KTH Computer Science
and Communication

# Automatic Grading System in Microsoft .NET Framework

Evaluating the performance of different languages on the Microsoft .NET platform

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# Abstract

A common challenge for software consulting companies is recruiting the right people. In the software industry the recruitment process usually involves several steps before a contract is signed, a single job interview is rarely enough. Thus, the interview tends to involve some sort of test to make sure that the person seeking the position is qualified. The testing procedure is usually part of the interview or conducted at the same occasion. Interviewing applicants who aren't qualified enough for the position might be a waste of time.

This waste can be minimized by only interviewing qualified applicants. In the software industry, qualifications are usually asserted by letting an applicant solve programming problems. This process can be automated using an Automatic Grader. Such systems already exist on several universities today and are used extensively in several programming courses and also in programming contests.

This thesis evaluates such a system with regards to execution speed and memory consumption. It also explains how such a system can be built and attempts to illustrate the performance differences between the supported programming languages. The system is unique in the aspect that it's built using only Microsoft .NET Framework while still supporting multiple programming languages. The supported languages are C#, Java and Python. This support is enabled through the use of a Java byte code to CIL compiler called IKVM and Python is supported through the use of IronPython.

The results showed that C# and Java performed almost equally in terms of execution speed, with Java being slightly behind. Python seemed to have greater performance issues than the other two. Java consumed the most memory out of the three, with Python as a close runner up.

Future work involves testing more languages and improving the system with usability in mind.

# Referat

## Automaträttning i Microsoft .NET Framework

En gemensam utmaning för konsultföretag inom mjukvaruutveckling är att rekrytera rätt personer. Rekryteringsprocessen inom mjukvaruindustrin innefattar vanligtvis flera steg innan ett anställningsavtal undertecknas. Enbart en anställningsintervju räcker sällan för att avgöra en sökandes lämplighet. Således tenderar intervjun att involvera någon form av test för att se till att sökanden är kvalificerad. Testproceduren är oftast en del av intervjun eller genomförs vid samma tillfälle. Att intervjua sökande som inte är kvalificerade för positionen i fråga kan vara ett slöseri med tid.

Detta slöseri kan minimeras genom att endast intervjua kvalificerade sökanden. Inom mjukvaruindustrin säkerställs kvalifikationer vanligtvis genom att låta sökanden lösa programmeringsproblem. Denna process kan automatiseras med hjälp av ett s.k.Automaträttningssystem. Sådana system finns redan på flera universitet i dag och används i stor utsträckning i flera programmeringskurser och förekommer även i samband med programmeringstävlingar.

Denna uppsats utvärderar ett sådant system med hänsyn till exekveringshastighet och minneskonsumtion. Den förklarar också hur ett sådant system kan byggas och hur de olika språken presterade. Systemet är unikt i och med att det är byggdes med enbart Microsoft .NET Framework och samtidigt klarar av att stödja flera olika programmeringsspråk. De språk som stöds är C#, Java och Python. Detta stöd möjliggjordes genom användning av en Java byte-kod till CIL kompilator som kallas IKVM och Python stöds genom användning av IronPython.

Resultaten visar att C# och Java presterar nästan lika med hänsyn till exekveringshastighet, med Java på andraplats. Python verkade ha större prestandaproblem än de andra två. Java konsumerade mest minne av de tre, med Python som tvåa.

Framtida arbete omfattar stöd för fler programmeringsspråk och förbättra systemet med användbarhet i åtanke.

# Foreword

This report is my Master Thesis project which was carried out at Valtech in Stockholm, Sweden. This thesis is part of my last course in the Masters Programme in Computer Science at The Royal Institute of Technology (KTH). The most difficult part of this thesis was finding out what subject to research. Then one day some words from my supervisor Alexander Baltatzis echoed in my head from one of his lectures: “Write code in any language and run it in .NET”. That sentence sparked my interest in finding out whether it was actually possible or not, since most people who write programs on the .NET platform do so using C# or sometimes Visual Basic, you rarely hear about someone using any other back-end language (even though many others are supported by the .NET platform).

# Glossary

| Term | Description |
|---|---|
| AGS | Automatic Grading System, a system for evaluating or grading code. |
| CIL | Common Intermediate Language, the lowest level human-readable programming language in .NET Framework. |
| CLI | Common Language Infrastructure, a specification that describes the runtime environment of Microsoft .NET Framework. |
| CLR | Common Language Runtime, is the virtual machine of Microsoft .NET Framework. |
| CLS | Common Language Specification, a set of rules and features that a .NET language must implement and understand. |
| GC | Garbage Collection, reclaim memory from objects that aren't in use. |
| GUI | Graphical User Interface, an interface that is image oriented rather than text oriented. |
| IKVM | An implementation of the Java for Mono and Microsoft .NET Framework. |
| IL | Intermediate Language, a language of an abstract machine. |
| IronPython | An implementation of the Python programming language targeting the Microsoft .NET Framework and Mono. |
| JVM | Java Virtual Machine, a program that executes byte-code. |
| Mono | An open source project created to enable .NET Framework cross platform ccompatibility. |
| MSIL | Microsoft Intermediate Language, a synonym for CIL. |

# Contents

# Chapter 1

# Introduction

This chapter introduces the problem at hand, the goal with this thesis and some short information about the company where all this work took place.

## 1.1 Problem Statement

A common challenge for Valtech and other consulting companies is to recruit the right people. The recruitment process in the IT business often involves several steps and can be very time consuming. This is due to the fact that knowledge and skill differ greatly from programmer to programmer and therefore a need to interview many people arises (just to find one that is deemed suitable for the job).

The recruitment process usually involves some kind of test to assert the skill of the programmer. A test which usually contains one or several programming problems. The test is sometimes performed on paper (questionnaire) or on a white board. Both of these environments aren't really suitable to program in, hence most programmers tend to do their work on computers with the assistance of a web browser and a suitable IDE.

These two issues present a challenge in which the optimal solution would result in less time spent recruiting and at the same time asserting the skills of the programmers before an interview is considered.

## 1.2 Goal

The main goal was to evaluate a system which could satisfy the demands stated above. Thus, since no such system was present at Valtech, there was a need to first build the system and then evaluate it through test cases with performance and memory consumption in mind.

The system would allow users to submit solutions to common programming problems and then have their code evaluated. Their code would have to have a limit on execution time since a "good" programmer should be able to solve problems efficiently. The results of the evaluation would be used to estimate how much time the different programming languages would need in order to solve specific problems, as all of these languages would be run in the Microsoft .NET Platform and some are likely to perform better than others.

## 1.3 About Valtech

Valtech is an independent, global IT-consulting company with offices in Europe, United States and Asia. The company was founded 1993 in France and has over 1600 employees worldwide. The Swedish branch is primarily oriented towards web solutions. Valtech's most well-known award winning projects include the websites 1177.se, Antagning.se and Riksbank.se.

All work concerning this thesis was carried out at Valtech in Stockholm, Sweden.

# Chapter 2

# Background

*This chapter gives a short presentation of what automatic grading is, some history and how the systems that are in use today are built.*

## 2.1 What is Automatic Grading?

An Automatic Grading System, is a computer system that has the ability to judge code. The process starts with the user being given a programming task or problem to solve. The user then attempts to solve this problem by writing some code which he or she then sends to the automatic grading system. The system compiles the code (if needed) and then runs it. The output generated is then compared with the correct output for that particular problem. If the output matches, the system returns a status message indicating a successful submission (e.g. “Accepted”) or if the output doesn’t match a different message is returned, indicating that something went wrong (e.g. “Wrong answer”).

There are some variations to the process above, sometimes more verbose feedback than “Wrong answer” is used, often indicating exactly which test went wrong and why [1]. This is usually done in order for university students to learn more about how to code by debugging/fixing their own code.

Having an automatic grading system results in several benefits [2]. There is no longer a need for humans correcting code in detail (a very time consuming process) since the system acts as a “judge”. Using this judge also gives greater consistency while evaluating code since it’s impartial and all submissions are judged equally. The system can provide instantaneous feedback, this is particularly useful for universities where students no longer have to wait for a teacher or an assistant to grade their homework. Submissions to this system are saved using a database, providing whoever administrates the system a way to trace all interactions with it.

## 2.2 History

The concept of automatic grading is not new. The earliest known system was built in 1960 by Hollingsworth [3]. This system used punch cards to write programs. The results from using this student-system approach rather than the traditional student-teacher was that it cut costs considerably for the staff since the time they needed to grade the students work was severely reduced. The students themselves also spent less time on each task, since they were able to have their work graded immediately instead of waiting for a teacher to do it. This system also made it possible to considerably increase the number of students taking the course. It did, however, have some shortcomings. For instance, a student's program could modify the grader program, making cheating possible.

An article from 2005 [4] describes three generations of automatic graders. The first generation systems were those regarded as being built and/or used in the 1960's and 1970's. Unsurprisingly, they used code that were close to pure machine code. In order to make them work, it was sometimes necessary to modify both the compiler and the operating system.

The second generation systems (1980-2000) introduced script-based tools. These involved various verification schemes and also asserted that the code was written in a certain way/style (decided by the teacher). Typically these graders involved command-line GUI:s. Languages like C and Java were used extensively.

The third generation (2000- ) differ from the second generation systems primarily in two ways. One is that they mostly use web based GUI:s. The other is that they often included a plagiarism detection system, since students sometimes shared code amongst each other. There were some minor issues among these detection systems [1] [4]. If the programming task was too simple or if a lecturer had been excessively thorough when describing the homework, the submissions would tend to be very much alike and thus picked up by the plagiarism detection system. Sometimes this made it difficult to distinguish between real plagiarism and the false positives.

## 2.3 Today's Systems

Today's modern systems, such as those in [1] [2] [4] [5] [6] (considered to be third generation systems), commonly contain a web based front-end together with a general back-end whose main purpose is to save submissions to the database and to send the submitted code (pipeline) to the other language specific back-ends (one for each language) while preserving system security through sandboxing. The database can be used to inspect specific submissions. The modern systems mainly differ in their support of different programming languages.

The modern systems also differ from the first generation in that most have adopted a test-driven education paradigm. Students are no longer penalized for attempting to submit more than one solution, in fact it's encouraged. An article from 1969 [7] describes how student were discouraged from ever making a mistake by giving them a lower score for each subsequent submission on the same problem. Not only that, but students received an even lower score if the program didn't run to completion or if some results were incorrect. The system described (and built) in this thesis adapts the modern test-driven paradigm in the sense that it doesn't penalize users for multiple submissions or any submission errors.

# Chapter 3

# Method

*This chapter explains how the system was implemented. It contains details about the work-flow, the GUI, how multiple languages are supported, how the security works and some of the difficulties and limitations encountered.*

## 3.1 System Description

The system was named CELINE, an abbreviation that comes from the descriptive phrase "**C**ode **E**va**L**uation **I**n .**NE**t" (the uppercase bolded letters forming the abbreviation).

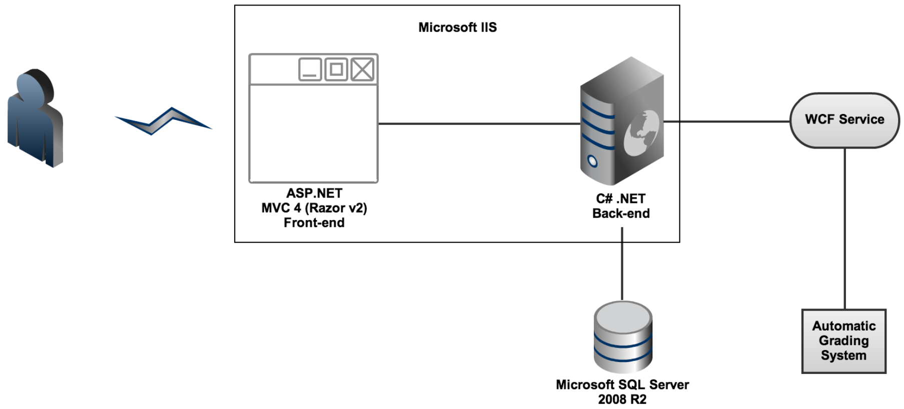
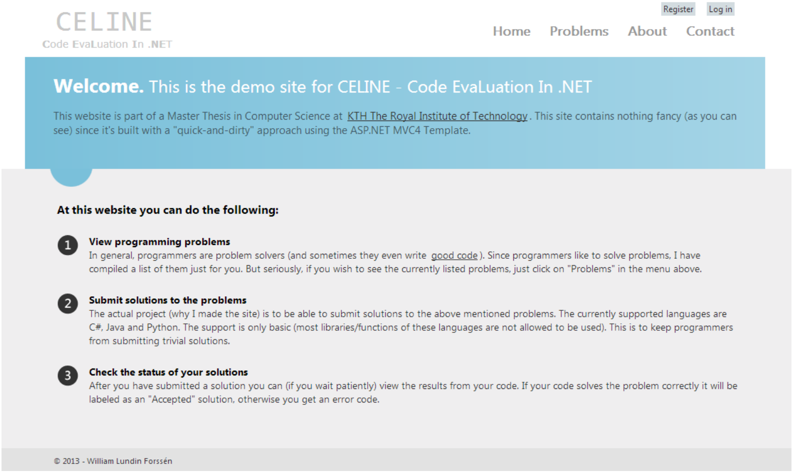


**Figure 3.1.** Overview of CELINE.

Figure 3.1 describes an overview of the system. The system uses a web based GUI for listing problems and submitting solutions to them. Going through this figure from left to right we can see that a user connects to the website through a web based GUI, which is built using a combination of ASP.NET MVC4 (Razor v2) technology and JavaScript. The system uses Microsoft IIS to enable this web support, which the standard web server software used in .NET. When the user submits code to solve a problem, that submission is saved to a database which is a Microsoft SQL Server 2008 R2 database. The submission is then forwarded to a WCF Service which in turn creates a new instance of the automatic grading system (built using C#) using the submission as input. The automatic grader compiles the source if needed and runs the code. It then returns a status code generated from the submission, this is described in section 3.1.3.

### 3.1.1 The Web GUI

The GUI is built using the ASP.NET MVC4 template. This saved both time and effort while still giving the website an easy to understand simplistic style.



**Welcome.** This is the demo site for CELINE - Code EvaLuation In .NET

This website is part of a Master Thesis in Computer Science at KTH The Royal Institute of Technology. This site contains nothing fancy (as you can see) since it's built with a "quick-and-dirty" approach using the ASP.NET MVC4 Template.

**At this website you can do the following:**

1. **View programming problems**
   In general, programmers are problem solvers (and sometimes they even write good code). Since programmers like to solve problems, I have compiled a list of them just for you. But seriously, if you wish to see the currently listed problems, just click on "Problems" in the menu above.
2. **Submit solutions to the problems**
   The actual project (why I made the site) is to be able to submit solutions to the above mentioned problems. The currently supported languages are C#, Java and Python. The support is only basic (most libraries/functions of these languages are not allowed to be used). This is to keep programmers from submitting trivial solutions.
3. **Check the status of your solutions**
   After you have submitted a solution you can (if you wait patiently) view the results from your code. If your code solves the problem correctly it will be labeled as an "Accepted" solution, otherwise you get an error code.

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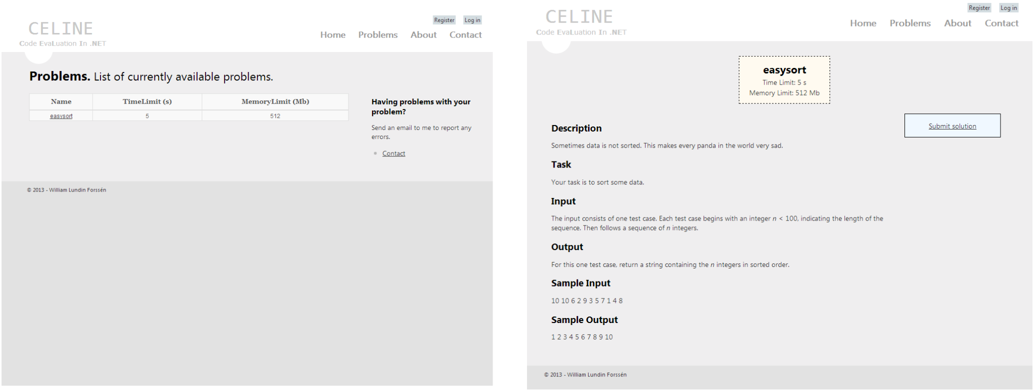
**Figure 3.2.** The start page of CELINE.

In Figure 3.2 we see the start page. The middle area contains some informative text, the top right contains the site menu, the register and login buttons.

Figure 3.3(a) shows what happens if you click on "Problems" in the menu. A list of currently available problems is displayed. The list contains details such as maximum run time and maximum memory usage. Clicking on one of the problems in this list will generate a page with more details of that particular problem, this is displayed in Figure 3.3(b). To the right of the problem details is a button for submitting a solution. Clicking it will generate a page containing a form for submitting code, illustrated in Figure 3.4(a). Apart from the submission form on the left side, this page contains some useful information on the right side concerning language specific signatures. These signatures specifies the point of entry for the application, that is, where the execution of the code starts. Users are free to name this method to anything they see fit, the only limitation is that it takes a string as input and returns a string as output. This is discussed in further detail in section 3.1.3.



**Problems.** List of currently available problems.

| Name | TimeLimit (s) | MemoryLimit (Mb) |
|---|---|---|
| easysort | 5 | 512 |

**Having problems with your problem?**

Send an email to me to report any errors.

- Contact

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(a) List of available problems.

**easysort**
Time Limit: 5 s
Memory Limit: 512 Mb

**Description**

Sometimes data is not sorted. This makes every panda in the world very sad.

**Task**

Your task is to sort some data.

**Input**

The input consists of one test case. Each test case begins with an integer $n$ < 100, indicating the length of the sequence. Then follows a sequence of $n$ integers.

**Output**

For this one test case, return a string containing the $n$ integers in sorted order.

**Sample Input**

10 10 6 2 9 3 5 7 1 4 8

**Sample Output**

1 2 3 4 5 6 7 8 9 10

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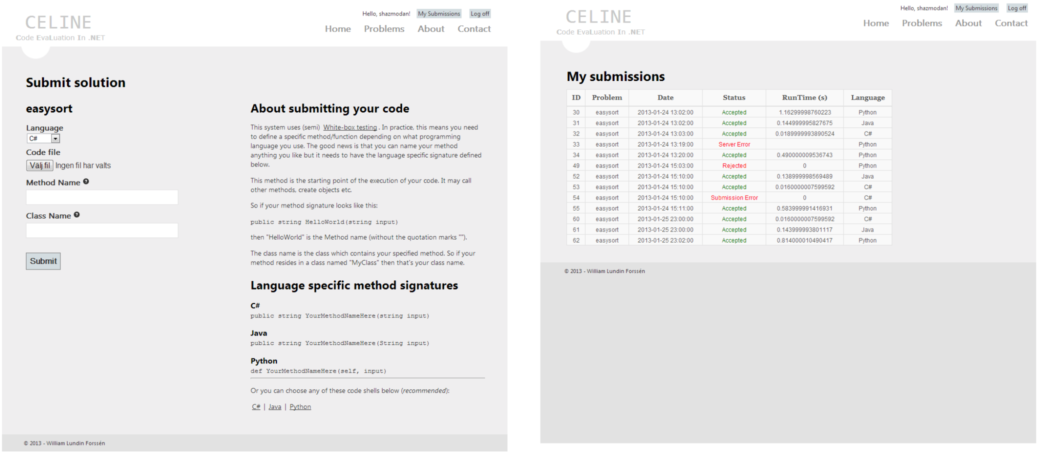
(b) One problem called "easysort".

**Figure 3.3.** Navigation in the Problems menu.



**Submit solution**

**easysort**

Language
C#

Code file

Ingen fil har valts

Method Name

Class Name

**About submitting your code**

This system uses (semi) White-box testing. In practice, this means you need to define a specific method/function depending on what programming language you use. The good news is that you can name your method anything you like but it needs to have the language specific signature defined below.

This method is the starting point of the execution of your code. It may call other methods, create objects etc.

So if your method signature looks like this:

```
public string HelloWorld(string input)
```

then "HelloWorld" is the Method name (without the quotation marks "").

The class name is the class which contains your specified method. So if your method resides in a class named "MyClass" then that's your class name.

**Language specific method signatures**

**C#**
```
public string YourMethodNameHere(string input)
```

**Java**
```
public string YourMethodNameHere(String input)
```

**Python**
```
def YourMethodNameHere(self, input)
```

Or you can choose any of these code shells below (*recommended*):

C# | Java | Python

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(a) Code submission page.

**My submissions**

| ID | Problem | Date | Status | RunTime (s) | Language |
|---|---|---|---|---|---|
| 30 | easysort | 2013-01-24 13:02:00 | Accepted | 1.16299998760223 | Python |
| 31 | easysort | 2013-01-24 13:02:00 | Accepted | 0.144999995827675 | Java |
| 32 | easysort | 2013-01-24 13:03:00 | Accepted | 0.0189999993890524 | C# |
| 33 | easysort | 2013-01-24 13:19:00 | Server Error |  | Python |
| 34 | easysort | 2013-01-24 13:20:00 | Accepted | 0.490000009536743 | Python |
| 49 | easysort | 2013-01-24 15:03:00 | Rejected | 0 | Python |
| 52 | easysort | 2013-01-24 15:10:00 | Accepted | 0.138999998569489 | Java |
| 53 | easysort | 2013-01-24 15:10:00 | Accepted | 0.0160000007599592 | C# |
| 54 | easysort | 2013-01-24 15:10:00 | Submission Error | 0 | C# |
| 55 | easysort | 2013-01-24 15:11:00 | Accepted | 0.583999991416931 | Python |
| 60 | easysort | 2013-01-25 23:00:00 | Accepted | 0.0160000007599592 | C# |
| 61 | easysort | 2013-01-25 23:00:00 | Accepted | 0.143999993801117 | Java |
| 62 | easysort | 2013-01-25 23:02:00 | Accepted | 0.814000010490417 | Python |

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(b) List of all submission made by the current user.

**Figure 3.4.** Navigation when submitting code.

Figure 3.4(b) shows the page listing all of the current user's submissions. The user is sent here after successfully submitting a solution (by filling out all the fields of the Submission page illustrated in Figure 3.4(a)) or by clicking on the button in the top right corner. This page contains information about each of the user's submissions. Each line details what problem the user attempted to solve, a timestamp, total runtime, the programming language used and the returned status code.

### 3.1.2 The Automatic Grading System

When a user has submitted his or her code, it eventually reaches the AGS. Figure 3.5 describes the flow of the most common paths for a submission through the system.

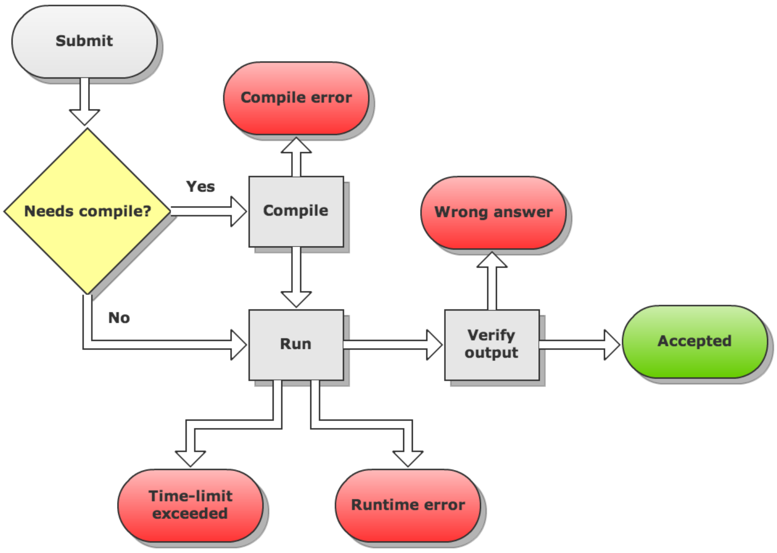


**Figure 3.5.** Common paths of problem flow in the AGS.

Depending on the programming language, a compiler is chosen. The code is then compiled into an assembly file and loaded into a separate and secure Application Domain (AppDomain, see section 3.3.1). The AGS then invokes the user specified method with a string containing the test data. The AGS waits for the code to complete or for the problem to timeout. It then compares the string returned by this method with another string containing what should be the correct output. If the strings match, the submission is regarded as being a success, otherwise it's regarded as a failure. The AGS then returns the appropriate status code.

### 3.1.3 System-User Feedback

The system gives feedback to the user in the form of a status code, one for each submission. The status code is a simple message indicating if the submission was successful or not. This system attempts to be more verbose on errors than other modern systems (described in section 2.3) since it uses grey-box testing which is more prone to submission related errors than black-box testing (commonly used in today's AGS:s). The concepts of white- and black-box testing are described more thoroughly in section 3.3.3. The following list contain the possible status codes:

- Accepted - The code has compiled, run and gave the correct answer.

- Wrong Answer - The code has compiled and run but gave the wrong answer.
- Server Assembly Error - The AGS failed to build an assembly from the code file, thus making the code unable to run.
- Submission Error - The code tries to reference a code library that isn't available/allowed.
- Illegal Operation - Occurs if the AGS detects a forbidden system call (e.g. accessing files, using the network etc...).
- Class or Function Error - Occurs if the class or method name doesn't correspond to the name provided by the user, thus resulting in the AGS being unable to invoke the method.
- Time Limit Exceeded - The code ran longer than the limit for this particular problem allowed. This could be an indication that the code needs to be improved (performance wise).
- Rejected - This is a general error, it indicates that the AGS has been unable to determine why the submission failed.
- Server Error - This indicates that the AGS instance has crashed.

The status messages "Server Assembly Error", "Submission Error", "Illegal operation" and "Class or Function Error" are all related to the user not having submitted code in the correct format. These might be less verbose than one would like (e.g. each submission could have returned exactly where in the code the error occurred) however any more verbose feedback would have required an expansion of the scope of this thesis.

## 3.2 Supported Languages

### 3.2.1 C#

The support for C# was implemented with the use of the Microsoft CSharp library [8] and the System CodeDom Compiler library [9]. Since C# can be considered a native .NET language, no 3rd party libraries were required to achieve this support.

### 3.2.2 Java

The Java support comes from using javac [10], the standard Java compiler that comes with the Java Development Kit (JDK) [11]. Javac compiles Java code to bytecode. This bytecode is then converted to CIL using ikvmc [12], a tool that is part of IKVM.NET (an implementation of Java for Mono and the Microsoft .NET Framework) [13].

### 3.2.3 Python

Python is supported through the use of IronPython [14]. IronPython provides a library (a dll) which contains a ScriptEngine from which python code can run without the need for compiling. Some issues encountered with the IronPython implementation are described in section 3.3.2.

## 3.3 Difficulties and Limitations

### 3.3.1 Security

Executing unknown code can be dangerous for several reasons, the code might have unforeseen side effects or even attempt to gain root access (compromise of the entire system). Thus it was necessary to avert this danger by running the code in a safe and secure sandboxed environment.

In .NET this can be handled through the use of AppDomains which act as a layer of isolation between applications [15]. AppDomains make it possible to protect the core application from malicious code and exceptions that might occur during the execution of unknown code. This protection comes at the cost of performance since AppDomains are able to load assemblies but cannot unload them. To get rid of a loaded assembly the entire AppDomain must be unloaded, which is the case with each new submission. CELINE creates a new AppDomain for each submission and then uses proxy objects (remotable objects) called “Marshals” [16] to enable communication between the core-AppDomain and the untrusted-AppDomain, in order to get the output that the unknown code produced.

When a new submission enters the AGS, the code is copied to a temporary location on disk and then gets executed with minimal privileges using this AppDomain. An alternate way to handle the security is mentioned in [2], where user impersonation is used by the core application, essentially letting the operating system handle the security through the use of a minimal privilege user.

There is an exception to the rule about AppDomains being safe from each other. That is when the code that is executing in the untrusted-AppDomain generates a stack overflow exception. This exception will travel back into its parents AppDomain (in this case the core-AppDomain) since it’s no longer possible to catch this exception as from .NET 2.0 and above [17]. In order to avoid crashes caused by stack overflow exceptions the AGS is instantiated with each new submission by the WCF Service. Thus the website never experiences any problems, only a timeout of the WCF Service.

### 3.3.2 IronPython Limitations

IronPython does not have the same performance as the other languages for a number of reasons. The first reason is that it’s 61.6% slower on average than CPython (version 2.7) [18]. The startup time is also significantly slower since this language is scripted using a ScriptEngine which adds another layer of interpretation (see Chapter 5 for performance results). However it's important to mention that IronPython does have the capability to compile the code into an assembly, but with a serious drawback, the assembly's methods and main entry point cannot be invoked like other assemblies since the MSIL is not CLS-compliant [19] and therefore cannot be directly accessed from other .NET languages [20].

### 3.3.3 White- and Black-box Testing

White-box testing is a method of testing a software's internal structures as opposed to black-box testing which test application functionality/behavior on a higher level (usually done with users in mind). These concepts are usually discussed in relation to Test-Driven Development (TDD) but are also relevant in this context since code is being tested and there are different ways of doing it.

As mentioned in section 3.1.3, CELINE is a mixture of both, a grey-box system, since it requires the user to define a method that has a pre-defined signature (used as the invocation point), but it doesn't care about any other implementation details. The choice for this type of implementation was made because it saved time compared with the approach of using standard system in and system out (black-box testing) to provide input and output channels.

# Chapter 4

# Testing Methodology

*This chapter discusses which aspects of the code that were tested and explain which algorithms were used.*

## 4.1 Aspects to Test

There are several ways to evaluate code. Code can be evaluated on its structure, understandability, execution speed, memory usage and others. Execution speed and memory usage are of particular interest since they are free of any human opinion. Since we do not yet have infinite time or memory these two aspects can be considered scarce resources and should ideally be fully optimized.

### 4.1.1 Execution Speed

The primary objective of the code should be to execute quickly. In general, the faster any code executes the more efficient the implementation. Apart from saving time this priority enables the users to compete amongst each other (using leaderboards on the website), for the shortest execution time by writing the most efficient code. The time is measured using the .NET Stopwatch class [21] which starts from the point of executing the thread which invokes the submissions entry method and ends when the thread ends, either by returning an answer or timing out.

### 4.1.2 Memory Consumption

The secondary objective is memory consumption. Every problem has the option to restrict memory consumption. This will allow administrators of the system to create problems in which the goal could be to force users to make a trade-off between speed and memory, illustrating real life situations such as optimizing code in order to avoid the unnecessary cost of purchasing more memory. The tool used to measure the memory consumption (and more) is the Windows Performance Monitor. This tool allows for tracking of specific Windows processes, and more specifically, tracking of individual resources contained in the .NET CLR.

## 4.2 The Chosen Tests

The tests are a mixture of general functionality and two specific algorithms. This section assumes that the reader is familiar with the Big O notation [insert Algorithm Design reference here FIXME].

### 4.2.1 Language Overhead

Each programming language has an overhead startup cost. This is measured by submitting code which does the minimum given this context. In Figure 4.1 a minimum code block for the C# programming language is demonstrated.

```
public class OverheadTest{
        public string SimpleReturn(string input){
                return "";
        }
        public static void Main(){}
}
```

**Figure 4.1.** C# code for language overhead testing.

This code will receive an empty string as input, and return an empty string. Measuring the overhead makes it possible to compensate for a language which has a slower start up time. For example, it would be unfair to restrict Python code to the same time-limit as C# code, since Python has a considerably longer startup time than the native .NET language C# (see Chapter 5).

### 4.2.2 Common Operators

The common operators are addition (+), subtraction (-), multiplication (*), division (/) and modulo (%). This test will measure how the language performs doing the simplest operations, giving an indication of its general performance. Figure 4.2 shows the code used for the addition test in Python.

```
class AdditionTest:
    def AddNumbers(self, input):
        input = input.split("␣")
        array = list(map(int, input))
        total = sum(array)
        return str(total)
```

**Figure 4.2.** Python code for testing the addition operation.

This code takes a string containing numbers as input, divides it into an array of strings, converts the strings to integers, sums these integers and returns this sum.

### 4.2.3 Insertion Sort

Insertion Sort is a comparison based sorting algorithm useful for sorting small inputs. The algorithm can be expressed using code, but this doesn't illustrate it very well for people not already familiar with it. So instead of code, playing cards (using a common 52 card deck) will be used to explain it.

- Start with an empty left hand and imagine yourself seeing a bunch of cards on a table.
- Pick a card from the table one at a time from left to right.
- Insert this card into the correct position in your left hand.
- The correct position is determined by comparing this card to each other card in your hand from right to left.
- The cards in your left hand are always sorted before each new card is picked.

The algorithm has a runtime of $O(n^2)$ but can still outperform more advanced algorithms such as Merge Sort (section 4.2.4) when the input is small enough (the definition of "small" varies from system to system) [22], because Merge Sort has an extra overhead from its recursive function calls and also uses more memory.

Insertion Sort is a suitable algorithm for testing performance between different languages since its implementation is very simple, straightforward and similar in these languages.

### 4.2.4 Merge Sort

Merge Sort is a divide and conquer, comparison based sorting algorithm. It's stable in the sense that it preserves the input order of equal elements in the output. The algorithm goes as follows (once again using the common 52 card deck analogy):

- Imagine yourself seeing a full deck of cards spread out in a line on a table.
- Divide all the cards into two equally sized piles. There should now be 26 cards on your left side and 26 cards on your right side.
- Keep dividing these piles into halves until you only have piles with one card in them.
- Now merge these one card piles together so that you end up with a pile that contains 2 cards that are sorted from left to right (in ascending order).

- Keep merging all piles together until you end up with one pile containing all of the cards (52) in sorted order.

Figure 4.3 illustrates this process using eight cards.

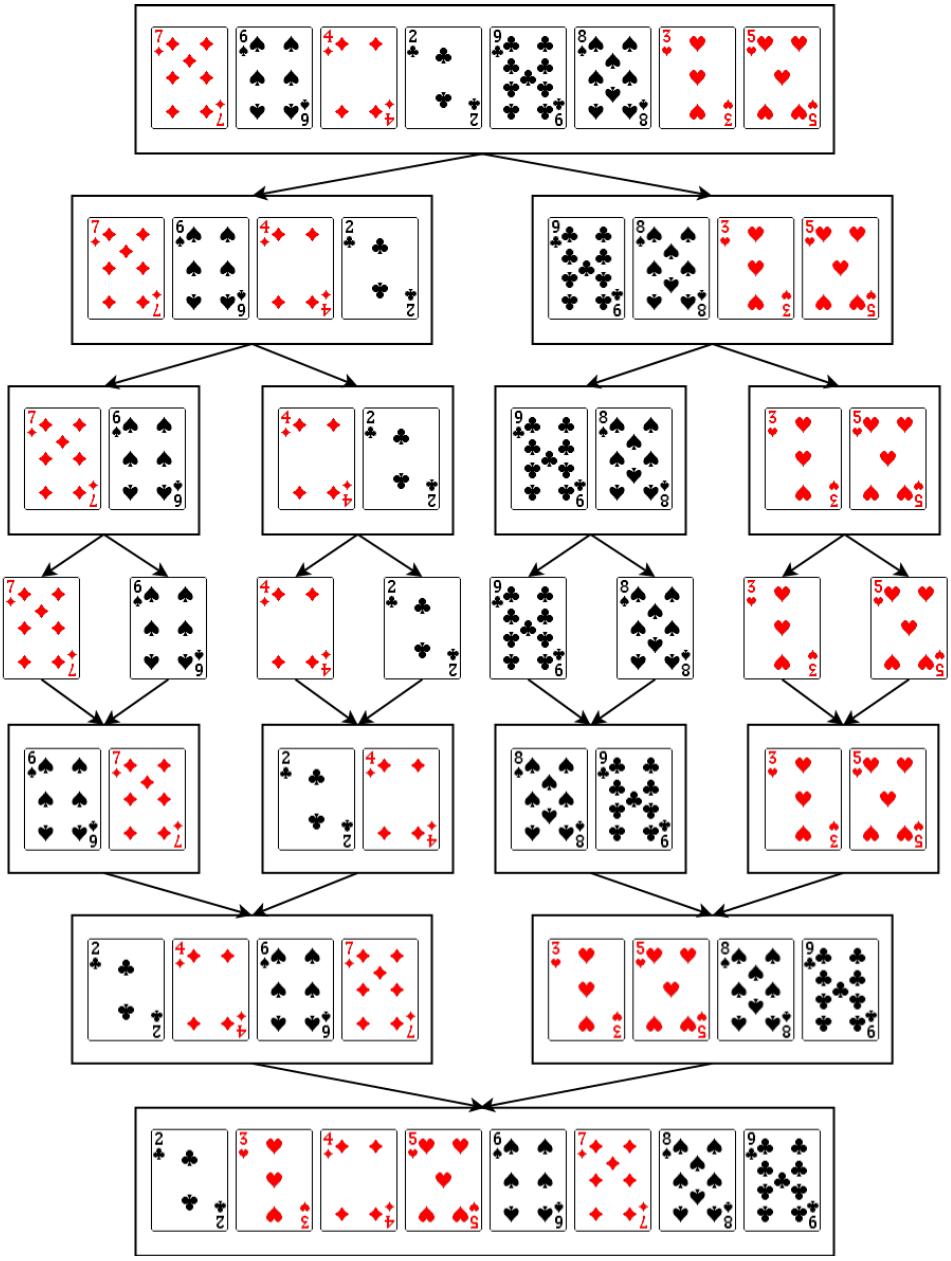


**Figure 4.3.** Illustration of the Merge Sort algorithm using eight cards. The cards are subsequently divided up and then merged back together in sorted order.

There are several sorting algorithms that have a worst time complexity of $O(n * log(n))$, Merge Sort was chosen because it has an auxiliary worst space complexity of $O(n)$, thus using more memory than other similar algorithms (e.g. Heap Sort) [23]. This helps in illustrating how different programming languages differ in memory consumption.

Chapter 5

# Testing Results

*This chapter describes the system specifications of the two computers that were used during testing, how to tests were carried out and presents the results of the tests.*

## 5.1 Testing Systems Specifications

The tests were conducted on two computers. The system specifications can be seen in Table 5.1. The MacBook Pro runs Windows 7 with the help of Parallels Desktop 8.

| | **MacBook Pro** | **Windows 8 Desktop** |
|---|---|---|
| **Operating System** | OSX 10.8.2 | Windows 8 Pro 64-bit v6.2 |
| **Processor** | 2.6 GHz Intel Core i7 | 2.4 GHz Intel Core2Quad |
| **Memory** | 16 GB 1600 MHz DDR3 | 4GB 400 MHz DDR3 |
| **Parallels Memory** | 8 GB dedicated memory | — |
| **Parallels # CPU:s** | 4 dedicated cores | — |
| **Parallels OS** | Windows 7 64-bit v6.1 | — |

**Table 5.1.** System specifications for the computers used.

It may appear strange that Parallels have four dedicated cores when the Intel Core i7 processor only contains 4 cores, but this is made possible due to the use of virtual cores (8 in total).

## 5.2 Testing Procedure

All tests presented in this chapter were run on both computers. Test results show that the machine running Windows 8 natively is 2-3 times slower on every test, this seems to be hardware related. Due to this fact, the results from the native Windows computer will not be presented in this thesis. The results presented in this chapter are from the computer running Windows 7 (through Parallels) and should not be interpreted in absolute numerical values but rather in relative terms (which is why one table contain a ratio column). The ratios on the native Windows 8 computer were very close to the OSX computer, the small differences are likely due to pure variance.

While the best time is the only time presented in this chapter, the mean-time was also recorded to make sure that the best time was not just a one-time fluke (which could have depended on unknown factors).

Every test was run 100 times on each computer in order to reduce variance. All results were adjusted according to the overhead for each language (see section 5.3.1). The input for each test varies from 1000 elements up to 10 million elements, the elements are randomly generated positive integers.

## 5.3 Results

In this section, the results are presented in table and chart forms. Note that on some charts the vertical axis is base 10 logarithmic (for viewing purposes). The implementation of all the algorithms for all languages can be found in [Appendix — FIXME].

### 5.3.1 Language Overhead

| Language | Time | Ratio |
|---|---|---|
| C# | 0.014s | 1:1 |
| Java | 0.038s | 1:2.7 |
| Python | 1.006s | 1:71.9 |

**Table 5.2.** The overhead startup cost for each language.

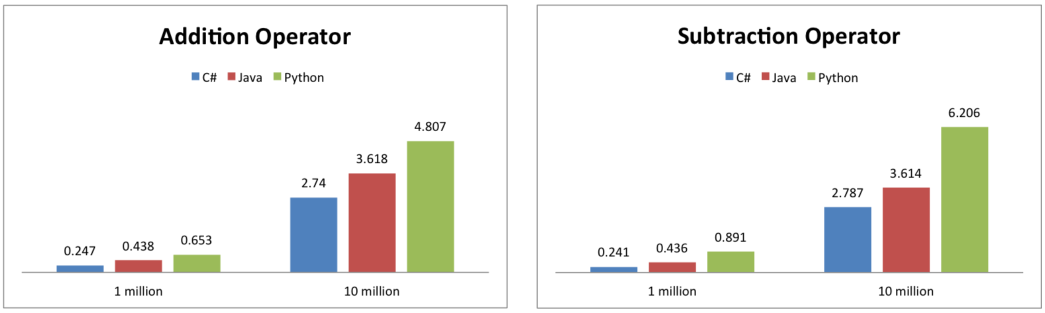
As can be seen in Table 5.2 Python has a greater overhead cost than the other two.

### 5.3.2 Common Operators

As can be seen in Figure 5.1 - 5.3 the time is proportional (linearly) to the number of elements operated on, it takes about 10 times longer to operate on 10 million numbers compared to 1 million.

### 5.3.3 Insertion Sort

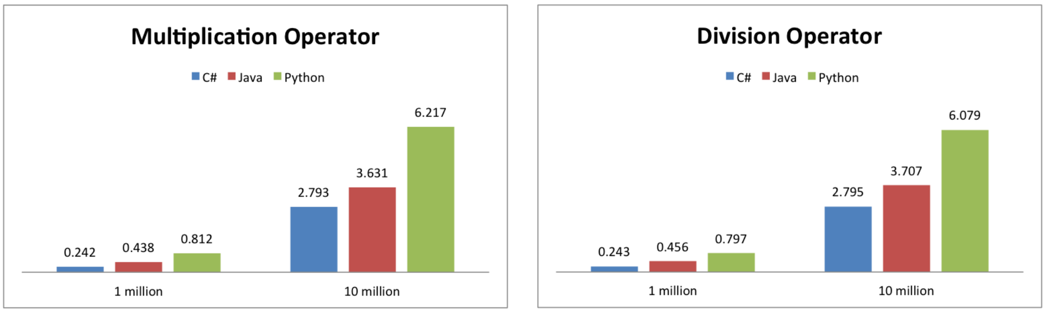
Figure 5.4 illustrates the time it takes for each language to sort 10’000 positive integers in random order. Note the time differences between Python and the other languages.



(a) Test results from addition operator.

(b) Test results from subtraction operator.

**Figure 5.1.** Test results for the addition operator to the left and subtraction to the right.



(a) Test results from multiplication operator.

(b) Test results from division operator.

**Figure 5.2.** Test results for the multiplication operator on the left and division to the right.

Figure 5.5 illustrates the relation between the number of positive integers in random order (horizontal-axis) and the time (vertical-axis), the graph looks like the expected quadratic curve since the algorithm runs in $O(n^2)$ in its worst case (the perfect curve would require the input to be in reverse order). Note the time difference on the vertical axis when comparing Figure 5.5(a) and 5.5(b).

The memory consumption was similar for C# and Java, Python however consumed 30-40% more (see Figure 5.6).

### 5.3.4 Merge Sort

Running code in its native environment provides a big increase in performance for Merge Sort as well, see Figure 5.7. This gap seemed to get narrower when increasing the amount of numbers to be sorted.

C# still outperforms Java when run in the .NET environment. But the gap between them seemed to narrow the more elements were added (see Figure 5.7(a)).

Figure 5.8 illustrates the performance gained from using the built-in Python

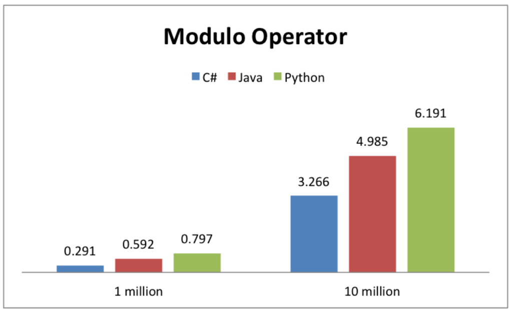
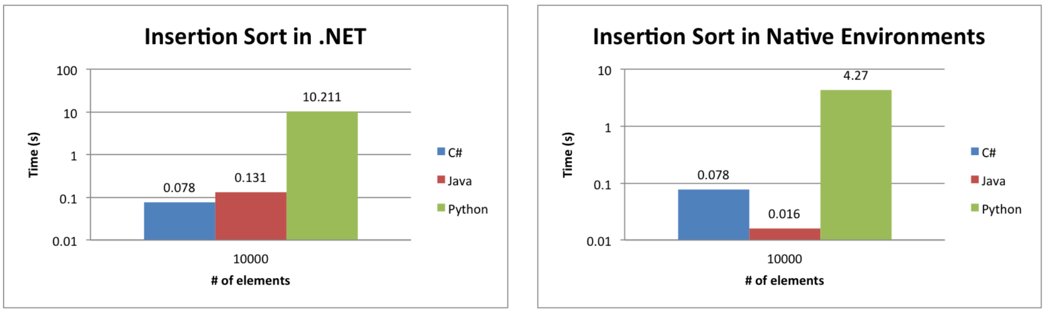


**Figure 5.3.** Test results from modulo operator.



(a) Test results from Insertion Sort when run in .NET.

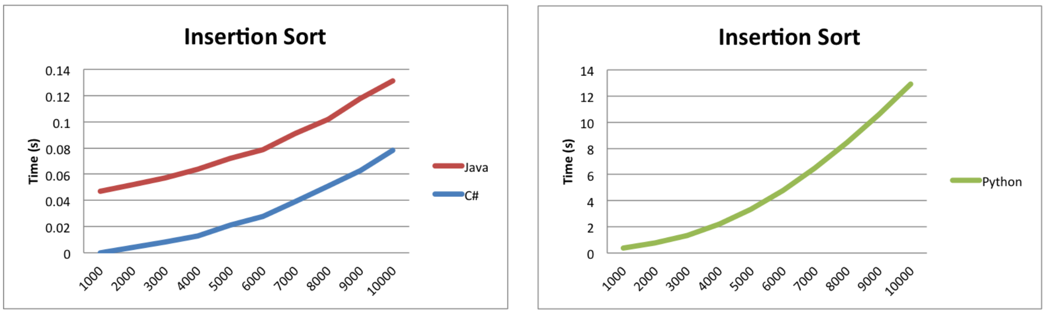
(b) Test results from Insertion Sort when run in native environments.

**Figure 5.4.** Test results for Insertion Sort in .NET to the left and the native environments to the right.

sorting function Tim Sort natively.

Figure 5.9 illustrates 100 runs with one million elements of the Merge Sort algorithm with each language run in .NET (all Python runs are not visible). It would appear that since the algorithm runs on the same input each run, one would expect a pattern to emerge. But due to restrictions in the Microsoft Performance Monitor it could only take one sample every second, and since C# and Java ran faster than that, the plot is uneven. Therefore it is important to only consider the peak for each language. Several more runs were made in order to reduce the risk of data collection error, Figure 5.9 is just an example run with all languages present to illustrate their differences (see Figure 5.10 for maximum values). The red line is the number of times the garbage collector was induced, note that Java forces this induction every other run.

The maximum memory consumption can be seen in Figure 5.10. Java consumed the most memory while C# consumed the least.



(a) Test results for Insertion Sort in Java and C#.

(b) Test results from Insertion Sort in Python.

**Figure 5.5.** Test results for Insertion Sort in C# and Java to the left and Python to the right.

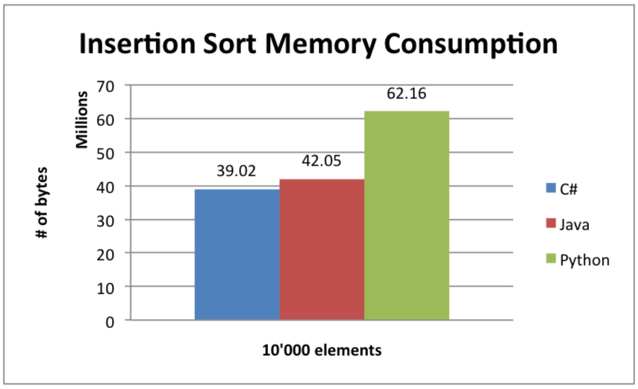
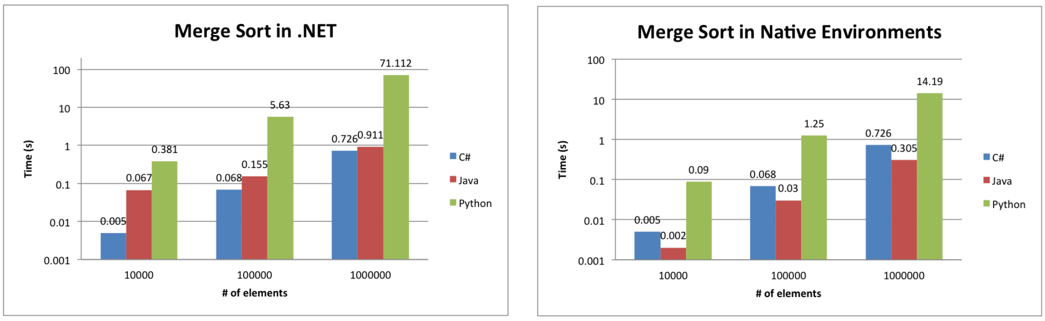


**Figure 5.6.** Comparison of the memory consumption between the three languages run in .NET.



(a) Test results from Merge Sort when run in .NET.

(b) Test results from Merge Sort when run in native environments.

**Figure 5.7.** Comparison of running Merge Sort in .NET to the left and each language native environment to the right.

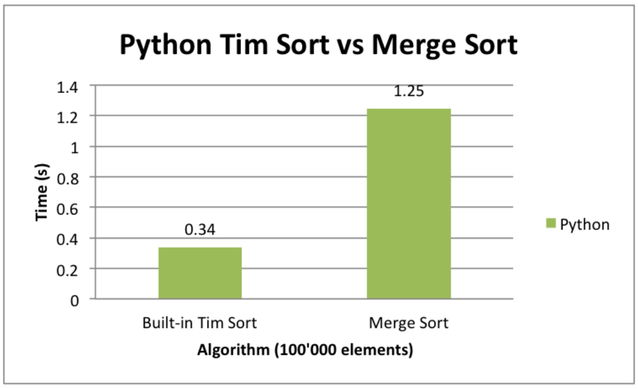


**Figure 5.8.** Python built-in function Tim Sort vs Merge Sort.

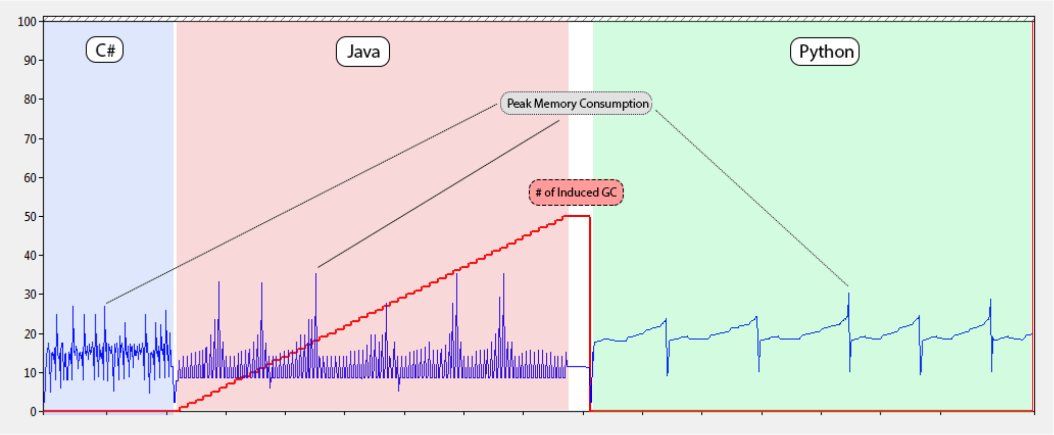


**Figure 5.9.** Memory consumption over 100 test runs with one million elements for each language. Blue line represents memory consumption and red line represents the number of induced GC.

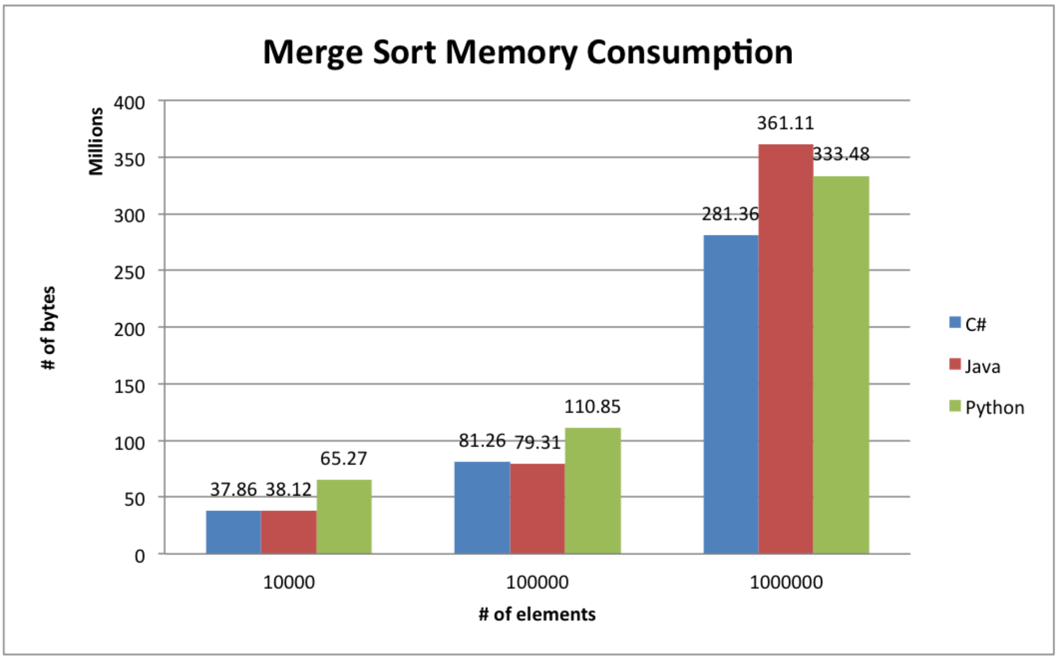


**Figure 5.10.** Comparison of the memory consumption between the three languages.

# Chapter 6

# Discussion

*This chapter contains reflections on the test results as well as the thesis conclusion and possible future work.*

## 6.1 Result Analysis

The common operator tests doesn't contain any surprises other than that Python addition is faster than its other operator tests. The reason is because that particular code uses a built-in *sum* function [24] (see Figure 4.2), while the others use the *reduce* function [25].

Many of the slow execution results from Python derives from a couple of things. Firstly, Python is an interpreted language which means it suffers from a rather significant performance penalty from the start, this can be seen in Figure 5.4(b) where Python gets heavily outperformed by the other two languages, both of which are compiled languages. Also, in the .NET environment the Python code is run by a ScriptEngine, adding another layer of interpretation. This is also reflected in the language overhead test in Section 5.3.1. Good Python performance seem very dependent on using the built-in functions of the language (since these are written in C), for instance a 3-4 time speed increase can be seen using the built in sort function *Tim Sort* [26] (a hybrid algorithm using a mix of insertion sort and merge sort), see Figure 5.8.

Java outperforms C# on every test when run in the native environment. An even further speed increase could be achieved by adding the *-server* tag to the JVM making Java the fastest language by far in the native comparison tests.

The memory consumption of Merge Sort with 10'000 elements is about the same as with Insertion Sort. It would seem that this amount of elements is too small to have an impact on the amount of memory consumed. One would expect Merge Sort to consume significantly more memory, but the data obtained is seem to simply be a reflection of a static cost.

Java is the least conservative language in relation to memory consumption. This can be seen in Figure 5.9. It's in fact so memory hungry that the GC gets invoked every other run. It also happens to be the fastest native language regardless of the number of elements that needs to be sorted, both of these tendencies are also confirmed by [27] [28], however keep in mind that these articles concerns native Java and not CIL compiled byte code in .NET. The memory consumption could either be a result of *javac* producing memory inefficient byte code or of IKVM compiling the byte-code to CIL inefficiently.

## 6.2 Conclusion

The goal of this thesis was to evaluate the performance of different languages run in the .NET environment. The results indicate that Python suffers from significant performance problems. One could argue that the problem isn't Python but rather the tests. Sorting for instance is best handled using the built-in functions. However if one was to apply for a job and the task was to implement simple sorting algorithms in order to demonstrate their programming proficiency, the recruiter wouldn't have them use the built-in functions as this would not reveal whether the applicant understands how to implement the algorithm or not.

This thesis concludes that while implementing multiple language compatibility in .NET is possible, it's not feasible for all languages with concerns to performance. See for example the time it takes for Python to sort 1 million elements in .NET using Merge Sort (Figure 5.7(a)). The compensation times of the Python code varies greatly depending on how many built-in functions one can use or is allowed to use for solving a problem. This makes compensating for Python performance troublesome as it differs greatly depending on the type of problem.

Instead of having .NET be the only back-end, it could be used for handling input/output, security and then use separate processes for each language where this process simply executes the submitted code in its native language environment (e.g. Java code using *java.exe* or Python code using *python.exe*). This is the way many modern systems are built (see Section 2.3), and for good reason.

## 6.3 Future Work

Evaluating if other languages are suited for the .NET environment. Among these are, JavaScript using JavaScript.NET [29] or Jint [30], PHP using Phalanger [31], Ruby using IronRuby [32]. There are many more languages that have a CLI implementation but based on the current popularity of programming languages [33] those are primarily the ones of interest.

CELINE can also be improved in many ways since the focus of this thesis was language compatibility and testing, rather than usability. An administrative web interface could be built along with better feedback on submissions. Energy can also be spent on usability testing in order to improve the user experience.

# Appendix A

# RDF

And here is a figure

**Figure A.1.** Several statements describing the same resource.

that we refer to here: A.1

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