

# **An X86 emulator written using Java**

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Jonathan Kenneth William Burcham

School of Computer Science

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## **Abstract**

An extension to the program Pearcolator is presented that allows emulation of the x86 architecture. Pearcolator is an emulator written in Java and runs as a front end to the Jikes Research Virtual Machine.

The work presented was carried out as part of the Jamaica Project in the School of Computer Science at the University of Manchester. The long term aim of the Jamaica Project is to develop a chip multiprocessor architecture. Pearcolator is needed as a way to run software compiled for legacy architectures. Jikes RVM has parallel translation and execution abilities. It is hoped performance will be better than that of more traditional emulators designed for single processor architectures.

## **Declaration**

No portion of the work referred to in this dissertation has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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The x86 portion of Pearcolator was developed using Slackware Linux 10 and Emacs. As such I am indebted to all those involved in the development of GNU/Linux.

The dissertation was prepared on Microsoft Windows using Microsoft Word and OpenOffice. I am therefore also indebted to Microsoft, and the Open Office developers.

## **The Author**

I graduated from Manchester University with a BSc(Hons) in Computer Science in 2004. Feeling that my formal education wasn't quite complete and that the University still had much to offer I took the MSc Advanced Computer Science. The final part is the work described in this dissertation carried out as part of the Jamaica Project in the Advanced Processor Technologies Group.

# 1 Emulation with Pearcolator

## 1.1 Emulation

An emulator is a program that allows programs compiled for one type of processor to run on a computer with another type of processor.

There are three ways to emulate a program: Static Binary Translation, Dynamic Binary Translation and Interpretation.

Static Binary Translation (SBT) translates the entire emulated program to native machine code before execution. This technique is not often used as it can be difficult getting things like dynamic linking and self modifying code to work.

Dynamic Binary Translation (DBT) converts only the parts of the emulated program that are likely to be executed. Each part that is translated is called a trace. A trace gets translated just before execution. Because the translation happens at run time there are not so many problems with dynamic linking and self modifying code.

The last method is to use an interpreter. An interpreter does not perform any translation. Instead, each time an instruction must be executed the instruction must first be decoded. Decoding is the act of determining which instruction an instruction is. Once the instruction is decoder a method is called that carries out the same operation as the emulated instruction.

DBT usually generates very fast code. The trade off is that to translate the emulated machine code to native machine code requires an expensive compilation process. If a trace is to be executed many times the speed of the generated code should offset the length of time spent on compilation. This ensures that the generated code is often not much slower than native machine code on long running programs such as servers.

An interpreter executes more slowly than the code generated by DBT. However, because there is no translation process the overhead is lower. For short lived programs where a piece of code is not run many times the interpreter can end up being faster.

## **1.2 Pearcolator**

Pearcolator is an emulator created by the Jamaica Project at the University of Manchester [1]. It is written in Java and acts as a front end to the Jikes Research Virtual Machine (RVM).

The long term goal of the Jamaica project is to design a chip multiprocessor architecture [5].

Jikes RVM is a sophisticated Java Virtual Machine (JVM) written in Java. Jikes RVM has an optimising compiler and supports parallelisation of code.

An emulator was needed by the Jamaica Project in order to run legacy code written for single processor architectures. Other emulators were found not to be suitable for the needs of the Jamaica Project so Pearcolator was created.

Initially Pearcolator was designed as a PowerPC emulator. This is because of the simplicity of the PowerPC instruction set. The design was found to produce a promising emulator so it was decided to expand to emulate other architectures.

The aim of this project is to extend Pearcolator to emulate the x86 architecture. The x86 was chosen as it is one of the most commonly found architectures.

## 2 Emulating x86 Linux

### ***2.1 Evaluation of the x86 Linux Environment***

Linux uses the ELF binary format. This has been developed over many years so has gained many features while remaining simple to process. One of the features allows statically linked binaries. This is a benefit for any fledgling emulator. It allows programs to be run without needing to worry about the intricacies of dynamic linking. Dynamic linking can cause many problems which need to be solved before a program can be executed.

The x86 architecture is quite complicated. Being fundamentally a CISC (Complex Instruction Set Computer) architecture means it has a lot of instructions. Most instructions are capable of loading any data they need without the use of load/store instructions. This means an x86 emulator must handle a large number of instruction-addressing mode combinations.

Each instruction can be of a variable length. This has the advantage that code density in memory is high, but the disadvantage that the instruction decoder tends to be more complex than that of a RISC (Reduced Instruction Set Computer) processor such as PowerPC.

Most instructions set condition bits in the eflags register. The condition bits are used relatively infrequently. This can generate a lot of wasted computation. This needs to be handled elegantly to prevent emulation slowing down too much.

Several x86 registers have sub-registers that can be used as unique registers. To prevent a lot of mask and shift instructions being generated these must also be handled elegantly.

## **2.2 X86 Architecture**

### **2.2.1 Overview**

Modern x86 processors can operate in several modes, these being 16 bit real mode, 32 bit protected mode, and 64 bit mode. Pearcolator emulates a 32 bit protected mode processor. It should be fairly simple to add support for other operating modes. Pearcolator has partial support for certain parts of 16 bit real mode.

Pearcolator models the instruction set, data types, registers and memory. It does not yet handle interrupts or virtual memory handling.

X86 processors use a little endian byte ordering. This means bit 0 is the least significant bit.

X86 recognises 8 bit bytes, words (defined as two 8 bit bytes), double words (defined as two words) all of which Pearcolator is able to handle. There is also a quad word data type which is used by SIMD and 64 bit mode instructions. Pearcolator does not yet handle these for x86 emulation, although a framework is in place which should make adding support straight forward. Values in memory do not need to be word aligned, although most compilers generate code where this is the case.

X86 processors support 32 bit single precision, 64 bit double precision and 80 bit double-extended precision floating point numbers. Pearcolator does not support this yet. SSE instructions also add support for 128 bit floating point numbers.

### **2.2.2 Registers**

X86 has eight general purpose 32 bit registers. The registers are EAX, EBX, ECX, EDX, EDI, ESI, ESP, EBP. ESP is the stack pointer and is used by so many instructions that it is usually a good idea to not alter its value unless absolutely necessary. Each other register only has a conventional purpose.

The first four general purpose registers contain a number of sub-registers that can be referenced as if they were unique registers. Each of these registers has a 16 bit register in the lower 16 bits. For EAX this 16 bit register would be AX. The 16 bit register is then split into two 8 bit registers – one in the lower 8 bits (for EAX this would be AL) and one in the upper 8 bits (for EAX this would be AH).

The last four general purpose registers are able to be referenced as 16 bit registers. These registers are generally used as pointers, so in 32 bit mode the 16 bit sub-registers are not generally used.

There are six segment registers : CS, DS, SS, ES, FS, GS. These are 16 bit registers used to enable 16 bit processors to address up to 1 MB of RAM. These are rarely if ever used now so will not be discussed further.

The instruction pointer is a 32 bit register that keeps track of the position in the program. No instructions are able to alter this directly.

X86 processors have five control registers that are used to control certain features of the processor. These are generally only used by operating systems, which Pearcolator does not yet emulate so will not be discussed further.

The x86 has a flags register called EFLAGS. It is a 32 bit register with 17 fields, each comprising 1 bit. Only six of the fields are used and are described in the following table:

Flag	Bit	Name	Description
CF	0	Carry Flag	Set to 1 if an unsigned integer operation generates a carry or borrow on the most significant bit, 0 otherwise.
PF	2	Parity Flag	Set to 1 if an integer operation produces a result with an even number of 1's, 0 otherwise.
AF	4	Adjust Flag	Set to 1 if a BCD operation produces a carry on bit 3, 0 otherwise.
ZF	6	Zero Flag	Set to 1 if an integer operation produces the result 0, 0 if result is not zero.
SF	7	Sign Flag	Set to the most significant bit of the result of an integer operation.
OF	11	Overflow Flag	Set to 1 if unsigned integer overflow occurs, 0 otherwise.

The other fields are used more by operating system kernels so will not be discussed further.

The x86 has eight 80 bit double-extended precision registers. Pearcolator models these using 64 bit double precision floating point values as it is faster for Java to do this and most programs will not notice the reduced precision.

The Floating Point Unit (FPU) is used as a stack machine.

The floating point status register is 16 bits. It is used to keep track of various aspects of results of floating point operations such as the outcome of comparisons or exceptions triggered.

The floating point control register is 16 bits. It is used to enable or disable certain functions of the FPU.

The floating point tag register is 16 bits. It is used to keep track of the value of each register in the FPU stack. Two bits of this register are dedicated to each element.

The possible values for each field are as follows:

Value	Description
0x00	Register contains valid value
0x01	Register contains 0
0x10	Register contains special value
0x11	Register contains invalid value

MMX adds eight 64 bit registers for performing vector operations and operations on large integers. Pearcolator does not currently support this so will not be discussed further.

SSE adds eight 128 bit registers for performing vector operations, operations on large integers, and operations on floating point numbers. Pearcolator does not currently support this so will not be discussed further.

Recently 8 64 bit general purpose registers were added to x86 as part of the x86-64 initiative. These can be referenced by sub-registers in a similar manner to the existing 32 bit general purpose registers. Pearcolator does not currently support these registers. Support should be simple to add as any instructions that wish to use these registers must simply add a prefix (see chapter 4) to the start of the instruction.

### 2.2.3 Addressing Modes

The formula

$$\text{segment\_register} + \text{immediate\_offset} + \text{base\_register} + \\ (\text{index\_register} * \text{scale\_factor})$$

is used by nearly all instructions that need to access memory.

*segment\_register* is one of the six segment registers. All other registers are general purpose registers. *immediate\_offset* is an immediate value given in the instruction.

Virtually any combination of variables may be used. If *scale\_factor* is used then *index\_register* must also be specified. *segment\_register* is not used very often as on Linux it is often fairly meaningless.

Using this formula allows fairly sophisticated array access operations to be carried out within a single instruction.

## **3 Environment**

### ***3.1 Introduction***

This chapter discusses how Pearcolator convinces an emulated binary it is being run within a real environment.

### ***3.2 Process Space***

#### **3.2.1 Overview**

The ProcessSpace class is the part of Pearcolator which holds everything together. It is about the only part to have complete knowledge of both the Operating System (OS) and processor being emulated. ProcessSpace has three main components, which are the registers, memory and system call interface.

The ProcessSpace ensures the correct set of system calls are used, and that instructions are handled by the correct decoders and translators for the processor being emulated.

Previous versions of Pearcolator did not use a modular Process Space class. All memory, register and System Call handling was inside the Process Space class. It was decided that instead of repeating a similar design for all future architectures Pearcolator might support all memory, register and system call handling should be placed in separate classes. This encapsulation allows each component to be far more flexible and allows for greater code reuse.

The PowerPC version had a PPC\_ProcessSpace class which handled everything. There is now a ProcessSpace super class which contains functionality common to all architectures and operating systems to be emulated.

Each architecture/operating system combination has a sub class of ProcessSpace which sets up each component in the appropriate manner.

### 3.2.2 Registers

A class named Registers has been created. Each type of register has methods used for performing low level operations on that register. Each method receives an index as an argument specifying which register of that type is to be accessed. The registers object is designed to allow support for any type of register.

The registers object currently supports the following operations:

- read 32 bit general purpose register
- read 16 bit general purpose register
- read 8 bit general purpose register
- write 32 bit general purpose register
- write 16 bit general purpose register
- write 8 bit general purpose register
- read 32 bit flags register
- read 16 bit flags register
- write 32 bit flags register
- write 16 bit flags register

How each register is implemented is left to sub classes of Register. Each method in Registers throws an exception if called.

Each method could have been declared as an abstract method. This was not chosen as many architectures do not support all the register types that the Register class supports. For example, PowerPC does not support 16 bit general purpose registers. If the methods in Registers were all declared abstract, the sub class of Registers for PowerPC would need to implement 16 bit registers, which obviously does not make much sense. The sub class for x86 implements all the above methods.

Encapsulation of the registers in this manner allows for a great deal of flexibility. Any other parts of the emulator that need to access registers do not need to know how each register type is implemented.

For the general purpose registers the x86 sub class only stores the value for the 32 bit registers. These are stored as an array of 32 bit integers. Accesses to 16 bit and 8 bit registers are implemented as masks and shifts performed on the 32 bit registers.

It should be possible to use native methods and a series of pointer manipulations to access the 16 bit and 8 bit sub registers without changing any code that uses registers. Using pointer manipulations like this may result in faster code, although this is currently untested. This will help speed up the interpreter more than the translator for reasons that are discussed in chapter 3.

### **3.2.3 Memory**

A new memory system has been created. This is based on the super class Memory.

Pearcolator now supports x86 and PowerPC processors. X86 is little endian while PowerPC is big endian which require different memory systems.

If x86 is being emulated on another x86 computer the emulated memories bytes are in the correct order. However, if x86 is being emulated on a PowerPC computer reading a multiple byte value requires the order to be reversed before the value can be used.

Different endian memory schemes are handled by different sub classes of Memory. The different memory schemes can also be addressed using either bytes or integers.

Each of the memory schemes contains three page tables. One page table stores all tracks pages with read permission, another with write permission and the last handles execute permission.

Assuming an address space of 4GB, each page table has 0x100000 elements, while each page is 4096 bytes long.

Each element of a page table contains a reference to an array containing the data (the page). If a type of access is not allowed on a page, that element of the page table for that type of access contains a null reference.

Previous versions of Pearcolator would explicitly check the permission of each memory access before it occurred. Newer versions now assume the memory access is allowed. If the page being accessed does not have the correct permissions set, Pearcolator will attempt to dereference a null reference, so an exception is thrown.

The sub classes of Memory are as follows:

### **CallBasedMemory**

Super class to all other Memory sub classes. Contains methods for translating memory reads and writes.

### **ByteAddressedMemory**

Data in each page is stored as array of bytes in the same order as the host processor would expect.

### **ByteAddressedByteSwapMemory**

Same as ByteAddressedMemory, but with multi-byte values being reversed.

### **ByteAddressedReversedMemory**

Data in each page is stored as array of bytes. All memory addresses are reversed (such as 0x00000000 being mapped to 0xffffffff and vice versa). Endian conversion is performed.

### **IntAddressedMemory**

Data in each page is stored as array of ints in the same order as the host processor would expect.

### **IntAddressedByteSwapMemory**

Similar to IntAddressedMemory except endian conversion is performed on reads and writes.

### **IntAddressedPreSwappedMemory**

Data stored as ints, with data stored in reverse order within the ints.

### **IntAddressedReversedMemory**

Similar to ByteAddressedReversedMemory except all data is stored in ints.

The x86 version of Pearcolator uses ByteAddressedMemory when run on an x86 computer and IntAddressedByteSwappedMemory when run on a PowerPC.

In the last section, a technique using pointer manipulations to possibly speed up register operations was described. It is hoped that similar techniques can be applied to memory. This should benefit the translated code and interpreter roughly equally. The effect of the memory optimisation will have a greater benefit for the translated code than the similar register optimisation.

## **3.2.4 System Calls**

In previous versions of Pearcolator all system call handling was handled by PPC\_ProcessSpace [12]. When a system call was to be made PPC\_ProcessSpace.doSysCall() was called. This would retrieve the system call number from the register r3 which would then be used in a large switch statement. The body of the switch statement would carry out the same action as the system call it was to emulate. The body of the switch statement would get arguments as needed from the registers. The return value of the system call would be written to register r3.

For the x86 version of Pearcolator the first problem is that the system call number is stored in register EAX not r3. As other architectures store the system call number in other ways it was decided to create an abstract method `getSysCallNumber()` in `ProcessSpace`. This would be implemented in each subclass of `ProcessSpace`. It was felt this should be a suitable way of selecting the correct system call in an architecture independent way. The x86 version simply returns the value held in the register EAX.

The next problem was how to get system call arguments in a architecture independent manner. Looking at the system call specifications it becomes clear that all arguments can be represented by 32 bit integers.

An abstract method `getSysCallArguments()` in `ProcessSpace` was created. This receives an int as an argument which specifies how many arguments are expected. `getSysCallArguments()` returns an array containing the arguments. Each subclass of `ProcessSpace` implements this method. For the x86 processor if the number of arguments is five or less the arguments in order are read from EBX, ECX, EDX, ESI, and EDI. If the number of arguments is greater than five, EBX contains a pointer to the list of arguments.

In a similar manner an abstract method `setSysCallReturn()` in `ProcessSpace` was created. As its name would suggest it sets the system call return value. For the x86 this involves setting EAX.

The next improvement was to move as much of the system call handling out of the `ProcessSpace` class. The method `doSysCall()` method was kept in the `ProcessSpace` class but was made abstract. The method `doSysCall()` is implemented by all subclasses of `ProcessSpace`. In the subclass for x86 Linux this method calls `doSysCall()` in the class `org.binarytranslator.LinuxSystemCaller`. This reads the return value of `getSysCallNumber()` which is then used as an index into an array of `SystemCall` objects.

The array index technique was used instead of a switch statement for a number of reasons. First is that it makes the code more object oriented. Second was that using an array instead of a switch statement tends to help the branch prediction.

Each system call is implemented by a separate subclass of the class SystemCall. For example, the exit system call is SysExit.

Any system calls as yet unimplemented are represented by the class USC. For example, the fork system call is not implemented so its position in the look up table is occupied by an instance of USC. If an unimplemented system call is used an exception is thrown stating which system call is being attempted.

The position of unimplemented system calls could have been occupied by a null reference. This would have thrown an exception automatically but would not give any information about which system call the emulator was attempting to use.

## ***3.3 Binary Loader***

### **3.3.1 Introduction**

Before it is possible to execute a program, whether natively or via emulation, it is necessary to read the program from disk and load it into memory ready to be run. This constitutes a number of stages. The stages to load a Linux binary are as follows:

- Determination of format
- Read Elf header
- Read Elf program header table
- Read Elf program headers
- Read program code
- Read initialized data
- Configure uninitialized space

- Environment variables
- Aux vector
- Stack initialisation

Each of these stages will be covered in the following sections.

### **3.3.2 Purpose of Binary Formats**

In order for the binary loader to function it must first know the layout of the file the binary is in.

The simplest layout would be if the file only contained the instructions to be executed as part of the program perhaps immediately followed by any preinitialized data. This is obviously quite an inflexible system. The user of the computer would be responsible for making sure the correct program was being used for the processor and operating system currently in use.

Fortunately, modern binary formats are much more sophisticated. Formats such as ELF enable a file to be split into a number of different sections each one usually containing either executable machine code or initialized data. Each section can also have access permissions applied to it so that, for example, the code section can not be written to and the data section is not executable.

### **3.3.3 The ELF Binary Format**

The Executable and Linkable Format (ELF) contains a large amount of data, a lot of which is not currently of interest to Pearcolator [13]. The parts that Pearcolator is interested in are the ELF Header, Program Header Table and segments.

The ELF Header contains data specifying the layout of the rest of the file. One of the most important fields of the header is `e_machine`. This specifies the architecture of the binary. Another important field is `ELF_OSABI`. `ELF_OSABI`

stores the operating system the binary is meant to run on. Unfortunately gcc appears not to give very much detail in this field at the current time, only specifying that the operating system is some variant of Unix.

Other fields of interest in the ELF header are `e_ehsize` which is the length in bytes of the header, `e_phnum` which gives the number of entries in the Program Header Table, and `e_phentsize` which gives the size of each entry in the Program Header Table.

The Program Header Table contains a list of Program Headers. Program Headers give information about each segment in the file such as segment size and access permissions.

Two segments are usually of interest to a program: the code segment and the data segment.

ELF is currently the only format supported by Pearcolator, although it does contain a framework for supporting other formats.

### **3.3.4 A problem with the Old Binary Loader**

In previous versions of Pearcolator one of the first objects to be created would be the `PPC_ProcessSpace` object. The `PPC_ProcessSpace` object stored the memory of the process and all registers of the processor being emulated. This was adequate when the only platform being emulated was PowerPC on Linux. The binary being loaded could be assumed to be for PowerPC Linux.

However, this version introduced support for the x86 instruction set. This created an equivalent `X86_ProcessSpace` object. It would be a simple matter to copy most of the code from the PowerPC Linux version and create a separate branch that dealt only with x86 Linux.

This raises a number of issues. Support for Sparc and Arm processors is currently under consideration. This means a total of four different branches of Pearcolator would be needed each needing to be executed from a different command eg.

```
rvm org.binarytranslator.PPC_Main executable
rvm org.binarytranslator.X86_Main executable
rvm org.binarytranslator.ARM_Main executable
rvm org.binarytranslator.Sparc_Main executable
...
rvm org.binarytranslator.xxx_Main executable
```

If support for the OS X, Solaris and Windows operating systems were added in the future even more `org.binarytranslator.xxx_Main` classes would be needed – one for each operating system, architecture and binary format combination – all to ensure the correct `xxx_ProcessSpace` class was loaded at run time. The computer user may not even know or care what platform the architecture is designed for making selecting the correct `org.binarytranslator.xxx_Main` class to use.

The solution is to load enough of the binary to detect which `xxx_ProcessSpace` object to select. This means there is only one entry point for Pearcolator which solves the above problems.

### **3.3.5 Determination of Binary Format**

The first task to be carried out is to detect the binary format. This is the job of the class `org.binarytranslator.BinaryLoader`.

Commonly the first four bytes of a binary file are used to specify the format of the file.

Currently the only format of interest to Pearcolator is ELF. It should be fairly easy to add support for Java classes, which can be passed to Jikes RVM without to much problem. For an ELF file to be detected the first four bytes must contain

the characters 'E', 'L', 'F', and '\0' in that order. When an ELF binary has been found control passes to the class `org.binarytranslator.ELF_BinaryLoader`.

### **3.3.6 Reading ELF Header**

Reading the ELF Header is handled by the class `org.binarytranslator.ELF_Header`. Once the `ELF_Header` has been loaded `Pearcolator` has enough information to select the correct `xxx_ProcessSpace` class. The ELF Header is directly after the binary format identifier.

### **3.3.7 Creating ELF Program Header Table**

The Program Header Table is implemented as an array in the class `org.binarytranslator.ELF_X86_ProgramHeaderTable`. It has the responsibility of calling `org.binarytranslator.ELF_ProgramHeader` to populate each element of the array.

### **3.3.8 Reading ELF Program Headers**

Reading ELF Program Headers is handled by `org.binarytranslator.ELF_X86_ProgramHeader`. Program Headers are stored directly after the ELF Header in the file.

### **3.3.9 Copy Executable Code**

Up to this point no data has been copied to memory. The first step is to copy executable code. This uses the method `mmap` in `ProcessSpace` to allocate space in memory and then copy the code from the binary file to memory.

The `mmap` method allows various parameters specifying how the memory should be set up. These include, `MAP_GROWSDOWN`, `MAP_PRIVATE`, and `MAP_SHARED`. The only parameter currently handled is `MAP_PRIVATE`.

Pages allocated for executable code have read and execution permissions set.

### **3.3.10 Copy Initialised Data**

This step is similar to copying executable code, except initialised data is copied from the binary file and the permissions are set to read and write access.

### **3.3.11 Configure Uninitialised Data**

At the end of the initialised data, ELF often specifies that there should be an area for uninitialised data.

If the last page of initialised data is not full, the uninitialised data starts there. Otherwise the uninitialised data starts in the next page.

The method `mmap` is called without a file to read from for this stage. This version of `mmap` should only need to allocate space. However, for some reason `gcc/glibc` generates code that relies on all uninitialised data areas being set to 0. This can cause strange problems, so all data that according to ELF is uninitialised must in fact be initialised to 0.

### **3.3.12 Environment Variables**

In old versions of Pearcolator, all environment variables were fixed. The values were set up for a different computer to the one this version was developed on. Rather than simply changing the values for each computer Pearcolator is run on, a more flexible way of setting environment variables was needed.

This version of Pearcolator relies on Jikes RVM only running on variants of Unix. This seems a reasonable assumption which should stay valid for the foreseeable future.

The Unix command `env` is run from within Pearcolator. This outputs all environment variables and the corresponding values. The output text of the command is stored in an array and then placed on the stack.

### **3.3.13 Aux Vector**

The aux vector is an array of key-value pairs. It gives information about the architecture Pearcolator is emulating. Since automatically obtaining such information does not appear to be possible at present the data is constant.

### **3.3.14 Stack Initialisation**

Stack initialisation involves copying everything needed to access environment variables, command line arguments and the aux vector to the stack.

First, the length of the stack once it has been initialised is calculated. This is so that the stack can be built from the lowest memory location up to the highest.

The lowest memory location of the stack is called the stack top. The stack pointer is set to the stack top using the method `setStackPtr` in `ProcessSpace`. The method `setStackPtr` is abstract in `ProcessSpace` and needs to be implemented by its sub classes. In the x86 Linux emulator `setStackPtr` sets the register `ESP` to the stack top.

Directly above the stack top are the pointers to command line arguments. Next is 4 byte value `0x00000000`. This is to show where the list of pointers ends.

This is followed by the environment variable pointers, followed by `0x00000000` again.

Next is the aux vector. This already has an end of vector marker built in.

It is often useful for multiple byte values such as pointers to be word aligned, so the stack now has a number of padding bytes to ensure this.

Finally, the environment variable and command line strings themselves are copied on to the stack. Because of the way the stack initialisation works, each string needs to be reversed.

## **4 Register Handling**

### ***4.1 Introduction***

This chapter deals with register handling for the translation portion of Pearcolator. Register handling is not covered in the section on code translation as it is a very complex area.

### ***4.2 Register handling in PowerPC Pearcolator***

Before register handling in the x86 version of Pearcolator can be covered it is useful to explain how the PowerPC version works. This is to show why PowerPC register handling does not translate well to x86.

The PowerPC has 32 general purpose registers. Each is 32 bits in length and unlike the x86 does not allow sub registers.

At the start of a trace the translator commands that all registers be filled. Filling a register is the act of specifying that at the start of the execution of the trace a register used in the trace should be given the value held in the ProcessSpace.

Throughout the translation, whenever a register is used by the trace (used being defined as reading from or writing to a register) the translator records that that register has been used.

At the end of the trace the register used in the trace should be spilled. This means the register held in the ProcessSpace is updated with the value held by its counterpart in the executed trace.

After this, a second pass is made through the translated trace. If a register has not been marked as being used in the trace any fills or spills for that register are deleted. This results in the trace only performing useful work on the registers.

## 4.3 Register Handling in x86 Pearcolator

### 4.3.1 Introduction

The x86 allows referencing of sub registers. This tends to complicate matters.

The simplest way to handle sub registers is to use masks and shifts from the 32 bit register. Reading from the register ah requires the following operations to be performed:

```
(EAX >>> 8) & 0xFF
```

Writing val8 to ah requires the following operations:

```
EAX = (EAX & 0xFFFF00FF) | (val8 << 8)
```

Writing val16 to ax requires the following operations:

```
EAX = (EAX & 0xFFFF0000) | val16
```

This is obviously a complicated, time consuming set of operations to perform each time a sub register is to be accessed.

Reading can be simplified substantially by treating each sub register as a unique register. Each time a sub register is updated Pearcolator must ensure each sub register that is dependent on the data written contains the correct data.

Reading from a sub register simply involves reading the value from the variable representing it. Writing val8 to ah requires the following set of operations:

```
EAX = (EAX & 0xFFFF00FF) | (val8 << 8)
AX = EAX & 0xFFFF
AH = val8
```

Writing val16 to ax requires the following set of operations:

```
EAX = (EAX & 0xFFFF0000) | val16
AX = val16
AH = AX >>> 8
AL = AX & 0xFF
```

While reading sub registers is made far simpler, writing is made far more complex. A technique where only sub registers that are used are updated is required. Such a technique is Sub Register Synchronisation Laziness

### 4.3.2 Sub Register Synchronisation Laziness

Each group of registers (such as EAX, AX, AH and AL) is given a state. This state is the Lazy State. The lazy state specifies at the current time in the translation which states are valid for reading.

The Lazy State is represented by 4 bits. Each bit shows the state of a specific sub register. The following table shows for EAX which sub register is represented by which bit:

Sub Register	Bit
EAX	4
AX	3
AH	2
AL	1

If a bit is set it means the corresponding sub register can be read from with no extra work. If a bit is cleared it means the corresponding sub register must have instructions inserted to synchronise it with the rest of the registers in a group.

As an example, if the EAX group has the lazy state 0x8, it means EAX is the only sub register that is valid. Any other sub registers that are to be read from

need to obtain updated data from EAX. If the Lazy State is 0x6, AX and AH are both valid, while EAX and AL are invalid.

When a sub register is written to it “creates laziness”. This means Pearcolator sets the sub register bits in the Lazy State and clears all bits for sub registers that depend on the data just written. If the Lazy State for EAX is 0xF, writing to AL results in the Lazy State becoming 0x3. Writing to AX directly after this results in a Lazy State of 0x4.

When a sub register is read from it “resolves laziness”. If the sub registers bit is already set in the Lazy State, the register can be read. If the sub registers bit is cleared when the read is demanded Pearcolator must:

1. Synthesise the sub register from the data held in the valid sub registers.  
This usually involves some degree of masking and shifting.
2. Set the sub registers bit in the Lazy State.
3. Translate the read.

If the Lazy State before a read is 0x4, then a read from AH will perform the following actions:

1. Mask top 8 bits of AX, and shift right by 8 bits, putting the result in AH.
2. Set the Lazy State to 0x6.
3. Translate the read from AH.

Although this looks like it requires more work than the non lazy register handling it must be remembered that all Lazy State handling happens at translation time, not execution time. This means if generated code using sub registers must be executed many times, the Lazy State must only be handled once.

### **4.3.3 Removing Unnecessary Fills and Spills**

Register Synchronisation Laziness reduces the amount of code to be executed during the trace for register handling, but it does not help when fills and spills are needed at the beginning and ends of traces respectively.

The PowerPC version of Pearcolator adds all fills and spills possible to the trace and uses a second pass to remove any that are unneeded.

For the x86 version, due to Register Synchronisation Laziness it was found to be unfeasible to add all fills and spills on a first pass and remove them later. This is because each register could be in too many states to handle in this way. Using a second pass to remove instructions also seemed inelegant.

### **4.3.4 First Version**

The first version of the lazy evaluator was very simple. It did not make any attempt to remove fills or spills. This was done merely to see if the generated code would be acceptable.

At the beginning of a trace all sub registers would be filled. The body of the trace would be translated, using laziness to reduce unneeded register operations. At the end of the trace all laziness would be resolved. All sub registers would be spilled.

No benchmarks needed to be run on this technique to know that it was slow. Emulating a four instruction program with no looping took roughly 2 seconds to translate and execute.

### **4.3.5 Second Version**

The goal of the second version was to remove fills and spills of register groups that were not used.

In this version no register fills occurred at the start of the trace. Instead registers were only filled as they were used. At first use of a register group, all sub registers in the group were filled.

At the end of the trace, laziness for all sub registers in all register groups was resolved. If a register group had been used, then all sub registers were spilled.

This version had a substantial speed increase over the first version. There was very little delay between starting the translation and execution completing.

#### **4.3.6 Third Version**

Although the second version seemed adequate, it still appeared to be inefficient. All sub registers in a group were filled and spilled even if most were not used. This version was to remove unnecessary fills and spills of sub registers within a group.

On first use of a sub register from a group, instead of filling all sub registers only the 32 bit sub register was filled. If another sub register was needed it would be resolved from the data in the 32 bit sub register.

At the end of the trace the 32 bit sub register would be resolved from any altered data in the other sub registers in the group. The 32 bit sub register only would then be spilled. This was possible as this sub register now contained all data held in the other sub registers.

#### **4.3.7 Fourth Version**

The fourth and final version implemented removed more fills and spills.

Every version covered so far used a coarse grained view of register use. If a register group was either read from or written to then it would be filled and spilled.

This version keeps more fine grained data on register use. It separates usage data into reading and writing.

If the first use of a sub register is a write, no fill is performed. This is because the filled result will be over written any way so is wasted computation.

If a sub register needs to be read from, and can be resolved from data available in the other sub registers in the group then laziness is resolved to get the required data. If insufficient data is available to resolve from, the 32 bit register is filled. The 32 bit sub register is updated from any data that may have been written and the sub register is resolved from that.

If a register group is written to, the 32 bit sub register is resolved at the end of the trace (filling if necessary), and then is spilled.

This version tends to reduce the number of register fills and spills over earlier versions.

#### **4.3.8 Alternative Implementation**

Another technique for handling fills and spills was also considered. For completeness it will be covered briefly here.

Currently the 32 bit sub register in a group is filled if a read is required. The alternative is to fill each individual sub register when a read is required. At the end of the trace the most encompassing sub register would be written. If AL and AH were written to then they would be spilled. If AX were also written to then only AX would be spilled as it encompasses AL and AH.

This technique was rejected. With the currently implemented version the 32 bit sub register always contains data, even if it is no longer valid. The top half of the 32 bit sub register is always valid. This allows the 32 bit sub register to be used easily if required by other sub registers for synchronisation purposes.

As an example, let AL be written to. This will cause EAX to be filled if it currently contains no data. The Lazy State is 0x1. If a read from AX is required, EAX can be resolved, and then AX resolved from EAX.

With this alternative implementation, after AL has been written to, there is difficulty when AX needs to be read from. One of two things can happen:

1. Fill AX, resolve AX from AL, read AX
2. Fill EAX, update EAX from AL, resolve AX from EAX, read AX

The first option seems to be more efficient, while the second closely follows the behaviour of the current implementation only in a slightly different order.

The first option seems more efficient until a read from EAX is needed. This would be the following operations:

1. Fill EAX
2. Update EAX from AX
3. Read EAX

The second option merely requires a read operation on EAX. There are many similar cases. This implementation seems to require a potentially larger number of fills than the current implementation.

Even if this implementation could be adapted to fall back on to the current behaviour if it seemed more efficient, a far greater number of Lazy States would be required to keep track of which sub registers contain data.

## **4.4 Flag Handling**

### **4.4.1 Introduction**

A similar problem exists for the EFLAGS register. It is updated by nearly every instruction with each update requiring various masks of the EFLAGS register. The EFLAGS register is only very rarely read from, so keeping it up to date at all times is very inefficient.

### **4.4.2 Flag Laziness**

To solve this problem flag laziness was developed. Each time a flag needs updating a copy of the result that the flag is to be based on is copied along with the type of the operation (such as integer, short or byte).

When a flag needs to be read from the operation of updating EFLAGS can be performed.

## 5 Instruction Decoder

### 5.1 Introduction

In order for Pearcolator to run a program, it must first know the instructions it is to emulate. This is the job of the instruction decoder. The instruction decoder must read a series of bytes from the Memory object and ensure the correct action is performed.

### 5.2 Instruction Format

Unlike the PowerPC instruction format that is simple and fast to decode, the x86 instruction format is much slower and more complicated to decode.

Each PowerPC is 32 bits in length. Due to its constant length it is easy to extract information from. The x86 has variable length instructions ranging from 1 byte to 17 bytes.

Each instruction has a number of fields:

- Instruction Prefix
- Opcode
- ModR/M
- SIB
- Displacement
- Immediate Data

Each field is optional within the instruction except for the opcode field, which is obligatory.

### 5.2.1 Instruction Prefix Field

The instruction prefix field can be between 0 to 4 bytes in length. There are a large number of prefixes that can be used. Currently Pearcolator only has full support for the Operand Size Override prefix. The Operand Size Override prefix changes the default operand size from 32 bits to 16 bits.

Other notable prefixes include:

- Lock, which ensures any memory locations used by the instruction are not used by any other instructions run concurrently.
- Branch Hint, which offers a suggestion to the processor of which conditional branch is likely to be taken.
- Wait, which commands floating point instructions to wait for exceptions to be resolved.
- Rex, which tells the processor to use the registers added by the x86-64 extension.

### 5.2.2 Opcode Field

This is the only obligatory field. It must be at least 1 byte and no more than 3 bytes long.

Most instructions only require a 1 byte opcode. If an instruction requires a longer opcode the first byte must contain a value from a specific set of values. Often the multi-byte opcodes simply offer instructions similar to the 1 byte opcodes but with slightly different functionality.

### 5.2.3 ModR/M Field

When present the ModR/M field has 1 byte. It has the following structure:

Mod Bits 6 - 7	Reg/Opcode Bits 3 - 5	R/M Bits 0 - 2
-------------------	--------------------------	-------------------

As can be seen from the diagram it is split into three further fields, i.e. the Mod, Reg/Opcode and R/M fields.

The Mod and R/M fields are often combined. They can represent up to 32 different values. This corresponds to 8 general purpose registers (by default on Linux the general purpose registers are 32 bit) and 24 addressing modes. If one of the addressing modes is used the SIB field (described in the next section) must be present.

The encoding used by this byte for the register and addressing modes is very complex so will not be discussed here.

The Reg/Opcode field is usually used to specify a register to use in the instruction. If necessary this field can also be used to further refine the opcode.

Very occasionally the entire byte can be used as part of the opcode field.

#### 5.2.4 SIB Field

The SIB field is used when one of the operands to be used is a register indirect operand. It is used when the ModR/M field specifies an addressing mode. When present it is 1 byte long and has the following structure:

Scale Bits 6 - 7	Index Bits 3 - 5	Base Bits 0 - 2
---------------------	---------------------	--------------------

In an earlier chapter the formula for building a register indirect address was given as:

```
segment_register + immediate_offset + base_register +  
    (index_register * scale_factor)
```

The variable *scale\_factor* is given in Scale. The mapping of values given in Scale to values of *scale\_factor* is given by  $\text{Scale}^2$  (Scale to the power of 2).

The variables *index\_register* and *base\_register* are given by the Index and Base fields respectively. Each specifies a 32 bit general purpose register by a default. If the instruction make use of the Address Size Override prefix

### 5.2.5 Displacement Field

This field is used as *immediate\_offset* in the formula in the previous section. When present it can be 1, 2 or 4 bytes.

### 5.2.6 Immediate Data

This field is used when one of the operands is a constant. When present it can be 1, 2 or 4 bytes long.

## 5.3 Decoder Implementations

Instead of building a decoder from scratch it was decided to try to find an already written decoder that could be used easily by Pearcolator. The x86 instruction set was deemed too complicated to build a decoder from scratch in the time available.

First, research centred on finding a decoder written using Java. None were found so the search was expanded to cover decoders written using C and C++.

Since any decoder written in C or C++ would need to be altered to fit the specific needs of Pearcolator it was decided that any decoder chosen should be ported to Java.

This produced far more results. The most promising found are covered in the following sections.

### **5.3.1 QEMU**

Qemu is an emulator that supports a number of architectures [6].

QEMU has two decoders: one to decode the emulated instructions and the other to act as an interface to GDB (the GNU DeBugger). The decoder for the emulator seemed quite tightly integrated with the rest of the emulator and proved difficult to try to extract.

The decoder for the interface to GDB seemed at first to be fairly straight forward to convert to Java. It did not appear to use any macros or similar language constructs that might be difficult to convert. Unfortunately it did use lots of strange pointer manipulations that made conversion difficult.

### **5.3.2 Bochs**

Bochs is an x86 emulator that runs on a number of architectures[7].

The decoder from Bochs has the same problem as QEMU in that it is tightly integrated with the rest of the decoder. The documentation seems to be under development and is not any use at the moment.

### **5.3.3 libdisasm**

libdisasm is a disassembler library used by The Bastard disassembler [8]. It works using a series of array lookups based on each byte of the instruction. It is written using C. Documentation is excellent for this library. The code is nicely laid out and is easy to follow.

The problem with libdisasm is that it is currently undergoing a complete rewrite. The current version seems to have a number of serious bugs which aren't being corrected by the developers. Another problem is that the design of the lookup means that it would be very time consuming to convert.

### **5.3.4 libopcodes**

libopcodes is used by objdump for its disassembler output. It is largely undocumented. It does not appear to support many of the newer instructions.

### **5.3.5 Jikes RVM**

Jikes RVM has a disassembler that was borrowed from IBM Visual Age. It is written in C++ and as a consequence uses very few features that have no analogue in Java.

It is quite old and lacks many of the newer instructions that have been added to the x86 architecture. It is however fairly clear how to add the missing instructions.

It is well laid out with no ambiguity as to which code is actually part of the decoder.

### **5.3.6 ndisasm**

ndisasm is part of nasm [10]. It is fairly similar in design to libdisasm but has more active development.

It is designed to reuse much of nasm, and was not built from the ground up to be a disassembler. It was built purely because it seemed a waste not to have a disassembler when various parts were already available.

### **5.3.7 Sled**

Sled is a tool for building instruction decoders [9]. It works in a similar way to a lexer and parser with the user creating specifications for the format of an instruction.

It is written in a combination of C and Icon. Although decoders are already available for the x86 meaning writing the decoder is theoretically trivial, Sled only outputs decoders in C and Modula at present. It is not clear how to add an output language without rewriting large parts of Sled.

It would be possible to use Sled using the Java Native Interface (JNI) but this is messy.

### **5.3.8 Chosen Implementation**

The disassembler from Jikes RVM was chosen as the base for the decoder for Pearcolator. Despite its age it seemed to be the easiest to port to Java. Also it meant that Pearcolator would not be perceived by people as being merely a conglomeration of work taken from other emulator projects.

Another advantage is that it should be fairly simple to separate the decoder from the interpreter and translator and reintroduce disassembler functionality. There is still a reasonable amount of disassembler functionality hidden in Pearcolators decoder. Each Instruction class (covered in section 5.4.2) contains a String representation of the name of the instruction. This would mean Jikes RVM would have a disassembler written in Java rather than C++. There is a trend in Java currently to rely less on JNI and legacy code that this would appear to fit in with.

## ***5.4 Decoder Components***

This section will give details of some of the major components of the decoder.

### **5.4.1 X86\_BaseInstructionDecoder Class**

This is the entry point for the decoder. It contains an array of 32 bit Instruction objects, an array of 16 bit Instruction objects and an array of OpcodeFunction objects. The first byte of an instruction is read from memory which is used to select the correct Instruction and OpcodeFunction from the arrays.

After this the selected OpcodeFunction is used to decode the rest of the instruction.

### **5.4.2 Instruction Class**

There is one Instruction for each instruction in the x86 architecture. It handles the translations and interpretations for that instruction.

### **5.4.3 OpcodeFunction Class**

The OpcodeFunction objects handle further instruction decoding needed by groups of instructions. It might handle reading extra opcode bytes or selecting the correct operands.

### **5.4.4 Opcode Decoder**

Each OpcodeFunction creates an opcode decoder. This is a where all information that the OpcodeFunction finds is stored. This includes the instruction and list of operands.

## 5.4.5 Operands

Each Instruction object must know how to deal with a large number of operand types and addressing modes. It was for this reason the Operand class was conceived.

The Operand class has a sub class for each size of operand (such as byte, short and int). Each size sub class has a sub class for each operand type (such as register, constant and register indirect).

An instruction class is able to specify which operand sizes it accepts and what to do when operands are of a certain size. The Instruction object should not need to know any more information than that.

The Operand class and its sub classes also provide a means of storing information about the operand in a way that is meaningful to both the translator and the interpreter.

The Operand class has several methods for reading and writing different sized operands for both translation and interpretation. Each method returns an exception if called.

The Operand sub classes are as follows:

**ByteOperand:** Super class of all operands that represent a byte.

**ByteConstantOperand:** Represents an immediate byte value.

**GP8RegisterOperand:** Represents an 8 bit general purpose register.

**ShortOperand:** Super class of all operands that represent a 16 bit value.

**ShortConstantOperand:** Represents an immediate 16 bit value.

**GP16RegisterOperand:** Represents a 16 bit general purpose register.

**IntOperand:** Super class of all operands that represent a 32 bit value.

**IntConstantOperand:** Represents an immediate 32 bit value.

**GP32RegisterOperand:** Represents a 32 bit general purpose register.

**GP32RegisterIndirectOperand:** Represents a register indirect operands where all registers used are 32 bit general purpose registers. It has a method for obtaining the address for the translator and interpreter (this is mainly used externally of this class by the Lea instruction). It has methods for reading and writing 8, 16 and 32 bit values.

Currently GP32RegisterIndirectOperand must be treated differently from all other operand types as the values it deals with can be of any size. Each other operand type has a specific size of values it deals with. It is hoped that in the near future it will be possible to have indirect operands that have specific sizes. GP32RegisterIndirectByteOperand, GP32RegisterIndirectShortOperand and GP32RegisterIndirectIntOperand operand types are all planned. This should reduce the number of operand types each instruction translator must deal with.

Sign extended and zero extended operands are also planned. Many instructions deal with one integer operand and one byte operand that must be sign extended to an integer. Currently the instruction translator must perform the sign extension. These instructions end up having a translator that deals with two integer operands and another that deals with one integer and one byte. After sign extension both translators perform much the same task. By making the operand perform the sign extension it can be treated as a perfectly stand integer operand, removing the need for a second translator.

## ***5.5 Improving the Decoder***

As well as the improvements mentioned in the last section several other improvements can be made in the future. These mostly involve reducing the number of redundant branches the decoder needs to make.

One of the first improvements would remove the need to perform an array access to find the instruction followed by another array access to get the operand

decoder. Since these two operations both use the first byte of the instruction it should be simple to have a decoder for each value of the first byte which will know which instruction it is operating on.

The next improvement involves optimising instructions where register operands are encoded in the opcode. The x86 has one byte push and pop instructions that act on a 32 bit register. These instructions are quite frequently used. The decoder must currently mask off part of the byte to obtain the register. Making the first improvement in this section makes it unnecessary to mask the byte as the decoder will already know the value of the byte. Removing a single And instruction from the decoder may not sound like much of an improvement but it must be remembered that for the interpreter it may be a great improvement. One instruction may take up a large proportion of the time taken to interpret an instruction. Removing the need for the instruction may result in a significant performance increase. A similar idea can be applied to many other instruction decoders.

The final improvement should make the most significant improvement in performance. Currently each time an instruction is decoded, several operand objects must be created. Once the instruction has been translated or interpreted, the operand values are often never used again. Object creation tends to be an expensive operation to perform. For the interpreter this is of particular concern as it severely limits the speed at which instructions can be executed. The values stored in the operand object are not needed after the instruction has been translated or interpreted so it seems reasonable to reuse the object and simply change the values. A similar optimisation can be carried out with other objects created by the decoder.

The improvement should be large for the interpreter. Instead of needing to create several objects for each instruction, it should be possible to create only about 20-30 objects for the entire life of the interpreter. The improvement should help the translator as well, but not as much.

## **6 Emulation Modes**

### ***6.1 Introduction***

Once the environment a program is to be emulated in has been set up (covered in the last chapter) Pearcolator then must run the program somehow. Pearcolator has two modes of accomplishing this: code translation and interpretation.

### ***6.2 Code Translation***

#### **6.2.1 Introduction**

Code translation involves converting instructions of the machine code to be emulated into native machine code. It does this by first translating the emulated machine code to the High level Intermediate Representation (HIR). The HIR is then passed through to a compiler which generates native machine code.

HIR is the first of many intermediate languages used by Jikes RVM. HIR has a very similar structure and instruction set to that of a modern RISC processor.

Each emulated instruction is converted to a Basic Block. A Basic Block contains a sequence of HIR instructions that are to be executed in order. Each basic block has a link to the next basic block to be executed. There can optionally be a branch at the end of a Basic Block which affects which block must be

The aim of the code translator is to approximate java methods from the emulated machine code. The return value is the memory location of the last instruction executed.

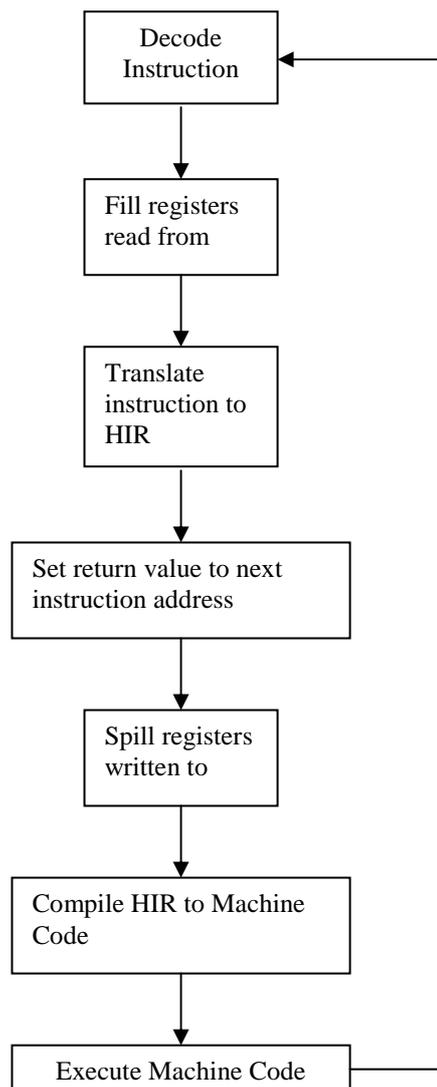
Pearcolator has two modes of translation: single instruction and trace translation.

## 6.2.2 Single Instruction Translation

Single Instruction Translation mode generates HIR for one instruction, runs the compiler on that instruction and then executes the generated machine code.

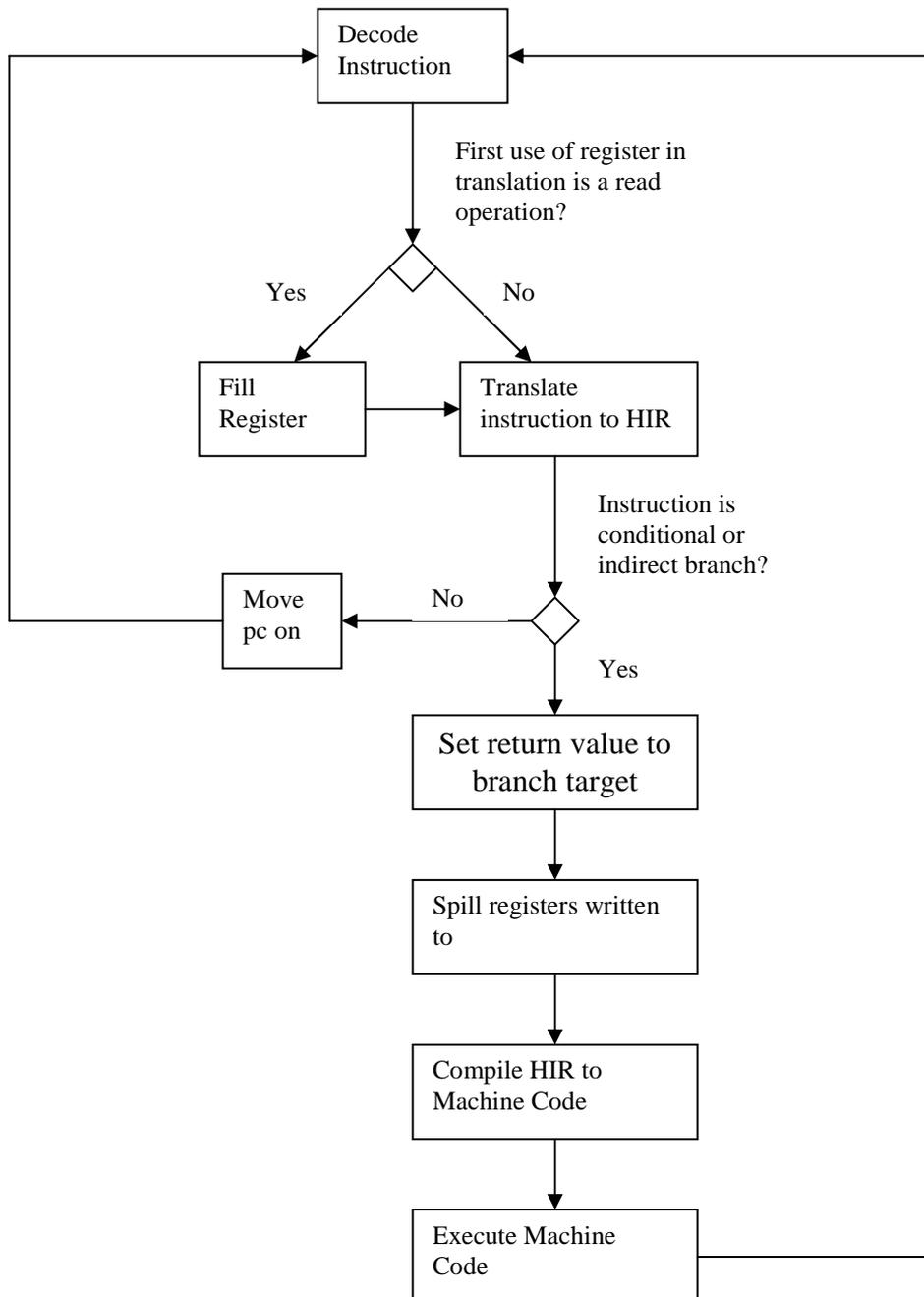
This mode has the advantage of being very simple to program and debug. It is much easier to find the debugging output for a particular instruction.

It has the disadvantage of being slow. After each instruction decode the processor must run the compiler. This obviously takes some time to start, which will be roughly constant no matter how much code it must translate. Another reason is that executing the translated code in such a disjointed fashion effectively disables branch prediction and pipelining on the host processor. The following flow diagram shows the translation for this mode:



### 6.2.3 Trace Translation Mode

This translates instructions to HIR until either a branch is located for which it is not possible to predict the target or until a certain number of instructions have been translated. When this point is reached the HIR is passed to the compiler and the generated machine code is executed. Following is the flow diagram for this mode.



## **6.2.4 Structure**

There are three components that control translation of x86 machine code to native machine code. These are the classes `X86_OptimisationPlanner`, `X86_ConvertX86toHIR`, `MC2IR` and `X862IR`.

`X86_OptimisationPlanner` is used to control the stages of the HIR to machine code compiler. It specifies which translators to use at each stage.

`X86_ConvertX86toHIR` coordinates the x86 machine code to HIR translator with the other stages, ensuring the generated HIR is in a form that is suitable for later stages. `X86_ConvertX86toHIR` ensures `X862IR` gets used correctly.

`MC2IR` and `X862IR` control the translation itself. `MC2IR` handles the parts of the translation that are not architecture specific such as method call planting, controlling how the trace should be built. `X862IR` handles all architecture specific operations such as using the correct instruction decoder/translator and register handling.

## **6.2.5 Branch Handling**

The x86 has three classes of branch. These are constant branch, conditional branch and indirect branch.

A constant branch has the branch target encoded into the instruction. When the translator finds this type of branch it continues from the branch target. It does not add any HIR to the trace.

A conditional branch has the branch target encoded into the instruction, but whether the branch is taken or not is decided by the state of the condition flags at the time of the instructions execution. When the translator reaches this type of

branch, it inserts code to resolve the flag laziness and then code to return the next instruction location based on that result. The translation then stops.

An indirect branch has a target stored in a specific register or memory location. The branch will always be taken. When the translator reaches this type of branch, code is inserted to resolve register the register if necessary, and then return the branch target address. The `retn` instruction is classed as this type of branch.

### **6.2.6 Reusing HIR**

Quite often different traces will use instructions from the same memory location. This is usually due to several branch instructions having the same target.

It is obviously inefficient to generate HIR which is identical to that previously generated.

To solve this, a cache of previously generated HIR is kept in a hash map in the class `MC2IR`. The current lazy state is used as the key.

Before each instruction is translated `Pearcolator` checks that the instruction has not previously been translated with the same lazy state. If the instruction translation is found in the cache then the cached translation is linked into the current trace. The translation can then end. This is because all translated instructions after the cached instruction are linked into the cached instruction so the trace is complete.

If a suitable translation is not found in the cache the instruction is translated as normal, and the translation is added to the cache.

### **6.2.7 Planting Method Calls**

It is often necessary for the translated HIR to make method calls. This is needed for filling and spilling registers, making system calls and accessing memory.

It is fairly simple to make method calls from HIR. It is simply a matter of specifying the object the method is in, the name of the method, the arguments to use and where to put the return value.

Before a method can be called it must be compiled and useable by the generated HIR. To ensure this the class `DummyDynamicCodeRunner` was created. It contains method calls to all methods that can be planted. It is referenced by parts of the code translator and ensures each method is compiled into a form useable by the translated code. It is possible to dynamically compile methods but tends to be messy so this feature is not used.

### **6.2.8 Compilation**

Once a trace has been converted to HIR it is time to compile it to native machine code.

Pearcolator has two compilers i.e. the baseline and adaptive compilers.

The baseline compiler compiles to native machine code as quickly as possible. It performs only minimal optimisations. For this reason the code it generates tends to be fairly inefficient. It does have the advantage of compiling quickly.

The adaptive compiler is an optimising compiler. It has many levels of optimisation. The more that a piece of code is executed the more heavily it is optimised. For this reason it tends to generate efficient code. Unfortunately, the compiler tends to be slower.

Pearcolator uses the optimising compiler. This is because Pearcolator is designed primarily for emulating long running programs such as web servers or databases. As such, any machine code generated will be executed many times. Any deficiencies will impact performance considerably. Due to the nature of the

programs to be emulated any extra time spent compiling is offset by the overall speed increase in the execution of the program.

By default, Pearcolator sets the initial optimisation level to 0. When code is executed it gets profiled by Jikes RVM. When warranted Jikes RVM can increase the optimisation level of a trace. This results in the trace being recompiled with the extra optimisations.

For this to work Pearcolator must cache traces that have been compiled. The cache stores `VM_CodeArray` objects which contains translated machine code. Note that this cache of compiled HIR (i.e. machine code) is different to the cache of emulated machine code converted to HIR mentioned EARLIER.

Before translation of a trace into HIR starts Pearcolator checks the cache of compiled traces to ensure a trace will not be retranslated.

## **6.2.9 Execution**

Once a trace has been compiled it must be executed. This is accomplished by passing the `VM_CodeArray` object associated with the trace to the method `VM_Magic.dynamicBridgeTo`.

## **6.3 Interpretation**

### **6.3.1 Introduction**

Although the primary role of Pearcolator is to emulate long running programs it was felt desirable that performance should be improved for short running programs.

With code translation the generated HIR must pass through several stages of compilation and optimisation. This produces fast code but makes the compiler relatively slow. Even if a block of code is only to be executed once it must still

pass through the same compiler as code that is executed several million times. If a program will only run for a few seconds a considerable amount of time will still be spent on compilation.

By only running the adaptive compiler on parts of the program that execute frequently it is hoped the execution time of short lived programs can be significantly reduced.

### 6.3.2 Operation of the Interpreter

Once an instruction has been decoded (instruction decoding is covered in the next chapter) it is then executed immediately without passing through a compiler. The operation of the instruction to be emulated is implemented in a method that is called after the instruction has been decoded.

As an example, the method that implements adding two integers is the following:

```
int interpret(int pc, int nextPc, ProcessSpace ps,
             IntOperand op1, IntOperand op2) {
    op1.write(ps, op1.read(ps) + op2.read(ps);
    return nextPc;
}
```

### 6.3.4 Switching from Interpretation to Code Translation

Pearcolator must know at what point in the execution of a program it is suitable to stop interpreting a section of code and instead translate it to machine code. A simple way is to count the number of times an instruction at an address is interpreted. Once the instruction has been executed a certain number of times, invoke the code translator. This is the current behaviour of Pearcolator.

Although the current behaviour works as it should, keeping track of every instruction carries a lot of overhead which slows down the performance considerably.

A better system is to ignore how many times an individual instruction has been executed and make the decision to switch at a branch. When interpreting a branch, Pearcolator should keep track of how many times the target has been branched to. When a target has been branched to a certain number of times then it should be translated.

This technique has a number of benefits:

- 1 Less overhead for the interpreter.
- 2 Allows certain optimisations in the instruction decoder.
- 3 Ensures translated traces start at a branch target and end at a branch. This keeps the traces similar to methods in Java. It is hoped in the future Pearcolator may output Java bytecode so that emulated programs may be executed on other Java Virtual Machines.

Another technique that has only received minimal research up to now is to use Compiler DNA. Compiler DNA is the system used by the adaptive compiler in Jikes RVM to decide when the next level of optimisation should be applied. It works by keeping track of how long an optimisation will take to apply and how much of an improvement is likely. If the length of time to perform the optimisation is not offset by the improvement in speed no optimisation is applied.

## ***6.4 Improving the Translator***

The code translator currently has a problem with branch handling. When the translator reaches a conditional or an indirect branch a decision must be made as to which instruction to decode next. Either the translation can halt with the generated code returning the address of the next instruction to be executed, or the translator can translate all possible branch targets. Currently Pearcolator uses the former technique.

With the introduction of an interpreter it becomes possible to profile the branches before translation. This allows Pearcolator to detect which branch targets are

used most so they can be translated. All other branch targets can continue to be interpreted.

## ***6.5 Status of Interpreter***

Unfortunately the current functionality of the interpreter is behind the translator. Whereas the translator is able to handle fairly substantial programs, the interpreter is missing some vital feature such as conditional branching.

Lack of conditional branching in the interpreter has also impacted the translator. The branch handling of the translator was built to ensure easy addition of profiled branching in the future. It was hoped that it would then be possible to put an if instruction at the branch. If either of the branch targets had been interpreted enough times or had been previously translated the translation could continue. For any branch targets for which this is not the case the translation would finish.

However, the interpreter has not reached a point which allows this. Currently when the translator reaches a conditional or indirect branch, translation halts. It should be a simple but time consuming matter to add the required functionality to the interpreter.

## 7 Current Status and The Future of x86 Pearcolator

### 7.1 Current Status

The x86 version of Pearcolator is not as advanced as the PowerPC version. The PowerPC version can run many benchmarks, substantial programs and is currently under development to run Linux under emulation.

The x86 version can run substantial assembly programs. It can handle simple programs written in C making use of glibc. Programs written using glibc tend to be good tests that an emulator is working correctly. The following features of Pearcolator have been tested by emulating simple glibc programs:

- The memory system
- Binary Loading
- Stack Layout
- The decoder
- Instruction translation
- Lazy register handling
- Lazy flag handling
- System calls

All features tested above have been found to work correctly. To get x86 Pearcolator to execute more complex programs is a matter of simply implementing the instructions and system calls that are missing. The interpreter has been tested on small assembly language programs and seems to work adequately for the parts that are implemented.

## **7.2 The future of x86 Pearcolator**

As work on Pearcolator is ongoing it seems useful to describe some of the future advances that should be possible. Many of these have already been mentioned throughout the dissertation, but will be summarised here for clarity.

### **7.2.1 Completing Instruction Set and System Calls**

Only a small fraction of all the instructions and system calls are currently implemented. The decoder is currently able to decode most instructions. The instructions are merely missing translations and interpretations.

### **7.2.2 Dynamic Linking**

Pearcolator for the x86 only handles statically linked binaries at present. Most programs use dynamic linking. It is unknown how much work will be required to enable dynamic linking.

### **7.2.3 Parallelisation**

One of the benefits of Jikes RVM is that it allows use of multi processor architectures. Pearcolator does not currently take advantage of this.

### **7.2.4 The Decoder**

The Decoder currently works but as mentioned in section 5.5 could be made faster with a few simple changes.

### **7.2.5 Native Memory**

The memory system could be made a lot faster if JNI was used to access the memory. This will avoid several mask and shift instructions being generated for each memory access, replacing them with a single pointer manipulation.

## References

- [1] Ian Rogers, Richard Matley, and Ian Watson. Dynamic binary translation with a Java Virtual Machine. Submitted to 2005 International Symposium on Code Generation and Optimization, 2004.
  
- [2] Raymond J. Hookway, Mark A. Herdeg. Digital FX!32: Combining Emulation and Binary Translation. Digital Technical Journal Vol. 9 No. 1 1997
  
- [3] IA-32 Intel Architecture Software Developer's Manual Volumes 2A and 2B. 2005
  
- [4] Steve Heller. Efficient C/C++ Programming. Academic Press, 1995.
  
- [5] The Jamaica Project. <http://www.cs.man.ac.uk/apt/projects/jamaica/>.
  
- [6] QEMU. <http://fabrice.bellard.free.fr/qemu>.
  
- [7] Bochs. <http://bochs.sourceforge.net>.
  
- [8] libdisasm. <http://bastard.sourceforge.net>.
  
- [9] Sled. <http://www.eecs.harvard.edu/~nr/toolkit/>
  
- [10] ndisasm. <http://nasm.sourceforge.net>
  
- [11] Richard Blum. Professional Assembly Language. Wrox, 2005.
  
- [12] Richard Matley. Native Code Execution within a JVM. MSc Thesis, The University of Manchester, 2004
  
- [13] ELF man page on Unix systems.