Upon execution the IL code is just-in-time-compiled to native machine instructions that can be executed by the operating system [13].

One fundamental part of the .NET ecosystem are so called assemblies [10]. An assembly is a unit of types and resources that form a logical building block of functionality [10]. Assemblies do not contain C# source code, but IL code [11].

Similarly to many other programming languages, functions in C# are generally referred to as *methods* [1]. These two terms will be used interchangeably in this thesis. Each

method belongs to a *class*, which is an encapsulations of data and behaviours [1]. C# also supports anonymous functions [1].

3.1 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) {
        return number + 1; // this method is now pure
    }

    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 [18]. 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 [18].

However, `in` is not a purity guarantee. Consider the example in Figure 4. The `in` keyword before the argument `list` ensures that `list` is read-only. 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* [19]. 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 [17]. 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.

3.2 The .NET Abstract Syntax Tree and the CodeAnalysis library

Abstract syntax trees (ASTs) are the primary data structure used when analysing source code [15]. It encapsulates every piece of information held in the source code [15]. A syntax tree generated by a parser can be re-built into the exact same text that was originally parsed [15].

The abstract syntax tree (AST) generated from a given piece of C# code by Microsoft's code analysis library `Microsoft.CodeAnalysis` represents the lexical and syntactic structure of the C# program [15]. The tree consists primarily of *syntax nodes* which represent syntactic constructs including declarations, statements, clauses and expressions [15]. Each node is derived from the `Syntax-Node` class [15]. Every node is non-terminal, meaning that they always have children - either other nodes or *tokens* [15]. Tokens are the smallest syntactic pieces of the program, consisting of keywords, identifiers, literals and punctuation [15].

3.3 C# Events

Events are a way for classes or object to notify other classes or objects when something happens [12]. 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) [12]. 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

3.4 Impure built-in C# methods

The following methods that are built into C# and are non-deterministic [30]:

- `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 [30]:

- `System.Threading.Thread.Start` and `Thread.Abort` mutate states.
- `Console.Read`, `Console.ReadLine`, `Console.ReadKey`, `Console.WriteLine` 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.

3.5 .NET code contracts and the `[Pure]` attribute

.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 [16]. One available code contract is the `[Pure]` attribute, which is placed in front of a method signature to indicate that the method is pure [16]. However, current analysis tools do not enforce that methods marked with `[Pure]` actually are functionally pure [9], and so the attribute does not guarantee functional purity. Microsoft defines pure methods as methods that don't modify any pre-existing state, i.e. methods can only modify objects that were created *after* the `[Pure]` method was called [16]. Note that their definition of functional purity does not include determinism, which the definition used in this thesis does. Because of this, the `[Pure]` attribute does not consider throwing exceptions as functionally impure.

The following code elements are assumed by the code contract tools to be pure [16]:

- 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.

4 Problems with determining purity in object oriented languages

Analyzing functional purity in object oriented programming languages yields a number of dilemmas. This section describes them, as well as how they were dealt with.

4.1 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 [22]:

```
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 [22]. 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.

4.2 Modifying a fresh object

If an object o is allocated inside the analysed method m , the object o is said to be *fresh* [22]. 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 [definition 1](#):

A function is functionally 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. The function is also deterministic since it does not read any value outside of the function besides its own 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*:

Definition 4 (Local Impurity). *Any method that is functionally pure except for modifying any of its own object's fields is locally impure.*

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()` `Foo()` 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 $F_{OO}()$ is still pure. I have chosen to categorize methods like this *parametrically impure*:

Definition 5 (Parametrical impurity). *Any method that is pure except for modifying the state of its input is 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 (e.g. writing to a file on the file system) or throw exceptions, m is pure.

In Python, which also is an object-oriented programming language, the instance object equivalent to C#'s `this` (in Python usually referred to as `self`) always has to be explicitly listed as the first parameter of a method when declaring it, and gets automatically passed as the method's first argument when the method is called [27]. Similarly, in C# the reference to the instance object `this` is in fact an implicit parameter for all methods [8]. This means that a method m that reads the value of a field of its own object still is considered deterministic even though that field has not been explicitly added as a method parameter. Recall from [definition 3](#) that m is deterministic if m 's output depends purely on its input parameters. This still holds with m , since its entire object `this` where that field lives gets implicitly passed as an argument to m .

Moreover, the implicit passing of `this` to every method also implies that any method that is locally impure is also parametrically impure. As [definition 4](#) states, a method m that is locally impure modifies its object `this`'s fields. Since `this` is always the first parameter of any method, this means that modifying a field in `this` always means modifying a parameter, which implies parametrical impurity.

Although local impurity implies parametrical impurity, the opposite does not always necessarily hold since a method could be parametrically impure without modifying a field in `this`. Therefore, distinguishing between local and parametrical impurity could be of value, for instance when implementing other methods in the same class; since locally impure methods modify the state of their object, and those object-local side-effects are visible for methods inside the same object.

4.3 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 [14]. 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 9: 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 9, 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.

4.4 Method overloading

While method overloading is not unique to object oriented programming, it seems appropriate to mention here as well. Method overloading is when there multiple method implementations share the same method name but have different function signatures, i.e. return types, parameter types and/or number of parameters [1]. One could consider all overloads to be the same method m , since they share the same name. However, this would make it difficult to calculate m 's purity level, since one overload of m could be pure, while another overload is impure. Which purity level should then be given to m ?

Instead, when given an overloaded method named m the analysis treats each overload of m as a unique method, independent of other overloads. This way overloads with different purity levels can co-exist in the result of an analysis. Because overloads by definition share the same name, in order to differentiate them in this thesis the notation m_1, m_2, m_3, \dots is used, where m_1 denotes the first implementation of the method m , m_2 denotes the second, and so on.

5 The analysis method

As established in [section 4](#) this thesis defines four functional purity levels: *pure*, *locally impure*, *parametrically impure*, and *impure*. Because in some cases the purity level of a method cannot be determined, for instance when the method's definition is missing, a fifth purity level *unknown* is added as well. This can happen when one method calls another method from an assembly. Assemblies contain IL code, and not C# source code and therefore CsPurity cannot analyze them. Following is a description of the static analysis method developed and used in this thesis in order to determine the purity level of a program:

Traverse the program's 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*.

Since object constructors can perform impure actions just like methods, they are in this section included in the term "function".

Because of the problem with inheritance and method overriding discussed in [subsection 4.1](#), 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 in the checklist in [subsection 5.1](#) below. Then, for each function f in W , 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.

Ignoring the purity level *unknown*, the other four purity levels can be ordered in terms of impurity, from least impure to most impure, like so: *pure* < *locally impure* < *parametrically impure* < *impure*. A method m 's purity level should during the analysis only be updated if the new purity level is less impure than m 's current one. For instance, if in an arbitrary instance during the analysis, m has the purity level *parametrically impure*, and a check determines its purity level to be *impure*, it's purity level should be updated since *impure* is more impure than *locally impure*. However, if for instance another check says that m is *locally impure*, its purity level should not be updated since *locally impure* is less impure than *impure*.

5.1 Checklist to determine the purity level

The following is how to determine the purity level p for the currently analyzed method m .

1. If any object field or property of the currently analyzed method m 's object is read from or modified, mark m as *locally impure*.
2. If m calls a locally impure method belonging to m 's object (i.e. `this`) m is marked *locally impure*.
3. If the method m reads or modifies a static field of any class or object, m is marked *impure*. This is because reading a static field is a non-deterministic action, and

modifying a static field is a side-effect since it mutates the field for all instantiations of that object's class.

4. If the method m calls a *locally impure* method of an object assigned to a static field of any class or object, m is marked *impure*.
5. 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.
6. 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*.

7. 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.
8. Any method that raises an event is marked *impure*.
9. Any method that raises an exception is marked *impure*.
10. Any method mentioned in the two lists of impure built-in C# methods in [subsection 3.4](#) is marked *impure*.

We do not have to explicitly handle the case mentioned in [subsection 4.2](#) 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 parametric impurity.

5.2 Example

Figure 10 contains a simple implementation of a linked list in C#. In order to illustrate all types of impurities, the implementation contains some odd design choices.

The method `Length()` takes a `LinkedList` as input and returns its length. This method is deterministic since it only depends on its input argument, and it is side-effect free since it does not mutate any value that exists outside its scope, including its parameter object. Therefore, `Length()` is pure.

`Add()` appends an `Object` to the end the list. It is not deterministic since it reads from and mutates the state of `this` in multiple locations. For instance, the first location where it modifies `this` is where it assigns a new `Node` to `head`, which is a field that is visible outside the method. Therefore, `Add()` is locally impure – it depends on and/or mutates the state of its object.

`Remove()` deletes an item at a given index from a `LinkedList` which is passed as an argument to the method. To simplify the method and reduce its size, its input list is assumed to be non-empty and the index value is assumed to be a valid position inside the list. `Remove()` only operates based on its input and is therefore deterministic. However, it does modify fields of the parameter `list` and is therefore parametrically impure.

The first overloading of the method `Concatenate()` modifies the static class field `numberOfConcatenates` and therefore has a side-effect, making it impure. The second overloading of `Concatenate()` depends on the former method, and is therefore also impure. The static field `numberOfConcatenates` was added to illustrate the propagation of impurity.

```

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

    // Static counter used by Concatenate()
    public static int numberOfConcatenates;

    // 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;
    }

    // Removes item at an index from list.
    // Assumes that list is non-empty and
    // that index is non-negative and less
    // than list's length
    public static 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;

            // If index refers to the last element
            if (index == Length(list))
            {
                list.tail = pre;
            }
        }
    }

    // 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;
        }
    }

    // Concatenates two lists by
    // appending a list to the end of
    // this list
    public void Concatenate(LinkedList
        list)
    {
        if (head == null) head = list.head;
        else
        {
            this.tail.next = list.head;
            this.tail = list.tail;
            list.head = this.head;

            // This gives the method a
            // side-effect
            numberOfConcatenates++;
        }
    }

    // Overloading of Concatenate that
    // allows passing both lists as
    // parameters
    public static void Concatenate(
        LinkedList l1, LinkedList l2)
    {
        l1.Concatenate(LinkedList l2);
    }

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

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

```

Figure 10: Simple implementation of a linked list. For the sake of this example, it contains some odd design choices.

The analysis starts off by building the dependency set for each function and setting all

purities to *pure*, as seen in [Table 1](#).

f	D_f	p
Length()		<i>pure</i>
Remove()	Length()	<i>pure</i>
Add()	Length()	<i>pure</i>
Concatenate ₁ ()		<i>pure</i>
Concatenate ₂ ()	Concatenate ₁ ()	<i>pure</i>
$W = \{\text{Length}(), \text{Concatenate}_1()\}$		

Table 1 Initial state of the lookup table after computing each function’s dependency set. The working set W is the set of all functions with empty dependency sets.

The working set W is the set of all functions in the lookup table with empty dependency sets, which in this case is `Length()` and `Concatenate1()` (the first overloading of `Concatenate()` in [Figure 10](#)). We now go through each item in the checklist in [subsection 5.1](#) for each method in W , and check which items apply to the methods:

Since none of the items in the checklist apply to `Length()`, its purity level remains *pure*. As for the method `Concatenate1()` the items [1](#), [3](#) and [6](#) apply to it. Item [6](#) since `Concatenate1()` modifies the fields `list` and `tail` of its input parameter, item [1](#) since it modifies its own `head` and `tail`, and item [3](#) since `Concatenate()` modifies the static class field `numberOfConcatenates`. Thus `Concatenate1()` should be marked with the purity levels *locally impure*, *parametrically impure* and *impure*, and since *impure* is the impurest of the three the method gets marked *impure*.

Since `Concatenate1()`’s purity level was marked *impure* its purity level is propagated to its callers, which in this case is `Concatenate2()`. `Concatenate1()` is then removed from the dependency set of `Concatenate2()`, and `Length()` is removed from `Add()` and `Remove()`’s dependency sets. The methods `Length()` and `Concatenate1()` are now removed from the working set W , and `Remove()`, `Add()` and `Concatenate2()` are added to W , as their dependency sets now are empty. At this point the state of the lookup table is as shown in [Table 2](#).

f	D_f	p
Length()		<i>pure</i>
Remove()		<i>parametrically impure</i>
Add()		<i>pure</i>
Concatenate ₁ ()		<i>impure</i>
Concatenate ₂ ()		<i>impure</i>
$W = \{\text{Remove}(), \text{Add}(), \text{Concatenate}_2()\}$		

Table 2 Remove() and Concatenate₁()’s purity levels have been updated, and after analysing them they are removed from the dependency set of their callers. Also Concatenate₁()’s purity level has been propagated to Concatenate₂().

Now we perform the same actions again with the new working set $W = \{\text{Remove}(), \text{Add}(), \text{Concatenate}_2()\}$, starting with Remove(). Out of the items in the checklist in subsection 5.1, item 6 applies since Remove() directly mutates its input parameter list in multiple locations. Therefore Remove() is marked *parametrically impure*.

As for Add() item 1 applies to it since Add() modifies its object in multiple locations, for instance by assigning to the field tail, and so Add()’s purity level is set to *locally impure*.

Looking at Concatenate₂(), none of the items in the checklist apply, and so it remains its purity level *impure* that was propagated to it from Concatenate₁().

Remove(), Add() and Concatenate₂() are then removed from W .

f	D_f	p
Length()		<i>pure</i>
Remove()		<i>parametrically impure</i>
Add()		<i>locally impure</i>
Concatenate ₁ ()		<i>impure</i>
Concatenate ₂ ()		<i>impure</i>
$W = \{\}$		

Table 3 Add()’s purity level has been updated to *locally impure*. Since W is now empty, this is the final result of the analysis.

At this point the working set W is empty, and so there can be no more changes to the lookup table. Therefore the analysis stops here. The final result is thus what is shown in the lookup table in Table 3. Looking at the table we can see that Length() is the

only truly pure method out of the five. Thus we can conclude that `LinkedList`'s total purity level is $1/5 = 20\%$ functionally pure.

6 Implementation of the analysis tool *CsPurity*

Because there was a clear goal for the software and its requirements, test driven development was used when implementing the analysis tool in C#.

Because .NET has many libraries in the form of pre-compiled assemblies, the source code of the functions used in these libraries is not always available. Because of this, the purity level "unknown" has to be added for when we cannot compute a function's purity level.

The implementation of the code analysis tool is called *CsPurity* and is built using .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. Upon calling the program it can be provided either with a single file to be analyzed, or a directory. In the second case, all C#-files in the directory and all sub-directories are analyzed as one program.

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.

The tool is not able to determine the purity of methods that invoke delegate functions. Delegate functions are higher-order functions that invoke methods passed to them as arguments. Invoking delegate functions is done relatively sparsely in C# and handling them would require a disproportional amount of extra work. The delegate functions themselves however are analyzed just like regular methods.

Something that was realized while implementing the tool is that the C# compiler does not perform tail call recursion. Recursion is a very common technique when it comes to functional programming. The initial implementation of *CsPurity* built the lookup table by calculating each function's dependency set recursively. When analyzing larger code bases the program crashed due to an immense memory usage. Therefore, its recursive implementation had to be changed to an iterative one which worked C# better.

TODO

7 Results and discussion

The implemented analysis program CsPurity works backwards through the analyzed program's function dependencies and for each function visited that function's functional purity level is calculated. The purity levels *impure* and *unknown* also get propagated from callee to caller. Out of all ten items in the checklist in [subsection 5.1](#), the following three were implemented:

- [item 3](#): "If the method *m* reads or modifies a static field of an object, *m* is marked *impure*".
- [item 9](#): "Any method that raises an exception is marked *impure*".
- [item 10](#): "Any method mentioned in the two lists of impure built-in C# methods in [subsection 3.4](#) is marked *impure*".

The reason why three out of the total ten checks were implemented was due to the sheer amount of time that the implementation took. After implementing the whole lookup table and all of its functionality, calculation of each method's dependency set, propagation of impurities from callee to caller, etc. there was not time left to implement every item in the checklist in a reasonable amount of time, and so the three items above were chosen. Because of this, CsPurity is unable to detect local and parametrical impurity, and can only detect full impurity caused by side-effects.

7.1 Evaluation method

To evaluate CsPurity's accuracy it is run on the example code in [Figure 10](#) and the result is compared to the one in [Table 3](#), which was yielded by manually applying the analysis method to the example code. CsPurity is also run on a larger code base in order to evaluate its performance in real life, non-trivial, cases. The code base consists of the 11 most popular open source GitHub repositories that use C# and the `[Pure]` attribute in at least 1% of methods were chosen. The popularity was measured based on the number of stars, which is GitHub's user rating system for repositories.

As mentioned in [subsection 3.5](#) the `[Pure]` attribute can be placed in front of a method definition to signal that the method pure. That means that running CsPurity on a code base where a portion of the methods use the `[Pure]` attribute CsPurity's accuracy can be evaluated by comparing what the methods with and the methods without the `[Pure]` attribute were categorized as by CsPurity. It is assumed that any method with

the `[Pure]` attribute is functionality pure. This does not necessarily have to be true in general, and as will be discussed later, a large portion of `[Pure]` methods do in fact have side-effects. But the `[Pure]` attribute can still tell us something about how CsPurity performs.

CsPurity also assumes that methods without `[Pure]` are impure. There could be exceptions to this, i.e. pure methods that haven't been given the `[Pure]` attribute by the code's author, and this will also be discussed later in this section. However, this assumption still lets us say something about CsPurity's ability to classify impure methods. Also, since all 11 repositories were selected specifically because they contain `[Pure]`'s it is therefore reasonable to assume that most methods without the attribute are impure.

7.2 Results from scanning simple implementation of linked list

Following is the result of running CsPurity on the linked list program in [Figure 10](#). By looking at the result from running CsPurity on it and comparing it to the expected result in [subsection 5.2](#) we can evaluate its performance.

METHOD	PURITY LEVEL
LinkedList.Length	Pure
LinkedList.Add	Pure
LinkedList.Remove	Pure
LinkedList.Concatenate	Impure
LinkedList.Concatenate	Impure

Figure 11: Result from running CsPurity on the linked list implementation in [Figure 10](#).

As seen in [Figure 11](#) CsPurity correctly identifies the impurity of both overloads of `Concatenate()`, who's implementations can be seen in [Figure 10](#). CsPurity has thereby successfully spotted the first overload's side-effect and propagated its impurity to the second overload, which depends on the first.

However, the three other analyzed methods `Length()`, `Add()` and `Remove()`'s purity levels – which are always initialized to *pure* in the lookup table – were unchanged by the analysis. As seen in [Table 3](#), `Length()`'s purity level should be unaffected and remain *pure*. However, `Add()`'s and `Remove()`'s purity levels are not identified, since CsPurity only can detect methods with maximum impurity level *impure* – i.e. [item 3](#) in the checklist – and not local or parametrical impurity.

Therefore, what we can say for sure about the linked list implementation based on the result in [Figure 11](#) is that its purity level is *at most* three pure methods out of a total of

five methods, i.e. it is $\leq 3/5 = 60\%$ functionally pure. Since the true purity level of 20% that we expect from [subsection 5.2](#) is less than or equal to 60%, the upper bound on the program's level of functional purity calculated by CsPurity is shown to be correct.

7.3 Results from running CsPurity on a large codebase

The results from running CsPurity on each of the 11 repositories are divided into two different tables; [Table 4](#) which contains CsPurity's classification for methods with the `[Pure]` attribute, and [Table 5](#) with the result for methods without the attribute. Methods with the `[Pure]` attribute make up 47% percent of the total number of methods analyzed, and so 53% of methods do not have the attribute. [Table 6](#) contains the distribution of purity levels for all analyzed methods, and [Table 7](#) contains CsPurity's precision and recall based on the numbers in [Table 4](#) and [Table 5](#). Precision is the number of true positives in relation to the number of selected items. Recall (or sensitivity) is the number of true positives in relation to all relevant items (the items that should be selected).

Repository name	Pure	Impure: throws exception	Impure: other	Unknown	Total
nodatime	10	23	72	56	161
WindowsCommunityToolkit	42	38	64	124	268
CsConsoleFormat	3	17	15	63	98
optentk	452	17	53	156	678
opencvsharp	0	2	0	2621	2623
nuke	4	114	10	17290	17418
linq2db	3	114	11	31	159
language-ext	365	954	16599	5935	23853
MetadataExtractor .NET	2	9	9	43	63
Spreads	0	31	3	1	35
fluentassertions	53	0	4	20	77
Total number of methods	934	1319	16840	26340	45433
Total percentage	2%	3%	37%	58%	100%

Table 4 CsPurity's classification of the methods with the `[Pure]` attribute after being run on 11 different open source repositories.

Repository name	Pure	Impure	Unknown	Total
nodatime	88	2631	1038	3757
WindowsCommunityToolkit	477	3480	3342	7299
CsConsoleFormat	35	272	576	883
optentk	532	462	1394	2388
opencvsharp	198	2517	965	3680
nuke	554	2056	965	3575
linq2db	998	7613	4316	12927
language-ext	85	5362	2678	8125
MetadataExtractor .NET	36	1267	341	1644
Spreads	261	1094	546	1901
fluentassertions	703	3771	1114	5588
Total number of methods	3967	30525	17275	51767
Total percentage	8%	59%	33%	100%

Table 5 CsPurity’s classification of the methods with no [Pure] attribute after being run on 11 different open source repositories.

	Total # of Pures	Total # of Impures	Total # of Unknowns	Total
Amount	4901	48684	43615	97200
Percentage	5%	50%	45%	100%

Table 6 The ratio of CsPurity’s classification of all analyzed methods, i.e. both methods with and without the pure [Pure] attribute.

	Precision	Recall
Pure method classification	19%	2%
Impure method classification	63%	59%

Table 7 Precision and recall of CsPurity’s classification of pure and impure methods.

As seen in [Table 6](#), nearly half of all methods were classified with the purity level *unknown*, meaning that their purity levels could not be determined by CsPurity. This will typically occur when a method depends on a method from an imported library that lacks C# source code like an assembly. The high number of *unknowns* contributes greatly to the low recall for CsPurity that is seen in [Table 7](#), in particular when it comes to classifying pure methods.

7.4 Discussion

As discussed in [subsection 3.5](#), Microsoft’s definition of functional purity used for the `[Pure]` attribute does not include determinism like the definition used in this thesis, [definition 1](#), does. That means that methods that read or modify static fields, or that throw exceptions do not violate the `[Pure]` attribute. This may explain why $3\% + 37\% = 40\%$ of methods in [Table 4](#) were classified by CsPurity as *impure* (“Impure: throws exception” and “Impure: other” in the table), despite having the `[Pure]` attribute. This was confirmed to be the case when looking manually at smaller samples of methods in each repository as no incorrectly classified method based on [definition 1](#) was found. These 40% of all `[Pure]` methods also directly contribute to the low recall for classification of pure methods, as well as the relatively low *impure* classification precision seen in [Table 7](#).

Moreover, CsPurity’s stricter definition of functional purity compared to the `[Pure]` attribute’s, together with almost 60% `[Pure]` *unknowns* significantly impact the low amount of true positives when it comes to pure methods. As seen in [Table 4](#) only 2% of `[Pure]` methods were classified as *pure* by CsPurity.

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 to including determinism is that one doesn’t have to explicitly check whether potentially global (i.e. static) object fields are read from or modified by a function f , in order to determine f ’s purity. As long as a static variable appears in f we know that f is non-deterministic since it depends on a global state. On the other hand, if determinism were ignored we would have to check whether the static field is modified by f or not – or by some method called by f – in order to determine f ’s purity, which would be even trickier.

As stated in [subsection 7.1](#) it is assumed that any method without `[Pure]` is *impure*. While this is a necessary assumption in order to be able to say anything about CsPurity’s ability to classify *impure* methods, this is not always the case, and this is reflected in [Table 5](#) in the 8% of methods with no `[Pure]` attribute that were classified as *pure* by CsPurity. While 8% may not sound like much, in combination with the amount of `[Pure]` methods classified as *pure* at only 2% of all `[Pure]` methods, this significantly impacts the *pure* classification precision which is 19%, as seen in [Table 7](#).

If C# had another attribute similar to `[Pure]` called for instance `[Impure]`, which explicitly indicated that its method performs a functionally *impure* action that would make it easier to evaluate CsPurity more fairly. Since if it were used on the analyzed code base it would likely change a number of the currently false positives to true positives in regards to *impure* methods.

While not nearly as much, the 8% of methods with no `[Pure]` attribute also contribute in part to the 59% impure classification recall. However, the most contributing factor reducing the impure classification recall is the 33% of `[Pure]`s classified as *unknown*.

The data set is somewhat nonuniform, primarily in Table 4. The two by far most impactful repositories are *language-ext* and *nuke* which together make up over half of the code base (54%) in terms of number of methods. The majority of `[Pure]` methods in *language-ext* were classified as *impure* by CsPurity, and those methods contribute to 97% of all `[Pure]` methods classified as *impure* by CsPurity. However, in *nuke* the majority of `[Pure]` methods were classified as *unknown*, and these methods make up 66% of all *unknown* `[Pure]`'s. In order to compensate for this we can normalize the purity levels of CsPurity's classification for each repository and calculate the purity and precision based on those normalized values. That yields the precision and recall shown in Table 8, with significantly higher values.

One could argue that normalized precision and recall is more fair because each repository's purity level distribution contributes equally to the value. Since the repositories have different code and different authors that may be varying strict with what methods should have the `[Pure]` attribute it is reasonable to assume that each repository should be viewed as a separate entity, and that each repository therefore should be accounted for evenly.

	Precision (normalized)	Recall (normalized)
Pure method classification	64%	15%
Impure method classification	59%	56%

Table 8 Precision and recall of CsPurity's classification of pure and impure methods after normalizing each repository's purity level distribution.

As mentioned at the start of section 7 CsPurity only implements a subset of the analysis method described in section 5, which is important to keep in mind. This likely has a big, if not the biggest impact on CsPurity's precision and recall. Presumably if all items in the checklist in subsection 5.1 got implemented, we would see in improvement in both recall and precision. However, despite not being fully implemented CsPurity still shows the potential of the analysis method.

Because most methods use built-in C# methods for which the source code is not necessarily public, a majority of the analyzed methods get the purity level *unknown*. One way of tackling this during implementation was to search online for the source code of classes like `List`, run the analyzer on them and permanently store the calculated purity level for each method in a dictionary in CsPurity, so that whenever a call to a built-in `List` method is encountered by CsPurity that method's purity level (if it is not

unknown) can be retrieved from the dictionary. However, this relies on the fact that the source code for a particular built-in method is available, and the process of searching for its code, running the analyser on it and adding any known result to the program's dictionary is cumbersome. Therefore a lot of methods are marked as *unknown* by CsPurity because they depend on a method whose source code is not available to, or has been priorly analyzed by CsPurity.

An alternative way to compare programs' total purity levels, i.e. the ratio between number of pure methods and the total number of methods, could be to profile each program and weight the purity level of each method depending on how often that method is called. For example, let's say that only 10% of program *A*'s methods are pure compared to program *B* where 20% of its methods are pure. Now say that *A*'s pure methods make up 90% of the total function calls during execution and *B*'s pure methods only are called 10% of the times during execution. In this case, one could argue that *A* is purer than *B* since it makes more calls to pure methods than impure ones compared to *B*, even though *B* has a higher ratio of the number of pure methods.

Since CsPurity is unable to detect local and parametrical impurity it cannot for certain determine the purity of any program. CsPurity does however identify true impurity – the impurest purity level – and does therefore compute a lower bound to a program's impurity, which is equivalent to an upper bound to the program's purity level. CsPurity does not however give a definite lower bound to a program's purity level. This is due to the fact that all methods' purity levels are initialized to *pure*, and the purity level only changes if CsPurity detects a non-pure trait based on the checklist in [subsection 5.1](#). Since not every item in the checklist is implemented, we cannot know if a method was marked *pure* in the result of an analysis because it truly was pure, or because it had a non-pure trait that the implementation cannot detect.

One could argue that if choosing between computing an upper or a lower bound to a program's purity level, a lower bound is more interesting to a programmer. However, due to the nature of the analysis method this requires fully implementing the analysis method.

An alternative approach to handling called methods with unknown purity – as opposed to marking their purity level *unknown* – would be to simply assume that any unknown method's purity level always is *impure*, or to assume that it is always *pure*. The more conservative approach of assuming that any unknown method is impure would mean that the upper bound for the program's total possible purity level would be moved down, which could potentially give a lower bound that is too low, since some of the unknown methods that were marked *impure* could have been pure. Since the incomplete implementation does not give a lower bound, the assumption of impurity will have no effect on the lower bound.

For the same reason, assuming that any unknown method is *pure* will also not affect any lower bound of the program's total purity level. The upper bound for the program's total purity level will in this case be the same as the *unknown* approach. However, this assumption will be misleading with a complete implementation since it will potentially give false positives that indicate that some methods are pure when they are not. Therefore, since it clearly indicates to the user where the purity level could not be determined, the purity level *unknown* seems to be the best choice here.

8 Related work

8.1 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 [23]. It classifies functions into being functionally pure, or one of three levels of functional impurity [23]. 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 [23].

Their definition of purity uses *referential transparency*, as it implies purity [23]. Referential transparency means that an expression always produces the same value when evaluated [23]. This means that a referentially transparent function could always be replaced with its output without altering the program's behaviour in any way [23].

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 [23]. The dependency set is the set of functions being called by f and is constructed by parsing the program's Abstract Syntax Tree [23].

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 [23]. Impure actions in Erlang can only be done through BIFs, including performing I/O actions or writing to global variables [24]. 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 [23]. 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" [23]. 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 [23]. 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 [23]. Then remove f from the dependency set of each function depending on it [23]. If f has the highest impurity level, remove the entire dependency set of each function depending on f [23]. 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 [23]. Simplify their dependency sets by removing their dependency on each other from their dependency set [23]. Repeat this process until there are no more changes to the lookup table [23].

The foundation for the analysis method used in this paper is based off the method developed by Pitidis and Sagonas: The approach with using a lookup table to store the intermediate states of the analysis, dependency sets and propagation of impurity from callee to caller using dependency sets. However, the analysis by Pitidis and Sagonas is intended for programs written in Erlang, which is a functional programming language. Also, their analysis gets facilitated by Erlang's BIFs since impure actions can only be performed through them, and so they only need to propagate the impurity of the called BIFs to the callers, and therefore do not need to perform any intermediate analysis on other functions. Since no equivalence to BIFs exists in C#, our analysis can't only comprise of propagating impurities from callee to caller but also needs to check each function analysed to see if that function performs any impure action.

8.2 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 [22]. The system uses the properties *freshness* and *locality* to increase the system's ability to classify methods as pure [22]. An object is fresh if it is newly allocated inside a method [22]. An object's locality is its local state [22]. Pearce's definition of a pure method is one that does not assign (directly or indirectly) to any field that existed before the method was called [22].

The system uses the purity annotations `@Pure`, `@Local` and `@Fresh` [22]. The annotation `@Pure` indicates that a method is pure [22]. `@Local` indicates that a method only modifies an object's locality [22]. `@Fresh` indicates that a method only returns fresh objects [22]. These three annotations are modularly checkable, i.e. one method's purity annotations to be checked in isolation from all other methods [22].

The system consists of two parts, *purity inference* and *purity checker* [22]. 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 [22]. 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 [22].

Pearce's definition of functional purity does not include determinism, unlike the one used in this paper. The purity level *locally impure* used in this thesis is based on Pearce's `@Local` attribute. Moreover, the solution to method overriding used in this paper in subsection 4.1 is also based on the ideas developed by Pearce. However, Pearce's approach requires that the program is modularly checkable, i.e. that each method's purity can be evaluated independently from all other methods, and uses annotations to achieve this [22]. Pearce does not introduce an *unknown* purity level for called methods (referred to as methods from external packages) that are not analyzed, but assumes conservatively that such methods are always impure [22].

8.3 Purity and Side Effect Analysis for Java Programs

Similarly to Pearce, Alexandru Sălcianu and Martin 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, i.e. does not include determinism [25]. 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 [25]. Moreover, their analysis can recognize purity-related properties for impure methods, including *read-only* and *safe* parameters [25].

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 [25]. 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 [25]. Edges in the points-to graph model heap references [25]. 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) [25].

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 [25]. Since globally escaped nodes may be mutated by unknown code, the analysis has to handle them conservatively [25].

To check if a method m is pure, the analysis computes the set A consisting of nodes reachable from parameter nodes along outside edges [25]. In other words, A represents all objects existing before executing m [25]. 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 [25]. There is one exception to the purity constraint: constructors are allowed to mutate fields of the `this` object [25]. Therefore all mutated abstract fields of `this` are ignored by the analysis [25].

Similarly to this thesis, Sălcianu and Rinard explicitly mark parts of a method that are potentially accessed by unknown code, and deal with them conservatively. Their analysis uses a points-to graph to compute the purity of each method, unlike the method in this thesis that uses a lookup-table and checklist.

8.4 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]. If a method is written in this subset of Java and its 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 whitelist 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]. This is similar to the approach with a list of impure built-in C# methods used in this thesis and mentioned in [subsection 3.4](#).

Finifter et al. use the same definition of functional purity that is used in this thesis. The main disadvantage with Finifter et al.'s approach is that it requires the code to be written in a subset of Java code in order to be able to analyze the code.

8.5 Dynamic Purity Analysis For Java Programs

In their paper Xu et al. define four different definitions for functional purity, and they are as follows from the strongest to the weakest definition: *strong*, *moderate*, *weak* and *once-impure* purity [29], similarly to the purity levels presented in this thesis in [definition 1](#), [definition 4](#) and [definition 5](#). Their strongest definition, *strong purity*, includes

both determinism and side-effect freeness [29]. However, Xu et al. do not seem to consider object type parameters to be included in determinism, and so reading the state of an input object is not considered truly pure. *Moderate purity* is like *strong*, except that it also allows modification of newly allocated (i.e. fresh) objects [29]. *Weak purity* is like *moderate*, but it also allows non-determinism i.e. reading from objects that exist outside of the method [29]. *Once-impure purity* is equivalent to *weak purity* except that the first invocation of the method may be impure [29].

It is interesting that Xu et al. do not consider modification of fresh objects or reading the state of object type input parameters as truly pure, which this paper and most other work does. Moreover, none of Xu et al.'s purity levels however allow modification of input parameters. Xu et al. consider methods that modify their own object `this` to be impure, but do allow other methods that call such methods and remain *moderately pure*. This is similar to the approach used in this paper, which classifies the former type of method as *locally impure* and the calling method as *pure* if the called method belongs to a fresh object, as described in [subsection 4.2](#).

Xu et al.'s analysis is performed dynamically which requires looking at Java Virtual Machine code [29]. The nature of the dynamic analysis may be the reason why some of their purity definitions differ from most other work, for instance that any modification of any object that was created after the start of executing a method, including fresh ones, is not considered pure by their method of analysis.

9 Conclusion and Future Work

9.1 Conclusion

Functional purity is perhaps the most useful concept from functional programming that object oriented programmers can learn from. A function is functionally pure if it 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.

In this thesis a methodology for statically approximating functional purity in C# source code has been developed, as well as implemented in a program called CsPurity. The methodology was evaluated by running CsPurity on a code base of 11 open source C#

repositories that use the `[Pure]` attribute, with a total of 97200 methods.

The evaluation shows that the analysis method works, but that it is limited due to ...

- Not fully implemented
- Not all pure C# methods have the `[Pure]` attribute – Almost 10% of non-`[Pure]` methods are pure.
- Some methods with `[Pure]` still have side-effects
- Different definition of functional purity vs Microsoft's – mine is stricter
- Almost half of all methods were classified as *unknown* due to...

The evaluation of CsPurity shows, after normalizing the data, a precision of 64% and recall of 15% when it comes to classifying pure methods, and a precision of 59% and recall of 56% when classifying impure methods. The methodology seems to work even though the precision and recall are relatively low. By implementing the full methodology in CsPurity, and potentially improving it, we would have a fully working system for measuring a C# program's level of functional purity that could be used on any program. This could potentially be used to answer to what extent functional purity is being used in C# programs today.

9.2 Future work

The implementation of CsPurity used in this thesis does not incorporate the full analysis method described in [section 5](#). Therefore the obvious next step is to implement the full methodology in CsPurity.

CsPurity does not handle recursion, which if a recursive program is analyzed could cause it finish before all functions' purities have been calculated, because no more functions will be added to the working set. Support for recursive functions can be added by searching for independent strongly connected components [\[23\]](#).

One enhancement to CsPurity would be for it to point out the exact position of impurity in the analyzed code. Because impurity is calculated by passing the purity level of impure functions to their callers, this feature could be implemented by also passing the exact position in the code where the impurity was encountered to the caller, as well as the function's identifier and other useful information.

Moreover, the methodology developed in this thesis could potentially be used to check the validity of a function that uses the `[Pure]` attribute. As mentioned in [subsection 3.5](#) `[Pure]` is currently not enforced by any analysis tool, and so illegally assigned `[Pure]`s can currently not be detected.

This could prevent mistakes where the author of a piece of code falsely assigns `[Pure]` to an impure method from propagating. This could cause bugs to appear if somebody else uses that function unknowingly thinking that it is side-effect free. Of course the methodology used in this thesis would have to be slightly tweaked to consort with `[Pure]`'s non-deterministic definition of functional purity.

While perhaps more difficult to implement, another very useful feature would be if `CsPurity` after finding an impurity could suggest changes to the code that would make the function in question pure.

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