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.NET Decompiler

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Proforma

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Original Aim of the Project

The aim of this project was to create a .NET decompiler. That is, to create a program that translates .NET executables back to C# source code.

The concrete requirement was to decompile a quick-sort algorithm. Given an implementation of a quick-sort algorithm in executable form, the decompiler was required to re-create semantically equivalent C# source code. Although allowed to be rather cryptic, the generated source code had to compile and work without any additional modifications.

Work Completed

Implementation of the quick-sort algorithm decompiles successfully. Many optimizations were implemented and perfected to the point where the generated source code for the quick-sort algorithm is practically identical to the original[2]. In particular, the source code compiles back to identical .NET CLR code.

Further challenges were sought in more complex programs. The decompiler deals with several issues which did not occur in the quick-sort algorithm. It also implements some optimizations that are only applicable to the more complex programs.

Special Difficulties

None.

[1] This word count was computed by `detex diss.tex | tr -cd '0-9A-Za-z \n' | wc -w`

[2] See pages 60 and 61 in the evaluation chapter.

Declaration

I, David Srbecký of Jesus College, being a candidate for Part II of the Computer Science Tripos, hereby declare that this dissertation and the work described in it are my own work, unaided except as may be specified below, and that the dissertation does not contain material that has already been used to any substantial extent for a comparable purpose.

Signed

Date

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Chapter 1

Introduction

1.1 The goal of the project

The goal of this project is to create a .NET decompiler.

Decompiler is a tool that translates machine code back to source code. That is, it does the opposite of a compiler – it takes the executable file and it tries to recreate the original source code.

In general, decompilation can be extremely difficult or even impossible. Therefore this project focuses on something slightly simpler – decompilation of .NET executables. The advantage of .NET executables is that they consist of processor independent bytecode which is easier to decompile then the traditional machine code because the instructions are more high level and the code is less optimized. The .NET executables also preserve a lot of metadata about the code like type information and method names.

Note that despite its name, the *.NET Framework* is unrelated to networking or the Internet and it is basically the equivalent of *Java Development Kit*.

To succeed, the produced decompiler is required to successfully decompile a console implementation of a quick-sort algorithm back to C# source code.

1.2 Decompilation

Decompilation is the opposite of compilation. It takes the executable file and attempts to recreate the original source code. Despite of doing the reverse, decompilation is very similar to compilation. This is because both compilation and decompilation do in essence that same thing – translate program from one form to other form and then optimize the final form. Because of this, many analysis and optimizations used in compilation are also applicable in decompilation.

Decompilation may not always be possible. In particular, self-modifying code is very problematic.

1.3 Uses of decompilation

- Recovery of lost source code.
- Reverse engineering of programs that ship with no source code. This, however, might be a bit controversial use due to legal issues.
- Interoperability.
- Security analysis of programs.
- Error correction or minor improvements.
- Porting of executable to other platform.
- Translation between languages. Source code in some obscure language can be compiled into an executable which can in turn be decompiled into C#.
- Debugging of deployed systems. Deployed system might not ship with source code or it might be difficult to 'link' it to the source code because it is optimized. Also note that it might not be acceptable to restart the running system because the issue is not easily reproducible.

1.4 The .NET Framework

The *.NET Framework* is a general-purpose software development platform which is very similar to the *Java Development Kit*. It includes an extensive class library and, similarly to Java, it is based on a virtual machine model which makes it platform independent.

To be platform independent the program is stored in form of bytecode (also called Common Intermediate Language or *IL*). The bytecode instructions use the stack to pass data around rather then registers. The instructions are aware of the object-oriented programing model and are more high level then traditional processor instructions. For example, there is special instruction to allocate an object in memory, to access a field of an object, to cast an object to a different type and so on.

The byte code is translated to machine code of the target platform at run-time. The code is just-in-time compiled rather then interpreted. This means that the first execution of a function will be slow due to the translation overhead, but the subsequent executions of the same function will be very fast.

The .NET executables preserve a lot of information about the structure of the program. The complete structure of classes is preserved including all the typing information. The code is still separated into distinct methods and the complete signatures of the methods are preserved – that is, the executable includes the method name, the parameters and the return type.

The virtual machine is intended to be type-safe. Before any code is executed it is verified and code that has been successfully verified is guaranteed to be type-safe. For example, it is guaranteed not access unallocated memory. However, the framework also provides some inherently unsafe instructions. This allows support for languages like C++, but it also means that some parts of the program will be unverifiable. Unverifiable code may or may not be allowed to execute depending on the local security policy.

In general, any programming language can be compiled to *.NET* and there are already dozens, if not hundreds, of compliers in existence. The most commonly used language is *C#*.

1.5 Scope of the project

The *.NET Framework* is mature comprehensive platform and handling all of its features is out the scope of the project. Therefore, it is necessary to state which features should be supported and which should not.

The decompiler was specified to at least handle all the features required to decompile the quick-sort algorithm. This includes integer arithmetic, array operations, conditional statements, loops and system method calls.

The decompiler will not support so-called unverifiable instructions – for example, pointer arithmetic and access to arbitrary memory locations. These operations are usually used only for interoperability with native code (code not running under the .NET virtual machine). As such, these instructions are relatively rare and do not even occur in many programs at all.

Generics also will not be supported. They were introduced in the second version of the Framework and many programs still do not make any use of them. The generics also probably does not provide any theoretical challenge for the decompilation. It just involves handing of more bytecodes and more special cases of the existing bytecodes.

1.6 Previous work

Decompilers are in existence nearly as long as compilers. The very first decompiler was written by Joel Donnelly in 1960 under the supervision of Professor Maurice Halstead. Initially, decompilers were created to aid in the program conversion process from second to third generation computers. Decompilers were actively developed over the following years and were used for variety of applications.

Probably the best know and most influential research paper is *Cristina Cifuentes' PhD Thesis "Reverse Compilation Techniques", 1994.* As part of the paper Cristina created a prototype *dcc* which translates Intel i80286 machine code into C using various data and control flow analysis techniques.

The introduction of virtual machines made decompilation more feasible then ever (e.g. *Java Virtual Machine* or *.NET Framework Runtime*).

There are already several closed-source .NET decompilers in existence. The most known one is probably Lutz Roeder's *Reflector for .NET*.

Chapter 2

Preparation

This chapter explains the general idea behind the decompilation process. The implementation chapter then explains how these methods were implemented and what measures were taken to ensure the correctness of the produced output.

2.1 Overview of the decompilation process

The first step is to read and disassemble the *.NET* executable files. There is an open-source library called *Cecil* which was created exactly for this purpose. It loads the whole executable into memory and then it provides simple object-oriented API to access the content of the executable. Using this library, the access to the executable is straightforward.

It is worth noting the wealth of information we are starting with. The *.NET* executables contain quite high-level representation of the program. Complete typing information is still present – we have access to all the classes including the fields and methods. The types and names are also preserved. The bytecode is stored on per-method basis and even the local variables used in the method body are still explicitly represented including the type.[1]

Ultimately, the challenge is to translate the bytecode of a given method to a C# code.

For example, consider decompilation of following code:

[1] However, the names of local variables are not preserved.

```
// Load "Hello, world!" on top of the stack
ldstr "Hello, world!"
// Print the top of the stack to the console
call System.Console::WriteLine(string)
```

We start by taking the bytecodes one by one and translate them to C# statements. The bytecodes are quite high level so the translation is usually straightforward. The two bytecodes can thus be represented as the following two C# statements (`output1` and `some_input` are just dummy variables):

```
string output1 = "Hello, world!";
System.Console.WriteLine(some_input);
```

The first major challenge of decompilation is data-flow analysis. In this example, we would analyze the stack behavior and we would find that `output1` is on the top of the stack when `WriteLine` is called. Thus, we would get:

```
string output1 = "Hello, world!";
System.Console.WriteLine(output1);
```

At this point the produced source code should already compile and work as intended.

The second major challenge of decompilation is control-flow analysis. The use of control-flow analysis is to replace `goto` statements with high-level structures like loops and conditional statements. This makes the produced source code much more easier to read and understand.

Finally, there are several sugarings that can be done to the code to make it more readable – for example, replacing `i = i + 1` with the equivalent `i++` or using rules of logic to simplify boolean expressions.

2.2 Translating bytecodes into C# expressions

The first task is to convert naively the individual bytecodes into equivalent C# expressions or statements.

This task is reasonably straightforward because the bytecodes are quite high level and are aware of the object-oriented programming model. For example, there are bytecodes for integer addition, object creation, array access, field access, object casting and so on; all of these trivially translate to C# expressions.

Any branching commands are also easy to handle because C# supports labels and `goto`s. Unconditional branches are translated to `goto` statements and conditional branches are translated to `if (condition) goto Label;`.

C# uses local variables for data transfer whereas bytecodes use the stack. This mismatch will be handled during the data-flow analysis phase. Until then, dummy variables are used as placeholders. For example, `add` bytecode would be translated to `input1 + input2`.

2.3 Data-flow analysis

2.3.1 Stack in .NET

Bytecodes use a stack to pass data between consecutive instructions. When a bytecode is executed, it pops its arguments from the stack, it performs some operation on them and then it pushes the result, if any, back to the stack.

The number of popped elements is fixed and known before execution time - for example, any binary operation pops exactly two arguments and a method call pops one element for each of its arguments.

Most bytecodes either push only one element on the stack or none at all.[2] This makes the data-flow analysis slightly simpler.

The framework imposes some useful restrictions with regards to control-flow. In theory, we could arrive at a given point in program and depending on which execution path was taken, we could end up with two completely different stacks. This is not allowed. Regardless of the path taken, the stack must have the same number of elements in it. The typing is also restricted – if one execution path

[2]There is one exception to this – the 'dup' instruction. More on this later.

pushes an integer on the stack, any other execution path must push an integer as well.

2.3.2 Stack simulation

Bytecodes use the stack to move data around, but there is no such stack concept in C#. Therefore we need to use something that C# does have – local variables.

The transformation from stack to local variables is simpler then it might initially seem. Basically, pushing something on the stack means that we will need that value later on. So in C#, we create a new temporary variable and store the value in it. On the other hand, popping is a usage of the value. So in C#, we just reference the temporary variable that holds the value we want. The only difficult is to figure out which temporary variable it is.

This is where the restrictions on the stack come handy – we can figure out what the state of the stack will be at any given point. That is, we do not know what the value will be, but we do know who pushed the value on the stack and what the type of the value is. For example, after executing the following code

```
IL_01: ldstr "Hello''
IL_02: ldstr "world''
```

we know that there will be exactly two values on the stack – the first one pushed by bytecode labeled `IL_01` and the second one pushed by bytecode labeled `IL_02`. Both of them of are of type `String`. Let's say that the state of the stack is {`IL_01`, `IL_02`}.

Now, let us pop value from the stack by calling `System.Console.WriteLine`. This method takes one `String` argument. Just before the method is called the state of the stack is {`IL_01`, `IL_02`}. Therefore the value allocated by `IL_02` is popped from the stack and we are left with {`IL_01`}. Furthermore, we know which temporary local variable to use in the method call – the one that stores the value pushed by `IL_02`.

Let us call `System.Console.WriteLine` again to completely empty the stack and let us see what the produced C# source code would look like (the comments show the state of the stack between the individual commands).

```
// {}
String temp_for_IL_01 = "Hello'';
// {IL_01}
String temp_for_IL_02 = "world'';
// {IL_01, IL_02}
System.Console.WriteLine(temp_for_IL_02);
// {IL_01}
System.Console.WriteLine(temp_for_IL_01);
// {}
```

2.3.3 The 'dup' instruction

In general, bytecodes push either one value on the stack or none at all. There is only one exception to this – the `dup` instruction. The purpose of this instruction is to duplicate the value on top of the stack. Fortunately, it does not break our model. The only significance of the `dup` instruction is that the same value will be used twice - that is, the temporary local variable will be referenced twice.

The `dup` instruction, however, makes some future optimizations more difficult.

The `dup` instruction is used relatively rarely and it usually just saves a few bytes of disk space. Note that the `dup` instruction could always be replaced by store to a local variable and two loads.

The `dup` instruction can be used in expression like `this.a + this.a` – the value `this.a` is obtained once, duplicated and then the duplicates are added.

2.3.4 Control merge points

This in essence the most complex part of data-flow analysis. It is caused by the possibility of multiple execution paths. There are two scenarios that branching can cause.

The nice scenario is when a value is pushed in one location and, depending on the execution path, can be popped in two or more different locations. This translates well into the local variable model - it simply means that the temporary local variable will be referenced several times and there is nothing special we need to do.

The worse scenario is when a value can be pushed on the sack in two or more different locations and then it is poped only in one locations. Example of this

would be `Console.WriteLine(condition ? "true": "false")` – depending on the value of the condition either "true" or "false" is printed. This code snippet compiles into bytecode with two possible execution paths – one in which "true" is pushed on the stack and one in which "false" is pushed on the stack. In both cases the value is poped only once when `Console.WriteLine` is called.

This scenario does not work well with the local variable model. Two values can be pushed on the stack and so two temporary local variables are created – one holding "true" and one holding "false". Depending on the execution path either of these can be on the top of the stack when `Console.WriteLine` is executed and therefore we do not know which temporary variable to use as the argument for `Console.WriteLine`. It is impossible to know.

This can be resolved by creating yet another temporary variable which will hold the actual argument for the `Console.WriteLine` call. Depending on the execution path taken, one of the previous variables needs to be copied into this one. So the produced C# source code would look like this:

```
String sigma;
if (condition) {
  String temp1 = "true";
  sigma = temp1;
} else {
  String temp2 = "false";
  sigma = temp2;
}
Console.WriteLine(sigma);
```

Note that this is essentially the trick that is used to obtain single static assignment (SSA) form of programs during compilation.

In reality, this happens extremely rarely and it is almost exclusively caused by the C# `?` operator.

2.3.5 In-lining expressions

The code produced so far contains many temporary variables. These variables are often not necessary and can be optimized away. For example, the code

```
string output1 = "Hello, world!";
System.Console.WriteLine(output1);
```

can be simplified into a single line:

```
System.Console.WriteLine("Hello, world!");
```

Doing this optimization makes the produced code much more readable.

In general, removing a local variable from a method is non-trivial. However, these generated local variables are special – they were generated to remove the stack-based data-flow model. This means that the local variables are assigned only once and are read only once[3] (corresponding to the push and pop operations respectively).

There are some safety issues with this optimization. Even though we are sure that the local variable is assigned and read only once, we need to make sure that doing the optimization will not change the semantics of the program. For example consider the following code:

```
string output1 = f();
string output2 = g();
System.Console.WriteLine(output2 + output1);
```

The functions `f` and `g` may have side-effects and in this case `f` is called first and then `g` is called. Optimizing the code would produce

```
System.Console.WriteLine(g() + f());
```

[3]With the exception of the 'dup' instruction which is read twice and thus needs to be handled specially.

which calls the functions in the opposite order.

Being conservative, we will allow this optimization only if the declaration of the variable immediately precedes its use. In other words, the variable is declared and then immediately used with no possible side-effects in between these. Using this rule, the previous example can be optimized to

```
string output1 = f();
System.Console.WriteLine(g() + output1);
```

but it can not be optimized further because the function `g` is executed between the declaration of `output1` and its use.

2.4 Control-flow analysis

The main point of control-flow analysis is to recover high-level structures like loops and conditional blocks of code. This is not necessary to produce semantically correct code, but it does make the code much more readable compared to only using `goto` statements. It is also the most theoretically interesting part of the whole decompilation process.

In general, `goto`s can be always completely removed by playing some 'tricks' like duplicating code or adding boolean flags. However, as far as readability of the code is concerned, this does more harm than good. Therefore, we want to remove `goto`s using the 'natural' way – by recovering the high-level structures they represent in the program. Any `goto`s that can not be removed in such way are left in the program.

See figures 2.1, 2.2 and 2.3 for examples of control-flow graphs.

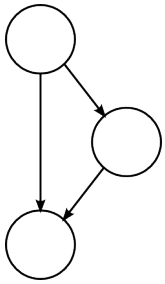


Figure 2.1: Conditional statement (if-then)

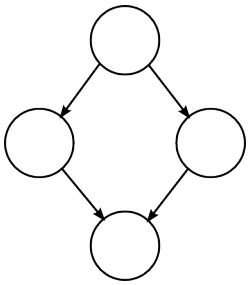


Figure 2.2: Conditional statement (if-then-else)

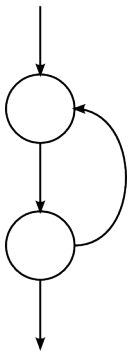


Figure 2.3: Loop

2.4.1 Finding loops

T1-T2 transformations are used to find loops. These transformation are usually used to determine whether a control flow graph is reducible or not, but it turns out that they are suitable for finding loops as well.

If a control-flow graph is irreducible, it means that the program can not be represented only using high-level structures. That is, `goto` statements are necessary to represent the program. This is undesirable since `goto` statements usually make the decompiled source code less readable. See figure 2.4 for the classical example of irreducible control-flow graph.

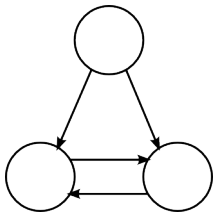


Figure 2.4: Ireducible control-flow graph

If a control-flow graph is reducible, the program may or may not be representable only using high-level structures. That is, `goto` statements still may be necessary on some occasions. For example, C# has a `break` statement which exits the inner most loop, but it does not have any statement which would exit multiple levels of loops.[4] Therefore in such occasion we have to use the `goto` statement.

The algorithm works by taking the initial control-flow graph and then repeatedly applying simplifying transformations to it. As we can see from the name, the algorithm consists of two transformations called T1 and T2. If the graph is reducible, the algorithm will eventually simplify the graph to only a single node. If the graph is not reducible, we will end up with multiple nodes and no more transformations that can be performed.

Both of the transformations look for a specific pattern in the graph and then replace the pattern with something simpler.

See figure 2.5 for a diagram showing the T1 and T2 transformations.

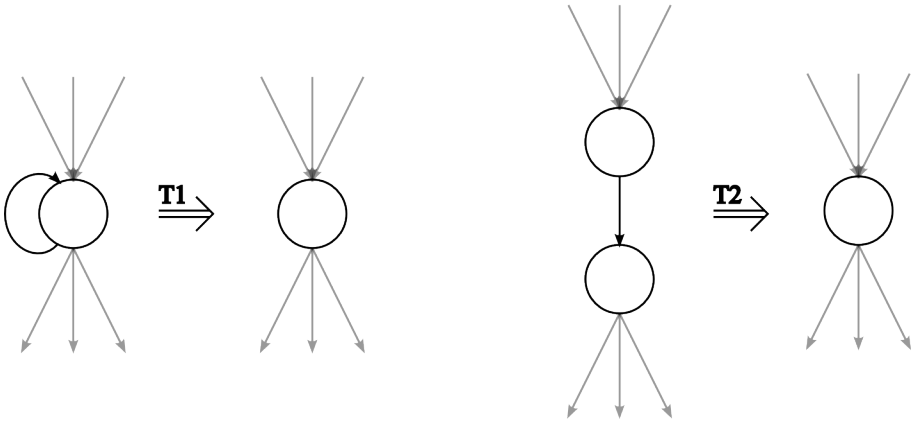


Figure 2.5: T1 and T2 transformations

The T1 transformation removes self-loop. If one of the successors of a node is the node itself, then the node is a self-loop. That is, the node 'points' to itself. The T1 transformation replaces the node with a node without such link. The number of preformed T1 transformations corresponds to the number of loops in the program.

The T2 transformation merges two consecutive nodes together. The only condition is the the second node has to have only one predecessor which is the first

[4]This is language dependent. The Java language, for example, does provide such command.

node. Preforming this transformation repeatedly basically reduces any directed acyclic graph into a single node.

See figures 2.6, 2.7 and 2.8 for examples how T1 and T2 transformations can be used to reduce graphs.

The whole algorithm is guaranteed to terminate if and only the graph is reducible. However, it may produce different intermediate states depending on the order of the transformations. For example, the number of T1 transformations used can vary. This affects the number of apparent loops in the program.

Note that although reducible graphs are preferred, irreducible graphs can be easily decompiled as well using `goto` statements. Programs that were originally written in C# are most likely going to be reducible.

2.4.2 Finding conditionals

Any T1 transformation (self-loop reduction) produces a loop. Similarly, T2 transformation or several T2 transformations produce a directed acyclic sub-graph. This sub-graph can usually be represented as one or more conditional statements.

Any node in the control-flow graph that has two successors is potentially a conditional – that is, `if-then-else` statement. The node itself determines which branch will be taken, so the node is the condition. We now need to determine what is the 'true' body and what is the 'false' body. That is, we look for the blocks of code that will be executed when the condition will or will not hold respectively. This is done by considering reachability. A code that is reachable only by following the 'true' branch can be considered as the 'true' body of the conditional. Similarly, code that is reachable only by following the 'false' branch is the 'false' body of the conditional. Finally, the code that is reachable from both branches is not part of the conditional – it is the code that follows the whole `if-then-else` statement. See figure 2.9 for a diagram of this.

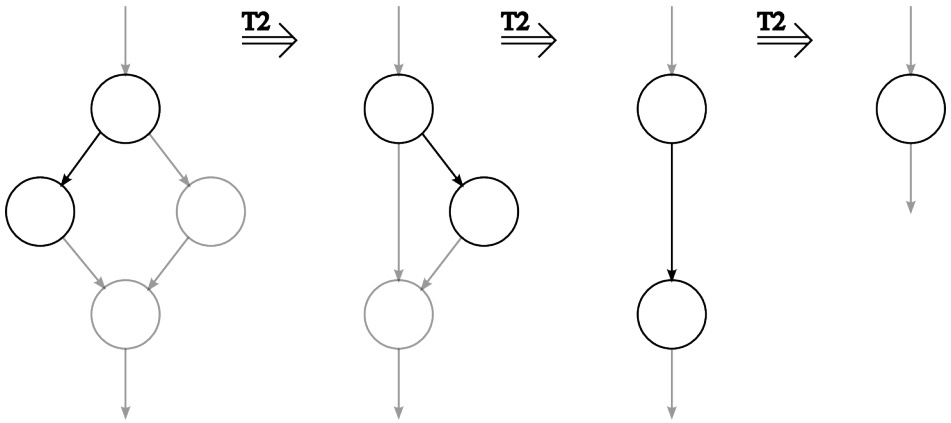


Figure 2.6: Reduction of if-then-else statement

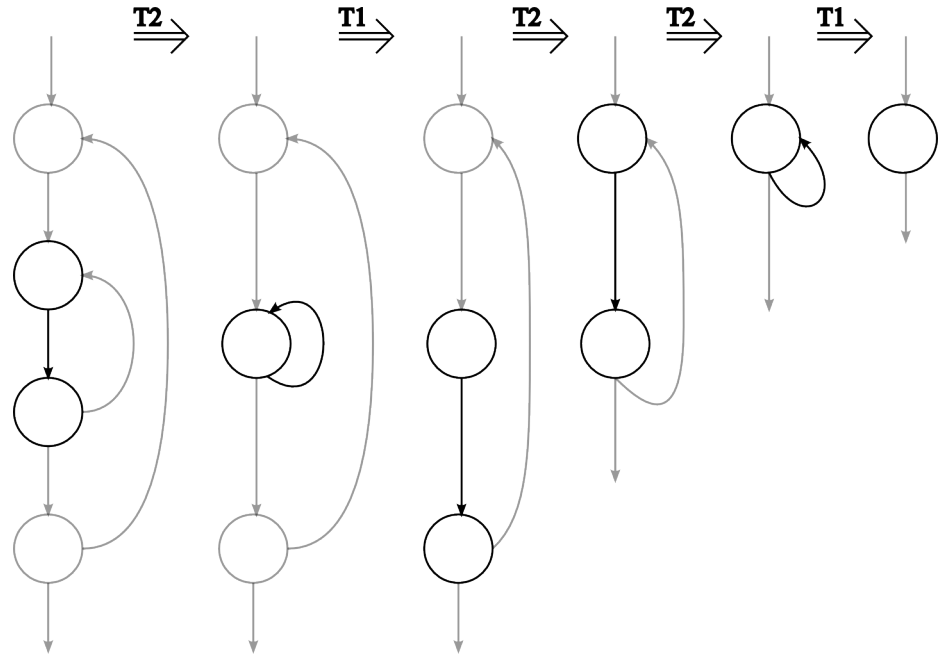
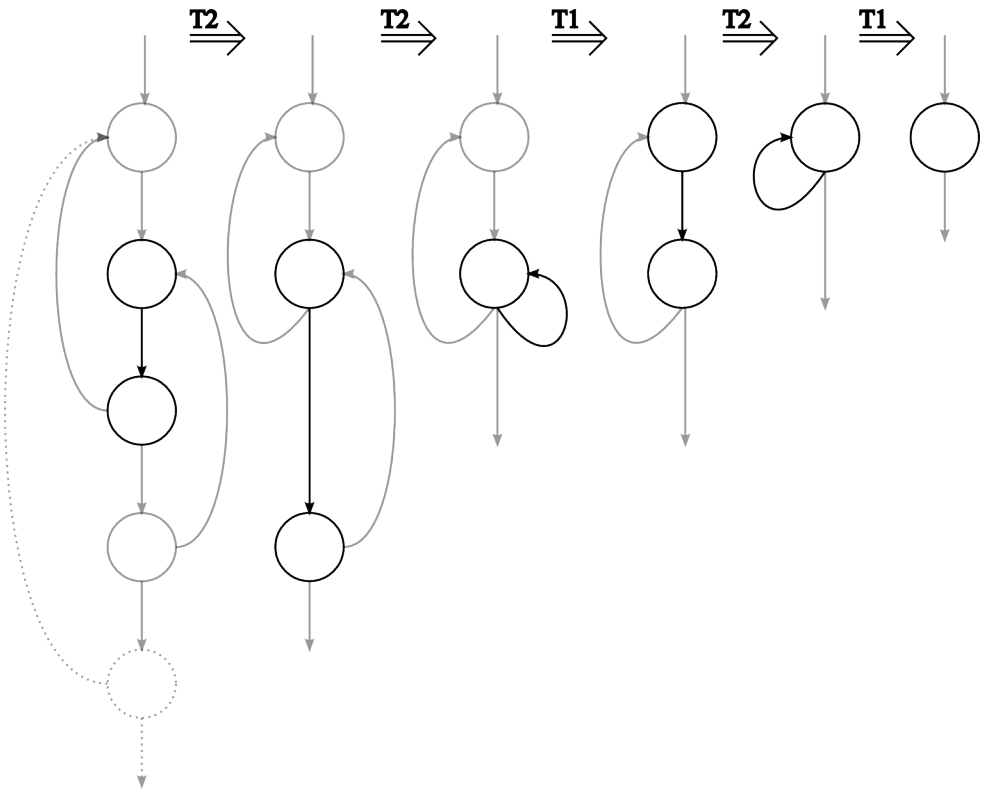


Figure 2.7: Reduction of two nested loops



It is not not immediately obvious that these are, in fact, two nested loops. Fifth conceptual node has been added to demonstrate why the loops can be considered nested.

Figure 2.8: Reduction of two nested loops 2

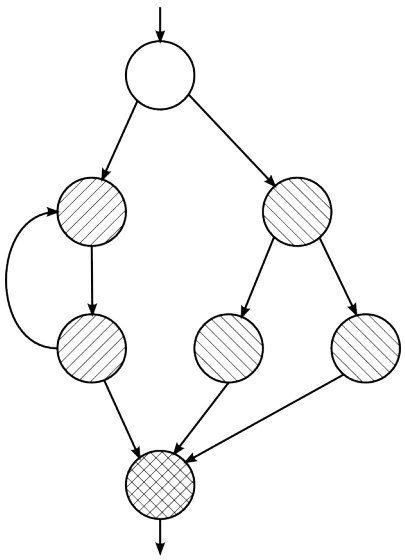


Figure 2.9: Reachablity of nodes for a conditional

2.4.3 Short-circuit boolean expressions

Short-circuit boolean expressions are boolean expressions which may not evaluate completely.

The semantics of normal boolean expression `f() & g()` is to evaluate both `f()` and `g()` and then return the logical 'and' of these.

The semantics of short-circuit boolean expression `f() && g()` is different. The expression `f()` is evaluated as before, but `g()` is evaluated only if `f()` returned *true*. If `f()` returned *false* then the whole expression will return *false* anyway and so there no point in evaluating `g()`.

In general, conditionals depending on this short-circuit logic cannot be expressed as normal conditionals without the use of `goto`s or code duplication. Therefore it is desirable to find the short-circuit boolean expressions in the control-flow graph.

The short-circuit boolean expressions will manifest themselves as one of four patterns in the control-flow diagrams. See figure 2.10.

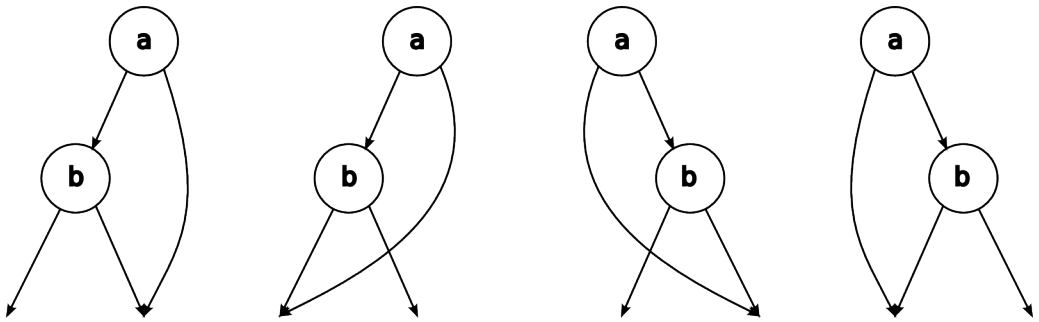


Figure 2.10: Short-circuit control-flow graphs

These patterns can be easily searched for and replaced with a single node.

Nested expressions like `(f() && g()) || (h() && i())` will simplify well by applying the algorithm repeatedly.

2.4.4 Basic blocks

Basic block is a block of code which is always executed as a unit. That is, no other code can jump in the middle of the block and there are no jumps from the middle of the block.

The implication of this is that as far as control-flow analysis is concerned, the whole basic block can be considered as a single instruction.

This primary reason for implementing this is performance gain.

2.5 Requirements Analysis

The decompiler must successfully round-trip a quick-sort algorithm. That is, given an executable containing an implementation of the quick-sort algorithm, the decompiler must produce C# source code that is both syntactically and semantically correct. The produced source code must compile and work correctly without any additional modifications to the source code.

To achieve this the Decompiler needs to handle at least the following:

- Integers and integer arithmetic
- Create and be able to use integer arrays
- Branching must be successfully decompiled
- Several methods can be defined
- Methods can have arguments and return values
- Methods can be called recursively
- Integer command line arguments can be read and parsed
- Text can be outputted to the standard console output

2.6 Development model

The development is based on the spiral model.

The decompiler will internally consist of several consecutive code representations. The decompiled program will be gradually transformed from one representation to other until it reaches the last one and is outputted as source code. This matches the spiral model well. Successful implementation of each code representation can be seen as one iteration in the spiral model.

Furthermore, once a code representation is finished, it can be improved by implementing an optimization which transforms it. This can be seen as another iteration.

2.7 Reference documentation

The .NET executables will be decompiled into C# source code. It is therefore crucial to be intimately familiar with the language. Evaluation semantics, operator precedence, associativity and other aspects of the language can be found in the *ECMA-334 Standard – C# Language Specification*.

In oder to decompile .NET executables, it is necessary to get familiar with the .NET Runtime (i.e. the .NET Virtual Machine). In particular, it is necessary to learn how the execution engine works – how does the stack behave, what limitations are imposed on the code, what data types are used and so on. Most importantly, it is necessary to get familiar with majority of the bytecodes. The primary reference for the .NET Runtime is the *ECMA-335 Standard – Common Language Infrastructure (CLI)*.

Chapter 3

Implementation

3.1 Development process

The whole project was developed in C# on the *Windows* platform. SharpDevelop[1] was used as the integrated development environment for writing of the code.

The source code and all files related to the project are stored on SVN[2] server. This has several advantages such as back-up of all data, documented project history (the commit messages) and the ability to revet back to any previous state. The graphical user interface for SVN also makes it possible to easily see and review all changes that were made since previous commit to the server.

The user interface of the decompiler is very simple. It consists of a single window which is largely covered by a text area containing the output of the decompilation process. There are only a few controls in the top part of the window. Several check boxes can be used to completely turn off or on optimization stages of the decompilation process. Numerical text boxes can be used to specify the maximal number of interactions for several transformations. By gradually increasing these it is possible to observe changes to the output step-by-step. These options significantly aid in debugging and testing of the decompiler.

The source code generated by the decompiler is also stored on the disk and committed to SVN together with all other files. This is the primary method

[1] Open-source integrated development environment for the .NET framework. I am actively participating in its development, currently being one of the major developers.

[2] Subversion (SVN) is an open-source version control system. It is very similar to CVS and aims to be its successor.

of regression testing. The generated source code is the primary output of the decompiler and thus any change in it may potentially signify a regression in the decompiler. Before every commit the changes to this file were reviewed to confirm that the new features did yield the expected results and that no regressions were introduced.

3.2 Overview of representation structures

The decompiler uses the following four intermediate representations of the program (sequentially in this order):

- Stack-based bytecode
- Variable-based bytecode
- High-level blocks
- Abstract Syntax Tree

The code is translated from one representation to other and some transformations/optimizations are done at each of these representations.

The representations are very briefly described in the following four subsections and then they are covered again in more detail.

Trivial artificial examples are used to aid the explanation. Note that the evaluation chapter shows the actual outputs for the quick-sort implementation.

3.2.1 Stack-based bytecode representation

The stack-based bytecode is the original bytecode as read from the assembly. It is never modified. However, it is analyzed and annotated with the results of the analysis. Most data-flow analysis is performed at this stage. This is an example of code in this representation:

```
ldstr "Hello, world!"
call System.Console::WriteLine
```

3.2.2 Variable-based bytecode representation

The variable-based bytecode is the result of removing the stack-based data-flow model. Local variables are now used instead. Even though the stack-based model is now completely removed, we can still use the bytecodes to represent the program. We just need to think about them in a slightly different way. The bytecodes are in essence functions which take arguments and return values. For example, the `add` bytecode pops two values and pushes back the result and so it is now a function which takes two arguments and returns the result. The `ldstr "Hello, world!"` bytecode used above is slightly more complicated. It does not pop anything from the stack, but it still has the implicit argument `"Hello, world!"` which comes from the immediate operand of the bytecode.

Continuing with the example, the variable-based from would be:

```
temp1 = ldstr("Hello, world!");
call(System.Console::WriteLine, temp1);
```

where the variable `temp1` was used to remove the stack data-flow model.

Some transformations are performed at this stage, modifying the code. For example, the in-lining optimization would transform the previous example to:

```
call(System.Console::WriteLine, ldstr("Hello, world!"));
```

Note that expressions can be be nested as seen in the code above.

3.2.3 High-level blocks representation

The next data representation introduces high-level blocks. In this representation, related parts of code can be grouped together into a block of code. The block signifies some high-level structure and blocks can be nested (for example, conditional within a loop). All control-flow analysis is performed at this stage.

The blocks can be visualized by a pair of curly braces:

```
{ // Block of type 'method body'
  IL_01: call(System.Console::WriteLine, ldstr("Hello, world"));
  { // Block of type 'loop'
    IL_02: call(System.Console::WriteLine, ldstr("!"));
    IL_03: br(IL_02) // Branch to IL_02
  }
}
```

Initially there is only one block containing the whole method body and as the high-level structures are found, new smaller blocks are created. At this stage the blocks have no function other than grouping of code.

This data representation also allows code to be reordered to better fit the ordinal high-level structure.

3.2.4 Abstract Syntax Tree representation

This is the final representation. The abstract syntax tree (AST) is a structured way of representing the produced source code. For example, the expression `(a + 1)` would be represented as four objects – parenthesis, binary operator, identifier and constant. The structure is a tree so the identifier and the constant are children of the binary operator which is in turn child of the parenthesis.

This initial abstract syntax tree will be quite verbose due to constructs that ensure correctness of the produced source code. There will be an especially high quantity of `goto`s and parentheses. For example, a simple increment is initially represented as `((i) = (i) + (1));` where the parentheses are used to ensure safety. Transformations are done on the abstract syntax tree to simplify the code in occasions where it is know to be safe.

Several further transformations are done to make the code more readable. For example, renaming of local variables or use of common programming idioms.

3.3 Stack-based bytecode representation

This is the first and simplest representation of the code. It directly corresponds to the bytecode in the .NET executable. It is the only representation which is not transformed in any way.

The bytecode is loaded from the .NET executable with the help of the Cecil library. Three fundamental pieces of information are loaded for each bytecode – its offset from the start of the method, opcode (name) and the immediate operand. The immediate operand is additional argument present for some bytecodes – for example, for the `call` bytecode, the operand specifies the method that should be called.

For bytecodes that can branch, the operand is the branch target. Each bytecode stores a reference to the branch target (if any) and each bytecode also stores a reference to all bytecodes that can branch to it.

3.3.1 Stack analysis

Once all bytecodes are loaded, the stack behavior of the program is analyzed. The precise state of the stack is determined for each bytecode. The .NET Framework dictates that this must be possible for valid executables. It is possible to determine the exact number of elements on the stack and for each of these elements is possible to determine which bytecode pushed it on the stack[3] and what the type of the element is.

There are two stack states for each bytecode – the first is the known state *before* the bytecode is executed and the second is the state *after* the bytecode is executed. Knowing what the bytecode does, the later state can be obviously derived from the former. This is usually easy – for example, the `add` bytecode pops two elements from the stack and pushes one back. The pushed element is obviously pushed by the `add` bytecode and the element is of the same type as the two popped elements[4]. The `ldstr` bytecode just pushes one element of type `string`. The behaviour of the `call` bytecode is slightly more complex because it depends on the method that it is invoking. Implementing these rules for all bytecodes is tedious, but usually straightforward.

[3] In some control merge scenarios, there might be more bytecodes that can, depending on the execution path, push the value on the stack.

[4] The 'add' bytecode can only sum numbers of the same type.

The whole stack analysis is performed by iterative algorithm. The stack *before* the very first bytecode is empty. We can use this to find the stack state *after* the first instruction. The stack state *after* the first bytecode is the initial stack state for other bytecode. We can apply this principle again and again until all states are known.

Branching dictates the propagation of the states between bytecodes. For two simple consecutive bytecodes, the stack state *after* the first bytecode is same as the state *before* the second. Therefore we just copy the state. If the bytecode is a branch then we need to copy the stack state to the target of the branch as well.

Dead-code can never be executed and thus it does not have any stack state associated with it.

At the bytecode level, the .NET Runtime handles boolean values as integers. For example, the bytecode `ldc.i4 1` can be interpreted equivalently as 'push `1`' and 'push `true`'. Therefore three integer types are used – 'zero integer', 'non-zero integer' and generic 'integer' (of unknown value). Bytecode `ldc.i4 1` therefore has type 'non-zero integer'.

3.4 Variable-based bytecode representation

This is a next representation which differs from the stack-based one by completely removing the stack-based data-flow model. Data is passed between instructions using local variables or using nested expressions.

Consider the following stack-based program which evaluates $2 * 3 + 4 * 5$.

```
ldc.i4 2
ldc.i4 3
mul
ldc.i4 4
ldc.i4 5
mul
add
```

The program is transformed to the variable-based form by interpreting the bytecodes as functions which return values. The result of every function call is stored in new temporary variable so that the value can be referred to latter.

```
int temp1 = ldc.i4(2);
int temp2 = ldc.i4(3);
int temp3 = mul(temp1, temp2);
int temp4 = ldc.i4(4);
int temp5 = ldc.i4(5);
int temp6 = mul(temp4, temp5);
int temp7 = add(temp3, temp6);
```

The stack analysis performed earlier is used to determine what local variables should be used as arguments. For example, the stack analysis tells us that the stack contains precisely two elements just before the `add` instruction. It also tells us that these two elements have been pushed on the stack by the `mul` instructions (the third and sixth instruction respectively). Therefore to access the results of the `mul` instructions, the `add` instruction needs to use the temporary variables `temp3` and `temp6`.

3.4.1 Representation

Internally, each expression ('function call') consists of three main elements – the opcode (e.g. `ldc.i4`), the immediate operand (e.g. `1`) and the arguments (e.g. `temp1`). The argument can be either a reference to a local variable or other nested expression. In the case of

```
call(System.Console::WriteLine, ldstr("Hello, world"))
```

`call` is the opcode, `System.Console::WriteLine` is the operand and `ldstr("Hello, world")` is the argument (nested expression).

Expressions like `ldstr("Hello, world")` or `ldc.i4` do not have any arguments other then the immediate operand.

There are bytecodes for storing and referencing a local variables (`ldloc` and `stloc` respectively). Therefore no special data structures are needed to declare and reference the local variables because we we can store program like

```
int temp1 = ldc.i4(2);
int temp2 = ldc.i4(3);
int temp3 = mul(temp1, temp2);
```

only using bytecodes as

```
stloc(temp1, ldc.i4(2));
stloc(temp2, ldc.i4(3));
stloc(temp3, mul(ldloc(temp1), ldloc(temp2)));
```

Local variables `temp1`, `temp2` and `temp3` are tagged as being 'single static assignment and single read'. This is a necessary property for the in-lining optimization. All generated temporary variables satisfy this property except for the ones storing the result of a `dup` instruction which does not satisfy this property because it is read twice.

3.4.2 In-lining of expressions

The variable-based representation passes data between instructions either using local variables or using expression nesting. Expression nesting is the preferred more readable form. The in-lining transformations simplifies the code by removing some temporary variables and using expression nesting instead.

Consider the following code.

```
stloc(temp1, ldstr("Hello, world!"));
call(System.Console::WriteLine, ldloc(temp1));
```

This code can be simplified into a single line by in-lining the local variable `temp1`: (that is, the `stloc` expression is nested within the `call` expression)

```
call(System.Console::WriteLine, ldstr("Hello, world!"));
```

The algorithm is iterative. Two consecutive lines are considered and if the first line assigns to a local variable which is used in the second line then the variable is in-lined. This is repeated until no more optimizations can be done.

There are some safety concerns with this optimizations. The optimization would break the program if the local variable was read later in the program. Therefore the optimization is done only for variables that have the property of being 'single static assignment and single read'.

The second concern is change of execution order. Consider the following pseudocode:

```
temp1 = f();
add(g(), temp1);
```

In-ling `temp1` would change the order in which the functions `f` and `g` are called and thus the optimization can not be performed. On the other hand, the following code can be optimized:

```
temp1 = f();
add(1, temp1);
```

The effect of the optimization will be that the expression `1` will be evaluated before `f` rather then after it. However, this does not change the semantics of the program because evaluation of `1` does not have any side-effects and it will still evaluate to the same value.

More importantly, the same property holds for `ldloc` (load local variable) instruction. It does not have any side-effects and it will evaluate to the same value even if evaluated before the function `f` (or any other expression being in-lined). This is true because the function `f` (or any other expression being in-lined) can not change the value of the local variable.

To sum up, it is safe to in-line a local variable if it has property 'single static assignment and single read' and if the argument referencing it is preceded only by `ldloc` instructions.

The following code would be optimized in two iterations:

```
stloc(temp1, ldc.i4(2));
stloc(temp2, ldc.i4(3));
stloc(temp3, mul(ldloc(temp1), ldloc(temp2)));
```

First iteration (in-line `temp2`):

```
stloc(temp1, ldc.i4(2));
stloc(temp3, mul(ldloc(temp1), ldc.i4(3)));
```

Second iteration (in-line `temp1`):

```
stloc(temp3, mul(ldc.i4(2), ldc.i4(3)));
```

3.4.3 In-lining of 'dup' instruction

The `dup` instruction can not be in-lined because it does not satisfy the 'single static assignment and single read' property. This is because the data is referenced twice. For example, in-lining the following code would cause the function `f` to be called twice.

```
stloc(temp1, dup(f()));
add(temp1, temp1);
```

However, there are circumstances where this would be acceptable. If the expression within the `dup` instruction is a constant then it is possible to in-line it without any harm. The following code can be optimized:

```
stloc(temp1, dup(ldc.i4(2)));
add(temp1, temp1);
```

Even more elaborate expressions like `mul(ldc.i4(2), ldc.i4(3))` are still a constant. The instruction `ldarg.0` (load `this`) is also constant relative to the single invocation of method.

3.5 High-level blocks representation

So far the code is just a sequential list of statements. The statements are in the exactly same order as found in the original executable and all control-flow is achieved only by the `goto` statements.

The 'high-level block' representation structure introduces greater freedom to the code. High-level structures are recovered and the code can be arbitrarily re-ordered.

The code is organized into blocks in this representation. A block can can contain executable code as well as other nested blocks. Therefore this resembles a tree-like data structure. The root block of the three represents the method and contains all of its code. A node in the three represents some high-level data structure (loop, `if` statement). Nodes can also represent 'meta' high-level structures which are used during the optimizations. For example, node can encapsulate a block of code that is known to be acyclic (without loops). Finally, all leaves in the tree are basic blocks.

3.5.1 Safety

This data representation allows the code to be restructured and reordered. Therefore care is needed to make sure that the produced code is semantically correct.

It would be possible to make sure that every transformation is valid. However, there is even more robust solution – give up at the start and allow arbitrary transformations. The only constraint is that the code can be only moved. It cannot be duplicated and it cannot be deleted. Deleting of code would indeed cause problems. Anything else is permitted.

When the code is generated, the correctness is ensured by explicit `label`s and `goto`s placed in front of and after every basic block respectively. For example consider the follow piece of code in which the order of basic blocks was reversed and two unnecessary high-level nodes were added:

```
goto BasicBlock1; // Method prologue

for(;;) {
  BasicBlock2:
  Console.WriteLine("world");
  goto End;
}

if (true) {
  BasicBlock1:
  Console.WriteLine("Hello");
  goto BasicBlock2;
}

End:
```

The inclusion of explicit `label`s and `goto`s makes the high-level structures and the order of basic blocks irrelevant and thus the produced source code will be correct. Note that in the code above the lines `for(;;) {` and `if (true) {` will never be reached during execution.

In general, the transformations done on the code will be more sane then in the example above and most of the `label`s and `goto`s will be redundant. In the following code all of the `label`s and `goto`s can be removed:

```
goto BasicBlock1; // Method prologue

BasicBlock1:
Console.WriteLine("Hello");
goto BasicBlock2;

BasicBlock2:
Console.WriteLine("world");
goto End;

End:
```

The removal of `label`s and `goto`s is done once the Abstract Syntax Tree is created.

To sum up, finding and correctly identifying all high-level structures will produce nice results, but failing to do so will not cause any harm as far as correctness is concerned.

3.5.2 Tree data structure

The data structure to store the tree is very simple – the tree consists of nodes where each node contains a link to its parent and a list of children. A child can be either another node or a basic block (leaf).

The API of the tree structure is severely restricted. Once the tree is created, it is only possible to add new empty nodes and to move basic blocks from one node to other. This ensures that basic blocks can not be duplicated or deleted which is the safety requirement as discussed in the previous section. All transformations are limited by this constraint.

Each node also provides events which are fired whenever the child collection of the node is changed.

3.5.3 Creating basic blocks

The previous data representation stored the code as a sequence of statements. Some of these statements will be always executed sequentially without interference of branching. In control-flow analysis we are primarily interested in branching and therefore it is desirable to group such sequential parts of code together to basic blocks.

Basic block is a block of code that is always guaranteed to be executed together without any branching. Basic blocks can be easily found by determining which statements start a basic block. The very first statement in a method naturally starts the first basic block. Branching transfers control somewhere else so the statement immediately following a branch is a start of a basic block. Similarly, the target of a branch command is a start of basic block.

Using these three simple rules the whole method body is slit into a few basic blocks.

It is desirable to store control-flow links between basic blocks. These links are used for finding high-level structures. Each basic block has *successors* and *predecessors*. *Successor* is an other basic block that may be executed immediately after this one. There can be up to two *successors* – the following basic block and the basic block being branched to. Both of these exist if the basic block ends with conditional branch. *Predecessor* is just link in the opposite direction of the *successor* link. Note that the number of *predecessors* is not limited – several `goto`s can branch to the same location.

3.5.4 Control-flow links between nodes

The *predecessor* and *successor* links of basic blocks reflect the control flow between basic blocks. However, once basic blocks are 'merged' by moving them into a node, we might be interested in flow properties of the whole node rather then just the individual basic blocks. Consider two sibling nodes that represent two loops. In other to put the nodes in correct order, we need to know which one is *successor* of the other.

Therefore the *predecessor* and *successor* links apply to whole nodes as well. Consider two sibling nodes A and B. Node B is a *successor* of node A if there exists a basic block within node A that branches to a basic block within node B.

The algorithm to calculate *successors* of a node is as flows:

- Get a list of all basic blocks that are children of node A. The node can contain other nested nodes so this part needs to be performed recursively.
- Get a list of all succeeding basic blocks of node A. This is the union of all successors for all basic blocks within the node.
- However, we do not want succeeding basic blocks, we want a succeeding siblings of the node. Therefore, for each succeeding basic block traverse the data structure up until a sibling node is reached.

The algorithm to calculate *predecessors* of a node is similar.

The *predecessor* and *successor* links are used extensively and it would be computationally expensive to recalculate them every time they are needed. Therefore the links and intermediate results of the calculation are cached. The events of the tree structure are used to invalidate relevant caches.

3.5.5 Finding loops

The loops are found by using the T1-T2 transformations which where discussed in the preparation chapter.

There are two node types that directly correspond to the results of these two transformations. Preforming a T1 transformation produces a node of type *Loop* and performing a T2 transformation produces a node of type *AcyclicGraph*.

The algorithm works by considering all the nodes and basic blocks in the tree individually and evaluating the conditions required for the transformations. If transformation can be performed for a given node, it is immediately preformed and the algorithm is restarted on the new transformed graph. The condition for the T1 transformation (*Loop*) is that the node must a be self-loop. The condition for the T2 transformation (*AcyclicGraph*) is that the node must have only one predecessor.

By construction each *AcyclicGraph* node contains exactly two nodes. For example, five sequential statements would be represented as four nested *AcyclicGraph* nodes. This makes the tree more complex and more difficult to analyse. The acyclic property is only required for loop finding and is not needed for anything else later on. Therefore once loops are found, the *AcyclicGraph* nodes are flattened (the children of the node are moved to its parent and the node is removed).

Note that the created loops are trivial – the *Loop* node represents an infinite loop without initializer, condition or iterator. The specifics of the loop are not represented in this tree data structure. However, they are eventually recovered in the abstract syntax tree phase of the decompiler.

3.5.6 Finding conditionals

In order to recover conditional statements three new node types are introduced: *Condition*, *Block* and *IfStatement*. *Condition* represents a piece of code that is guaranteed to branch into one of two locations. *Block* has no special semantics and merely groups several nodes into one. *IfStatement* represents the whole conditional including the condition and two bodies.

The *IfStatement* node is still a genuine node in the tree data structure. However, subtyping is used to restrict its children. The *IfStatement* node must have precisely three children of types *Condition*, *Block* and *Block* representing the condition, 'true' body and 'false' body respectively. This defines the semantics of the *IfStatement* node.

The algorithm starts by encapsulating all two-successors basic blocks with *Condition* node. Two-successor basic blocks are conditional branches and thus they are conditions of `if` statements. Note that the bytecode `br` branches unconditionally and thus is it not a condition of an `if` statement (basic blocks ending with `br` have only one successor).

The iterative part of the algorithm is to look for free-standing *Condition* nodes and encapsulate them with *IfStatement* nodes. This involves finding the 'true' and 'false' bodies for the if statements.

The 'true' and 'false' bodies of an `if` statement are found by considering reachability as discussed in the preparation chapter. Nodes reachable only by following the 'true' branch define the 'true' body of the `if` statement. Similarly for the 'false' body. The rest of the nodes is the set reachable from both and it is not part of the `if` statement – it is the code following the `if` statement. Note that these three set are disjoint.

The reachable nodes nodes are found by iterative algorithm in which successors are added to a collection until the collection does not change anymore. Nodes that are reachable *only* from the 'true' branch are obtained by taking the set reachable from 'true' branch and removing nodes reachable from the 'false' branch.

Consider the special case where there are no nodes reachable from both the 'true' and 'false' branches. In this case, there is no code following the `if` statement. Such code might look like this:

```
if (condition) {
  return null;
} else {
  return result;
}
```

In this special case the 'false' body is moved outside the `if` statement producing more compact code:

```
if (condtion) {
  return null;
}
return result;
```

3.5.7 Short-circuit conditionals

Consider condition like `a & b` (`a` and `b`). This or even more complex expressions compile into a code without any branches. Therefore the expression will be contained within a single basic block and thus the approach described so far would work well.

Conditions like `a && b` are more difficult to handle (`a` and `b`, but evaluate `b` only if `a` is true). These short-circuit conditionals introduce additional branching and thus they are more difficult to decompile.

The expression `a` is always evaluated first. The flow graph is characterized by two things – in which case the expression `b` is evaluated and which path is taken if the expression `b` is not evaluated.

The *Condtition* node was previously defined as a piece of code that is guaranteed to branch into one of two locations. This still holds for the flow graphs above. If two nodes that evaluate `a` and `b` are considered together, they still define a proper condition for an `if` statement. We define a new node type *ShortCircuitCondition* which is a special case of *Condition*. This node has exactly two children (expressions `a` and `b`) and a meta-data field which specifies which one of the four

short-circuit patters it represents. This is for convenience so that the pattern matching does not have to be done again in the future.

The whole program is repeatedly searched and if one of the four patters is found, the two nodes are merged into a *ShortCircuitCondition* node. This new node represents the combined expression (e.g. `a && b`). Since it is a single node is eligible to fit into the pattern again and thus nested short-circuit expressions will be also found (e.g. `(a && b) || (c && d)`).

Note that this is an extension to the previous algorithm rather then a new one. It needs to be preformed just before *Condition* nodes are encapsulated in *IfStatement* nodes.

3.6 Abstract Syntax Tree representation

Abstract syntax tree (AST) is the last representation of the program. It very closely corresponds to the final textual output.

3.6.1 Data structure

External library is used to hold the abstract syntax tree.

Initially the *CodeDom* library that ships with the *.NET Framework* was used, but it was soon abandoned due to lack of support for many crucial C# features.

It was replaced with *NRefactory* which is an open-source library used in SharpDevelop for parsing and representation of C# and VB.NET files. It focuses exclusively on these two languages and thus provides excellent support for them.

NRefactory allows perfect control over the generated code. Parsing arbitrary C# file and then generating it again will almost exactly reproduce the original text. Whitespace would be reformated but anything else is explicitly represented in NRefactory's abstract syntax tree. For example, `(a + b)` and `a + b` have different representations and so do `if (a) return;` and `if (a) { return; }`.

The decompiler aims to generate not only correct code, but also as readable code as possible. Therefore this precise control is desirable.

3.6.2 Generating skeleton

The first task is to generate code skeleton that is equivalent to the one in the executable. The *Cecil* library helps with reading of the executable meta-data and thus it is not necessary to work directly with the binary format of the executable.

The following four object types can be found in .NET executables: classes, structures, interfaces and enumerations. For the purpose of logical organization these can be nested within namespaces and, in some cases, nested within each other. Classes can be inherited and may implement one or more interfaces. Depending on the type, the objects can contain fields, properties, events and methods. Specific set of modifies can be applied to almost everything.

Handling all these cases is tedious, but usually straightforward.

3.6.3 Generating method bodies

Once the skeleton is created, high-level blocks and the bytecode expressions contained within them are translated to abstract syntax tree. For example, the *Loop* node is translated to a *ForStatement* in the AST and the bytecode expression `add` is translated to *BinaryOperatorExpression* in the AST.

In terms of lines of code, this is by far the largest part of the decompiler. The reason for this is that there are many bytecodes and every bytecode needs to have its own specific translation code.

Conceptually[5], the translation code consists of three main functions: *TranslateMethodBody*, *TranslateHighLevelNode* and *TranslateBytecodeExpression*. All of these return complete abstract syntax tree for the given input.

TranslateMethodBody is the simples function which encapsulates the whole algorithm. It takes tree of high-level blocks as input and produces the complete abstract syntax tree of the method. Internally, it calls *TranslateHighLevelNode* for each top-level node and then merely concatenates the results.

TranslateHighLevelNode translates one particular high-level node into abstract syntax tree. There are several types of high-level nodes and each of them needs to considered individually. If the high-level node has child nodes then this function is called recursively. Some comments about particular node types: The *BasicBlock* node needs to be preceded by explicit label and succeeded by explicit `goto` in

[5] In reality there are more functions that are loosely coupled.

order to ensure safety. The *Loop* node is easy to handle since it is just an infinite loop. The *IfStatement* node is most difficult to handle since it needs to handle creation of the condition for the `if` statement. Remember, that the condition can include short-circuit booleans and that these can be arbitrarily nested.

TranslateBytecodeExpression is the lowest level function. It translates the individual bytecode expressions. Note that bytecode expression may have other bytecode expressions as arguments and therefore this function is often called recursively. Getting abstract syntax tree for all arguments is in fact the first thing that is done. After that these arguments are combined in a way that is appropriate for the given bytecode and operand. This logic is completely different for each bytecode. Simple example is the `add` bytecode – in this case the arguments end up being children of *BinaryOperatorExpression* (which is an AST node). At this point we have the abstract syntax tree representing the bytecode expression. The expression is further encapsulated by parenthesis for safety and the type of the expression is recoded in the AST meta-data.

Unsupported bytecodes are handled gracefully and are represented as function calls. For example if the `add` bytecode would not be implemented, it would be outputed as `IL__add(1, 2)` rather then `1 + 2`.

Recoding the type of AST is useful so that it can be converted depending on a context. If AST of type `IntegerOne` is used in context where `bool` is expected, the AST can be simply replaced by `true`.

Here is a list of bytecodes whose translation into abstract syntax tree has been implemented (star is used to represent several bytecodes with similar names):

Arithmetic: `add* div* mul* rem* sub* and xor shl shr* neg not`
Arrays: `newarr ldlen ldelem.* stelem.*`
Branching: `br brfalse brtrue beq bge* bgt* ble* blt* bne.un`
Comparison: `ceq cgt* clt*`
Conversions: `conv.*.*`
Object-oriented: `newobj castclass call callvirt`
Constants: `ldnull ldc.* ldstr ldtoken`
Data access: `ldarg ldfld stfld ldsfld stsfld ldloc stloc`
Miscellaneous: `nop dup ret`

The complexity of implementing a translation for a bytecode varies between a single line (`nop`) to over a page of code (`callvirt`).

3.6.4 Optimizations

The produced abstract syntax tree represents a fully functional program. That is, it can be pretty printed and the generated source code would compile and work without problems. However, the produced source code is still quite verbose and therefore several optimizations are done to simplify it or make it 'nicer'.

The optimizations are implemented by using the visitor pattern provided by the NRefactory library. For each optimization a new class is created which inherits from the *AstVisitor* class. Instance of this class is created and it is applied to the root of the abstract syntax tree. As a result of this, NRefactory will traverse the whole abstract syntax tree and notify the visitor (the optimization) about every element it encounters. For example, whenever a `goto` statement is encountered, the method `VisitGotoStatement` will be invoked on the visitor. If the optimization wants to act upon this, it has to override the `VisitGotoStatement` method. The abstract syntax tree can be modified during the traversal. For example, when the `goto` statement is encountered, the visitor (the optimization) can modify it, replace it or simply remove it.

3.6.4.1 Removal of dead labels

This is not the first optimization to be executed, but it is the simplest one and therefore it is explained first.

The purpose of this optimization is to remove dead labels. That is, to remove all labels that are not referenced by one or more `goto` statements.

The optimization uses two visitors. The first visitor overrides the `VisitGotoStatement` method and is thus notified about all `goto` statements in the method. The body of the overridden `VisitGotoStatement` method records the name of the label being targeted and puts in into an 'alive' list.

The second visitor overrides the `VisitLabelStatement` method and is thus notified about all labels. If the label is not in the 'alive' list, it is removed.

Note that all optimizations are done on per-method basis and therefore we do not have to worry about name clashes of labels from different methods.

3.6.4.2 Removal of negations

In some cases negations can be removed by using the rules of logic. Negations are represented as *UnaryOperatorExpression* in the abstract syntax tree.

When a negation is encountered, it is matched against the following patterns and simplified if possible.

```
!((x)) = !(x)
!!(x) = (x)
!(a > b) = (a <= b)
!(a >= b) = (a < b)
!(a < b) = (a >= b)
!(a <= b) = (a > b)
!(a == b) = (a != b)
!(a != b) = (a == b)
!(a & b) = (!(a) | !(b))
!(a && b) = (!(a) || !(b))
!(a | b) = (!(a) & !(b))
!(a || b) = (!(a) && !(b))
```

3.6.4.3 Removal of parenthesis

To ensures safety, the abstract syntax tree will contain extensive amount of parenthesis. Even simple increment would be expressed as `((i) = ((i) + (1)))`.

This optimization removes parenthesis where it is known to be safe.

Parenthesis can be removed from primitive values (`(1)`), identifiers (`(i)`) and already parenthesized expressions (`(((...)))`).

Several parenthesis can also be removed due to the unambiguous context they are in. This includes cases like `return (...);`, `array[(...)]`, `if((...))`, `(...);` and several others.

The rest of the cases is governed by the C# precedence and associativity rules. There are 15 precedence groups in C# and expressions within the same group are left-associative[6].

[6]Only assignment and conditional operator (?:) are right associative, but these are never generated in nested form by the decompiler.

The optimization implements a function `GetPrecedence` that returns the precedence for the given expression as an integer.

Majority of expressions are binary expressions. When a binary expression is encountered, precedence is calculated for it and both of its operands. For example consider `(a + b) - (c * d)`. The precedence of the main binary expression is 12 and the precedences of the operands are 12 and 13 respectively. Since the right operand has higher precedence then the binary expression itself, its parenthesis can be removed. The left operand has the same precedence. However, in this special case (left operand, same precedence), parenthesis can be removed as well due to left-associativity of C#.

Similar, but simpler, logic applies to unary expressions.

3.6.4.4 Removal of 'goto' statements

This is the most complex optimization performed on the abstract syntax tree. Its purpose is the remove or replace `goto` statements.

In the following case it is obvious that the `goto` can be removed:

```
// Code
goto Label;
Label:
// Code
```

However, in general, more complex scenarios can occur. It is not immediately obvious that the `goto` statement can be removed in the following code:

```
if (condition1) {
  if (condition2) {
    // Code
    goto Label;
  } else {
    // Code
  }
}
for(;;) {
  for(;;) {
    Label:
```

```
    // Code
  }
}
```

This optimization is based on simulation of execution under various conditions. There are three important questions that the simulation answers:
What would happen if the `goto` was replaced by no-op (i.e. removed)?
What would happen if the `goto` was replaced by `break`?
What would happen if the `goto` was replaced by `continue`?

In the first case, the `goto` is replaced by no-op and the simulator is started at that location. The simulation will traverse the AST tree structure until it finds the next executable line of code or an label. If the reached location is the same as the one that would be reached by following the original `goto` then the original `goto` can be removed.

Similar simulation runs are performed by replacing the `goto` by `break` and `continue`.

After this optimization is done, it is desirable to remove the dead labels.

3.6.4.5 Simplifying loops

The `for` loop statement has the following form in C#:

```
for(initializer; condition; iterator) { body };
```

The semantics of the `for` loop statement is:

```
initializer;
for(;;) {
  if (!condition) break;
  body;
  iterator;
}
```

So far the decompiler generated only infinite loops in form `for(;;)`. Now it is time to make the loops more interesting. This optimization does pattern matching on the code and tries to identify the initializer, condition or iterator.

If the loop is preceded by something like `int i = 0;` then it is most likely the initializer of the loop and it will be pushed into the `for` statement producing `for(int i = 0;;)`. If it is not really the initializer, it does not matter – semantics is same.

If the first line of the body is `if (not_condition) break;`, it is assumed to be the condition for the loop and it is pushed in to produce `for(;!not_condition;)`.

If the last line of the body is `i = ...` or `i++`, it is assumed to be the iterator.

Consider the following code:

```
int i = 0;
for(;;) {
  if (i >= 10) break;
  // body
  i++;
}
```

Performing this optimization will simplify the code to:

```
for(int i = 0; !(i >= 10); i++) {
  // body
}
```

This is then further simplified by the 'removal of negation' optimization to:

```
for(int i = 0; i < 10; i++) {
  // body
}
```

3.6.4.6 Further optimizations

Several further optimizations are done which are briefly discussed here.

Integer local variables are renamed from the more generic names like `V_0` to `i`, `j`, `k`, and so on. Boolean local variables are renamed to `flag1`, `flag2` and so on.

C# aliases for types are used. For example, `System.Int32` is replaced with `int`. C# `using` (`import` in java) is used to simplify `System.Console` to just `Console`. Types in scope of same namespace also do not have to be fully qualified.

Explicit `this.field` is simplified to just `field`.

The increments in form `i = i + 1` are simplified to `i++`. The increments in form `i = i + 2` are simplified to `i += 2`. Analogous forms hold for decrements.

String concatenation `String.Concat("Hello", "world")` can be expressed in C# just as `"Hello" + "world"`.

Sometimes 'false' body of an `if` statement can end up being empty and can be harmlessly removed.

Some control-flow commands are sometimes redundant since the implicit behavior is equivalent. For example, `return;` at the end of method is redundant and `continue;` at the end of loop is redundant.

3.6.5 Pretty Printing

Pretty printing[7] is provided as part of the NRefactory library and therefore does not need to be implemented as part of the decompiler. The NRefactory provides provides several options that control the format of the produced source code (for example whether an opening curly brace is placed on the same line as `if` statement or on the following line).

NRefactory is capable to output the code both in C# and in VB.NET.

[7] Pretty printing is the act of converting abstract syntax tree into a textual form.

Chapter 4

Evaluation

4.1 Success Criteria

The principal criterion was that the quick-sort algorithm must successfully decompile. This goal was achieved. The decompiled source code is, in fact, almost identical to the original. This is demonstrated at the end of the following section.

4.2 Evolution of quick-sort

This section demonstrates how the quick-sort algorithm is decompiled.

Four different representations are used during the decompilation process. The output of each of these representations is shown.

Unless otherwise specified the shown pieces of code are verbatim outputs of the decompiler.

4.2.1 Original source code

To save space we will initially consider only the `Main` method of the quick-sort algorithm. It parses textual arguments, performs the quick-sort and then prints the result.

```
public static void Main(string[] args)
{
  int[] intArray = new int[args.Length];
  for (int i = 0; i < intArray.Length; i++) {
    intArray[i] = int.Parse(args[i]);
  }
  QuickSort(intArray, 0, intArray.Length - 1);
  for (int i = 0; i < intArray.Length; i++) {
    System.Console.Write(intArray[i].ToString() + " ");
  }
}
```

This code is compiled with all optimizations turn on and its binary form is considered is the following sections.

4.2.2 Stack-based bytecode representation

See section *3.3 Stack-based bytecode representation* on page 25 for reference.

This is a snippet of the bytecode as loaded from the executable. This part represents the line `intArray[i] = int.Parse(args[i]);`. `V_0` is `intArray` and `V_1` is `i`.

Comments denote the stack behaviour of the bytecodes.

The (manually) stared bytecodes represent just the part `int.Parse(args[i]);`.

```
IL_0F: ldloc V_0          # Pop0->Push1
IL_10: ldloc V_1          # Pop0->Push1
IL_11: ldarg args      *  # Pop0->Push1
IL_12: ldloc V_1       *  # Pop0->Push1
IL_13: ldelem.ref      *  # Popref_popi->Pushref
IL_14: call Parse()    *  # Varpop->Varpush Flow=Call
IL_19: stelem.i4          # Popref_popi_popi->Push0
```

The used bytecodes are `ldloc` (load local variable), `ldarg` (load argument), `ldelem` (get array element), `call` (call method) and `stelem` (set array element).

Here is the same snippet again after the stack analysis has been performed.

```
// Stack: {}
IL_0F: ldloc V_0              # Pop0->Push1
// Stack: {IL_0F}
IL_10: ldloc V_1              # Pop0->Push1
// Stack: {IL_0F, IL_10}
IL_11: ldarg args             # Pop0->Push1
// Stack: {IL_0F, IL_10, IL_11}
IL_12: ldloc V_1              # Pop0->Push1
// Stack: {IL_0F, IL_10, IL_11, IL_12}
IL_13: ldelem.ref             # Popref_popi->Pushref
// Stack: {IL_0F, IL_10, IL_13}
IL_14: call Parse()           # Varpop->Varpush Flow=Call
// Stack: {IL_0F, IL_10, IL_14}
IL_19: stelem.i4              # Popref_popi_popi->Push0
// Stack: {}
```

For example, we can see that bytecode `IL_13: ldelem.ref` pops the last two elements from the stack – `{IL_11, IL_12}`. These will hold the values `args` and `V_1` respectively.

The bytecode `IL_19: stelem.i4` pops three values.

4.2.3 Variable-based bytecode representation

See section *3.4 Variable-based bytecode representation* on page 26 for reference.

This is the same snippet after the stack-based data-flow is replaced with variable-based one: (code manually simplified for clarity)

```
expr0D = ldloc(V_0);
expr0E = ldloc(i);
expr0F = ldarg(args);
expr10 = ldloc(i);
expr11 = ldelem.ref(expr0F, expr10);
expr12 = call(Parse(), expr11);
stelem.i4(expr0D, expr0E, expr12);
```

Here is the actual unedited output:

```
stloc(expr0D, ldloc(V_0));
stloc(expr0E, ldloc(i));
stloc(expr0F, ldarg(args));
stloc(expr10, ldloc(i));
stloc(expr11, ldelem.ref(ldloc(expr0F), ldloc(expr10)));
stloc(expr12, call(Parse(), ldloc(expr11)));
stelem.i4(ldloc(expr0D), ldloc(expr0E), ldloc(expr12));
```

4.2.3.1 In-lining of expressions

See section *3.4.2 In-lining of expressions* on page 28 for reference.

Here is the same snippet after two in-lining optimizations. (this is actual output – the GUI of the decompiler allows performing of optimizations step-by-step)

```
stloc(expr0D, ldloc(V_0));
stloc(expr0E, ldloc(i));
stloc(expr11, ldelem.ref(ldarg(args), ldloc(i)));
stloc(expr12, call(Parse(), ldloc(expr11)));
stelem.i4(ldloc(expr0D), ldloc(expr0E), ldloc(expr12));
```

All posible in-lines are performed:

```
stelem.i4(ldloc(V_0), ldloc(i),
          call(Parse(), ldelem.ref(ldarg(args), ldloc(i))));
```

4.2.4 Abstract Syntax Tree representation (part 1)

See section *3.6 Abstract Syntax Tree representation* on page 37 for reference.

Let us omit the optimization of high-level structures for this moment and skip directly to the Abstract Syntax Tree.

After transforming a snippet of code to variable-based bytecode and then performing the in-lining optimization we have obtained

```
stelem.i4(ldloc(V_0), ldloc(i),
          call(Parse(), ldelem.ref(ldarg(args), ldloc(i))));
```

Let us see the same result for larger part of the method:

```
BasicBlock_1: stloc(V_0, newarr(System.Int32,
                                conv.i4(ldlen(ldarg(args)))));
BasicBlock_2: stloc(i, ldc.i4(0));
BasicBlock_3: goto BasicBlock_6;
BasicBlock_4: stelem.i4(ldloc(V_0), ldloc(i), call(Parse(),
                        ldelem.ref(ldarg(args), ldloc(i))));
BasicBlock_5: stloc(i, @add(ldloc(i), ldc.i4(1)));
BasicBlock_6: if (ldloc(i) < conv.i4(ldlen(ldloc(V_0))))
                  goto BasicBlock_4;
BasicBlock_7: call(QuickSort(), ldloc(V_0), ldc.i4(0),
                   sub(conv.i4(ldlen(ldloc(V_0))), ldc.i4(1)));
```

This code includes the first `for` loop of the `Main` method. Note that `br` and `blt` were already translated to `goto` and `if (...) goto`.

4.2.4.1 Translation of bytecodes to C# expressions

See section *3.6.3 Generating method bodies* on page 38 for reference.

Let us translate just the bytecodes `ldloc`, `ldarg` and `ldc.i4`.

```
BasicBlock_1: stloc(V_0, newarr(System.Int32,
                                conv.i4(ldlen((args)))));
BasicBlock_2: stloc(i, (0));
BasicBlock_3: goto BasicBlock_6;
BasicBlock_4: stelem.i4((V_0), (i), call(Parse(),
                        ldelem.ref((args), (i))));
BasicBlock_5: stloc(i, @add((i), (1)));
BasicBlock_6: if ((i) < conv.i4(ldlen((V_0)))) goto BasicBlock_4;
BasicBlock_7: call(QuickSort(), (V_0), (0),
                   sub(conv.i4(ldlen((V_0))), (1)));
```

This is a small improvement. Note the safety parenthesis that were inserted during the translation (e.g. `(0)`, `(args)`).

After all translations are performed the code will look like this:

```
BasicBlock_1: System.Int32[] V_0 =
                (new int[((int)((args).Length))]);
BasicBlock_2: int i = (0);
BasicBlock_3: goto BasicBlock_6;
BasicBlock_4: ((V_0)[(i)] = (System.Int32.Parse(((args)[(i)]))));
BasicBlock_5: (i = ((i) + (1)));
BasicBlock_6: if ((i) < ((int)((V_0).Length))) goto BasicBlock_4;
BasicBlock_7: (QuickSortProgram.QuickSort((V_0), (0),
                (((int)((V_0).Length)) - (1))));
```

4.2.4.2 Removal of parenthesis

See section *3.6.4.3 Removal of parenthesis* on page 41 for reference.

C# rules of precedence are used to remove unnecessary parenthesis:

```
BasicBlock_1: System.Int32[] V_0 = new int[(int)args.Length];
BasicBlock_2: int i = 0;
BasicBlock_3: goto BasicBlock_6;
BasicBlock_4: V_0[i] = System.Int32.Parse(args[i]);
BasicBlock_5: i = i + 1;
BasicBlock_6: if (i < (int)V_0.Length) goto BasicBlock_4;
BasicBlock_7: QuickSortProgram.QuickSort(V_0, 0, (int)V_0.Length - 1);
```

4.2.4.3 Removal of dead labels

See section *3.6.4.1 Removal of dead labels* on page 40 for reference.

Unreferenced labels are removed.

```
System.Int32[] V_0 = new int[(int)args.Length];
int i = 0;
goto BasicBlock_6;
BasicBlock_4: V_0[i] = System.Int32.Parse(args[i]);
i = i + 1;
BasicBlock_6: if (i < (int)V_0.Length) goto BasicBlock_4;
QuickSortProgram.QuickSort(V_0, 0, (int)V_0.Length - 1);
```

4.2.4.4 Further optimizations

See section *3.6.4.6 Further optimizations* on page 45 for reference.

The remainder of applicable AST optimizations is performed.

```
int[] V_0 = new int[args.Length];
int i = 0;
goto BasicBlock_6;
BasicBlock_4: V_0[i] = Int32.Parse(args[i]);
i++;
BasicBlock_6: if (i < V_0.Length) goto BasicBlock_4;
QuickSortProgram.QuickSort(V_0, 0, V_0.Length - 1);
```

4.2.5 High-level blocks representation

See section *3.5 High-level blocks representation* on page 30 for reference.

4.2.5.1 Initial state

This representation is based on tree structure. However, initially the tree is flat with all basic blocks being siblings.

These are the first four basic blocks in the `Main` method. The relations between the nodes are noted in the brackets (e.g. basic block 1 has one successor which is basic block number 2). See figure 4.1 for graphical representation of these four basic blocks.

```
// BasicBlock 1 (Successors:2 Parent:0)
BasicBlock_1:
int[] V_0 = new int[args.Length];
int i = 0;
goto BasicBlock_2;

// BasicBlock 2 (Predecessors:1 Successors:4 Parent:0)
BasicBlock_2:
goto BasicBlock_4;
```

```
// BasicBlock 3 (Predecessors:4 Successors:4 Parent:0)
BasicBlock_3:
V_0[i] = Int32.Parse(args[i]);
i++;
goto BasicBlock_4;

// BasicBlock 4 (Predecessors:3,2 Successors:5,3 Parent:0)
BasicBlock_4:
if (i < V_0.Length) goto BasicBlock_3;
goto BasicBlock_5;
```

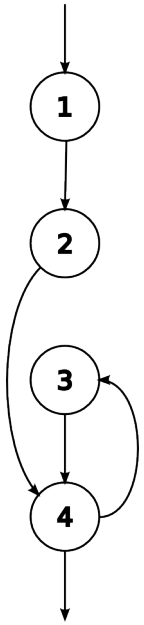


Figure 4.1: Loop in the 'Main' method of quick-sort

4.2.5.2 Finding loops and conditionals

See section *3.5.5 Finding loops* on page 34 for reference.

Loops are found by repeatedly applying the T1-T2 transformations. In this case the first transformation to be performed will be a T2 transformation on basic blocks 1 and 2. This will result in this 'tree':

```
// AcyclicGraph 10 (Successors:4 Parent:0)
AcyclicGraph_10:
{
    // BasicBlock 1 (Successors:2 Parent:10)
    BasicBlock_1:
    int[] V_0 = new int[args.Length];
    int i = 0;
    goto BasicBlock_2;

    // BasicBlock 2 (Predecessors:1 Parent:10)
    BasicBlock_2:
    goto BasicBlock_4;

}

// BasicBlock 3 (Predecessors:4 Successors:4 Parent:0)
BasicBlock_3:
V_0[i] = Int32.Parse(args[i]);
i++;
goto BasicBlock_4;

// BasicBlock 4 (Predecessors:3,10 Successors:5,3 Parent:0)
BasicBlock_4:
if (i < V_0.Length) goto BasicBlock_3;
goto BasicBlock_5;
```

Note how the links changed. Basic blocks 1 and 2 are now considered as a single node 10 – the predecessor of basic block 4 is now 10 rather then 2. Links within the node 10 are limited just to the scope of that node.

Several further transformations are performed until all loops are found.

Conditional statements are identified as well. This code has one conditional statement which does not have any code in the bodies other then the `goto`s.

```
// BasicBlock 1 (Successors:2 Parent:0)
BasicBlock_1:
int[] V_0 = new int[args.Length];
int i = 0;
goto BasicBlock_2;

// BasicBlock 2 (Predecessors:1 Successors:11 Parent:0)
BasicBlock_2:
goto BasicBlock_4;

// Loop 11 (Predecessors:2 Successors:5 Parent:0)
Loop_11:
for (;;) {
    // ConditionalNode 22 (Predecessors:3 Successors:3 Parent:11)
    ConditionalNode_22:
    BasicBlock_4:
    if (i >= V_0.Length) {
        goto BasicBlock_5;
        // Block 21 (Parent:22)
        Block_21:

    } else {
        goto BasicBlock_3;
        // Block 20 (Parent:22)
        Block_20:

    }

    // BasicBlock 3 (Predecessors:22 Successors:22 Parent:11)
    BasicBlock_3:
    V_0[i] = Int32.Parse(args[i]);
    i++;
    goto BasicBlock_4;

}
```

4.2.5.3 Final version

Let us see the code once again without the comments and empty lines.

```
BasicBlock_1:
int[] V_0 = new int[args.Length];
int i = 0;
goto BasicBlock_2;
BasicBlock_2:
goto BasicBlock_4;
Loop_11:
for (;;) {
    ConditionalNode_22:
    BasicBlock_4:
    if (i >= V_0.Length) {
        goto BasicBlock_5;
        Block_21:
    } else {
        goto BasicBlock_3;
        Block_20:
    }
    BasicBlock_3:
    V_0[i] = Int32.Parse(args[i]);
    i++;
    goto BasicBlock_4;
}
```

4.2.6 Abstract Syntax Tree representation (part 2)

4.2.6.1 Removal of 'goto' statements

See section *3.6.4.4 Removal of 'goto' statements* on page 42 for reference.

All of the `goto` statements in the code above can be removed or replaced. After the removal of `goto` statements we get the following much simpler code:

```
int[] V_0 = new int[args.Length];
int i = 0;
for (;;) {
    if (i >= V_0.Length) {
        break;
    }
    V_0[i] = Int32.Parse(args[i]);
    i++;
}
```

Note that the 'false' body of the `if` statement was removed because it was empty.

4.2.6.2 Simplifying loops

See section *3.6.4.5 Simplifying loops* on page 43 for reference.

The code can be further simplified by pushing the loop initializer, condition and iterator inside the `for(;;)`:

```
int[] V_0 = new int[args.Length];
for (int i = 0; i < V_0.Length; i++) {
    V_0[i] = Int32.Parse(args[i]);
}
```

This concludes the decompilation of quick-sort.

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4.2.7 Original quick-sort (complete source code)

```
1  using System;
2  static class QuickSortProgram
3  {
4      public static void Main(string[] args)
5      {
6          int[] intArray = new int[args.Length];
7          for (int i = 0; i < intArray.Length; i++) {
8              intArray[i] = int.Parse(args[i]);
9          }
10         QuickSort(intArray, 0, intArray.Length - 1);
11         for (int i = 0; i < intArray.Length; i++) {
12             Console.Write(intArray[i].ToString() + " ");
13         }
14     }
15     public static void QuickSort(int[] array, int left, int right)
16     {
17         if (right > left) {
18             int pivotIndex = (left + right) / 2;
19             int pivotNew = Partition(array, left, right, pivotIndex);
20             QuickSort(array, left, pivotNew - 1);
21             QuickSort(array, pivotNew + 1, right);
22         }
23     }
24     static int Partition(int[] array, int left, int right, int pivotIndex)
25     {
26         int pivotValue = array[pivotIndex];
27         Swap(array, pivotIndex, right);
28         int storeIndex = left;
29         for(int i = left; i < right; i++) {
30             if (array[i] <= pivotValue) {
31                 Swap(array, storeIndex, i);
32                 storeIndex = storeIndex + 1;
33             }
34         }
35         Swap(array, right, storeIndex);
36         return storeIndex;
37     }
38     static void Swap(int[] array, int index1, int index2)
39     {
40         int tmp = array[index1];
41         array[index1] = array[index2];
42         array[index2] = tmp;
43     }
44 }
```

4.2.8 Decompiled quick-sort (complete source code)

```
1  using System;
2  abstract class QuickSortProgram
3  {
4      public static void Main(string[] args)
5      {
6          int[] V_0 = new int[args.Length];
7          for (int i = 0; i < V_0.Length; i++) {
8              V_0[i] = Int32.Parse(args[i]);
9          }
10         QuickSortProgram.QuickSort(V_0, 0, V_0.Length - 1);
11         for (int j = 0; j < V_0.Length; j++) {
12             Console.Write(V_0[j].ToString() + " ");
13         }
14     }
15     public static void QuickSort(int[] array, int left, int right)
16     {
17         if (right > left) {
18             int i = (left + right) / 2;
19             int j = QuickSortProgram.Partition(array, left, right, i);
20             QuickSortProgram.QuickSort(array, left, j - 1);
21             QuickSortProgram.QuickSort(array, j + 1, right);
22         }
23     }
24     private static int Partition(int[] array, int left, int right, int pivotIndex)
25     {
26         int i = array[pivotIndex];
27         QuickSortProgram.Swap(array, pivotIndex, right);
28         int j = left;
29         for (int k = left; k < right; k++) {
30             if (array[k] <= i) {
31                 QuickSortProgram.Swap(array, j, k);
32                 j++;
33             }
34         }
35         QuickSortProgram.Swap(array, right, j);
36         return j;
37     }
38     private static void Swap(int[] array, int index1, int index2)
39     {
40         int i = array[index1];
41         array[index1] = array[index2];
42         array[index2] = i;
43     }
44 }
```

4.3 Advanced and unsupported features

This section demonstrates decompilation of more advanced application. The examples that follow were produced by decompiling a reversi game[1].

The examples demonstrate advanced features of the decompiler and in some cases its limitations (i.e. still unimplemented features).

4.3.1 Properties and fields

Properties and fields are well-supported.

Original:

```
private int[,] squares;
private bool[,] safeDiscs;

public int BlackCount {
  get { return blackCount; }
}
public int WhiteCount {
  get { return whiteCount; }
}
```

Decompiled:

```
private System.Int32[,] squares;
private System.Boolean[,] safeDiscs;

public int BlackCount {
    get { return blackCount; }
}
public int WhiteCount {
    get { return whiteCount; }
}
```

The decompiled code is correct.

The type `System.Int32[,]` was not simplified to `int[,]`.

[1] Taken from the CodeProject. Written by Mike Hall.

4.3.2 Short-circuit boolean expressions

Original:

```
if (r < 0 || r > 7 || c < 0 || c > 7 ||
    (r - dr == row && c - dc == col) ||
    this.squares[r, c] != color)
  return false;
```

Decompiled:

```
if (i < 0 || i > 7 || j < 0 || j > 7 ||
    i - dr == row && j - dc == col ||
    squares[i, j] != color) {
      return false;
}
```

The decompiled code is correct. Variable names were lost during compilation. By precedence rules it was possible to remove the parenthesis.

4.3.3 Short-circuit boolean expressions 2

Original:

```
if ((hasSpaceSide1  && hasSpaceSide2 ) ||
    (hasSpaceSide1  && hasUnsafeSide2) ||
    (hasUnsafeSide1 && hasSpaceSide2 ))
  return true;
```

Decompiled:

```
if (flag && flag2 || flag && flag4 || flag3 && flag2) {
  return true;
}
```

The decompiled code is correct. Variable names were lost during compilation.

4.3.4 Complex control nesting

Original:

```
bool statusChanged = true;
while (statusChanged)
{
  statusChanged = false;
  for (i = 0; i < 8; i++)
    for (j = 0; j < 8; j++)
      if (this.squares[i, j] != Board.Empty &&
         !this.safeDiscs[i, j] &&
         !this.IsOutflankable(i, j)) {
            this.safeDiscs[i, j] = true;
            statusChanged = true;
      }
}
```

Decompiled:

```
for (bool flag = true; flag;) {
  flag = false;
  for (int i = 0; i < 8; i++) {
    for (int j = 0; j < 8; j++) {
      if (squares[i, j] != Empty &&
         !safeDiscs[i, j] &&
         !IsOutflankable(i, j)) {
            safeDiscs[i, j] = true;
            flag = true;
       }
    }
  }
}
```

The decompiled code is correct.

A `for` loop was used instead of `while` loop. The decompiler always uses `for` loop.

In the example, four control structures are nested; even more levels do not cause any problems.

4.3.5 Multidimensional arrays

Multidimensional arrays are supported.

Original:

```
this.squares = new int[8, 8];
this.safeDiscs = new bool[8, 8];
// Clear the board and map.
int i, j;
for (i = 0; i < 8; i++)
  for (j = 0; j < 8; j++) {
    this.squares[i, j] = Board.Empty;
    this.safeDiscs[i, j] = false;
  }
```

Decompiled:

```
squares = new int[8, 8];
safeDiscs = new bool[8, 8];
for (int i = 0; i < 8; i++) {
  for (int j = 0; j < 8; j++) {
    squares[i, j] = Empty;
    safeDiscs[i, j] = false;
  }
}
```

The decompiled code is correct and even slightly simplified.

4.3.6 Dispose method

This is the standard .NET dispose method for a form.

Original:

```
if(disposing) {
  if (components != null) {
    components.Dispose();
  }
}
```

Decompiled:

```
if (disposing && components) {
  components.Dispose();
}
```

The decompiler did a good job identify that the two `if`s can be expressed as short-circuit expression.

On the hand, it failed to distinguish being 'true' and being 'non-null' – on the bytecode level these are the same thing (together with being 'non-zero').

4.3.7 Event handlers

Event handlers are not supported.

Original:

```
this.aboutMenuItem.Click +=
  new System.EventHandler(this.aboutMenuItem_Click);
```

Decompiled:

```
aboutMenuItem.add_Click(
  new System.EventHandler(this, IL__ldftn(aboutMenuItem_Click()))
);
```

Note how the unsupported bytecode `ldftn` is presented.

4.3.8 Constructors

Original:

```
this.infoPanel.Location = new System.Drawing.Point(296, 32);
```

Decompiled:

```
infoPanel.Location = new System.Drawing.Point(296, 32);
```

The decompiled code is correct including the constructor arguments.

4.3.9 Property access

Original:

```
this.infoPanel.Name = "infoPanel";
```

Decompiled:

```
infoPanel.Name = "infoPanel";
```

The decompiled code is correct.

Note that properties are actually set methods. This is, `set_Name(string)` here.

4.3.10 Object casting

Original:

```
this.Icon = ((System.Drawing.Icon)(resources.GetObject("$this.Icon")));
```

Decompiled:

```
Icon = (System.Drawing.Icon)V_0.GetObject("$this.Icon");
```

The decompiled code is correct.

4.3.11 Boolean values

In the .NET Runtime there is no difference between integers and booleans. Handling of this is delicate.

Original:

```
return false;
```

Decompiled:

```
return false;
```

The decompiled code is correct.

Original:

```
this.infoPanel.ResumeLayout(false);
```

Decompiled:

```
infoPanel.ResumeLayout(0);
```

This code is incorrect – the case where boolean is passed as argument still has no been considered in the decompiler. This is just case-by-case laborious work.

4.3.12 The 'dup' instruction

The `dup` instruction is handled well.

Decompiled: ('dup' unsupported)

```
expr175 = this;
expr175.whiteCount = expr175.whiteCount + 1;
```

Decompiled: ('dup' supported)

```
whiteCount++;
```

Chapter 5

Conclusion

The project was a success. The goal of the project was to decompile an implementation of a quick-sort algorithm and this goal was achieved well. The C# source code produced by the decompiler is virtually identical to the original source code[1]. In particular, the source code compiles back to identical .NET CLR code.

More complex programs than the quick-sort implementation were considered and the decompiler was improved to handle them better. The improvements include:

- Better support for several bytecodes related to: creation and casting of objects, multidimensional arrays, virtual method invocation, property access and field access.
- Support for the `dup` bytecode which does not occur very frequently in programs. In particular, it does not occur in the quick-sort implementation.
- Arbitrarily complicated short-circuit boolean expression are handled. Furthermore, both the short-circuit and the traditional boolean expressions are simplified using rules of logic (e.g. using De Morgan's laws).
- Nested high-level control structures are handled well (e.g. nested loops).
- The performance is improved by using basic blocks.
- The removal of `goto`s was improved to work in almost any scenario (by using the 'simulator' approach).

[1] See pages 60 and 61 in the evaluation chapter.

5.1 Hindsight

I am very satisfied with the current implementation. Whenever I have seen an opportunity for improvement, I have have refactored the code right away. As a result of this, I think that the algorithms and data structures currently used are very well suited for the purpose.

If I were to reimplement the project, I would merely save time by making the right design decisions right away.

Here are some issues that I have encountered are resolved:

- During the preparation phase, I have spend reasonable amount of time researching algorithms for finding of loops. I found most of the algorithms either unintuitive or not not sufficiently robust for all scenarios. Therefore, I have derived my own algorithm based on the T1-T2 transformations.
- I have initially used the *CodeDom* library for the abstract syntax tree. In the end, *NRefactory* proved much more suitable.
- I have eventually made the stack-based and variable-based code representations quite distinct and decoupled. This allowed greater freedom for transformations.
- Initially the links between nodes were manually kept in synchronization during transformations. It is more convenient and robust just to throw the links away and recalculate them.
- The removal of `goto`s was gradually pushed all the way to the last stage of decompilation where it is most powerful and safest.

5.2 Future work

The theoretical problems have been resolved. However, a lot of laborious work still needs to be done before the decompiler will be able to handle all .NET executables.

The decompiler could be extended to recover C# compile-time features like anonymous methods, enumerators or LINQ expressions.

The decompiler greatly overlaps with a verification of .NET executables (the code needs to be valid in order to be decompiled). The project could be forked to create .NET verifier.

I am the primary developer of the SharpDevelop debugger. I would like integrate the decompiler with the debugger so that is it possible to debug applications with no source code.

Chapter 6

Project Proposal

Part II of the Computer Science Project Proposal

.NET Decompiler

October 14, 2007

Project Originator: *David Srbecký*

Resources Required: See attached Project Resource Form

Project Supervisor: *Alan Mycroft*

Director of Studies: *Jean Bacon* and *David Ingram*

Overseers: *Anuj Dawar* and *Andrew Moore*

Introduction and Description of the Work

The *.NET Framework* is a general-purpose software development platform which is very similar to *Java*. It includes extensive class library and, similarly to Java, is based on the virtual machine model. The executable code for a *.NET* program is stored in a file called *assembly* which consists of class metadata and a stack-based bytecode called Common Intermediate Language (*CIL* or *IL*).

In general, any programming language can be compiled to *.NET* and there are dozens of compilers that compile into *CIL*. The most common language used for *.NET* development is *C#*.

The goal of this project is to decompile *.NET* assemblies back into equivalent *C#* source code. Compared to decompilation of conventional assembly code, this task is hugely simplified by the presence of metadata in the *.NET* assemblies. The metadata contains complete information about classes, methods and fields. The method bodies consist of stack-based *IL* code which needs to be decompiled into higher-level *C#* statements. Data-flow analysis will need to be employed to transform the stack-based data model into one that uses temporary local variables and composition of expressions. Control-flow analysis will be used to recreate high level control structures like `for` loops and conditional branching.

Resources Required

- **My own machine**
  (1.6 GHz CPU, 1.5 GB of RAM, 50 GB & 75 GB Disks, Windows XP SP2 OS)
  Used for development
- **Student-Run Computing Facility (SRCF)**
  Used for running the *SVN* server
- **Public Workstation Facility (PWF)**
  Used for storage of back-ups

Starting Point

I plan to implement the project in *C#*. I have been using this language for over five years now and so I do not have to spend any time learning a new language. It also means that I will not be having any problems neither with the syntax of the language nor with any peculiar error messages produced by the compiler or by the runtime.

I have written an integrated *.NET* debugger for the *SharpDevelop* IDE. During that I have obtained some basic knowledge about metadata and lower-level functionality in *.NET*. I can read *.NET* bytecode and, with the help of reference manual, I can write short programs in it.

The metadata and bytecode needs to be read form the assembly files. I plan to use the *Cecil* library for it. I am not familiar with this library, but I do not expect to have any difficulties with it.

Substance and Structure of the Project

The project consists of the following major work items:

1. **Preliminary research**
   I will have to research the following topics:

   - *Cecil* library - *Cecil* is the library which I will use for reading of the metadata. It will need to get familiar with its public API. Because it is open-source, it might be valuable to get some basic understanding of its source code as well.
   - *CIL* bytecode - The runtime of the *.NET Framework* is described in ECMA-335 Standard: *"CLI Specification – Virtual Machine"* (556 pages). I will need to get familiar with this document since I will be using it as the main reference. I will be especially interested in *Partition III – CIL Instruction Set*.
   - Decompilation theory - I will need to get familiar with the theory behind decompilation of programs. Cristina Cifuentes' PhD thesis *"Reverse Compilation Techniques"* might prove as especially useful starting point.

The research of these topics should not be too extensive. I only indeed to get sufficient background knowledge in these areas and then return to the finner details when I needed them.

2. **Create a skeleton of the code**
   It will be necessary to read the assembly metadata and create a *C#* source code that has the same classes, fields and methods. The method signatures have to match the ones in the assembly. At this point the method bodies can be left empty.

3. **Read and disassemble *.NET* bytecode**
   The next step is to read the bytecode for each method, disassemble it and output it as comments (for example, `// IL_01: ldstr "Hello world"`). This will help me learn how to use the *Cecil* library to read the bytecode and how to process it. I also expect that this output will be extremely helpful for debugging purposes later on.

4. **Start creating r-value expressions**
   Ignoring the stack of the virtual machine, some bytecodes can be straightforwardly converted into expressions. For example:

```
ldstr "Hello world"      - string "Hello world"
ldnull                   - 'null' reference
ldc.i4.0                 - 4 byte integer of value 0
ldc.i4 123               - 4 byte integer of value 123
ldarg.0                  - the first method argument
ldloc.0                  - the first local variable in the method
```

   The goal of this stage is to create *C#* expressions for several of the most important bytecodes.

   Function calls and arithmetic operations are also expressions, but at this stage I do not know their inputs and so I will have to use dummy values as their inputs.

5. **Conditional and unconditional branching**
   There are several bytecodes that investigate one or two values on the top of stack and then, if a given condition is met, branch to different location. (`br`, `brfalse`, `brtrue`, `beq`, `bge`, `bgt`, etc...)

The goal of this stage is to use *C#* labels and `goto` statements to recreate this flow of control. (eg translate `brfalse IL_02` to `if (input == false) goto Label_02;`)

As in the previous stage the inputs (ie the values at the top of stack) are still not know.

6. **Simple data-flow analysis**
   This is where it begins to be difficult. Consider the code:

```
// Load "Hello, world!" on top of the stack
IL_01: ldstr "Hello, world!"
// Print the top of the stack to the console
IL_02: call void [mscorlib]System.Console::WriteLine(string)
```

   Both of these are already decompiled as expressions, however the call has a dummy value as its argument. The goal of this stage is to perform as simple data-flow analysis as possible. The text "Hello, world!" must find its way to the method call. At this point it will probably be through one or even two temporary variables. For example:

```
String il_01_expression = "Hello, world!";
String il_02_argument_1 = il_01_expression;
System.Console.WriteLine(il_02_argument_1);
```

   The most difficult part will be handling of control flow. Different values can be on stack depending on which branch of code was executed. At this stage it will be necessary to create and analyse control flow graph. As a result of this stage, many temporary variables might be introduced to the code.

7. **Round-trip quick-sort algorithm**
   At this point very simple applications should probably successfully decompile and compile again (round-trip).

   The goal of this stage is to fix bugs and to add features so that simple algorithm like quick-sort can be successfully round-tripped without need to manually change the produced *C#* source code. At this point there is no restriction on the aesthetics of the source code. The only requirement is that it does compile.

There are many features of *.NET* that I do not plan to support at this point. For example, boxing & unboxing, casting, generics and exception handling. In general, all non-essential features are excluded.

8. **Further data-flow analysis**
   Employ more advanced data-flow analysis to simplify the generated *C#* code. Many temporary variables can be probably removed, relocated or renamed according to their use.

   [This task has variable scope and if the project starts falling behind schedule, simpler algorithms can be employed and vice versa.]

9. **Control-flow analysis**
   The goal of this stage is to use control-flow analysis to regenerate high-level structures like `if` statements and `for` loops. It will not be possible to eliminated all `goto` statements, but they should be avoided whenever possible.

   [This task has variable scope and if the project starts falling behind schedule, simpler algorithms can be employed and vice versa.]

10. **Assembly resources**
    .NET assemblies can have files embed in them. These files can then be accessed at runtime and thus the programs might require them.

    The goal is to extract the resources so that they can be included during the recompilation process.

    [Optional. This is an optional goal which will be done only if the project development goes much better then originally anticipated.]

11. **Advanced features**
    Add commonly used features which where ignored so far - for example, boxing & unboxing, casting, generics and exception handling.

    [Optional. This is an optional goal which will be done only if the project development goes much better then originally anticipated.]

12. **Round-trip Mono**
    The ultimate goal of this project is to be able to round-trip any *.NET* assembly. This means that for any given assembly the Decompiler should produce *C#* source code which is valid (does compile again without error). Even more importantly, the program produced by the compilation of the source code should be semantically same as the original one. Since the

bytecode will in general differ, this condition is difficult to verify. One way to check that the Decompiler preserves the meaning of programs is to simply try it.

Mono is open-source reimplantation of the *.NET Framework*. The major part of it are the *.NET* class libraries which can be used for testing of the Decompiler. The project is open-source and so if any decompilation problems occur, it is possible to investigate the source code of these libraries. Furthermore, the libraries come with extensive unit testing suite so it is possible to verify that the round-tripped libraries are not broken.

The goal of this final stage is to successfully round-trip all *Mono* libraries and pass the unit tests. This would probably involve enormous amount of bugfixing, investigation and handling of corner cases. All remaining *.NET* features would have to be implemented.

[Optional. This last stage is huge and impossible to be finished within the time frame of Part II project. If all goes well, I expect that it will take at least one more year for the project to mature to this point.]

13. **Write the dissertation**
    The last and most important piece of work is to write the dissertation. Being a non-native English speaker, I expect this to take considerable amount of time. I plan to spend the last seven weeks of project time on it. This includes the end of Lent Term and the whole Easter vacation. I plan to have the dissertation finished by the start of Easter term.

Success Criteria

The Decompiler should successfully round-trip a quick-sort algorithm (or any algorithm of comparable complexity). That is, when an assembly containing the algorithm is decompiled, the produced *C#* source code should be both syntactically and semantically correct. The bytecode produced by compilation of the generated source code is not expected to be identical to the original one, but it is expected to be equivalent. That is, the binary may be different but it still needs to be a correct implementation of the algorithm.

To achieve this the Decompiler will need to have the following features:

- Handle integers and integer arithmetic
- Create and be able to use integer arrays
- Branching must be successfully decompiled
- Several methods can be defined
- Methods can have arguments and return values
- Methods can be called recursively
- Integer command line arguments can be read and parsed
- Text can be outputted to the standard console output

See the following page for a *C#* implementation of a quick-sort algorithm which will be used to demonstrate successful implementation of these features.

I plan to achieve the success criteria by the progress report dead-line and then spend the rest of the time available by increasing the quality of the generated source code (ie “Further data-flow analysis” and “Control-flow analysis”).

Quick-sort algorithm

```
1  static class QuickSortProgram
2  {
3      public static void Main(string[] args)
4      {
5          int[] intArray = new int[args.Length];
6          for (int i = 0; i < intArray.Length; i++) {
7              intArray[i] = int.Parse(args[i]);
8          }
9          QuickSort(intArray, 0, intArray.Length - 1);
10         for (int i = 0; i < intArray.Length; i++) {
11             System.Console.Write(intArray[i].ToString() + " ");
12         }
13     }
14
15     /// For description of this algorithm see:
16     /// http://en.wikipedia.org/wiki/Quick_sort
17     public static void QuickSort(int[] array, int left, int right)
18     {
19         if (right > left) {
20             int pivotIndex = (left + right) / 2;
21             int pivotNew = Partition(array, left, right, pivotIndex);
22             QuickSort(array, left, pivotNew - 1);
23             QuickSort(array, pivotNew + 1, right);
24         }
25     }
26
27     static int Partition(int[] array, int left, int right,
28                          int pivotIndex)
29     {
30         int pivotValue = array[pivotIndex];
31         Swap(array, pivotIndex, right);
32         int storeIndex = left;
33         for(int i = left; i < right; i++) {
34             if (array[i] <= pivotValue) {
35                 Swap(array, storeIndex, i);
36                 storeIndex = storeIndex + 1;
37             }
38         }
39         Swap(array, right, storeIndex);
40         return storeIndex;
41     }
42
43     static void Swap(int[] array, int index1, int index2)
44     {
45         int tmp = array[index1];
46         array[index1] = array[index2];
47         array[index2] = tmp;
48     }
49 }
```

Timetable and Milestones

The work shall start on the Monday 22.10.2007 and is expected to take 20 weeks in total.

22 Oct - 28 Oct	*(week 1)*	**Preliminary research**
29 Oct - 4 Nov	*(week 2)*	**Create a skeleton of the code**
5 Nov - 11 Nov	*(week 3)*	**Read and disassemble *.NET* bytecode**
12 Nov - 18 Nov	*(week 4)*	**Start creating r-value expressions**
19 Nov - 25 Nov	*(week 5)*	**Conditional and unconditional branching**
26 Nov - 9 Dec	*(weeks 6 and 7)*	**Simple data-flow analysis**
10 Dec - 20 Jan		Christmas vacation
21 Jan - 27 Jan	*(week 8)*	**Round-trip quick-sort algorithm**
26 Jan - 27 Jan		**Write the Progress Report**
28 Jan - 10 Feb	*(weeks 9 and 10)*	**Further data-flow analysis**
11 Feb - 2 Mar	*(weeks 11 to 13)*	**Control-flow analysis**
3 Mar - 20 Apr	*(weeks 14 to 20)*	**Write the dissertation** (over Easter vacation)
21 Apr onwards		Easter term – Preparation for exams

Unscheduled tasks: **Assembly resources**; **Advanced features**; **Round-trip Mono**