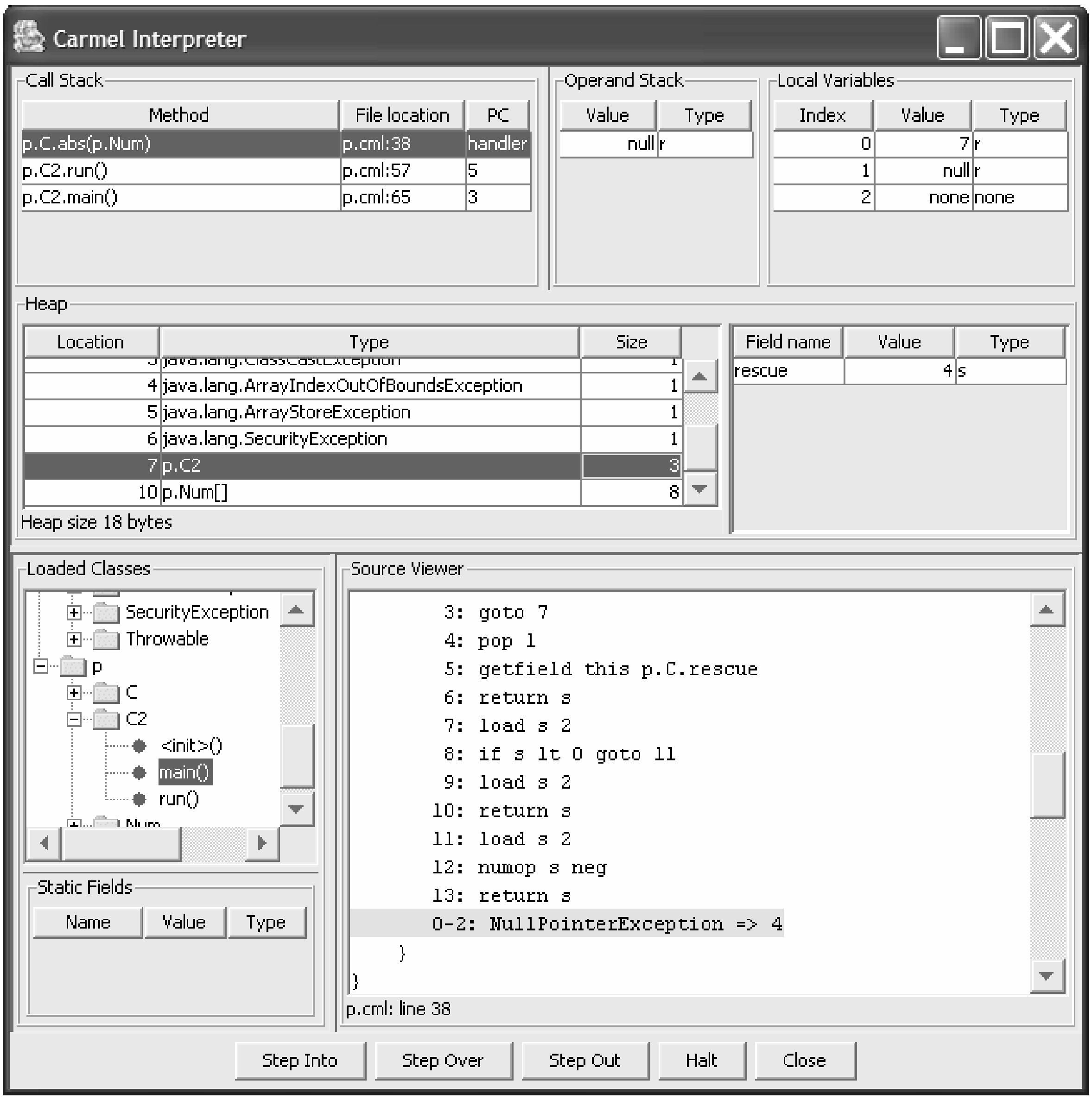
A Web-based Carmel Interpreter

A final year project for ENSIMAG, Grenoble

by Luke Jackson



Method	File location	PC
p.C.abs(p.Num)	p.cml:38	handler
p.C2.run()	p.cml:57	5
p.C2.main()	p.cml:65	3

Value	Type
null	r

Index	Value	Type
0	7	r
1	null	r
2	none	none

Location	Type	Size
4	java.lang.ArrayIndexOutOfBoundsException	1
5	java.lang.ArrayStoreException	1
6	java.lang.SecurityException	1
7	p.C2	3
10	p.Num[]	8

Heap size 18 bytes

Field name	Value	Type
rescue	4	s

Name	Value	Type

```
        3: goto 7
        4: pop 1
        5: getfield this p.C.rescue
        6: return s
        7: load s 2
        8: if s lt 0 goto 11
        9: load s 2
       10: return s
       11: load s 2
       12: numop s neg
       13: return s
       0-2: NullPointerException => 4
    }
}
```

p.cml: line 38

The interpreter can be found on the project web page, which also contains the source code, sample Carmel files, additional documentation, an electronic copy of this report, and a user's guide.

http://www.doc.ic.ac.uk/~lj97/project/

Abstract

Smart cards are becoming a widely used method to prove identity and safely store money and money equivalents. The Java Card platform brings Java's "write once run anywhere" promise and security model to the smart card platform. Carmel, a textual representation of the binary format Java Card virtual machine language, has been defined to aid the analysis and the development of formal proofs for the Java Card platform and Java Card applets.

This document introduces a web-based Java Card virtual machine. The machine runs Carmel programs according to a defined set of semantics and exposes its internal state via a graphical user interface. It is intended to be an aid to developers who wish to examine the structure and behaviour of Carmel programs and the Java Card virtual machine, as well as providing reusable components for use in future tools.

Acknowledgements

This project would not have been possible without the help of numerous people, to whom I am very grateful.

Renaud Marlet, at Trusted Logic in Versailles, consistently went out of his way to answer my questions, offer suggestions and ideas, and helped to evaluate the project. Despite a busy workload, he spent a lot of time on this project, at times sending several e-mails a week.

Igor Siveroni, at Imperial College, London, likewise helped me greatly in the latter stages of the project, helping me understand the operational semantics of the Carmel language and providing constructive and thoughtful remarks on the interpreter's user interface.

Jim Cunningham, also at Imperial College, London, made the effort to come to Grenoble to visit me, and provided me with general advice about the project.

I must also thank Steffen van Bakel, my personal tutor and project supervisor, who proposed such an interesting project when, at the very last moment, my first choice project fell through.

Finally, I'd like to thank Franck Rousseau at ENSIMAG, Grenoble, for offering to be my project supervisor at Grenoble.

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1. Introduction

In order to introduce the project, its context is first provided. The project goals are then described, similar work discussed and the structure of this report is described.

1.1 Smart Cards

Smart cards are plastic cards with an embedded chip, and have a wide range of everyday applications, such as:

- Bank cards, such as credit and debit cards
- Cards that hold money ("stored value cards") or money equivalents ("affinity cards", such as phone cards)
- Mobile phone SIM (Subscriber Information Module) Cards
- Identity cards, which provide identification when connecting to a computer network
- Subscription cards for satellite, cable and digital broadcast television set-top boxes

Recently developed are contact-less smart cards, which communicate electromagnetically with the card reader at a distance of about 5-8 centimetres. These are proving useful in situations where fast interaction is required, such controlling access to public transportation systems, or where transparency of the interaction is important, such as chips embedded into car keys as part of anti-theft systems.

Smart cards are tamper-resistant and generally use encryption to secure identity and prevent unauthorised access or piracy. Stored value cards hold information locally, and hence they do not need to access remote databases, incurring a much lower overhead than traditional magnetic-stripe card systems. This means that they can be used for large numbers of low value transactions, suitable for electronic cash systems and public telephones.

Invented in 1974, there are now over 3 billion smart cards in circulation, the majority of which are found in Europe, South America and Asia. Their use in the United States and the United Kingdom has lagged behind but is now growing rapidly.

There are two main types of smart cards: those with a microprocessor (commonly referred to as chip cards), and those with a pre-defined logic (memory cards). Memory cards can only perform a fixed set of operations, whereas chip cards can run programs stored in the card's memory and, importantly, can download and run new programs after the card has been made and issued. A typical chip card has a 16-bit processor, tens of kilobytes of ROM and EEPROM (writable memory that is not lost when power is removed), and about a kilobyte of volatile RAM.

Smart card development has always been driven by standards to ensure interoperability between different cards and card readers. Both international (the ISO 7816 series) and commercial (e.g. EuroPay/MasterCard/Visa) standards have been developed to define the communication protocol between cards and card readers.

However, with the advent of chip cards, there was no standard concerning the interaction with a chip card's operating system, nor a universal framework on top of which to build card applications (applets). Initially applets were written in a low-level language, tightly coupled to the type of processor, the operating system, which was often modified to suit the specificities of the applet. However, in 1996, a team of engineers at Schlumberger managed to squeeze a version of the Java Virtual Machine onto a chip card with only 12 kilobytes of memory, eventually leading to the development of the Java Card platform.

1.2 Java Card

Java is a high-level multi-platform object-oriented programming language. Java programs are not compiled directly to native code, but are compiled into virtual machine instructions, stored in a .class file, which are then run by a virtual machine.

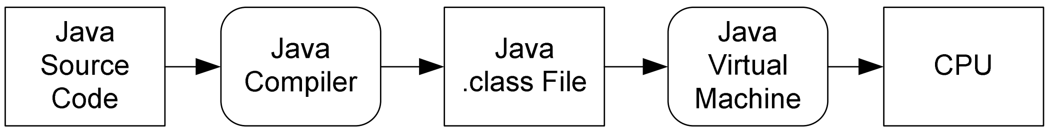


Figure 1 Compilation and execution of a Java program

Once a virtual machine has been implemented for a certain computing platform, the .class files generated by any Java compiler can be executed on it. As virtual machines are now available for many different platforms, a Java program can be run on any one of them without modification or recompilation.

The advantages that Java brings to a chip card environment, compared to the previous proprietary systems, are many, and all major developers for the chip card market have made commitments to the Java Card platform. Such advantages are:

- Java: applets can be written in a widely-known, high-level and object-oriented programming language.
- Interoperability: a Java Card applet can run on any Java Card, irrespective of its processor type or any other hardware specific.
- Common framework: a set of framework classes allows the developer to concentrate on application-specific code.
- Dynamic loading of applets: a company can easily load new applets onto a Java Card without having to reissue the card.
- Secure: a Java Card can contain applets from different companies which can interact with each other, but are prevented from accessing, modifying protected data and interfering with each other's behaviour.

However, to allow Java to run on such a limited platform, a number of simplifications and modifications had to be made to the Java language and the Java Virtual Machine. Full details of these changes can be found in [Sun00].

At a language level, the most important changes are as follows:

- No large primitive types like 64-bit integers, characters and floating point numbers. Support for 32-bit integers is optional.
- No threads.
- No multidimensional arrays.
- Garbage collection is optional, and hence finalisation is not supported.
- No dynamic class loading. Applets, however, can be dynamically loaded by a card reader.

The Java Card virtual machine is split into two parts. The first part, known as the converter, runs off-card on a normal workstation, and serves to make the second part, known as the interpreter, which runs on-card in the limited environment, as small and simple as possible.

The converter reads a Java .class file and performs two main operations: it verifies that no unsupported language features are used, and it converts all package, class, method and field names to numeric identifiers. This not only reduces the size of the program, which will be stored in a Java Card's limited memory, but performs a significant part of the linking process, which would have otherwise have been executed using the Java Card's limited processing power. The resulting representation is written to a CAP (converted applet) file.

Additionally, an EXP (export) file is created which stores the name and numeric identifier of the package and of each publicly accessible class, method and field, so that references to these objects made in other applets can be converted to the correct values.

The CAP file is loaded onto the Java Card by a card reader, and the interpreter is then able to perform the last stage of the linking process so that the applet is ready for use.

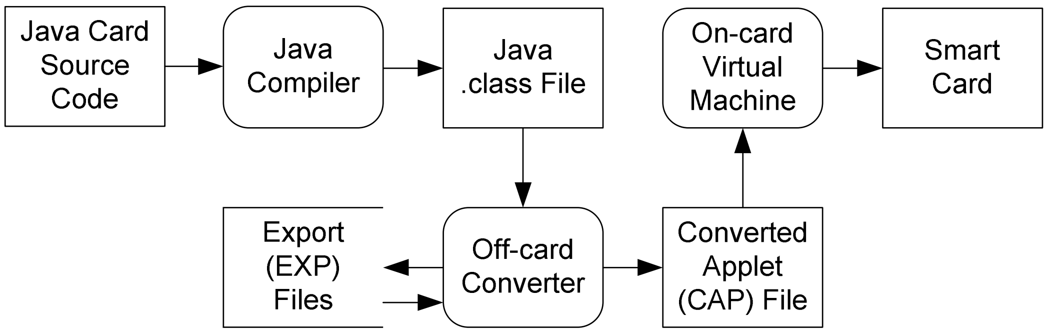


Figure 2 Compilation, conversion and execution of a Java Card applet

Although the interpreter is just the on-card part of the Java Card virtual machine, it is commonly referred to as the “virtual machine”. For this reason, the terms “virtual machine” and “interpreter” are used interchangeably in this report to refer to the on-card part of the Java Card virtual machine.

1.3 Carmel and the SecSafe Project

The SecSafe (SECure and SAFe) project is an EU-funded research project which is researching the use of static analysis to as a way of proving the security features of the Java Card platform and Java Card applets. Static analysis is performed without actually executing the applet, but by examining its structure.

While it would be possible to make proofs on a Java Card applet’s original Java source, a separate proof would be required to show that the Java compiler and the off-card converter preserve the result of the proof. As the translation between Java language and the Java Card virtual machine language (JCVML) is not simple, such proofs would be significantly more complex than proofs made directly on the JCVML.

However, JCVML instructions are represented in binary form, stored in CAP and EXP files. It is therefore important to define a textual syntax for this language to facilitate the expression of proofs, and for communicating JCVM programs between humans.

Carmel (also known as JCVMLe) is such a textual representation. Package, class, interface, field and methods are defined in a syntax based on the syntax of the Java language. However, method bodies, which contain JCVM instructions, are particular to JCVML and are represented in a different syntax. The full Carmel syntax, as defined in the context of this project, can be found in Appendix A.

1.4 Project Goals

The goal of this project is to model the operation of a Java Card, as defined by the operational semantics developed for the SecSafe project [SH01]. This involves implementing a Java Card virtual machine and providing a graphical interface to view its internal state and allow the user to simulate communication with a card reader. Instead of interpreting pre-compiled applets, the virtual machine will interpret Carmel source files directly.

The program has two purposes. Firstly, it is to be used a general-purpose tool by SecSafe members to aid the validation and proving of Java Card based systems. Secondly, the loading, linking and verification components are to be reused in a future tool to perform static analyses of Carmel programs.

Specifically, the goals are:

- The design and implementation of a program that models a Java Card, including its virtual machine and its external interface with a card reader.
- The virtual machine is to interpret programs express in the Carmel language.
- The behaviour of the interpreter is to respect the defined operational semantics.
- The program is to run from the web.
- The program is to provide a graphical representation of the Java Card's internal state at given points during a program's execution.
- The graphical user interface should be easy to use and express the internal state in a way understandable to the user.
- The program is to be designed in a modular fashion to facilitate code re-use.

Considering the size of the project, it was expected that the project would not be completed within the limited amount of time available (less than four months), and as such, the goals are to be considered as targets to work towards.

1.5 Similar Work

Sun Microsystems provides a Java Card simulator and debugger, called the Java Card Toolkit, to licensees of Java Card technology. It integrates with third-party IDEs (Integrated Development Environments) and helps Java Card developers implement and debug Java Card applets. However, it is not free: licensing Java Card technology from Sun is very costly. Sun also provides a simpler, free implementation of a Java Card virtual machine which runs on Windows and Solaris workstations.

While these are useful tools for developers of Java Card applets, they are not particularly suited for the needs of the SecSafe project, such as static analysis of Java Card applets, and conformity to the Carmel operational semantics. Additionally, neither of the tools supports the Carmel language.

1.6 Report Layout

The rest of the report is organised as follows:

Section 2 describes the initial decisions taken before the design stage, such as the choice of the program's architecture and language.

Sections 3, 4, and 5 describe the design and implementation of the three main components of the program: the loader, which loads Carmel programs into memory; the interpreter, which interprets them; and the user interface, which allows the user to control the interpreter, and represents its internal state.

Section 6 describes the creation of the project web site and the technology used to launch the program over the web.

Section 7 evaluates the work performed and section 8 provides a conclusion, along with possible improvements and extensions to the project.

References can be found in section 9, and there are two appendices: the first defining the grammar of the Carmel language and the second detailing security checks that were not implemented.

2. Initial Decisions

2.1 Client-side or Server-side

As the interpreter is to be launched over the web, I had a choice as to where the interpreter would execute: client-side or server-side. Client-side means that the interpreter's code is downloaded from the web server by the end-user, and then run on the user's computer. Server-side means that the interpreter's code executes on the web server, and that communication with the end-user takes place over the network via HTTP messages.

The disadvantage of a server-side approach is that all communication between the user and the interpreter has to take place between the browser and the web server, and therefore:

1. The time to react to a user's command would be noticeable, as a message needs to be sent, processed, the new contents of the web page generated and sent back again.
2. The interpreter's state would have to be represented in HTML. As the interpreter's state is complex, representing it in HTML would be difficult, and would not permit it to be displayed in an optimal manner.
3. The graphical controls for the interpreter would also have to be represented in HTML, which only has a limited support for buttons and links, making the design of a rich and easy-to-use graphical interface difficult.

The advantage of such an approach, however, is that the only requirement for the end-user to be able to use the interpreter is to have a web browser and an Internet connection; no specific platform, operating system or additional software is required.

However, given that the expected users of the interpreter are very likely to be Java Card researchers or developers, and that the development and execution of Java Card programs requires Java, it can safely be taken for granted that they will have Java installed on their machines. Java runs on all major computing platforms and supports client-side execution of applications over the web, and so such a solution seemed ideal.

2.2 Language Choice

Before making the decision to use a Java-based client-side solution, it was important to be sure that Java was a suitable language for the project. The main parts of the interpreter are: parsing Carmel programs, building and linking the abstract syntax tree, interpreting Carmel instructions, displaying the interpreter's state to the user, and the web-launcher.

Java is a general purpose, high-level, object-oriented language with which I was already familiar. I knew from experience and by researching existing programs that implementing a large project such as the interpreter would not pose any special problems at a language level. Indeed, as Carmel is a language very close to Java, with similar concepts and the same data types and operators, interpreting Carmel instructions and representing Carmel types in Java is intuitively a logical choice.

However, it was also important that the necessary tools were available in Java. Parsers are usually generated automatically from their grammars by parser generators. Similarly, there exist tools for building the first stage of an abstract syntax tree. I researched the availability of these tools for Java, and found that I had a wide range of frequently used tools to choose from. The decisions as to which tools I used can be found in sections 3.3.1 and 3.4.1.

Similarly, I wanted to be sure that Java provided suitable graphical components which to build the interpreter's graphical interface. I had a choice between AWT and Swing, and found that Swing satisfied the needs of the project. This decision is detailed in section 5.1.

Finally, I had to ensure that Java programs could be launched from the web. I found that I had a choice of web launch technologies, which are described in section 6.1.

Therefore, having ensured that Java was a suitable language, and that the required tools were available for it, I made the final decision to use it as part of a client-side solution.

3. Loader

In this section, I will describe the design and implementation of the loading, parsing, linking and verifying of Carmel programs. These processes progressively construct a valid internal representation of a Carmel program, which is in the form of an abstract syntax tree. Once the tree is built, the program is ready to be interpreted.

3.1 Static Structures

Before implementing the loading process, it was first necessary to design the classes with which to represent Carmel programs. The first three sections describe how the Java Card and Virtual Machine type systems are modelled, along with the singleton design pattern which influenced their design. The final two sections describe the design of the abstract syntax tree, along with the visitor design pattern which provides a useful way with which to process its nodes.

3.1.1 Java Card Types

There are two different sets of Java types: primitive types and reference types. Primitive types are those that are supported directly by the Java virtual machine, and reference types are classes and interfaces that are defined by the user.

Java Card supports a subset of the Java primitive types: boolean, byte, short and, optionally, int. It does not support char, long, float and double. Java Card supports all four Java reference types: classes, interfaces, arrays and null. Although never explicitly used in a Java or Java Card program, null is the type of the value null. There is a second special type: void. Void is only used for method return types, and denotes that the method does not return a value.

In creating classes to represent the Java Card types, I created abstract classes to group together related types. The class hierarchy is shown in Figure 3.

The root of the hierarchy is ResultType. ResultType encompasses VoidType, which cannot have a value, and Type, which represents the other types, which do have values. Type is further split into PrimitiveType and ReferenceType. The numeric primitive types are grouped together by NumericType. ReferenceType is split into ClassOrInterface, ArrayType and NullType.

ClassOrInterface is split into Class and Interface. Detail on the design of Class and Interface is given in section 3.1.4. ArrayType contains a reference to its component type, represented by the interface ComponentType. As multidimensional arrays are not permitted in Java Card, ComponentType is not implemented by ArrayType, but is implemented by all other types except VoidType and NullType.

ComponentType and ReferenceType, along with their supertypes, Type and ResultType, are implemented as interfaces to allow for multiple inheritance. In Java, classes can only have one superclass, but any number of superinterfaces. ClassOrInterface inherits from both ReferenceType and ComponentType, which would not be possible if they were not interfaces. This also leaves ClassOrInterface the possibility to have a superclass (which it does: see section 3.1.4 for more details).

Each type that implements the Type interface implements the method getJCVMType which returns the corresponding type in the virtual machine type system, as described in the next section.

Finally, each type implements the isAssignableFrom method. A type implements the method to tests whether the type of the specified parameter is the same, or can be converted to the same type via a widening reference conversion. A widening reference conversion can take place if the parameter's type is a class or interface, and the type is either a superclass or an interface that is implemented by the parameter's type.

As primitive types are neither classes nor interfaces, they simply check to see if the parameter's type is equal to them. Classes check to see if they are the same as, or a superclass of the parameter's type. Interfaces check to see if they are the same as, or are implemented directly or indirectly by, the parameter's type. Arrays check to make sure the other type is an array and, if so, checks the component types. An exception is made for the null type, whose value can be assigned to any reference type.

For more information, see section 5.1, and specifically section 5.1.4 of [GJSB00].

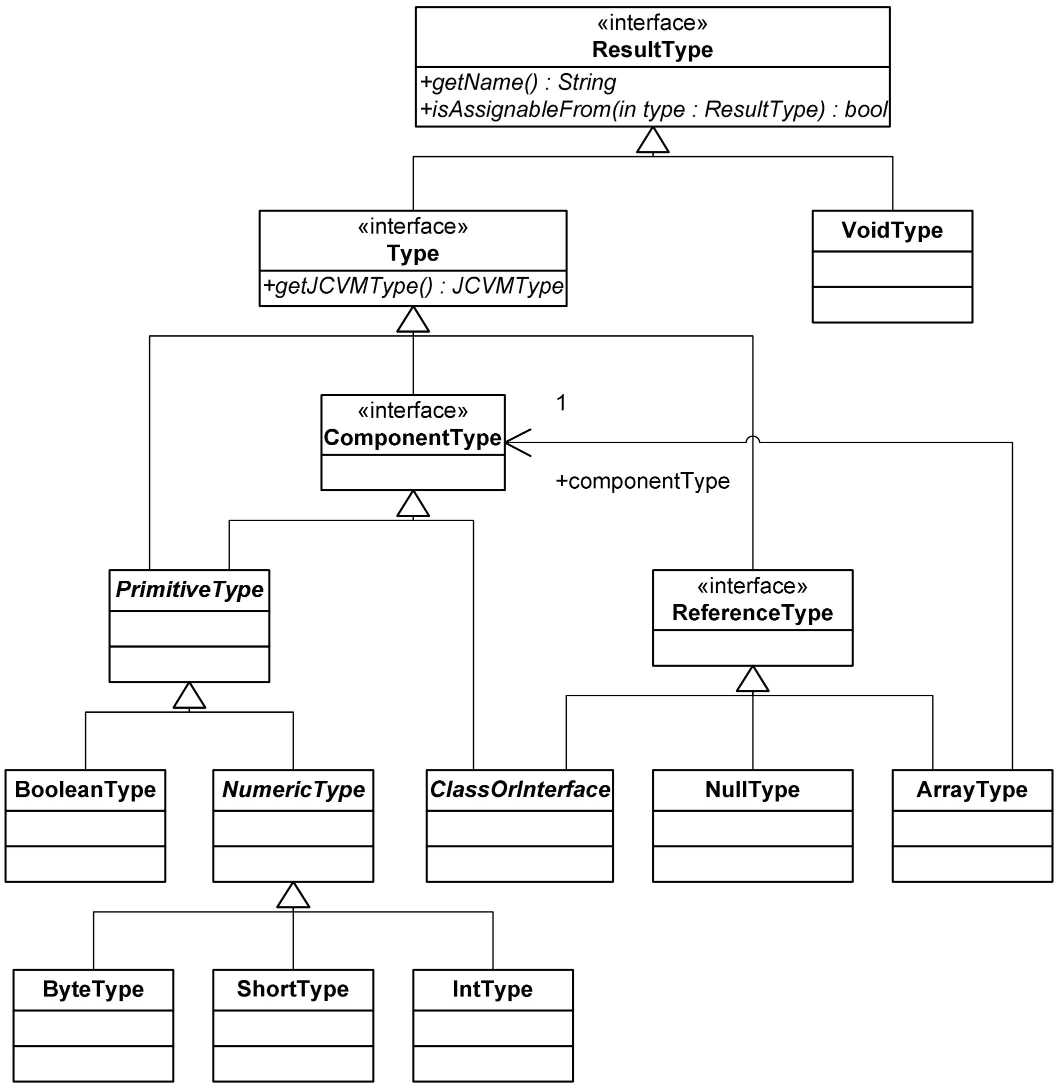


Figure 3 Java card types

Note: ClassOrInterface is shown in greater detail in Figure 5.

3.1.2 Virtual Machine Types

The type system of the Java Card virtual machine is related, but not identical, to that of Java Card. The boolean type does not exist at the virtual machine level, but is considered identical to the byte type. There is an additional return address type, which represents the type of a subroutine call's return address. Finally, there is the ⊥ type, which represents the type of an undefined value, such as that of an uninitialised local variable.

In creating classes to represent the virtual machine, I took into account the type hierarchy described in [SH01] and [Mar01] and made some minor modifications to take into account the requirements of the interpreter. The class hierarchy is shown in Figure 4.

The root of the hierarchy is JCVMType. JCVMType encompasses JCVMReturnAddressType, JCVMOperandType, and JCVMBottomType, which represents the ⊥ type. JCVMOperandType represents all types that can be used as an instruction operand, and is split into JCVMNumericType and JCVMReferenceType. JCVMReferenceType is the corresponding virtual machine type for classes, interfaces, arrays and the null type.

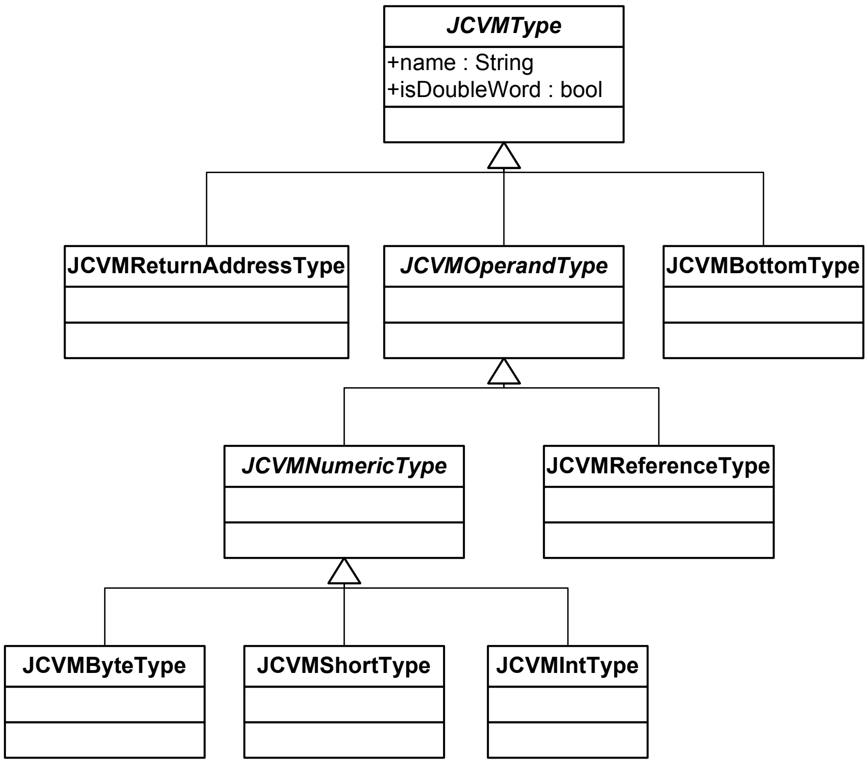


Figure 4 Virtual machine types

3.1.3 Singleton Design Pattern

In order to use object oriented programming techniques such as virtual methods with the classes that represent Java Card and virtual machine types, class instances are required. With the exception of an array type, it does not make any sense to have more than one instance of each type. In fact, multiple instances waste memory and complicate checking for equality.

The singleton design pattern, as defined in [GHVJ94], ensures that only one instance of a given class can ever exist. Instantiation can be controlled by giving constructors protected or private access modifiers, and then providing a publicly accessible static method or static final field that gives access to the single instance, which is created internally on class initialisation.

Each concrete class representing a Java Card or virtual machine type therefore has a private constructor and a public static final field named TYPE which provides access to the single instance.

3.1.4 Abstract Syntax Tree

The abstract syntax tree is simply a tree representation of a Carmel program that is in a format suitable for interpretation, unlike the flat textual representation which is suitable for humans to read, write and understand.

The first step in designing the abstract syntax tree was to make a list of all of the different classes I would need to implement in order to represent each node of the tree: package, class, interface, constructor, method, field, each of the instructions and exception handler. In doing so, I tried to stay close to the program structure defined in [Mar01].

Having done this, I looked at common attributes and behaviours amongst these classes and designed abstract superclasses to factorise these commonalities. Hence, I created the abstract classes “Field” as a parent for static and instance fields; “ConstructorOrMethod”; “ClassMember” for constructors, methods and fields; “ClassOrInterface”; “ClassOrClassMember” for classes, interfaces and class members; and “Instruction” for Carmel instructions.

A simplified UML diagram of the resulting abstract syntax tree is shown in Figure 5. To conserve space, the diagram does not include the 30 Carmel instructions, all of which inherit from the abstract class “Instruction”.

Up until the level of instructions, the tree structure is straightforward. The only notable property is that nodes reference both their parent and their children.

The getMethod, getField and getStaticField methods implemented by the Class and Interface classes look for the requested class member in it own class and, if it is not found, delegates the search to its superclass or superinterfaces.

The isAccessibleFrom method implemented by classes, interfaces and class members checks to see if, based on its access modifiers, the class specified in the parameter has the right to access it. This method is very important, as it is the basis of the Java Card security system, and prevents classes of one applet being improperly accessed by another. The rules for access are defined in section 2.7.4 of [LY99].

At the instruction level, I decided not to use a list or an array to store a method’s (or constructor’s) instructions. All instructions are referred to by their address, which is a non-negative number. There is, however, no requirement in the language that the first instruction be labelled 0, and that subsequent instructions have the address of one plus the address of its previous instruction, and therefore a direct mapping from an address to an array index would not be possible. While I could convert and replace the addresses by array indices, I would still have to store the original address to be presented to the user. I could have also used a map between instruction addresses and array indices, but this approach seemed inefficient.

Finally, I decided to implement a method’s instruction block as a direct reference to the first instruction. Each instruction then references its next instruction, as well as any other instructions to which control may pass as a result of its execution. For example, an “if” instruction would reference both its next instruction (used if the condition evaluates to false), and its target instruction (used if the condition evaluates to true). This is an efficient approach which, in setting the references, also verifies that all instruction address references are valid.

Instructions still hold their addresses, which are used for displaying to the user, and for exception handlers. An exception handler covers a range of instructions, denoted by start and finish addresses, and handles a certain type of exception by diverting program flow to a given target address. Although exception handlers are nested in Java, i.e. any one handler range either encloses, is enclosed by, or is disjoint of, any other handler range, this property is not enforced at the virtual machine level.

Due to this arbitrary arrangement, it wasn’t possible to add exception handling information efficiently to the instruction block data structure, and so I implemented it as a simple list, and had each handler reference the start and end instructions’ addresses, rather than the instructions themselves.

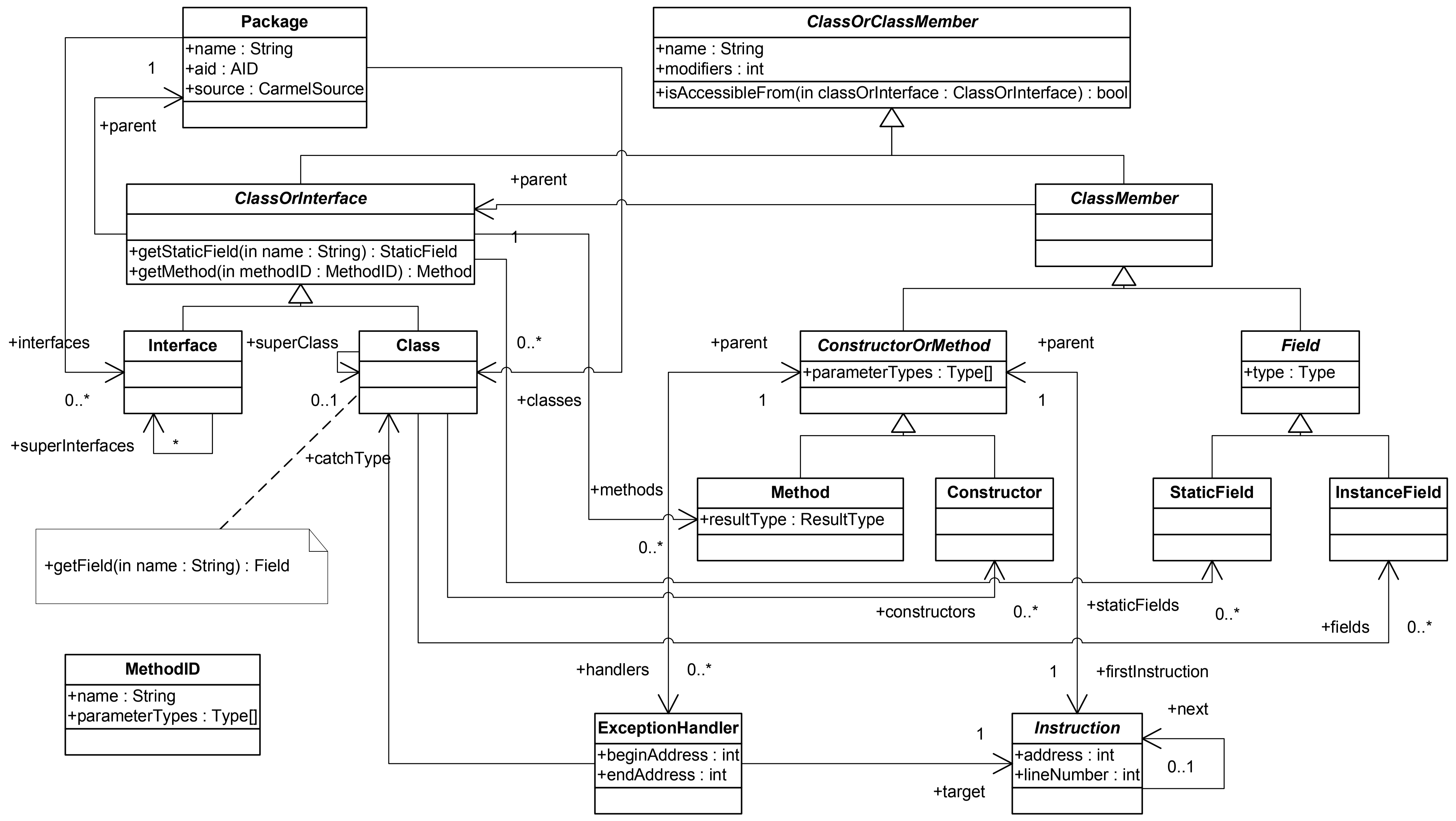


Figure 5 Abstract syntax tree

3.1.5 Visitor Design Pattern

Before describing the linker, verifier or interpreter, it is important to introduce the visitor design pattern [GHVJ94]. This is the design pattern used in the design of each of those components.

The visitor design pattern can be considered as an object-oriented way of implementing a switch statement over the runtime type of a given element.

The most obvious approach to implementing this solution would be to use a series of if-else checks using the instanceof operator. However, this is not efficient, produces dirty code, and is not an object-oriented solution.

Assigning each type a unique ID would allow the use of a switch statement. Although more efficient, the ID is redundant information that needs to be maintained by the programmer. Again, it is not an object-oriented solution.

A more object-oriented solution would be for all elements to implement an interface, which defines a method for the implementation of the desired action. The actual method that is implemented is then determined at runtime by the virtual machine. However, this means that code to perform a given operation, which is more logically grouped together, is spread out amongst the different elements. This also prevents an operation from gathering state information from one element to the next. Additionally, changing the operation's code involves recompiling the element classes, and adding new operations requires creating a new interface and adding a new method to each element, again requiring recompilation. This is especially problematic when the source code is not available for the different element types.

The visitor design pattern is a solution that avoids all of these drawbacks. The key to the visitor design pattern is a double method call, known as a double dispatch.

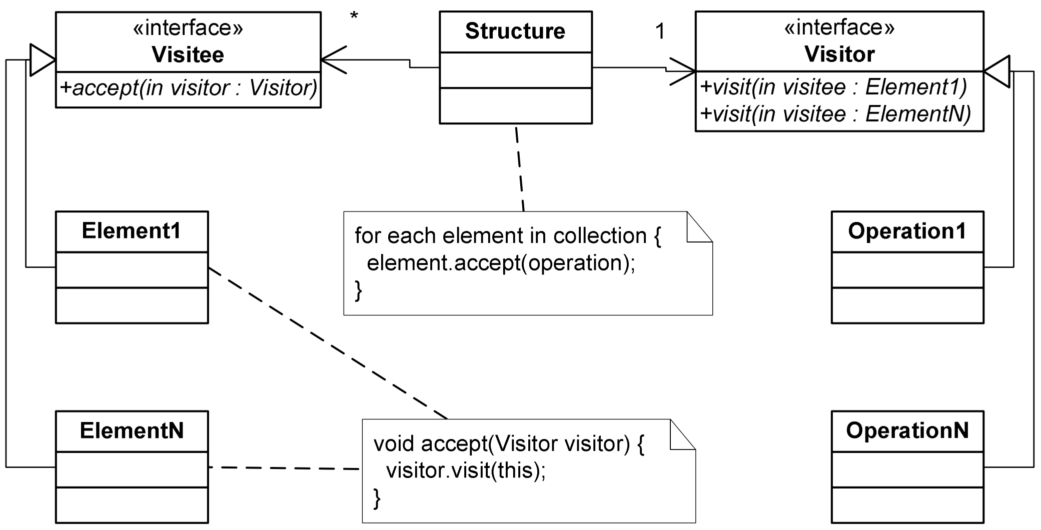

«interface»
Visitee
+accept(in visitor : Visitor)
*
Structure
1
«interface»
Visitor
+visit(in visitee : Element1)
+visit(in visitee : ElementN)
Element1
for each element in collection {
  element.accept(operation);
}
Operation1
ElementN
void accept(Visitor visitor) {
  visitor.visit(this);
}
OperationN

Figure 6 Participants in the visitor design pattern

Similar to the previous solution, each element implements an interface, which defines an "accept" method that takes a "Visitor" as a parameter. Instead of implementing the required action in this method, the method makes a second method call back on the "Visitor", which in turn implements the action.

Each operation that takes place on the elements implements thus implements this "Visitor" interface, which defines a "visit" method for each element type: it is these methods that are called by the elements. Each operation then implements the interface by implementing the methods to perform the required action.

For a class to execute an operation on a group of elements, it just asks each element to "accept" the operation passed as a parameter.

3.2 Source Reader

As a Carmel source can be stored in a number of ways, such as in a normal file in the local file system, in a JAR file, as string in memory, or on the Internet, I created an abstract definition of a Carmel source defining its basic properties and operations.

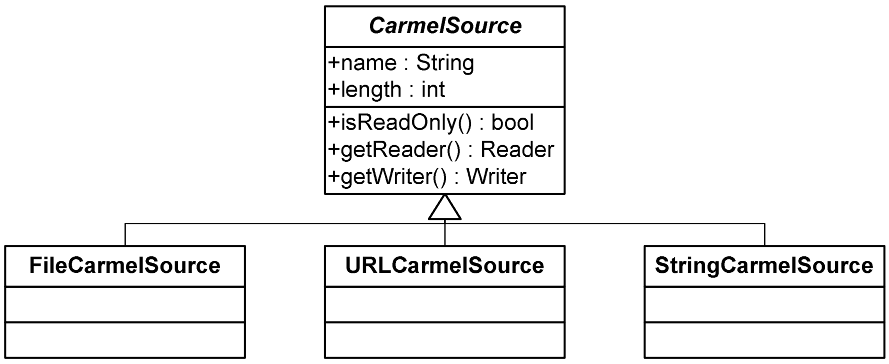


Figure 7 Carmel source

The URLCarmelSource encompasses both network addresses and JAR files. This is because Java references JAR files as URLs prefixed by “jar:”.

A source has a name, which is used to identify the source to the user, and a length in bytes. The methods getReader() returns an instance of a character reader interface, which abstracts away the implementation of how characters are actually read. The optional support for writing, not available for URLs, is useful for allowing the user to correct an error.

3.3 Parser

3.3.1 Parser Generator

The large majority of parsers are generated automatically by parser generators. Parser generators take as an input the grammar of the language to be parsed, and generate the required parsing code.

The advantages of using a parser generator is that it generates code that is more efficient and less error-prone than hand written parsers, in a fraction of the time. However, as parser generators are not specific to any language, heavily customising the generated parser can be problematic. As speedy development of the parser was of paramount concern, and that the resulting parser did not require much customisation, I decided to use a generator.

The main parser generators that I found for the Java language were JavaCC [Web01], SableCC [Gag01], ANTLR [Par00] and JLex/CUP [Hud99].

JavaCC, SableCC and ANTLR are all recursive-descent, or top-down, parsers, where as JLex/CUP is a bottom-up parser. Recursive descent parsers are generally much easier to program and debug, due to the intuitive nature of defining the grammar in a top-down approach. Hence, I decided against using JLex/CUP, development of which seemed to have stopped in late 1999.

Investigating SableCC showed it to be an interesting and well-designed parser generator, which also generates parse trees, also known as concrete syntax trees. However, experimentation proved it to be too restrictive: it enforces upon the developer a number of design decisions; it does not allow “action code”, which, although not always the most suitable solution in terms of object-oriented design, is nevertheless a very useful and powerful way of customising the parse process; and the parse tree it generates requires a large and costly transformation into a separate abstract syntax tree. Additionally, development of SableCC is on indefinite hold.

The two remaining parser generators, JavaCC and ANTLR, are largely similar. They are both top-down parsers, they both allow action code, and they do not enforce automatic building of a parse tree. I chose JavaCC over ANTLR because it supported Unicode (essential as Java, and therefore Carmel, identifiers are expressed in Unicode), was much more widely used, had more documentation and support available for it, and seemed under active development.

3.3.2 Implementation

As the Carmel grammar closely resembles Java up until the representation of method bodies, I based my grammar definition file on a Java grammar that is distributed with the JavaCC program. Although copyrighted by Sun, they grant the free use of the grammar for any purpose.

It took me some time to fully understand how JavaCC worked and the syntax of its grammar definition files. Fortunately, there was a lot of documentation available, as well as an Internet newsgroup dedicated to the program.

My first step was then to remove all of the grammar rules that applied to Java but not to Carmel. In doing so, I realised that the Carmel syntax specification document would not be sufficient in completely defining the Carmel grammar. For example, unsupported rules such as a Java expression or a statement block appeared in the productions for field declarations and static initialisers respectively, and new definitions for these rules were not specified.

In a series of emails with Renaud Marlet, the author of the syntax document, I was able to provide definitions for these rules. For example, he told me that static initialisers were not to be supported, and that fields could be initialised with constant values (including an array of constants where applicable), but not by complex Java expressions.

However, a replacement rule for an expression was needed because certain operators were still required, such as a negation operation to represent negative numbers. I therefore modified the rule for a numeric literal to allow for an optional minus sign as well as a casting operation to a numeric type.

I found that the casting operation is useful in defining bitmapped constant field values using hexadecimal: to define a byte with the most significant bit set, the hex value is 0x80. However, without a cast, this value is construed as a positive number, and as bytes are signed, the number is considered too large. Therefore adding an explicit cast, e.g. (byte) 0x80, allows the user to define the value intuitively without causing an error.

Other Java grammar rules that I had to modify were: the package declaration rule, to include the (optional) definition of a package's AID; the constructor declaration rule, to add an alternative syntax of "void <init>" in place of the class name; the array initialiser rule, to reflect the fact that arrays are one dimensional and thus cannot have arrays as their elements; and the parameter rule, to make the declaration of the parameter name optional, as it is purely informational.

At the lexical level, I removed the keywords that were no longer needed, such as long, float, synchronized, etc., and the lexical rules for floating point numbers.

The next step was to add the rules for Carmel instruction blocks. Using the syntax definitions in Renaud's document, I added the necessary keywords and created the necessary JavaCC grammar productions. Once this was completed, I was able to test the parser with sample Carmel files.

3.3.3 Testing

I soon noticed a problem involving the new Carmel keywords and the lexical definition of an identifier. A Java identifier is defined as any letter followed by an optional sequence of letters or digits, that is not a Java keyword. In the grammar definition, a Carmel identifier was defined as any letter followed by an optional sequence of letters or digits that is not a Carmel keyword. As identifiers are not changed in the compilation process, Carmel identifiers should be equivalent to Java identifiers, but the addition of extra keywords (such as the names of Carmel instructions and their parameters) meant that a identifier with the name of one of the new Carmel keywords would be valid in Java but not in Carmel.

For example, “i” is a widely used and valid identifier in Java, whereas it is a keyword in Carmel denoting the JCVM integer type. Similarly, any Carmel instruction name or instruction parameter name would be a valid Java identifier but not a valid Carmel identifier.

I tried several ways to solve this problem, the first of which was to use lexical states. This first idea was to create two lexical states: one which correctly recognised Java identifiers, but not Carmel keywords, and the other which recognised Carmel keywords but not Java identifiers. When a Java identifier is expected, the lexical state would change so that it could be properly recognised, and then the state would switch back to the normal “Carmel” state.

Unfortunately, my implementation of this solution did not work as JavaCC is designed such that lexical state changes have to be affected by lexical rules, not parsing rules. There was no way to detect when the state should change at a lexical level, and trying to switch state in a parser rule didn’t work because of the loose coupling between the lexical analyser (lexer) and the parser: generally the lexer had already read and processed the upcoming identifier before the parser matched its input to the production in which the state change would take place.

Another solution I considered was not to define Carmel keywords as keywords, but replace them in the grammar with identifiers. The parser would then have to check manually that the identifier matched the expected Carmel keyword. I soon abandoned this approach when I realised its disadvantages: the parser would no longer generate useful errors, and would tell the user that it was expecting an identifier when it really wasn’t and, as the rule for a Carmel instruction can start with one of approximately 30 different Carmel keywords, implementing it without the help of the lexer would have been very complex.

Finally the solution I chose was to use a parser rule for an identifier in place of a lexical rule: the parser rule would be a production which could either match to the previous, erroneous, definition of an identifier, or it could match with any one of the Carmel keywords. While still not a very clean approach, the dirtiness is confined to only one rule, and the changes needed in the rules which used to use the lexer rule and now use the parser rule are minimal.

However, this solution did have one drawback: when the parser was expecting an identifier but didn’t find one, it would tell the user that it was expecting either an identifier or one of the 48 extra Carmel keywords, listing them one by one. This would certainly have confused the user, and so I modified the error reporting mechanism such that, if an identifier was present in the list of expected tokens, the extra keywords were removed from the list before the error message was generated.

A BNF representation of the Carmel grammar can be found in Appendix A, and the actual JavaCC file can be downloaded from the project website.

3.4 Tree Builder

3.4.1 Parse Tree Generator

Parse trees (or concrete syntax trees) can also be built by automatically. There are two tree builders that are designed to work with JavaCC: JJTree and JTB. I experimented with both, using the parser I had already written, but found that the automatically built parse trees required a significant transformation into abstract syntax trees. I decided to create the tree manually as I did not think it would not incur any more development time, and would minimise later transformations.

3.4.2 Implementation

Building the tree involved adding action code to the JavaCC grammar. Action code is code that is inserted by the parser generator into the generated parser at specific points in the grammar.

JavaCC parsing rules are represented in the generated parser as methods, and as such can be configured to take parameters and return values. I modified each parser rule to return either a node in the tree, or a value that would be used as a property of a node.

For example, the rule for a class declaration returns an object of type "Class" which contained references to its fields and methods, and the rule for integer values returns a value of type "int", which can then be included as required as a property of the relevant node.

To better demonstrate the addition of tree building code and the use of return values and parameters, take for example the simple rule for a boolean literal. A boolean literal represents an occurrence of either "true" or "false" in a Carmel program.

The parsing rule, which needs no explanation, is as follows:

```
void booleanLiteral() :
{}
{
  "true" | "false"
}
```

In order to modify this code so that it generates part of the abstract syntax tree, it needs to return a boolean value. As boolean values are implemented as byte values by the interpreter, it should return an instance of the class "ByteValue". Also, as the Java (and hence Carmel) grammar is defined in such a way that the expected type of a constant value is always known, the expected type can be passed as a parameter, and a check made straight away to make sure that a boolean value is really expected. The new rule, annotated with action code, is as follows:

```
ByteValue booleanLiteral(Type type) :
{
  Token t;
  ByteValue value;
}
{
  (
    t = "true"  { value = new ByteValue((byte) 1); }
  |
    t = "false" { value = new ByteValue((byte) 0); }
  )
  {
    if (type == BooleanType.TYPE) return value;
    throw new ParseException("Boolean value not allowed here", t);
  }
}
```

The variable t, of type Token, contains information about the token being parsed. In this example, it is passed as a parameter to the ParseException constructor so that the line and column number of its occurrence can be included in the error message.

Constant values and primitive types can be easily handled at the tree building stage; however it is not possible for a parsing rule, given the name of a class, to return a reference to it in the abstract syntax tree. As the tree is still under construction, it is possible that the definition of the reference class appears later in the same file. The same applies for class members and instruction addresses. In these cases, a placeholder reference is used, which is then resolved at a later stage by the linker.

3.5 Linker

The linker resolves indirect references in the tree that could not be resolved (de-referenced) at parse time. The linker is also responsible for finding invalid references, such as a reference to a field that does not exist, in which case the class loading process is aborted and an exception is thrown. This exception contains the error message and the location (file name, line number, column number) of where the error occurred.

The references that need to be resolved are those of instructions, classes, fields and methods.

3.5.1 Instructions

Instructions are referenced by their address. As references are local to a method, instruction references can be resolved very simply by means of constructing a map. For each instruction, except the last, the linker also creates a reference to the next instruction.

3.5.2 Classes

Classes are referenced by their name. It is not specified in [Mar01] whether class names should be fully qualified (i.e. include their package component). While this would have simplified the implementation of the linker, it was decided in consultation with Renaud that enforcing this restriction would both make Carmel programs difficult to read, and overly burden the programmer. In defining how an unqualified class name should be resolved, I consulted [GJSB00] and implemented the Java language rule specified in section 6.5.5.

Class references do not necessarily refer to classes declared within the same file, in which case the declaring file has to be found and loaded (see section 3.7). However, it is important to keep in mind the fact that two classes may refer to each other. Resolving a class reference by loading the referenced class normally (i.e. parsing, linking and verifying it) is not possible since, if the referenced class makes a reference to the original class, resolving that reference will cause the original class, not yet fully loaded, to be loaded again and linked again, causing an infinite loop.

The solution to this problem was to not to link classes immediately when resolving class references, but delaying the linking process until the referring class had finished being linked.

3.5.3 Fields

Fields are referenced by their name. Once the parent class of the field is resolved, as described above, resolving a field reference is simple.

The linker is also responsible for the creation of field IDs. Field IDs allow a class instance's field values to be efficiently stored and accessed in an array. The Field ID of a field remains the same in all class instances, whether it is a direct instance of the declaring class, or a subclass of it.

Such a solution is more efficient than storing field values in a map, indexed by their name, or maintaining a chain of class values containing declared field values, one for the instance's class and one for each its superclasses, and implementing a lookup mechanism.

Field IDs are assigned by the following algorithm:

1. If the class has a superclass, its instance fields are recursively assigned identifiers.
2. If no superclass declares an instance field, the first field ID to be assigned by this class is 0; otherwise it is one greater than the highest field ID defined by its superclasses.
3. For each field declared by the class, a field ID is assigned. The first field is assigned the field ID found in step 2, and subsequent fields are assigned IDs one greater than that of the previous field.
4. If the ID assignment was requested by a subclass, return the highest field ID.

3.5.4 Methods

A method is identified by both its name and its parameter types, together known as its signature. As parameter types may be classes, these classes need to be resolved before a method’s signature is created. This means that to resolve a method reference, not only does the method’s parent class need to be loaded, but it also needs to be linked so that its method’s parameter types are resolved. However, as explained in 3.5.2, immediately linking referenced classes can result in an infinite loop.

To avoid this problem, the linking process is split into two passes. In the first pass, instructions, classes (including parent classes of method references, and method parameter types) and fields are resolved. The first pass delays the linking of resolved classes, as explained earlier. Once all classes have been linked by the first pass, the second pass is launched.

The second pass resolves method references. As the parent class of all method references has now been linked by the first pass, the method signatures have been determined and the linking can take place. The first pass creates a map from method signatures to methods, and the second pass simply performs a lookup in the map.

This algorithm is explained in much greater detail in section 3.7.2.

3.5.4.1 Note on Virtual Methods

The Java Card Virtual Machine, and hence Carmel, supports virtual methods. Virtual methods are method calls whose target method depends on the runtime type of the object on which the method is invoked. For example, a method invoked on an object whose type is known only as an interface at compile time will always result in a method invocation on a class. The actual implementing class that is whose method is invoked is determined by the runtime type of the object concerned.

Although the second pass of the linker resolves virtual method references, it does so only to ensure that a method will be found at runtime, and to provide the interpreter with the required information to perform the runtime method lookup procedure.

3.5.5 Implementation

The two passes of the linker were implemented as tree walking visitors that visit the node in a depth-first manner (see section 3.1.5), starting at the package declaration node.

Resolving class references is performed by both the linker and the package loader (see section 3.7). The linker is responsible for implementing the conversion of unqualified class names to qualified names. The package loader, given the qualified name and required state in the linking process, is responsible for loading the class. The package loader is also responsible for launching the delayed linking of referenced classes.

3.6 Verifier

The verifier ensures that a given Carmel program is safe and structurally correct. In [LY99], the verification process is defined as “a set of required checks to verify that [a class or interface] obeys the semantics of the Java virtual machine language and that it cannot violate the integrity of the Java Virtual Machine”.

Verification is a vital part of ensuring the security of the Java Card platform, without which it would be possible to write programs that crash the virtual machine, or illegally access and modify other card applets’ data. Verification also prevents problems associated with version skew: although a Java Card program compiles correctly with external classes, these classes may have changed since compile time, and a re-verification checks for unanticipated problems.

As Carmel is simply a representation of the Java Card virtual machine language, the relevant checks are specified in the Java Card virtual machine specification (specifically, chapter 4 of [Sun00]), which in turns refers to checks for the Java virtual machine in [LY99]. Additionally, some of these checks are formalised in the operational semantics of the Carmel language [SH01].

There are two types of checks to be carried out: static checks and structural checks. Static checks can be carried out by simple analysis of the abstract syntax tree, but structural checks require a data-flow analysis of instruction blocks.

3.6.1 Static Verification

The majority of the static verification checks specified in [Sun00] and [LY99] are either not applicable (such as those concerned with the structural integrity of the binary format .class file) or are implemented by the linking process (such as verifying that class, field, method and instruction references are valid).

I read the relevant sections of the three documents and made a list of the checks that needed to be made. I reviewed the implementation of the parser, tree builder and linking passes to ensure that either each check was either implicitly respected (for example, references to field objects are guaranteed by the Java type system not to refer to another type of object), or were made explicitly.

In doing so, I added accessibility checks to the linking passes: each time the linker creates a link between one class and another, it calls the isAccessible method (see section 3.1.4) of the referenced class or class member, and throws an exception if the reference is not allowed.

3.6.2 Structural Verification

Structural verification checks are more difficult to make than static checks, as they require a flow analysis of each instruction block. Examples of such checks are:

- No matter the path of execution, each instruction will execute with the correct number and type of parameters on the operand stack.
- The operand stack will never overflow or underflow.
- Local variables are always assigned a value before they are accessed.
- Class instances are initialised before they are accessed.

Although the large majority of these checks can be performed at runtime, performing them a load time increases runtime performance, and helps uncover errors more quickly.

Although a detailed algorithm to perform these checks is presented in section 4.9.2 of [LY99], its implementation is not simple and requires each element of the virtual machine state (see section 4.1) to be modelled. Rather than holding values, these models just hold type information, and during the course of verification calculate the most specific superclass of every value they could hold.

Due to time constraints, I did not implement this part of the verification process. Although important, I decided to concentrate on developing the components required for a functioning system before returning to add non-essential ones. I did, however, implement most structural checks at runtime. The checks that are performed neither at loading time nor at runtime are detailed in Appendix B.

3.7 Package Loader

The package loader provides access to packages in the abstract syntax tree. It is responsible for finding Carmel packages and managing their addition to the abstract syntax tree. It stores references to loaded packages in the abstract syntax in a cache so that a package and its classes only ever have one representation in memory.

The package loader also provides access to classes. It simply loads the class' package and returns a reference to the class from the resulting package.

3.7.1 Source Search Algorithm

It is necessary to define where the package loader expects to find the source file for a given package name. This had not been specifically defined in any of the Carmel specifications, and therefore a decision had to be made.

In discussion with Renaud Marlet, it was decided that, as Carmel files are representations of CAP files, it would best to use a loading strategy based on the directory structure and file names used by Sun's Java Card converter in creating CAP files.

Before being converted into CAP files, packages are represented by set of .class files, which are stored in a subdirectory of the class path defined by replacing each "." in the package name with a path separator. For example, the java.lang package is represented by a series of .class files in the "java/lang" subdirectory, such as "java/lang/Object.class" and "java.lang.Throwable.class".

During the conversion process, the converter reads all of the package's .class files and creates a CAP file in a subdirectory "javacard" of the directory containing the .class files. The CAP file's name is the last component of the package name appended with the ".cap" extension. For example, the java.lang classes in "java/lang" would be converted into the file "java/lang/javacard/lang.cap" file.

The creation of Carmel files was then defined to work in a similar manner. However, instead of creating a subdirectory called "javacard", the subdirectory is called "carmel". Likewise, the ".cap" extension is replaced with a ".cml" extension. For example, the java.lang package would be represented by the file "java/lang/carmel/lang.cml".

If the assumption is made that the original .class files are located correctly in the Java class path, then the Carmel package loader can reuse this class path in appending the relative file paths described above. If this is not the case, the user can simply be asked to adjust the class path accordingly.

Although not supported in Java Card, Java supports the use of a default package, which is a package without a name. To allow the greatest flexibility to the developer, it was decided with Renaud to support this concept in Carmel. However, as the package has no name, the search algorithm defined above would not work. The solution was to define that the unnamed package is to be found in a file referred to by the relative path "carmel/null.cml". As null is a Java keyword and therefore not a valid package name, one can be sure that this name will not conflict with that of a named package.

I discovered that the Java class loader supported the loading of resources, which are files other than Java classes, using a path relative to an entry in the Java class path. This meant that I could delegate the search process to the Java class loader rather than implementing it myself. This solution also brought about the advantage that the Java class loader supports the loading of files from within JAR files (essentially ZIP files containing Java classes and resources), and from locations on a network specified by a URL, and I could therefore take advantage of these features for free.

3.7.2 Loading Algorithm

Once a package source has been found, it must then be parsed (during which process the tree is built) and linked. As discussed in section 3.5, the linker may ask for the referenced packages to be loaded, but not immediately linked, or only linked by the first pass of the linker. Once the requested package has been successfully linked, the package loader then has to ensure that these unlinked or partially linked packages complete the linking process before the requested package is returned and used.

The algorithm and data structures I used are described as follows:

I defined four stages in the package loading process:

1. Unlinked, but parsed.
2. Linked by the first pass.
3. Fully linked (i.e. by the first and second pass).
4. Fully linked, with all referenced packages also fully linked.

Packages are stored by the package loader in a map whose key is the package's name. There is a map for each of the four stages. A package can only be in one of the maps at a given time.

When requesting a package from the package loader, the minimum required stage can be specified. For example, the first link pass asks for packages that are in stage 1 or higher, to ensure that the first link pass is not executed on the requested package as a result of the request, hence avoiding the possibility of an infinite loop. If no minimum stage is specified, as is the case for requests which are not made by the linker, then the last stage is assumed, and hence the package is fully loaded and linked.

First, the loader checks to see what stage the package has already reached in the loading process. If the package has not started the loading process, its source is found and parsed, and is therefore placed in the first stage.

If the package has already reached the requested minimum stage, it is simply returned with no processing. If it has not, then the package is processed to reach the requested stage:

To do this, the package loader first ensures that all packages that have not yet finished the loading process (including the requested package) have reached the stage just before that of the requested stage. This is property is required for the functioning of the different linking processes. The relevant packages are those in the first stage through to packages two stages before the requested stage. Starting with those in the first stage and progressing upwards, the following sequence of actions is performed, where applicable:

1. Launch the first linking pass on all packages in the first stage, thus moving them to the second stage. As the first linking pass can load new packages, this repeats until there are no more packages in the first stage.
2. Launch the second linking pass on all packages in the second stage, thus moving them to the third stage. Again, this repeats until there are no more packages in the second stage.

Once all of the packages have reached the stage before the requested stage, the loader can now launch the relevant linking process on the requested package. This process is one of the following actions, depending on the requested stage:

1. Do nothing: the package would have already been parsed and returned, as described above.
2. Launch the first linking pass.
3. Launch the second linking pass. All packages referenced by the requested package are now assured to have been linked by the first linking pass, and hence the second linking pass can function correctly.
4. Move all packages in the third stage to the fourth stage. All referenced packages have been fully linked, and all of their referenced package have now also been fully linked, and hence they fulfil the requirements of the last stage.

The requested package has now reached the required loading stage and is returned.

If at any stage an error occurs, whether it is an error in parsing or linking, all packages that have not reached stage 4 are unloaded. These packages are not needed by packages already fully loaded (as all such packages must be in stage 4), and cannot ever be moved to stage 4 because they depend on a package that could not be loaded.

3.7.3 Example

This algorithm is best demonstrated with an example. Assume there are two packages, A and B, both of which refer to methods in the other.

To load package A, a request is made to package loader with no specified minimum loading stage. The package loader therefore assumes that A is to be fully loaded, i.e. should be in stage 4. As A has not already started the loading process, its source is found and parsed, and A is placed in stage 1. All packages in stages 1 to the two stages before the requested stage, that is stages 1 and 2, are then processed to reach stage 3.

A is then linked by the first pass. The first pass encounters the reference to package B and requests it to be loaded, this time with a minimum loading stage of 1, which avoids an infinite loop. As B has not started the loading process either, its source is found and parsed, and it is placed in stage 1. As it has now reached the required stage, B is returned immediately. The first pass of A then completes, and A is moved to stage 2.

Before progressing to the packages in stage 2, the loader checks to make sure that there are no more packages in stage 1. As the first pass of the linker has loaded B, it is now in stage 1, and hence it too is linked by the first pass. When the first pass encounters the reference to package A, it requests it to be loaded with a minimum loading stage of 1. As package A is in stage 2, the package is returned immediately. The first pass of B then completes, and B is moved to stage 2.

As there are no longer any packages in stage 1, the loader starts processing the packages in stage 2. It (arbitrarily) picks A and links it with the second pass. The second pass, when it encounters the method reference in a class in package B, is sure that B has at least been linked by the first pass, and hence the method reference can be resolved safely. The second pass of A then completes, and A is moved to stage 3.

B is still in stage 2, and is also linked with the second pass. It too is moved to stage 3.

Now that all of the packages are at the stage (3) before the requested stage (4), A can now be processed to reach stage 4 and therefore, all packages in stage 3 are moved to stage 4. A and B are now in stage 4 and the class in A is now returned. As A is fully linked, and the packages it references (B) are fully linked, this package is now fully loaded and safe to use.

3.7.4 Multi-Package Sources

Having implemented the above search and loading algorithms, I received from Renaud a sample Carmel program which was comprised of several packages all defined in the same file. Unfortunately, in order for the package loader to find a package definition, each package must be defined in a separate file, and as such, this file could not be loaded by the package loader.

As Renaud told me that it would be desirable for the interpreter to support such files, I had to devise a way that they could be used without breaking the existing search algorithm. The solution was as follows:

First, I added a new starting rule for the grammar to accept this alternative syntax. The associated method returned a list of packages. Secondly, each one of these packages was then added to stage 1 of the linking process (see section 3.7.2). This ensures that any requests for the packages would succeed without having to search the class path. Finally, to link all of the packages, a request is made to fully load each package.

4. Interpreter

Once a program's packages have been successfully loaded and added to the abstract syntax tree, they are ready to be interpreted. The first section details how the internal state of the virtual machine is modelled. The second section discusses how the virtual machine communicates with applets. The third and fourth sections describe how the interpretation of method calls and Carmel instructions are implemented.

4.1 Runtime Structures

The result of interpreting a Carmel instruction is a change in the virtual machine's internal state. To facilitate the implementation of the Carmel instruction set's defined operational semantics, I closely followed the model described in [SH01], which defines three main components of the interpreter's state: the method call stack; the heap, which stores all instantiated classes and arrays; and the set of static field values.

The method call stack and the heap, along with the package loader, which represents the loaded Carmel programs as well as static field values, are held by a parent class called VirtualMachine, which represents the overall state of the virtual machine.

4.1.1 Call Stack

The method call stack contains all currently executing method calls. Each method invocation pushes the new method onto the method call stack, and a method return pops the method back off again. The method at the top of the call stack is the method currently being interpreted. The method below it is the invoking method, whose interpretation is paused until the currently executing method is popped from the stack by returning a value or throwing an exception.

Each method has its own operand stack and local variable array, along with its current program counter.

The operand stack is used to hold the operands for Carmel instructions. Unlike most machine languages, Carmel instructions are stack-based. Instead of taking their operands from registers and returning their result in a register, they take their operands from and place their results onto the operand stack. For example, adding two integers requires pushing both numbers on the stack and executing the add instruction, which pops the two numbers from the stack and pushes the result.

The local variable array holds the values of a method's parameters, as well as any other temporary variables that the programmer may use.

A UML diagram of the call stack and the information that it holds is shown in Figure 8.

The CallStack class represents the call stack, and provides standard stack manipulation methods. The values are held internally as a linked list, which provides fast addition and removal of elements at the beginning and end of the list.

For each method on the call stack, the call stack must hold its local variable array, its operand stack and the current program counter. These values are held by the StackFrame class.

The local variable array is implemented by the array-backed LocalVariables class, which provides fast random access to its values. The operand stack is implemented by the OperandStack class. Like the call stack, it is backed by a linked list and provides standard stack manipulation methods.

The program counter is represented by the ProgramCounter interface, which is implemented by both instructions and exception handlers. Although a real JCVM's program counter would only ever reference an instruction, representing the use of an exception handler as if it were an instruction is an effective way to make the user aware of when an exception causes the execution branch away from the normal program flow.

Finally, the StackFrame class holds a reference to the method's node in the abstract syntax tree, from which its instructions and exception handlers can be obtained for interpretation.

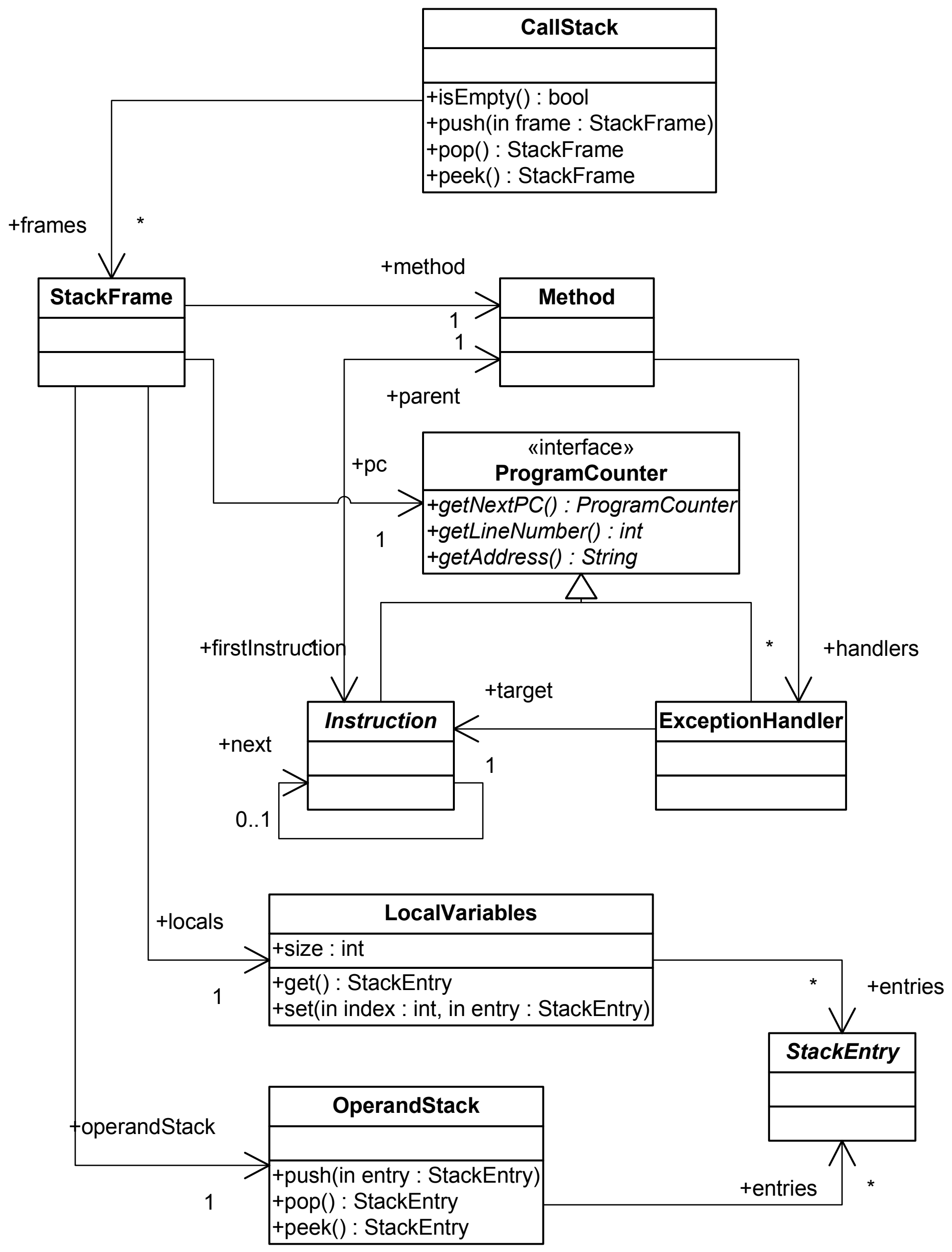


Figure 8 Call stack

Note: Method, Instruction and ExceptionHandler are shown in greater detail in Figure 5, and StackEntry is shown in greater detail in Figure 10.

4.1.2 Heap

The heap is responsible for allocating memory, and assigning heap locations to newly created objects. In a real JCVM, the operand stack, local variable array and static fields reference class and array values by their heap location. The heap then maps these heap locations to the actual values in memory.

While I could have represented class and array values as heap locations, and used the heap to look up their actual values from memory, closely mimicking the action of the real JCVM heap, I decided that such an approach was unnecessary. Instead, to make the implementation simple and more efficient, class and array values are referenced directly.

However, in order not to lose the useful heap location information, I added a heap location field to each reference value, so that it could be used to represent the value to the user, as if it were in fact just a heap location.

The mapping of heap locations to objects, while not used by the interpreter, is maintained to show to the user. This was implemented as an array-backed list of mapping objects to allow for fast random access.

This implementation is both efficient while still allowing the “real” behaviour to be modelled.

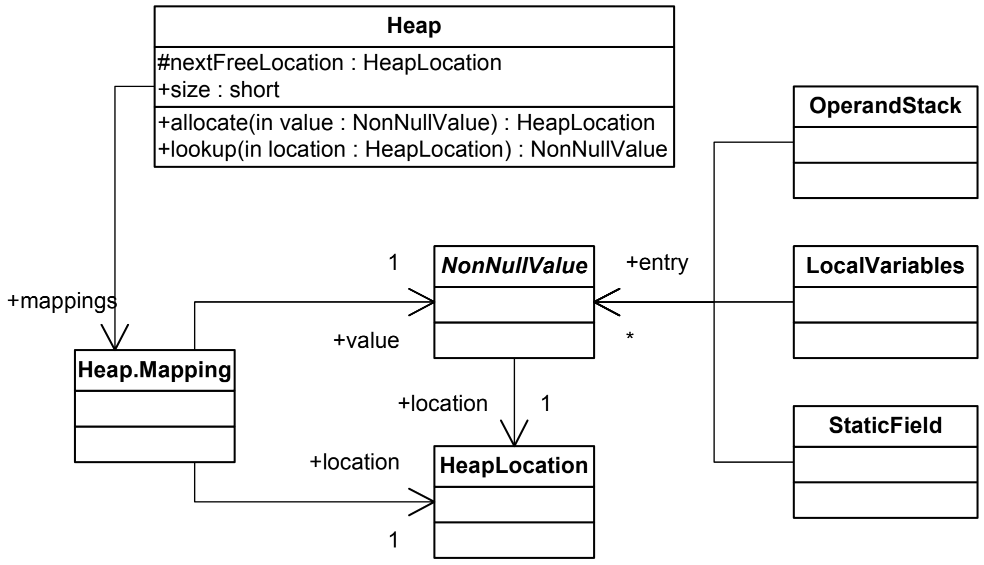


Figure 9 Modelling of the heap

Note: although HeapLocation is implemented by an integer, it is represented by a class in the above diagram for clarity.

4.1.3 Static Fields

Static field values are stored directly in the StaticField node of the abstract syntax tree, and are made accessible to instructions by the linker (see section 3.5.1), which replaces an instruction’s textual reference to a static field with a direct reference to the respective StaticField instance.

Static field values can be shown to the user by retrieving their values from the abstract syntax tree, which is made accessible by the package loader (see section 3.7).

4.1.4 Values

There is a value for each virtual machine type (see section 3.1.2).

The simplest value to implement was the undefined value, ⊥. This was implemented by a singleton class BottomValue.

The value of a return address is not implemented by a class holding the address of an instruction, by directly by the instruction itself in the abstract syntax tree. This removes a layer of indirection, and is a consequence of the abstract syntax tree design, discussed in section 3.1.4.

The rest of the values fall into two categories: numeric values, represented by the abstract class NumericValue, and reference values, represented by the abstract class ReferenceValue.

I defined a class for each type of numeric value: ByteValue, ShortValue and IntValue. Their value is represented internally by a Java value of the corresponding type. As Carmel and Java numeric operators are identical, this means that the implementation of arithmetic instructions can be performed directly by the Java language.

There are two types of reference value: null, which is implemented by the singleton NullValue class, and non-null values, represented by the abstract class NonNullValue. Non-null values can be either be array or class instances.

Array instances are implemented by the ArrayValue class. Arrays are represented internally by a Java array of Value objects.

Class instances are implemented by the ClassValue class. The value of a class instance is determined by the values of its instance fields, both those declared in the class itself, and those declared in its superclasses. These field values are held in an array of Value objects. The indices of the array correspond to Field IDs, which are assigned during the linking process, described in section 3.5.3.

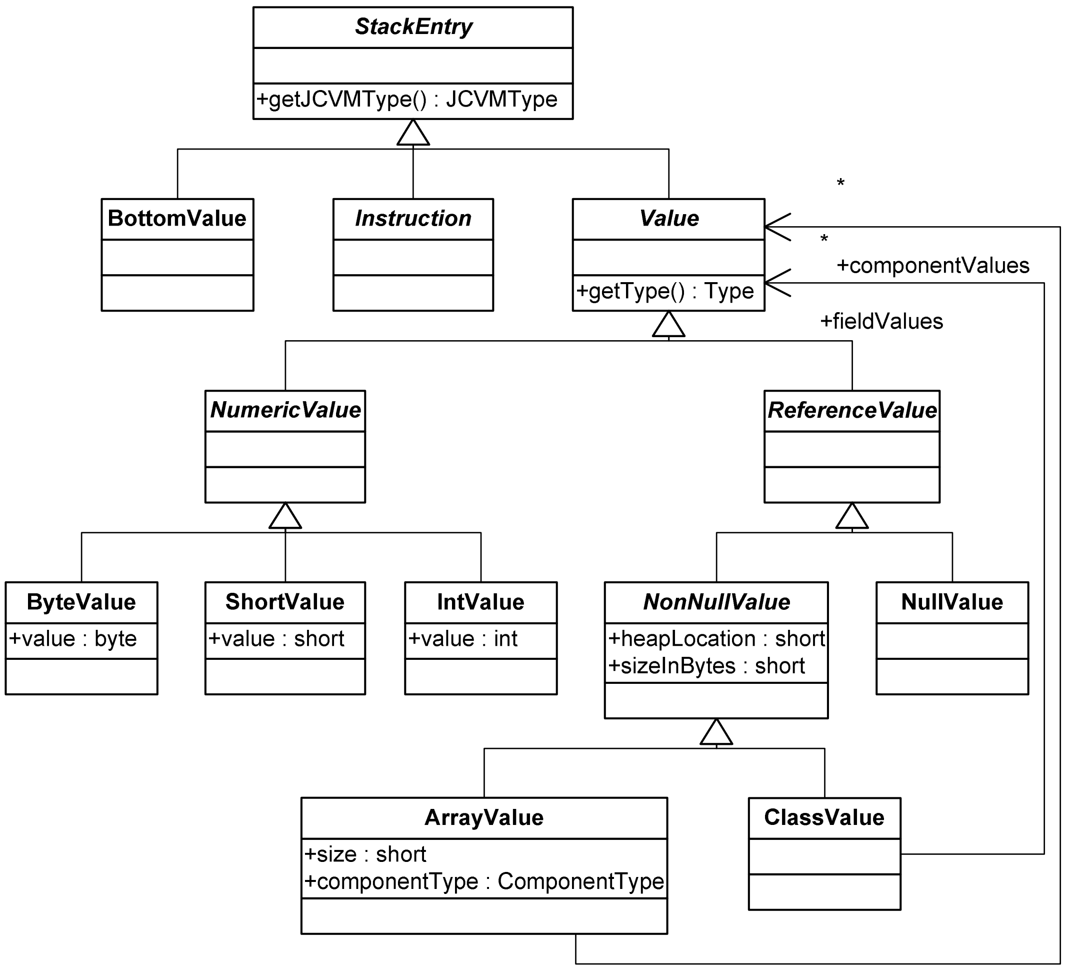


Figure 10 Representation of values

Note: Instruction is shown in greater detail in Figure 5.

4.2 Interpreter-Applet Interaction

A real Java Card interacts with a card reader. Communication between a Java Card and a Card reader takes place using packets called APDUs (application protocol data unit), and takes place as follows:

1. The card reader sends a message to the card specifying the applet to be executed. Applets are identified by AIDs (applet identifiers), unique numbers which are assigned by the International Standards Organisation (ISO).
2. The card reader then sends the data that the applet is to process. This is represented by one or more APDUs.
3. The JCVM creates class instances to represent the received APDUs, and begins interpretation of the requested applet.
4. The applet processes the request and returns its result in an APDU. This APDU contains a status word (SW) and can optionally include additional data.
5. The JCVM returns the APDU to the card reader.

The Java Card platform provides a framework of classes that simplify receiving, processing and sending of APDUs, so that programmers can concentrate on application specific code. Each Java Card applet extends the framework class java.framework.Applet, which defines a number of methods which are called by the virtual machine upon the receipt of an APDU. Applets respond to these messages by returning a value or throwing an exception. Applets can also access certain internal structures of the virtual machine via the framework classes, which are implemented using native methods.

However, to support this type of interaction, I would have needed to implement the Java Card framework classes, their required native methods, and I would have had to design a way for native methods to be called. Unfortunately, due to a lack of time, I was not able to implement such a solution.

Instead, I implemented subset of the framework classes, containing only those which are essential to the virtual machine itself. These classes are in the java.lang package and include Object, the superclass of all other classes; Exception, the superclass of all exceptions; and all of the classes for exceptions thrown internally by the virtual machine.

As for the interaction between the virtual machine and applets, I implemented a simpler but more flexible form of interaction. For any class, the user is able to:

1. Invoke static methods that don’t take any parameters. This is similar to the static void main method that Java programs implement, with the exception that methods are not obliged to return void, but can return any value.
2. Invoke constructors that don’t take any parameters. The initialised class instance is returned.
3. Invoke instance methods that don’t take any parameters on a class instance (either created by step 2, or in the code of another method).

4.3 Interpreting Methods

I decided to implement Carmel method invocations directly with Java method invocations by adding an “interpret” method to the StackFrame class, which is responsible for interpreting its method. This means that the interpreter’s call stack is in fact implemented by the underlying Java call stack. However, to be able to represent the call stack to the user, the “interpret” method pushes itself onto the CallStack class’ stack immediately on being invoked, and pops itself off again when it returns or throws an exception. In this way, the state of call stack is modelled while not incurring the cost of explicitly modelling its behaviour.

The interpret method comprises of a loop that interprets the instruction at the program counter, advances the program counter, and repeats. While this represents the normal sequence of event in a Carmel method, there are three notable exceptions: branches, method returns and exceptions.

There are a number of instructions that cause instruction to branch away from the next instruction, such as the goto and if instructions. To handle these special cases, I had the implementation of those methods throw an exception, BranchException, containing the new value of the program counter. The interpret method then catches this exception and sets the program counter accordingly.

The return instruction takes the value at the top of the operand stack and returns it to the invoking method. As the interpret method does not implement the return instruction directly, the implementing method cannot simply return the required value. Therefore, as before, I had the method that implemented the return method throw an exception, ReturnException, containing the value to be returned. The interpret method then catches this exception and returns the enclosed value.

Finally, Carmel exceptions are implemented in much the same way by an exception called CarmelException. CarmelException is caught internally within the interpret method, which then searches the method's exception handlers for a suitable handler. If no handler is found, the exception is rethrown to the invoking method's interpret method, which then performs a search on its own exception handlers, etc., until the exception is either handled or caught by the virtual machine itself.

Pseudo-code of the interpret method is shown in Figure 11. At the time of its invocation, the method's parameters have already been passed to the StackFrame class' constructor, which puts them in the local variable array.

```
method interpret, returns Value, throws CarmelException
      set program counter to first instruction
      push ourselves onto the call stack

      repeat forever
            try
                  interpret instruction at program counter
                  advance program counter
            except for BranchException
                  set program counter to branch address
            except for ReturnException
                  pop ourselves off of the call stack
                  return value
            except for CarmelException
                  if handler found
                        set program counter to handler target
                  else
                        pop ourselves off of the call stack
                        rethrow exception
                  end if
            end try
      end repeat
end method
```

Figure 11 Method interpretation pseudo-code

4.4 Interpreting Instructions

In the abstract syntax tree, each method references its first instruction, and each instruction references their next instruction, along with each other instruction that may be executed after it (for example, goto instructions reference their target). As these references may be any type of instruction, their declared type is the abstract type Instruction. This means that in order to interpret an instruction, its runtime type is needed.

The visitor design pattern, as discussed in section 3.1.5, provides an efficient and clean way to implement the interpretation of instructions based on their runtime type. I therefore created an inner class called InterpreterVisitor which implemented the InstructionVisitor interface. The InstructionVistor interface declares a method for each instruction type, and the InterpreterVisitor implements them with the code to interpret each instruction.

As interface methods must always be public, the advantage of using an inner class is that it these public methods, which should never be called directly, are not accessible outside of the StackFrame class. At the same time, the inner class has unrestricted access to the enclosing StackFrame class.

In implementing the instruction set, I constantly referenced their operational semantics, as defined in [SH01]. The effect of the code that I wrote for each instruction on the state of the virtual machine had to be exactly the same effect defined for the instruction's semantic rule or rules. As I had based the design of the runtime structures on their definition in this document, I found that the code was simple to implement.

As mentioned in section 3.6, as I had not implemented the structural verifier, the interpreter cannot assume that all operands will always be of the correct type, that local variable indices will always be valid, and that the operand stack will never underflow. Such checks therefore have to be performed at runtime, and I created a new exception called VerificationException to represent the occurrence of verification errors that would normally have been detected during the loading process.

With the exception of the nop instruction, which is implemented by an empty method, the following sections group the Carmel instruction set by functionality, and briefly describe how it was implemented. As most of the virtual machine had already been modelled, the instructions' implementation delegates most of its work to methods of the classes that model the relevant structures.

A useful one-page synopsis of the Carmel instruction set can be found in [Mar01].

4.4.1 Operand Stack Instructions

There are stack instructions to push a value, pop a value, pop multiple values, duplicate values, and swap values. The push and pop actions were already implemented by the operand stack, and I decided to add the additional actions to the operand stack class itself. Therefore, the interpreter simply takes the instruction's parameters, if any, and calls the relevant method on the operand stack.

4.4.2 Local Variable Instructions

There are three local variable instructions, get, set and inc. For get and set the interpreter simply calls the relevant method on the local variable array, pushing the result and popping the new value respectively. The inc instruction increments a value in the local variable array by a constant value. I implemented this by getting the value from the local variable array, incrementing it using the add operation described in the next section, and setting the variable to its new value.

4.4.3 Numeric Operation Instructions

Although there is only one arithmetic instruction, it encompasses all numeric operations on all types. As the implementation of a numeric operator depends on its type, I decided to add the methods needed to perform them to the classes that represent JCVM numeric types, namely JCVMByteType, JCVMShortType and JCVMIntType.

I implemented two methods, one for unary operators and the other for binary operators. Operators are identified by integer values, which are defined by constant fields in the JCVMNumericType class.

The methods simply apply the equivalent Java operator on the Value objects' underlying Java values. The method then constructs and returns a new Value object to hold the result.

The interpreter therefore checks to see whether the operator is unary or binary, pops the appropriate number of operands from the stack, calls the appropriate method on the instruction's type value, and pushes the result onto the stack. It also catches java.lang.ArithmeticException, which is thrown by Java when dividing by zero, and throws a CarmelException with an instance of the corresponding Carmel java.lang.ArithmeticException class.

4.4.4 Branch Instructions

As described in section 4.3, methods in the InterpreterVisitor class throw a BranchException in order for the program counter to jump to a new instruction.

There are three unconditional branch instructions: goto, jsr and ret, the simplest of which, goto, is implemented simply by throwing a BranchException containing its target address. The jsr and ret instructions jump to and return from subroutines respectively. The jsr instruction pushes its next instruction onto the operand stack, and the ret instruction retrieves the return address from a local variable. Both of these were easily implemented with existing methods.

The three remaining branch instructions are conditional. They are if, tableswitch and lookupswitch. The if instruction compares two values with a given conditional operator. I implemented conditional operators in much the same way as numeric operators, by adding a method to each class that represented a JCVM type, and implementing the operators by applying the equivalent Java operator.

The lookupswitch instruction defines a mapping of values to instruction addresses along with a default address. The tree builder creates instances of the referenced values and the linker creates a mapping from the values directly to the relevant instructions. The interpreter has then only to pop the value from the top of the operand stack, pass it to the map's lookup method and jump to the returned instruction. In case the lookup fails, it jumps to the default instruction.

The tableswitch instruction is similar to the lookupswitch instruction, except that it deals with a set of consecutive numeric values starting at a given value, which can be more efficiently stored in an array. The tree builder creates this array of the instructions, and the interpreter pops the value from the top of the operand stack, subtracts the start value and uses the result as an index into the array. It jumps to the indexed instruction, and if the index is out of bounds, it jumps to the default instruction.

4.4.5 Object Instructions

The instanceof and checkcast instructions both perform the same operation, which is to check whether the value on the top of the operand stack is assignable to the instruction's reference type parameter. This check is performed using the isAssignableFrom method of the reference type, as described in section 3.1.1.

In the case of the instanceof instruction, the reference value is popped off the stack, and the short value 1 or 0 is pushed onto the stack depending whether the value is or is not assignable, respectively. In the case of the checkcast instruction, the value is left on a stack and a java.lang.ClassCastException is thrown if the value is not assignable.

The new instruction creates a new instance of a class, or a new array value. In order to produce cleaner code, and to increase type safety, I represented the new instruction in the abstract syntax tree by two different classes, one for creating a new class instance and the other for creating a new array value. The operational semantics of the instruction remain unchanged.

The new class instruction creates a new instance of the ClassValue class, passing the required type as a parameter to its constructor. The value registers itself with the heap and creates its field array, setting them to their types' default values. The new class instance is then pushed onto the stack.

The new array instruction performs exactly the same operation with the ArrayValue, which again registers itself with the heap and initialises its elements to its component type's default value. The new array value is pushed onto the stack.

The four field access instructions get and set instance and static field values. In all cases, the linker generates a direct reference to the field node in abstract syntax tree and puts it in the instruction's node. All that remains to be done is to call the get or set method on the field node. Accessing instance fields requires a class instance, which either is popped from the operand stack or is designated by the instruction as being the class instance of the currently executing method.

There are two instructions for getting and setting array elements. They take an index and array value from the stack and call the get and set methods of the ArrayValue class. The last object instruction is arraylength, which pops an array value from the operand stack and pushes its length as a short value.

4.4.6 Method Instructions

The Carmel language defines three instructions with which to invoke methods: invokedefinite, invokevirtual and invokeinterface.

invokedefinite is used to invoke non-virtual methods such as static methods and constructors, and to bypass virtual method lookup when invoking instance methods. Like the new instruction, to produce cleaner code and to increase type safety, I represented the invokedefinite instruction by two instructions, one to invoke constructors and the other to invoke methods. invokevirtual is used to invoke instance methods, and invokeinterface methods is used to invoke interface methods.

All instructions take method parameter values, if any, from the operand stack, along with the class instance on which to invoke them, with the exception of static methods. invokevirtual and invokeinterface perform a virtual method lookup to determine the actual method to be invoked, whereas the invokedefinite derivatives hold a direct reference to the method to be invoked.

A new stack frame is created, with the method to interpret, the class value (if relevant) and the method parameters (if any) passed as parameters to the constructor. The interpret method of the stack frame is called which causes the interpretation of the calling method to be suspended until the interpret method returns. If the method has a return type other than void, its result is placed on the operand stack.

The last method instruction, return, takes the return value (if any) from the operand stack and throws a ReturnException containing this value. As described above, the interpret method catches this exception and returns the value to the calling method.

4.4.7 Throw Instruction

The throw instruction simply pops a class instance representing the exception to be thrown from the operand stack and throws a CarmelException containing this instance. As described above, the interpret method catches this exception and handles the exception accordingly.

5. User Interface

Now that the interpreter had been implemented, its user interface had to be implemented. The user interface allows the user to control the interpreter by loading packages and invoking and stepping through methods. The interface graphically displays the interpreter's state so that the user can see the effect of his or her actions.

In the first section, I describe which set of graphical components I decided to use. The following two sections describe the Model-View-Controller and Adapter design patterns, which were used in designing the interaction between the graphical components and the interpreter. The remaining three sections describe the design and implementation of the different components of the user interface.

5.1 Graphical Component Choice

Java supports two different sets of graphical components: the Abstract Windowing Toolkit (AWT) and the Java Foundation Classes (JFC, although commonly referred to as Swing).

AWT components are implemented by the underlying operating system, and as Java runs on multiple operating systems, AWT components represent the lowest common denominator amongst its supported operating systems. Unfortunately, this means that the set of AWT components is limited, and hence they are not suitable for use in the development of complex user interfaces such as that of the interpreter.

Swing components, however, are implemented in Java. There are many components to choose from, and new components can easily be created using subclassing and composition. As they are not implemented in native code, they can often be slow to interact with, although on a modern computer system their performance is acceptable. Additionally, performance is not a major concern in the implementation of the interpreter.

For these reasons, I chose to use Swing to implement the graphical user interface. All non-trivial Swing components use the model-view-controller design pattern, which is discussed in the following section.

5.2 Model-View-Controller Design Pattern

The Model-View-Controller (MVC) design pattern, discussed in [BMRSS95], is a modular way to design user interfaces.

It separates the user interface into three types of components: the model, which maintains the state and data to be represented; the view, which graphically represents it to the user; and the controller, which effectuates the user's commands as changes to the model. The views register themselves with the model, which sends notifications each time its state or data is changed, so that the views can update their display.

The design pattern has a number of advantages. It results in a clear and easily understandable design. Its modularity means that an addition or modification of a view or a controller can be performed without modifying any other component. Finally, it supports multiple views and controllers.

Swing provides a number of different views, such as lists, tables and text areas, as well as number of different controls, such as buttons and menus. Some Swing components, like text areas, encapsulate both a view and a controller.

In order to use Swing components, the developer must implement its data model, which is an interface which defines the interaction between the Swing component's view and the underlying data model. This interface defines the methods which are used to register and deregister a view with a model, and the methods used to retrieve the data. The model must also send update events to the component in a predefined type of object.

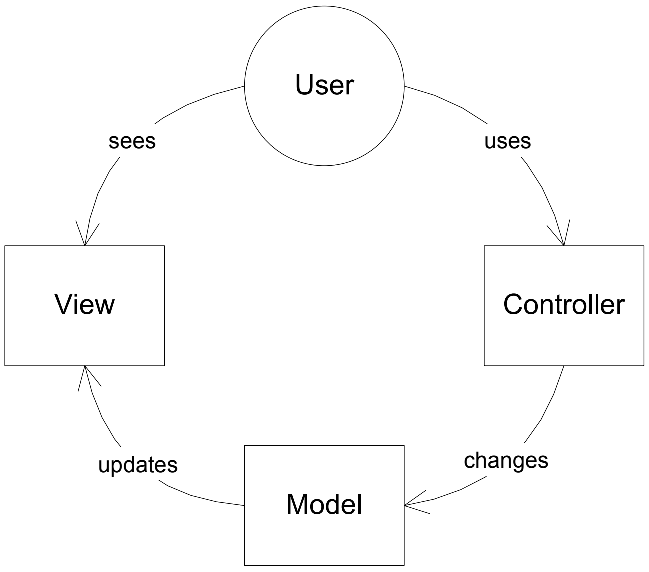


Figure 12 Model-View-Controller and the user

5.3 Adapter Design Pattern

As the model and event are quite specific to the view, it is very common to implement them using an adapter. In this design pattern, the data model has its own interface for accessing the data, which is specific to the type of data stored, and sends its own type of event object when its data changes. An adapter is therefore a class which implements the Swing component's data model interface and translates requests for data into method calls using the model's interface. Likewise, it receives events from the model in the model's event type and translates them into the Swing component's event type and forwards them to the component.

5.4 Models

The data models for each of these components were already implemented. Each of them implemented methods for a view to retrieve their state, and for controllers to change it. However, in order to use them as models in the MVC design pattern, I had to implement the sending of notifications each time the state changed.

State	Existing model class	Types of Changes
Loaded packages	PackageLoader class	New package loaded
Static field values	StaticField nodes in AST	Value changed
Heap values	Heap class	New value allocated
Method call stack	CallStack class	Method invoked
		Method returned
Program counter	StackFrame class	Program counter changed
Operand stack values	OperandStack class	Value(s) pushed
		Value(s) popped
Local variable values	LocalVariables class	Value changed

Figure 13 Interpreter state models

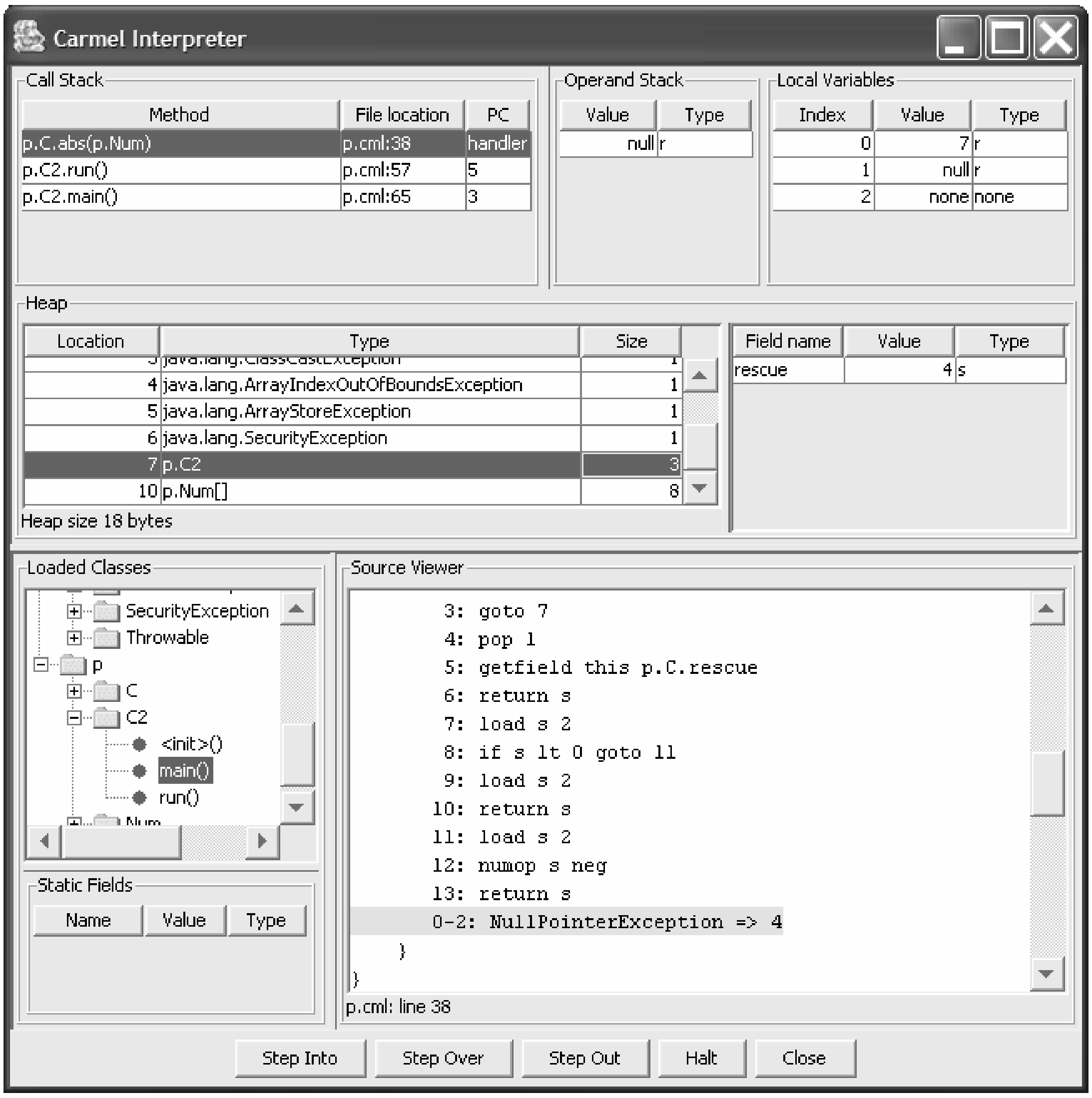
The preceding table lists each element of the interpreter's state, its existing model class, and the types of changes that can occur to the state.

Therefore, for each model class, I implemented the following:

- An event object to represent the possible changes to the model
- A listener interface to be implemented by any class that receives these events: event notifications are sent by invoking one of these interface methods with the event object as a parameter
- A list of currently registered listeners and methods for listeners to register and deregister themselves
- For each type of change, a method which creates an event object and calls the relevant interface method on each of the registered listeners.
- Each time the model changed its state, a call to the relevant method to perform the notification.

5.5 Views and Adapters

Each element of the interpreter's state needs to be represented graphically to the user. The following screenshot of the final user interface shows the decisions I made.



Call Stack

Method	File location	PC
p.C.abs(p.Num)	p.cml:38	handler
p.C2.run()	p.cml:57	5
p.C2.main()	p.cml:65	3

Operand Stack

Value	Type
null	r

Local Variables

Index	Value	Type
0	7	r
1	null	r
2	none	none

Heap

Location	Type	Size
4	java.lang.ArrayIndexOutOfBoundsException	1
5	java.lang.ArrayStoreException	1
6	java.lang.SecurityException	1
7	p.C2	3
10	p.Num[]	8

Heap size 18 bytes

Field name	Value	Type
rescue	4	s

Loaded Classes

```
  ⊞ SecurityException
  ⊞ Throwable
⊟ p
  ⊞ C
  ⊟ C2
      ● <init>()
      ● main()
      ● run()
```

Static Fields

Name	Value	Type

Source Viewer

```
        3: goto 7
        4: pop 1
        5: getfield this p.C.rescue
        6: return s
        7: load s 2
        8: if s lt 0 goto 11
        9: load s 2
       10: return s
       11: load s 2
       12: numop s neg
       13: return s
       0-2: NullPointerException => 4
    }
}
```

p.cml: line 38

Figure 14 Screenshot of user interface

5.5.1 Abstract Syntax Tree

The loaded packages in the abstract syntax tree are represented graphically by a tree. Starting at the top level, the tree shows the loaded packages, then their classes and interfaces defined by them, and then the methods declared by those classes and interfaces. The rest of the program structure can be examined in the source viewer panel, which automatically opens the source file at the definition of the selected node in the abstract syntax tree.

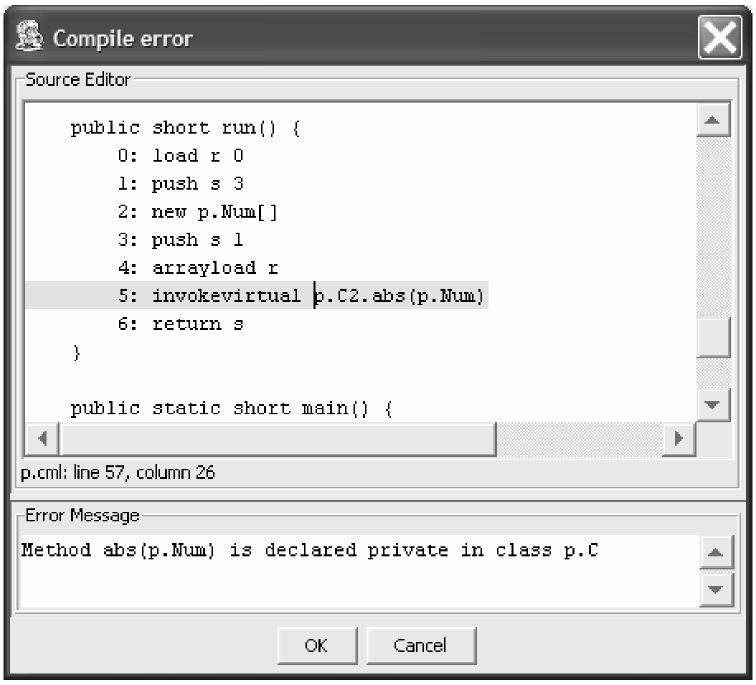
The source viewer panel, which can also support editing, is a custom component comprised of a text area, and takes a CarmelSource class as its model (see section 3.2).

The tree's data model is an adapter which takes its data from the abstract syntax tree, which is modelled by the package loader. The package loader event signifying the loading of a new package is transformed into an event to tell the tree view that a tree node has been added.

The static field values, which are stored in the abstract syntax tree, are viewed in a table. In selecting a node in the abstract tree, if the node is a class or interface, or the child of a class or interface, that class or interface's static fields are shown in the table.

The table data model is an adapter which represents each of a class' static fields, and presents them together in alphabetical order. Field value update events are transformed into table row update events.

The source viewer panel, this time not in read-only mode, is also used when informing the user of an error in the loading process. I implemented a dialog box which represents a loading error, which displays the erroneous file at exact location of the error along with the error message. The user then has the opportunity to edit the source file and correct the error.



```
    public short run() {
        0: load r 0
        1: push s 3
        2: new p.Num[]
        3: push s 1
        4: arrayload r
        5: invokevirtual p.C2.abs(p.Num)
        6: return s
    }

    public static short main() {
```

p.cml: line 57, column 26

```
Method abs(p.Num) is declared private in class p.C
```

Figure 15 Loading error dialog

5.5.2 Call Stack

The call stack is represented as a table, with each row representing a method invocation. The first row in the table represents the top of the stack, and hence the currently executing method. The table data model is an adapter of both the stack frame and the program counter classes, presenting the two classes' state together in the same view. Selecting a method's row in the call stack table also represents the program counter by opening the

Carmel source file in which it was defined and highlighting the instruction or exception handler to which the program counter refers to.

The operand stack is represented as a table, whose rows represent its values. The first row represents its topmost element. The local variable array is also represented as a table of values, this time with an additional column for the value's index.

5.5.3 Heap

The state of the heap is represented by two tables. The first table lists the memory allocated, showing the start location of the block, its size in bytes, and the type of the object which was allocated the block. By selecting a heap location, the second table shows the value of the referenced object, whether an array value or a class instance. Array values are represented by a row for each element whereas class instances are represented by a row for each instance field.

5.6 Controllers

The remaining parts of the user interface were the controllers. The controllers are the components that allow the user to modify the state of the models. In terms of the interpreter, the controllers allow the user to configure and launch the package loading process and to run and step through method invocations.

5.6.1 Loader

When a method is not being interpreted, the interpreter window, shown in Figure 14, displays the following buttons at the bottom of the window.

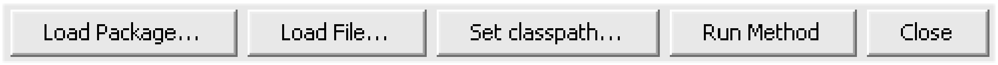


Figure 16 Loading control buttons

The addition of an ellipsis to the button's caption is a convention to indicate to the user that further information will be demanded before the action takes place, which also means that the user will have a chance to cancel the action.

The first two buttons launch the loading process. The "Load Package…" button asks the user for the name of the package to load, and asks the package loader to load it. If the package is found, its new node in the abstract syntax tree view is highlighted automatically, causing its declaring file to be shown in the source viewer window. If the package could not be found, the user is informed and is suggested to check the class path.

The "Load file…" button allows the user to bypass the class path search algorithm and specify directly a file to be loaded. The user can either enter the file's URL or browse the local file system for the file. The first package declared in the file is selected in the AST tree view, and the source viewer shows the file.

The "Set classpath…" button allows the user to change the Java class path, which is used by the package loader to find packages. A directory chooser dialog box is available to find and automatically add a directory.

The "Run Method" button begins method invocation. As described in section 4.2, the interpreter is able to invoke static and instance methods, as well as constructors, providing that they take no parameters. To invoke a static method or constructor, the user must first select the method or constructor in the AST tree view. To invoke an instance method, the user must additionally select the class instance on which to invoke the method from the heap.

5.6.2 Interpreter

Once a method has been invoked, the following set of buttons are shown to the user with which to pause execution to have time to examine the interpreter's state, or to halt execution altogether:

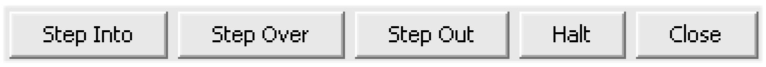


Figure 17 Interpreting control buttons

The first three buttons allow the user to control the number of instructions that are interpreted before the interpreter pauses.

“Step Into” interprets the instruction at the program counter and pauses on the next instruction. If the instruction is a method invocation, it pauses at the first instruction of the invoked method. “Step Over” is similar, with the exception that it fully invokes methods and pauses on the instruction following the method invocation instruction. “Step Out” interprets the remaining instructions in the current method and pauses execution on the following instruction in the invoking method. “Halt” aborts interpretation of all methods on the call stack without executing any more instructions.

To be able to pause interpretation while at the same time allowing the user interface to control the virtual machine, I had the interpretation (i.e. the StackFrame’s interpret method) execute in a separate thread.

Just after it sends a program counter update event to its listeners, it calls a method in the VirtualMachine class called waitBeforeNextInstruction. By default, the VirtualMachine class suspends the thread in this method, waiting for a shared variable called wait to become false.

When the user clicks on one of the step buttons, the relevant step method in the VirtualMachine class is called. This sets the wait variable to false and reactivates the waiting thread, which then executes the next instruction. Depending on the step operation, it registers a program counter listener which, each time the program counter changes, checks to see whether the interpretation should be paused. If so, it sets the wait variable to true and deregisters itself, causing the interpreter thread to be suspended by the next waitForNextInstruction method.

To completely halt the execution, there is a second shared variable called halt. If the waitForNextInstruction method finds that this variable is true, it throws an exception which is caught by the main run method of the executing thread, which stops execution.

6. Web Site

This section describes the web-based aspects of the program. The first section describes the technology I chose to allow the interpreter to be launched from the web and the second section describes the steps taken to set up the web server and package the application.

The web site is hosted by the Imperial College Department of Computing web server, and its address is http://www.doc.ic.ac.uk/~lj97/project/.

6.1 Web Launch Technology

There are two ways in which to launch a Java application over the Web. The first is by means of a Java Applet, and the other is by using Java Web Start.

Java Applet technology is designed for small programs that add functionality to a web page. Their execution is controlled by the web browser, and their lifetime is only as long as the user is viewing the web page: navigating away from the page or closing the web browser causes the applet to stop executing. As applets are embedded into a web page, network access is required to run them.

Java Web Start, however, is designed to be a way to deploy Java applications over the web. Clicking a link to a Web Start application causes it to be automatically installed onto the hard drive, with icons added to the desktop and/or start menu (or the equivalent on a non-Windows platform). Each time the program is run, Web Start checks to see if a new version is available, in which case it is downloaded and installed. A Web Start application can be configured so that this step is bypassed if there is no available network connection.

Because the interpreter is an application in its own right which is not expressly linked to a particular web page, and which does not require Internet access to run, I decided to use Web Start.

6.2 Implementation

For security reasons, Web Start applications have limited access the local file system and can only make network connections to the web server from which they were downloaded. However, if the application is digitally signed, the user is able to grant it extra permissions.

A Java Web Start application consists of two files. The first is a JAR (Java Archive) file which packages together the program's .class files into one file. If the application is signed, this file also contains the public key used to sign the program, and a digital signature for each .class file.

The second is a descriptor file known as a JNLP (Java Network Launcher Protocol) file. Clicking on a link to this file in a properly configured browser will automatically launch Java Web Start to start the application. The file is an XML document that contains, among other things:

- The name and description of the application
- The URL of the application's JAR file, along with any other resources it needs
- Which additional permissions, such as access to the local file system, the application requires
- Which class to execute to run the program

- Whether the application is allowed to run offline, when it is not possible to check for an update

In order for a web browser to correctly associate JNLP files with Java Web Start, the web server must be configured to describe the file correctly when it is downloaded. I am grateful to the Computing Support Group at Imperial College for configuring their secondary web server accordingly.

I therefore packaged the application into a JAR file, digitally signed it, and created a JNLP descriptor file which included file system access as an additional permission. This is required so that Carmel files can be found and loaded. I then published the files and verified that everything was working properly.

The final step was then to create the web page itself. The web page provides a brief overview to the project, information on how to install Java Web Start along with some troubleshooting information, and a step-by-step guide to using the interpreter.

7. Evaluation

This section describes the steps that taken to evaluate the interpreter. The first three sections concerning the parser, verifier and interpreter evaluate these components in terms of their specifications: the Carmel syntax, the Java Card virtual machine specification and the Carmel operational semantics respectively. The fourth section evaluates the user interface based on the feedback received from SecSafe members who took time to test the interpreter. The final section evaluates the use of Java Web Start as a web launching mechanism, and details some problems experienced by the testers.

7.1 Parser

Before starting the project, the syntax of the Carmel language was defined informally as a human readable way to represent Java Card programs. However, to implement the parser, it was necessary to define the syntax in a formal and complete manner. This formal definition, given in Appendix A, arose from issues directly relating to the implementation of the parser, and as such, the parser could be considered as a “reference implementation” of the Carmel syntax.

There also exists a printer of Carmel programs, which converts Java .class files into the Carmel syntax. The development of this printer, by Renaud Marlet, ran in parallel to the development of the parser, and frequent communication between us ensured that Carmel programs produced by the printer were being parsed correctly by the parser. The Carmel programs being tested were several thousand lines in length and encompassed the large majority, if not all of the Carmel syntax.

Additionally, during the parser’s development, I created a number of test files with which to check that correct programs were being accepted and that incorrect programs were being rejected.

While the parser was tested extensively, it was not tested in a systematic and complete fashion. Such testing would have taken a prohibitive amount of time, and the value of doing such testing was not apparent.

7.2 Verifier

As described in section 3.6, I consulted the specifications of the Java Card virtual machine [Sun00], the Java virtual machine [LY99] and the operational semantics of the Carmel language [SH01] and made a list of the verification checks that needed to be carried out.

The verification checks that required a flow analysis of methods were not implemented, are listed in Appendix B for reference. The remainder of the checks were implemented, and I wrote a very simple Carmel program for each check that ensured that a violation of the check was being properly detected. This enabled me to find and correct some errors I had made in their implementation.

Given the importance of the verifier in ensuring the security model of the Java Card platform, and the importance of security in the SecSafe project, such informal test cases are not sufficient to make a formal, quantitative analysis of the verifier’s correctness. However, developing a complete set of test cases would be a project in its own right, and given the limitation of time and scope of this project, this was not possible.

7.3 Interpreter

In implementing the Carmel instruction set, I closely followed the operational semantics, as defined in [SH01] by translating the semantic rule or rules for each instruction directly into Java, then performing careful factorisation and cleaning up of the resulting code. In testing this code, I wrote and ran a number of test programs to check that the semantics were being honoured, and that there were no other bugs.

Formal and complete testing of the interpreter's conformance to the operational semantics was not possible. Such testing requires the careful development of a large number of test cases, and is outside the scope of this project. I did look, however, for existing test suites that could be adapted to test the interpreter and came across two.

The first is Sun Microsystems' Java Card Technology Compatibility Kit. All commercial implementations of Java Card virtual machine are required to pass the tests defined in the kit. However, this test suite is only available to Java Card licensees.

The second test suite is called the Mauve project (http://sources.redhat.com/mauve/) and is free, but is for the Java virtual machine. However, it could be possible to base a Carmel test suite on this suite by converting the test cases that apply to both Java and Java Card into Carmel, and then adding test cases for Carmel-specific features.

7.4 User Interface

The user interface, the final version of which is described in section 5, was developed incrementally. By analysing the information that the interpreter modelled, and its structure, I developed an initial user interface which I then provided to two potential users: Renaud Marlet at Trusted Logic, and Igor Siveroni at Imperial College. Both of them provided useful feedback which led to a number of improvements and changes. This process repeated several times before the interface reached its final version.

Generally, the comments I received from Renaud and Igor were positive, and I was able to address most of the problems they found. However, two issues remained unresolved at the end of the project, due to a lack of time to implement possible solutions.

The first concerns the representation of the call stack and the operand stack. While the use of a table was a suitable way to represent the entries in the two stacks, it was not immediately clear to the user whether the top or bottom row represented the top of the stack. While I chose to use the top row as the top element, the stack appears to grow downwards. This is because, when the table doesn't fill the space assigned to it, the free space is positioned below it. Therefore, when a new row is added, the old top row is moved downwards to make space for the new top row. If the free space were to appear above the table, additions to the stack would cause the stack to appear to grow upwards, intuitively letting the user know the direction of the stack.

The second issue concerned starting the interpreter by invoking a method. The interface does not give any visual cues to suggest that he or she needs to select a method from the loaded packages tree and then press the "Run Method" button. The solution would be to make the "Run Method" button show a dialog box which then presents a second view of the tree, specifically asking the user to choose the method. If the method were an instance method, the dialog box could then ask the user to choose a class instance on which to invoke it.

Overall, however, comments from the two test users lead me to believe that the user interface well represents the internal state of the virtual machine, and is easy to use.

7.5 Web Installation

Java Web Start, while promising a lot of interesting features such as automatic installation, support for multiple platforms and automatic updating of programs to their latest version, did not fare well in practice.

While I was always able to launch the interpreter on my computer under both Windows XP and Mandrake Linux, it would continually download the 250Kb application each time it was started, regardless of whether I had made any modifications to it. Luckily I had a fast connection and this did not take more than a couple of seconds, but the possible implications for modem users is much more serious.

Renaud Marlet, running Linux, was unable to launch the application, and continually received the error that the web server could not be found. However, he was able to access the web server with his browser without any problems.

Finally, Rene Rydof Hansen, running Linux on an old Apple PowerBook, was running on a platform unsupported by Web Start.

Fortunately, each of these users was able to download the application's JAR file directly and run the interpreter manually.

One last problem I encounter with Web Start was to do with its class loader. As described in section 3.7.1, the Carmel package loader uses the Java class loader to search for Carmel sources. While this worked well when running the interpreter as a normal application, I discovered that the class loader provided to Web Start applications did not recognise changes to the Java class path, and hence the user cannot specify the location of Carmel files. The solution to this problem, again, was to download the application's JAR file directly and run the interpreter manually. A better solution would be not to use the Java class loader and implement the search process explicitly: again, time proved a limiting factor, and this solution has not been implemented.

8. Conclusions

This section concludes the report by giving an overview of what the project achieved, how this relates to the project's goals, and finishes by proposes possible improvements and extensions.

8.1 Achievements

In this project, I designed and implemented:

- A parser, abstract syntax tree builder, linker and verifier for the Carmel language [Mar01], which is a textual representation of the Java Card virtual machine language (see section 3)
- A functional Java Card virtual machine, which interprets the constructed abstract syntax tree in accordance with a defined operational semantics [SH01] (see section 4)
- A graphical user interface with which to load applets onto the simulated Java Card, execute methods, display the internal state of the virtual machine, and which allows the user to step through the interpretation (see section 5)
- A web page from which the program can be automatically installed and which contains a users' guide; additionally, the program automatically updates itself when new versions are made available (see section 6)

I made use of a number of technologies in implementing the program. The program is a client-side and is written in the Java programming language. I used the JavaCC parser generator [Web01] to create the parser, and Java Web Start technology to automatically install and update the program over the web.

In implementing the parser, I formalised a previously informal grammar definition of the Carmel language (see section 3.3.2 and Appendix A).

I developed a complex loading algorithm (see section 3.7.2) to handle a multi-pass loading, linking and verification process. The algorithm is extensible and supports the addition of further passes.

In the design process, I used several design patterns. Notably, the design of the linker and interpreter make use of the Visitor design pattern [GHVJ94] to cleanly, and in an object-oriented fashion, execute code based on an object's runtime type. The graphical user interface was implemented using the Model-View-Controller design pattern [BMRSS95], which separated clearly the code responsible for modelling the state of the virtual machine and interpreting instructions from the graphical components used to view the state and control the interpretation.

The program was designed in a modular fashion, to support the reuse and future extension of its components.

8.2 Goals Not Achieved

Largely due to lack of sufficient time, the program did not meet all of the project's initial goals. Specifically:

- The external interface between the Java Card and the card reader was not modelled. This is because only a subset of the Java Card framework classes was implemented, and native method support was not implemented.

- The structural verifier of the Java Card virtual machine was not implemented. This is a complex component and there was not enough time for its implementation.
- Although the program uses Web Start as a web-launching technology, its effectiveness was not proven.

However, I believe that the program that I have designed and implemented is a functional, self-contained program whose usefulness is not overly hindered by these omissions, and that implementing these missing features certainly would not have been possible in the time available. Indeed, my project supervisor did not expect me to finish the project.

8.3 Improvements and Extensions

Looking back on my design decisions having completed the project, there is are a couple of decisions that I would have taken differently with the benefit of hindsight. While choosing JavaCC [Web01] as a parser generator enabled me to start coding the parser more quickly, I believe that taking the extra time to use SableCC [Gag01] would have provided me with a better tree builder. The current tree builder is very tightly coupled with the parser, which generally is not a desirable design property. Similarly, I believe that implementing the verification steps in a separate pass of the loading process instead at the same time as the linking passes, while being less efficient, would have also reduced the coupling between these two distinct operations.

Two improvements have been mentioned in section 7. The first is to implement the search of the class path manually, rather than relying on the Java class loader. This would avoid problems experienced when using Web Start. I also suggested solutions to two user interface problems, one concerning the representation of stacks, and the other concerning invoking methods.

Finally, the possibilities to extend this project are numerous. A few possibilities include:

- The addition of a structural Carmel verifier
- The implementation of the Java Card framework classes and a user interface allowing the user to send and receive APDUs, which are messages used by the card reader to control the Java Card.
- The extension of the user interface to allow the invocation of methods that take parameters. The interface would allow the user to enter primitive values and select reference values from the heap.
- The development of a test suite to properly test the virtual machine’s adherence to the Java Card virtual machine specification [Sun00] and operational semantics [SH01].
- The addition of an undo mechanism which would allow the user to step backwards as well as forwards through a program’s execution. Each instruction would register the actions that would need to be taken to undo its effect on the virtual machine state with a centralised “undo manager”, which could then be controlled by a back button.

9. References

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Appendix A Carmel Syntax

The Carmel Grammar is based on the grammar to the Java Language, which is defined in §18.1 of [GJSB00].

The grammar uses the following BNF-style conventions:

- *[x]* denotes zero or one occurrences of *x*.
- *{ x }* denotes zero or more occurrences of *x*.
- *x* | *y* denotes one of either *x* or *y*.

The lexical structure of the Carmel language is identical to that of Java, with the exception of its additional keywords, which is defined, along with identifiers and literals in section 3 of [GJSB00]. As discussed in section 3.3, an identifier can take the value of any Carmel keyword that is not also a keyword in the Java language.

A.1 Identifiers, Literals and Types

```
Identifier:
   IDENTIFIER

QualifiedIdentifier:
   Identifier { . Identifier }

Literal:
   NumericLiteral
   BooleanLiteral
   NullLiteral

NumericLiteral:
   [ ( NumericType ) ] [ - ] IntegerLiteral

VariableInitializer:
   Literal
   ArrayInitializer

ArrayInitializer:
   { [ Literal { , Literal } [ , ] ] }

Type:
   Identifier { . Identifier } BracketsOpt
   BasicType

BasicType:
   NumericType
   boolean

NumericType:
   byte
   short
   int

BracketsOpt:
   [ [] ]
```

A.2 Packages, Classes and Interfaces

CompilationUnit:
PackageDeclaration

PackageDeclaration:
`package` *QualifiedIdentifier AID* `;` *PackageBody*

SpecialCompilationUnit:
{ *SpecialPackageDeclaration* }

SpecialPackageDeclaration:
`package` [*QualifiedIdentifier*] [*AID*] `;` *PackageBody*

AID:
`{` *NumericLiteral* { `,` *NumericLiteral* } `}`

PackageBody:
{ *ImportDeclaration* } { *TypeDeclaration* }

ImportDeclaration:
`import` *Identifier* { `.` *Identifier* } [`. *`] `;`

TypeDeclaration:
ClassOrInterfaceDeclaration
`;`

ClassOrInterfaceDeclaration:
ModifiersOpt (*ClassDeclaration* | *InterfaceDeclaration*)

ModifiersOpt:
{ *Modifier* }

Modifier: one of
`public protected private static abstract final native`

ClassDeclaration:
`class` *Identifier* [`extends` *Type*] [`implements` *TypeList*] *ClassBody*

InterfaceDeclaration:
`interface` *Identifier* [`extends` *TypeList*] *InterfaceBody*

TypeList:
Type { `,` *Type* }

ClassBody:
`{` { *ClassBodyDeclaration* } `}`

InterfaceBody:
`{` { *InterfaceBodyDeclaration* } `}`

ClassBodyDeclaration:
ModifiersOpt MemberDecl
`;`

MemberDecl:
MethodOrFieldDecl
`void` *Identifier MethodDeclaratorRest*
Identifier ConstructorDeclaratorRest
`void <init>` *ConstructorDeclaratorRest*

MethodOrFieldDecl:
Type Identifier MethodOrFieldRest

MethodOrFieldRest:
VariableDeclaratorRest
MethodDeclaratorRest

VariableDeclaratorRest:
BracketsOpt [= *VariableInitializer*]

InterfaceBodyDeclaration:
ModifiersOpt InterfaceMemberDecl
`;`

InterfaceMemberDecl:
InterfaceMethodOrFieldDecl
`void` *Identifier VoidInterfaceMethodDeclaratorRest*

InterfaceMethodOrFieldDecl:
ConstantDeclaratorsRest `;`
InterfaceMethodDeclaratorRest

ConstantDeclaratorsRest:
ConstantDeclarator { `,` *ConstantDeclarator }*

ConstantDeclarator:
Identifier ConstantDeclaratorRest

ConstantDeclaratorRest:
BracketsOpt = VariableInitializer

MethodDeclaratorRest:
FormalParameters BracketsOpt [`throws` *QualifiedIdentifierList] (MethodBody* `|` `;` *)*

VoidMethodDeclaratorRest:
FormalParameters [`throws` *QualifiedIdentifierList] (MethodBody* `|` `;` *)*

InterfaceMethodDeclaratorRest:
FormalParameters BracketsOpt [`throws` *QualifiedIdentifierList]* `;`

VoidInterfaceMethodDeclaratorRest:
FormalParameters [`throws` *QualifiedIdentifierList]* `;`

ConstructorDeclaratorRest:
FormalParameters [`throws` *QualifiedIdentifierList] MethodBody*

QualifiedIdentifierList:
QualifiedIdentifier { `,` *QualifiedIdentifier }*

FormalParameters:
`(` *[FormalParameter {* `,` *FormalParameter }]* `)`

FormalParameter:
[`final` *] Type [VariableDeclaratorId]*

VariableDeclaratorId:
Identifier BracketsOpt

MethodBody:
InstructionBlock

A.3 Instructions

InstructionBlock:
`{` *{ LabeledInstruction } { ExceptionHandler }* `}`

LabeledInstruction:
Address `:` *Instruction*

ExceptionHandler:
Address – Address `:` *CatchType => Address*

CatchType:
ClassType
`*`

Address:
DecimalNumeral

Instruction:
`nop`
`push` *OperandType Constant*
`pop` *NbWords*
`dup` *NbWords NbWords*
`swap` *NbWords NbWords*
`numop` *OperandType NumericOperator [OperandType]*
`load` *OperandType LocalVariableIndex*
`store` *OperandType LocalVariableIndex*
`inc` *OperandType LocalVariableIndex IntegerConstant*
`goto` *Address*
`if` *OperandType ComparisonOperator [NullComparison]* `goto` *Address*
`lookupswitch` *OperandType [MatchTableEntries]* `, default =>` *Address*
`tableswitch` *OperandType IndexTableEntry* `, default =>` *Address*
`new` *ReferenceType*
`checkcast` *ReferenceType*
`instanceof` *ReferenceType*
`getstatic` *Name*
`putstatic` *Name*
`getfield` *[* `this` *] Name*
`putfield` *[* `this` *] Name*
`invokedefinite` *Signature*
`invokevirtual` *Signature*
`invokeinterface` *Signature*
`return` *[OperandType]*
`arraylength`
`arrayload` *OperandType*
`arraystore` *OperandType*
`throw`
`jsr` *Address*
`ret` *LocalVariableIndex*

OperandType: one of
`r b s i`

Constant:
NullLiteral
NumericLiteral

NbWords:
DecimalNumeral

ComparisonOperator: one of
`eq ne gt le lt ne`

NullComparison: one of
`0 null`

NumericOperator: one of
`neg add sub mul div rem and or xor shl shr ushr to tob cmp`

LocalVariableIndex:
DecimalNumeral

MatchTableEntries:
MatchTableEntries { `,` *MatchTableEntry }*

MatchTableEntry:
NumericLiteral => Address

IndexTableEntry:
NumericLiteral => { Address }

Signature:
Name `(` *[TypeList]* `)`

Appendix B Unimplemented Verification Checks

The following verification checks from chapter 4 of [LY99], have not been implemented by the Carmel interpreter:

1. There must never be an uninitialised class instance on the operand stack or in a local variable when any backwards branch is taken. There must never be an uninitialised class instance in a local variable in code protected by an exception handler. However, an uninitialised class instance may be on the operand stack in code protected by an exception handler. When an exception is thrown, the contents of the operand stack are discarded.
2. Each instance initialisation method, except for the instance initialization method derived from the constructor of class Object, must call either another instance initialization method of this or an instance initialisation method of its direct superclass super before its instance members are accessed. However, instance fields of this that are declared in the current class may be assigned before calling any instance initialization method.
3. If getfield or putfield is used to access a protected field of a superclass, then the type of the class instance being accessed must be the same as or a subclass of the current class.
4. If invokevirtual or invokedefinite is used to access a protected method of a superclass, then the type of the class instance being accessed must be the same as or a subclass of the current class.
5. The instruction following each jsr instruction may be returned to only by a single ret instruction.
6. No jsr instruction may be used to recursively call a subroutine if that subroutine is already present in the subroutine call chain. (Subroutines can be nested when using try-finally constructs from within a finally clause. For more information on Java virtual machine subroutines, see section 4.9.6 of [LY99].)
7. Each instance of type returnAddress can be returned to at most once. If a ret instruction returns to a point in the subroutine call chain above the ret instruction corresponding to a given instance of type returnAddress, then that instance can never be used as a return address.
8. At any given point in the program, no matter what code path is taken to reach that point, the operand stack is always the same size and contains the same types of values.