



**KTH Computer Science
and Communication**

Code Evaluation System in Microsoft .NET Framework

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

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Abstract

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Referat

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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. I wanted to evaluate something in Microsoft .NET Framework, but I didn't know what. 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 on .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 Visual Basic, you barely ever hear about someone using any other language (even though many others are supported by the .NET platform).

Glossary

Term	Description
CES	Code Evaluation System, also known as 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.
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.
Mono	An open source project created to enable .NET Framework cross-platform compatability.
MSIL	Microsoft Intermediate Language, a synonym for CIL.

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Chapter 1

Introduction

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. 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 would be able to solve problems efficiently. The results of this 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.

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

In this chapter I give a short presentation of what automatic code evaluation is, some history and how the systems that are used today are built.

2.1 What is automatic code evaluation?

Automatic code evaluation, or automatic grading, is a computer system that has the ability to judge code. This is usually done in the following steps:

1. A user is given a programming task or problem.
2. The user attempts to solve this problem by writing code.
3. The user sends this code to the automatic code evaluation system.
4. The system compiles the code (if needed).
5. The resulting program is then run by the system with some test data as input.
6. The system verifies that the program output is correct (or incorrect).
7. An answer is then returned to the user indicating the status of the code which he or she submitted (i.e. “Accepted” or “Wrong answer”).

There are some variation 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 debugging their code.

2.2 History

Evaluating code automatically is nothing new. The earliest known system was built in 1960 by Hollingsworth [2]. This system was used in an introductory course in Algol programming. 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 reduced by as much as one third. The students themselves also spent less time, 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 [3] 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 and some even used punched cards. In order to make them work, it was necessary to modify both compiler and 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 GUIs. 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 GUIs. 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 [3] [1]. 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. This made it somewhat difficult to distinguish between real plagiarism and the false positives.

2.3 Todays systems

Todays modern systems [1] [3] [4] [5] (considered to be third generation systems) commonly contain the following features:

- A web based front-end.
- A general purpose back-end.
- A separate back-end for each programming language the system supports (which is invoked by the general purpose back-end system).
- A database used to store submissions for later review by users and/or teachers.
- Sandboxing of submitted code to maintain a solid system state (avoids malicious code causing damage to the system).

Between these modern systems they mainly differ in their support of programming languages.

Chapter 3

Method

In this chapter I explain 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 **.NET**” (the uppercase bolded letters forming the abbreviation).

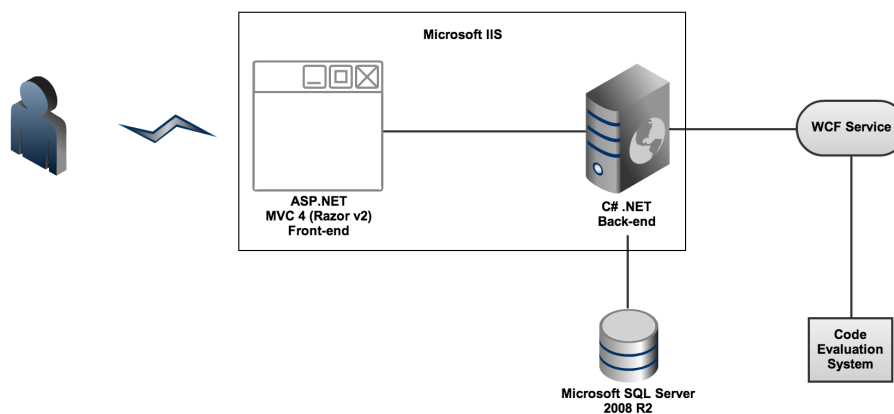


Figure 3.1. Overview of CELINE.

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 code evaluation system (built using C#) using the submission as input. It then returns the 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.

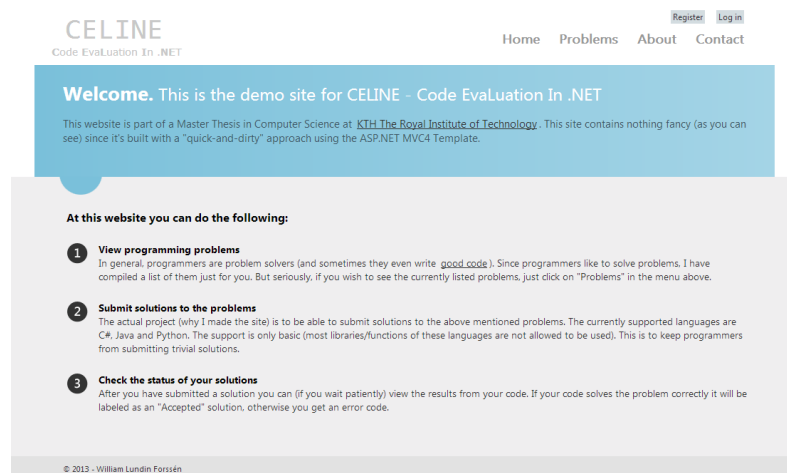


Figure 3.2. The start page of CELINE.

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 details-text 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 form itself on the left side, this page contains some useful information on the right side.

Figure 3.4(b) shows the page listing all of the current users 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 users 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. SYSTEM DESCRIPTION

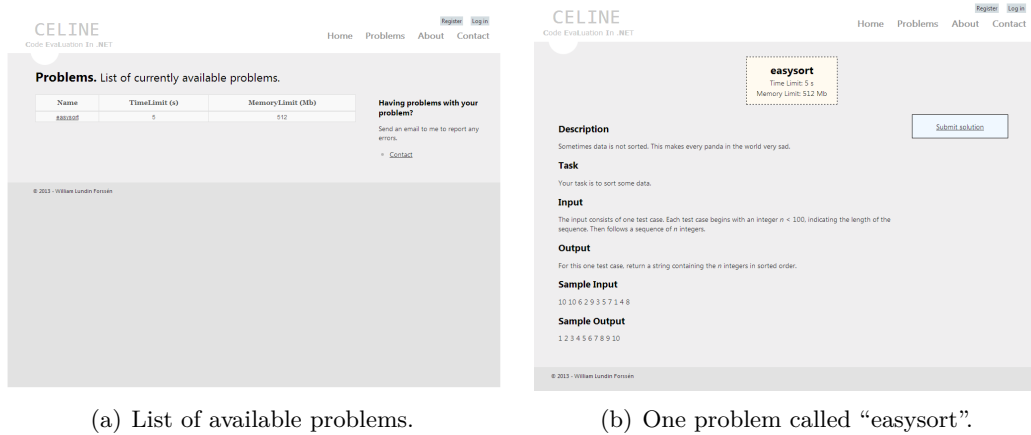


Figure 3.3. Navigation in the Problems menu.

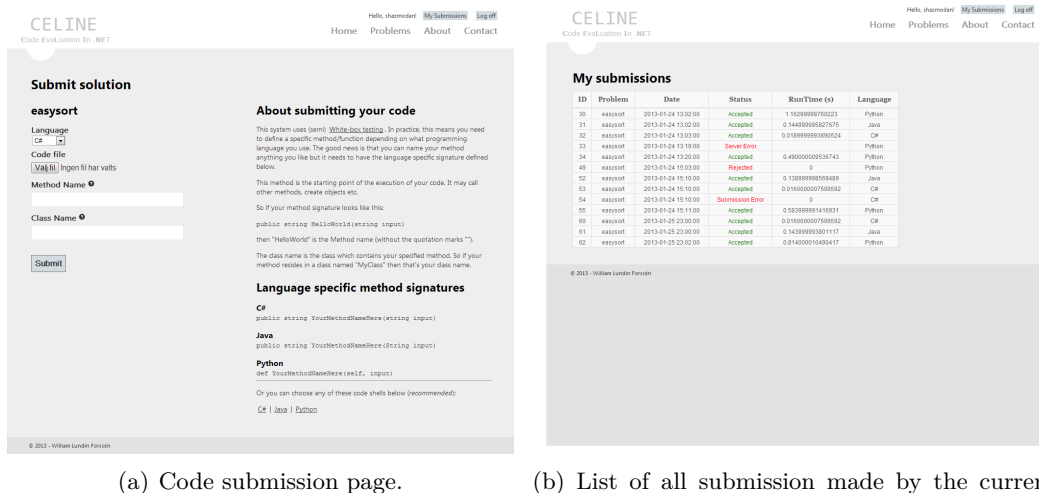


Figure 3.4. Navigation when submitting code.

3.1.2 The code evaluation system

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

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 CES then invokes the user specified method with a string containing the test data. The CES 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

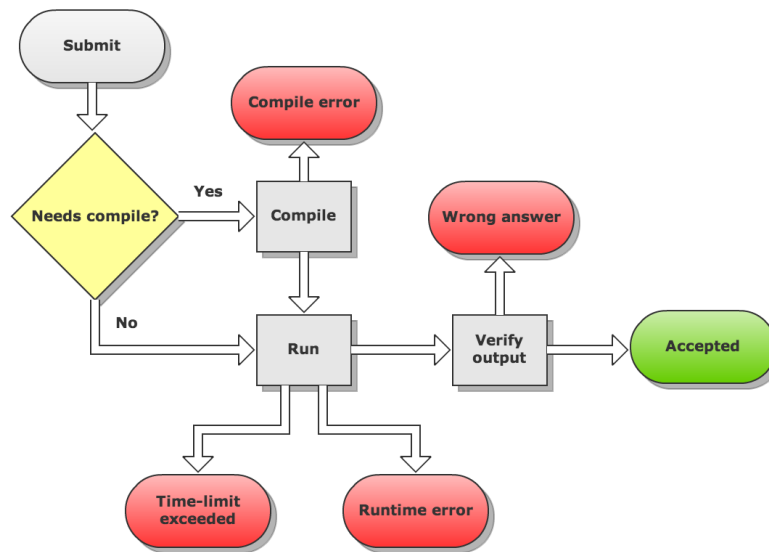


Figure 3.5. Common paths of problem flow in the CES.

regarded as a failure. The CES then returns the appropriate status code.

3.1.3 The status codes

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. The concepts of white- and black-box testing are described more thoroughly in section 3.3.3. The following list are 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 CES failed to build an assembly from the codefile, 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 CES detects a forbidden system call (i.e. accessing files, using the network etc...).

3.2. SUPPORTED LANGUAGES

- 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 CES being unable to invoke the method.
- Time Limit Exceeded - The code ran longer than the limit for this particular problem.
- Rejected - This is a general error, it indicates that the CES has been unable to determine why the submission failed.
- Server Error - This indicates that the CES 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 [6] and the System CodeDom Compiler library [7]. Since C# can be considered a native .NET language, no external libraries were required to achieve this support.

3.2.2 Java

The Java support comes from using javac [8], the standard Java compiler that comes with the Java Development Kit (JDK) [9]. Javac compiles Java code to bytecode. This bytecode is then converted to CIL using ikvmc [10], a tool that is part of IKVM.NET (an implementation of Java for Mono and the Microsoft .NET Framework) [11].

3.2.3 Python

Python is supported through the use of IronPython [12]. IronPython provides a library 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 sideeffects or even be an 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 is handled through the use of AppDomains which act as a layer of isolation between applications [13]. AppDomains make it possible to protect the core application from malicious code and exceptions that might occur during execution of the 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” [14] to enable communication between the core-AppDomain and the untrusted-AppDomain, in order to get the output that the unknown code produced.

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. In order to avoid crashes caused by stack overflow exceptions the CES 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) [15]. The startup time is also significantly slower since this language is scripted using a ScriptEngine which adds another layer of interpretation (see section blablabla for performance results FIXME). It is however important to mention that IronPython does have the capability to compile the code into an assembly, but with a serious drawback, the assemblies methods and main entry point cannot be invoked like other assemblies since the MSIL is not CLS-compliant [16] and therefore cannot be directly accessed from other .NET languages [17].

3.3.3 White- and black-box testing

White-box testing is a method of testing a softwares internal structures as opposed to black-box testing which test application functionality/behaviour on a higher level (usually done with users in mind). These concepts are usually discussed in relation

3.3. DIFFICULTIES AND LIMITATIONS

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 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

In this chapter I discuss which aspects of the code that was tested and explain which algorithms that were used.

4.1 Aspects to tests

There are several ways to evaluate code. Code can be evaluated on its structure, understandability, execution speed, memory usage and others. I've decided on execution speed and memory usage since they are free of any human opinion. Since we do not yet have infinite time or memory these two aspects are 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 [18] which starts from the point of executing the thread which invokes the submissions entry method and ends when the thread ends, either by the same thread returning an answer or timing out.

4.1.2 Memory usage

The secondary objective is memory usage. Every problem has the option to severely 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.

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 execution 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#.

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(" ")
        sum = 0
        for x in range(0, len(input)):
            sum += int(input[x])
        return str(sum)
```

Figure 4.2. Python code for testing the addition operation.

4.2. THE CHOSEN TESTS

This code takes a string containing numbers as input, divides it into an array of numbers, sums these numbers 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 I will explain it using playing cards (using a common 52 card deck):

- 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 (described in section 4.2.4) because Merge sort has an extra overhead from its recursive function calls and also uses more memory, but this is only true for small inputs (what "small" is varies from system to system) [19].

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):

- Imagine yourself seeing a full deck of cards in a line on a table.
- Divide 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 in half 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.

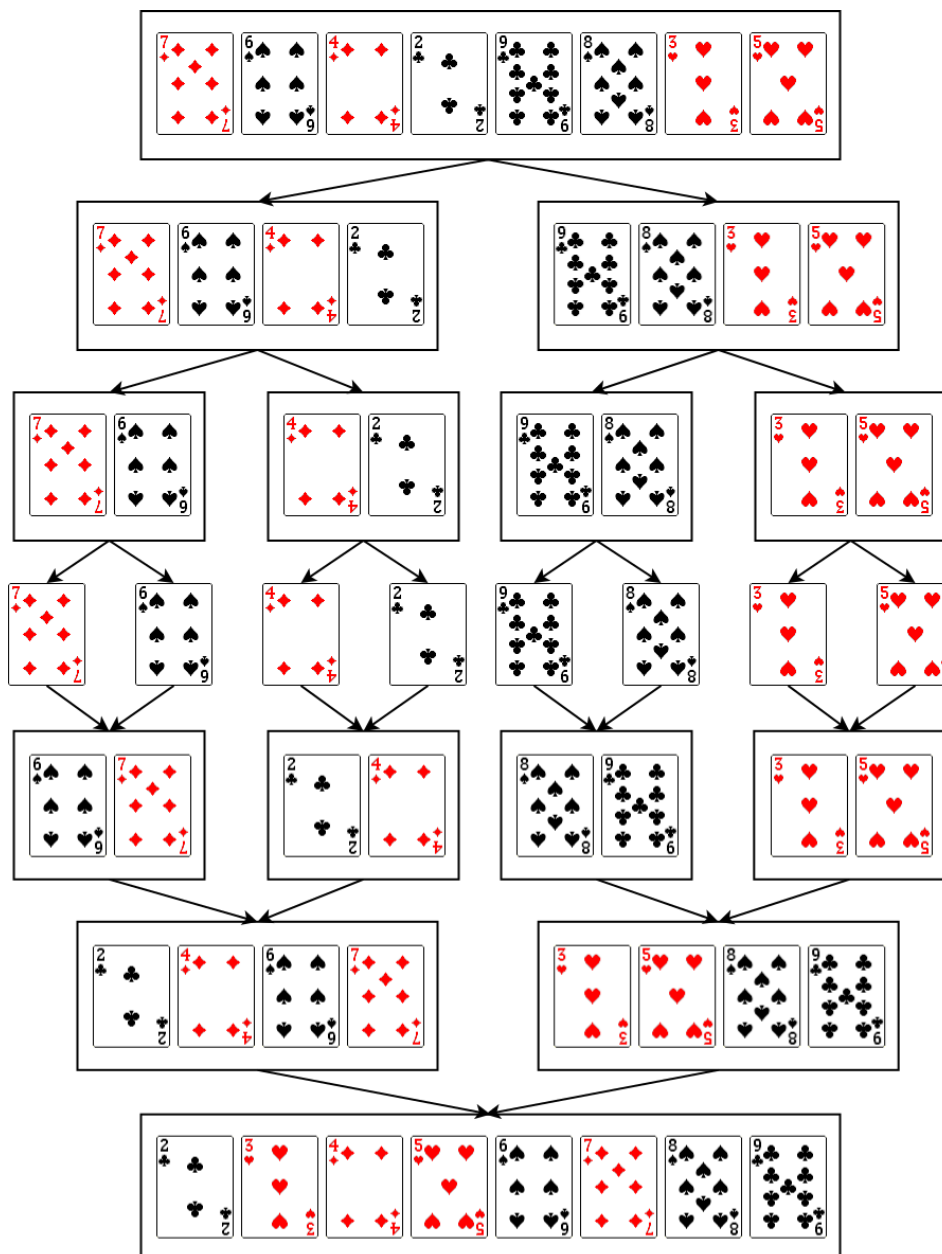


Figure 4.3. Illustration of the Merge Sort algorithm using eight cards. The cards are subsequently divided up and then merged back together in sorted order.

4.2. THE CHOSEN TESTS

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) [20]. This helps in illustrating how different programming languages differ in memory consumption.

Chapter 5

Testing Results

In this chapter I describe the system specifications of the two computers that were used during testing and also present the results of these 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	—

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 (section 5.1). 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 OSX and should not be interpreted

in absolute numerical values but rather in relative terms (which is why some tables contain a ratio column). The ratios on the native Windows 8 computer were very similar to the OSX computer running Windows 7 under Parallels, the differences are mostly likely due to 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 while measuring. All results were adjusted according to the overhead for each language. The input for each test varies from 1000 elements up to 10 million elements, the elements are randomly generated positive integers.

5.3 Results

5.3.1 Language overhead

Language	Time	Ratio
C#	0.014s	1:1
Java	0.038s	1:2.7
Python	1.401s	1:10

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. This is because both C# and Java code are pre-compiled before execution while Python code needs to be parsed and interpreted in an extra layer before the code itself can be executed.

5.3.2 Common operators

As can be seen in Figure 5.1 - 5.3 the time complexity is linear, it takes about 10 times longer to operate on 10 million numbers compared with 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.

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 $O(n^2)$. Note the time difference on the vertical axis when comparing Figure 5.5(a) and 5.5(b).

5.3. RESULTS

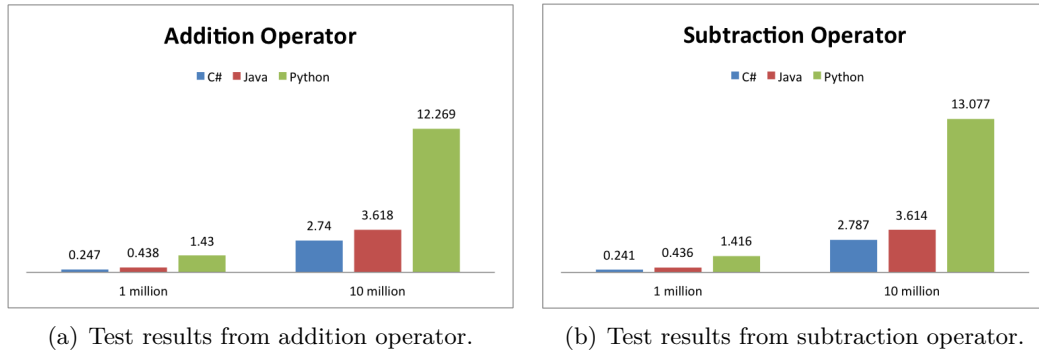


Figure 5.1. Test results for the addition operator to the left and subtraction to the right.

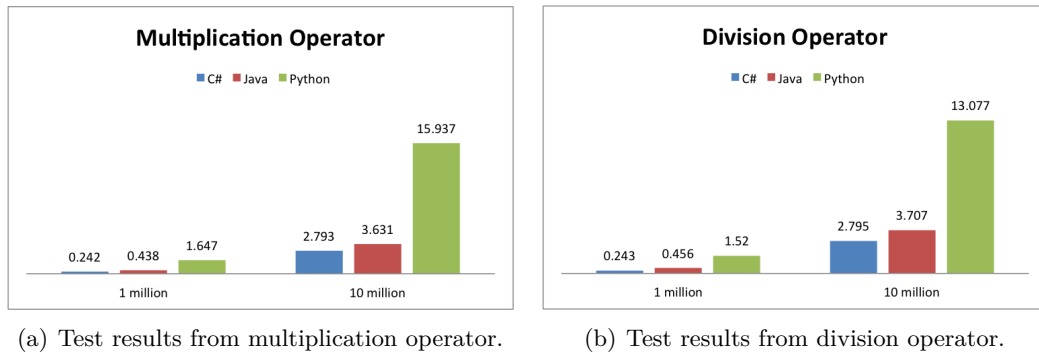


Figure 5.2. Test results for the multiplication operator on the left and division to the right.

The memory consumption is similar among all languages for Insertion Sort. Python consumed about 10-15% more with 40 Mb compared with C# at 36 Mb and Java at 34 Mb (see Figure 5.6).

5.3.4 Merge Sort

Since the runtime for Python was already over the one minute mark with just 100'000 elements (see Figure 5.7(a)) I decided not to test one million elements with Python. Instead I tested C# and Java with one million elements and compared the runtimes with one hundred thousand elements in Figure 5.8.

C# still outperforms Java when run in the .NET environment. But the gap between them seemed to narrow the more elements were added. I attempted to run the Java implementation in its native environment, and it outperformed C# (see Figure 5.9).

Java run in .NET is about equal to C# when it comes to memory management (Figure 5.10). Python consumed more memory, performing 40-50% worse than the

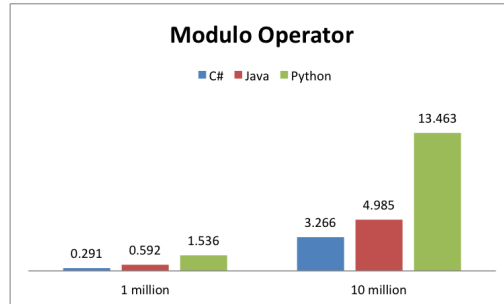
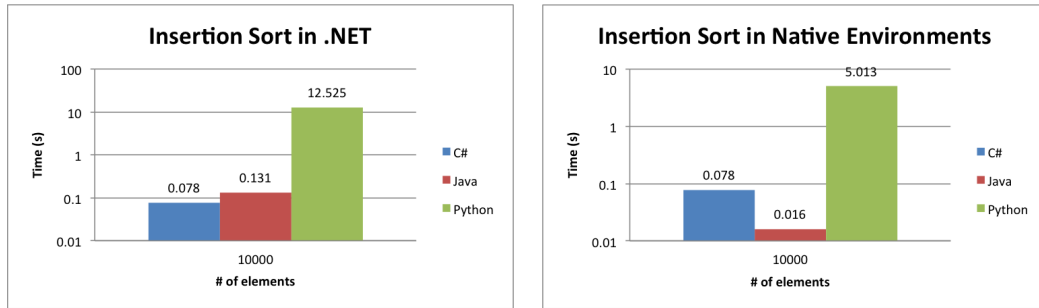


Figure 5.3. Test results from modulo operator.



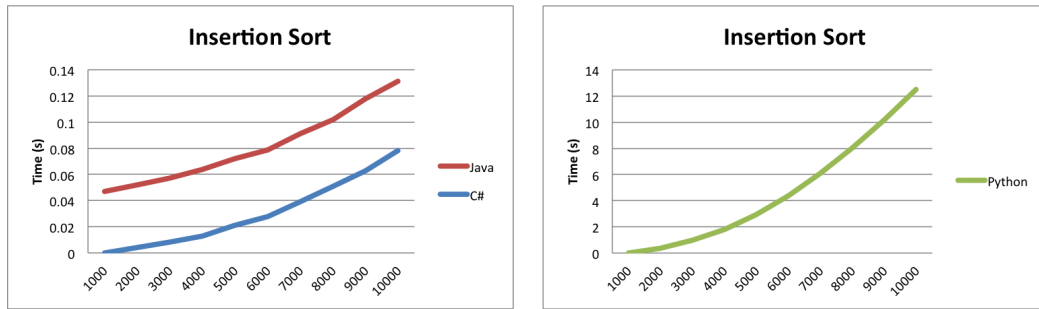
(a) Test results from Insertion Sort when run in .NET. (b) Test results from Insertion Sort when run in native environments.

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

other two.

Running code in its native environment provides a big increase in performance for Merge Sort as well. Java is about 5-6 times faster and Python is more than 70 times faster (see Figure 5.11). The slow execution of Python code in .NET seem to depend on the size of the input as seen in Figure blsblalbla FIXME.

5.3. RESULTS



(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.

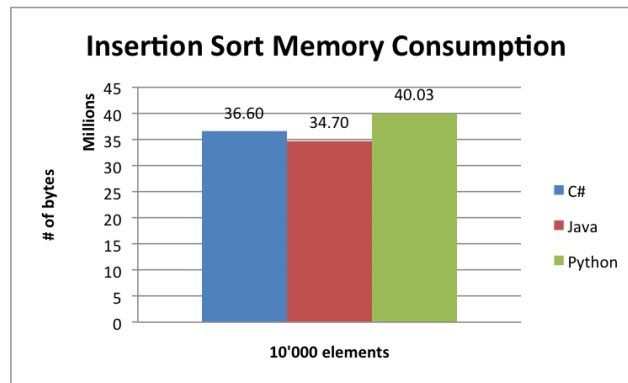
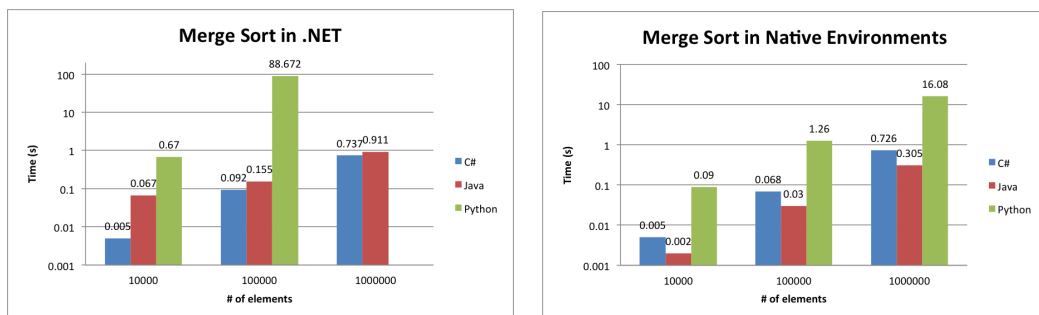


Figure 5.6. Comparison of the memory consumption between the three languages.



(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.

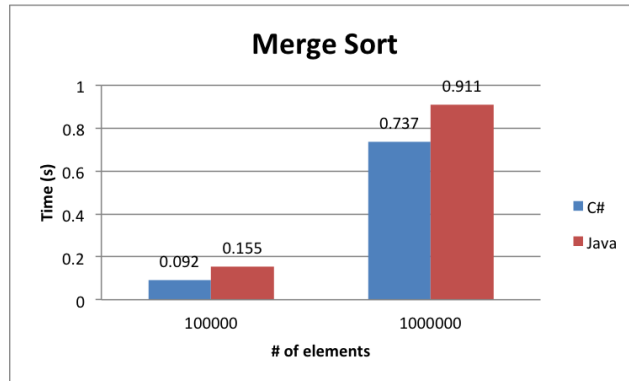


Figure 5.8. Time difference between using 100'000 elements and a million.

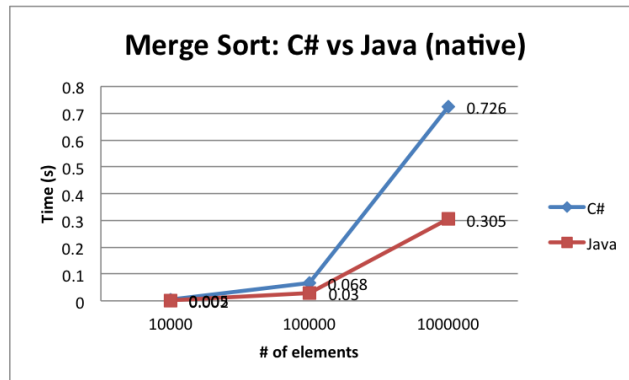


Figure 5.9. Comparing Java and C# when both are run in their respective native environments.

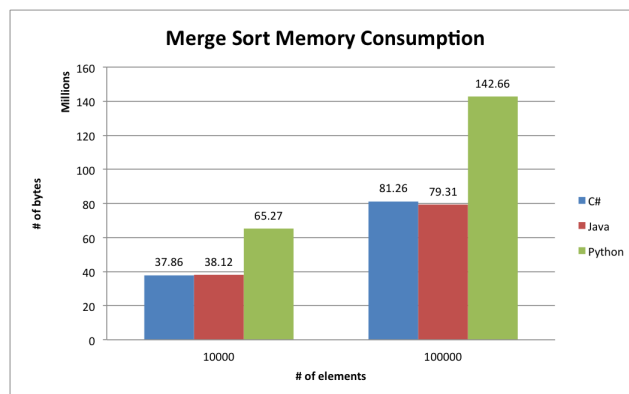
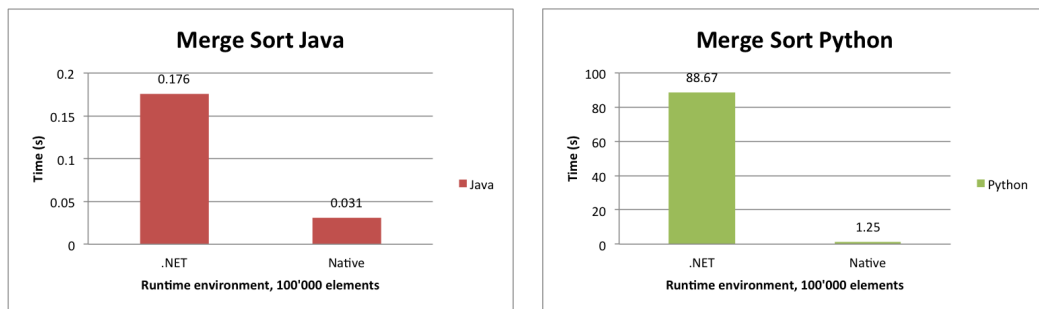


Figure 5.10. Comparing Java and C# when both are run in their respective native environments.

5.3. RESULTS



(a) Java under the .NET Environment and the native environment. (b) Python under the .NET Environment and the native environment.

Figure 5.11. Comparison of running under the .NET Environment and the native environment with Java to the left and Python to the right (using 100'000 elements).

Chapter 6

Discussion

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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