

The JavaTM
Virtual Machine
Specification

Java SE 7 Edition

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Virtual Machine
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To Lucy, Beatrice, and Arnold —TL

To Mark —FY

To Weihong and Teva—GB

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Preface

THE Java™ virtual machine specification has been written to fully document the design of the Java virtual machine. It is essential for compiler writers who wish to target the Java virtual machine and for programmers who want to implement a compatible Java virtual machine. ~~It is also a definitive source for anyone who wants to know exactly how the Java programming language is implemented.~~

The Java virtual machine is an abstract machine. References to the *Java virtual machine* throughout this specification refer to this abstract machine rather than to Sun's or any other specific implementation. This book serves as documentation for a concrete implementation of the Java virtual machine only as a blueprint documents a house. An implementation of the Java virtual machine (known as a runtime interpreter) must embody this specification, but is constrained by it only where absolutely necessary.

The Java virtual machine specified here is compatible with the Java Platform™, Standard Edition 7, and supports the Java programming language specified in *The Java™ Language Specification, Third Edition* (Addison-Wesley, 2005).

We intend that this specification should sufficiently document the Java virtual machine to make possible compatible clean-room implementations. If you are considering constructing your own Java virtual machine implementation, feel free to contact us to obtain assistance to ensure the 100% compatibility of your implementation.

~~Send comments on this specification or questions about implementing the Java virtual machine to our electronic mail address: jvm@java.sun.com. To learn the latest about the Java Platform, or to download the latest JDK™ release, visit our World Wide Web site at <http://java.sun.com>. For updated information about the Java Series, including errata for *The Java™ Virtual Machine Specification*, and previews of forthcoming books, visit <http://java.sun.com/Series>.~~

The virtual machine that evolved into the Java virtual machine was originally designed by James Gosling in 1992 to support the Oak programming language.

The evolution into its present form occurred through the direct and indirect efforts of many people and spanned Sun’s Green project, FirstPerson, Inc., the LiveOak project, the Java Products Group, JavaSoft, and today, Oracle’s Java Platform Group. The authors are grateful to the many contributors and supporters.

This book began as internal project documentation. Kathy Walrath edited that early draft, helping to give the world its first look at the internals of the Java programming language. It was then converted to HTML by Mary Campione and was made available on our Web site before being expanded into book form.

The creation of *The Java™ Virtual Machine Specification* owes much to the support of the Java Products Group led by General Manager Ruth Hennigar, to the efforts of series editor Lisa Friendly, and to editor Mike Hendrickson and his group at Addison-Wesley. The many criticisms and suggestions received from reviewers of early online drafts, as well as drafts of the printed book, improved its quality immensely. We owe special thanks to Richard Tuck for his careful review of the manuscript. Particular thanks to Bill Joy whose comments, reviews, and guidance have contributed greatly to the completeness and accuracy of this book.

Notes on the Second Edition

The second edition of *The Java™ Virtual Machine Specification* brings the specification of the Java virtual machine up to date with the Java® 2 platform, v1.2. It also includes many corrections and clarifications that update the presentation of the specification without changing the logical specification itself. We have attempted to correct typos and errata (hopefully without introducing new ones) and to add more detail to the specification where it was vague or ambiguous. In particular, we corrected a number of inconsistencies between the first edition of *The Java™ Virtual Machine Specification* and *The Java™ Language Specification*.

We thank the many readers who combed through the first edition of this book and brought problems to our attention. Several individuals and groups deserve special thanks for pointing out problems or contributing directly to the new material:

Carla Schroer and her teams of compatibility testers in Cupertino, California, and Novosibirsk, Russia (with special thanks to Leonid Arbouzov and Alexei Kaigorodov), painstakingly wrote compatibility tests for each testable assertion in the first edition. In the process they uncovered many places where the original specification was unclear or incomplete.

Jeroen Vermeulen, Janice Shepherd, Peter Bertelsen, Roly Perera, Joe Darcy, and Sandra Loosemore have all contributed comments and feedback that have improved this edition.

Marilyn Rash and Hilary Selby Polk of Addison Wesley Longman helped us to improve the readability and layout of this edition at the same time as we were incorporating all the technical changes.

Special thanks go to Gilad Bracha, who has brought a new level of rigor to the presentation and has been a major contributor to much of the new material, especially chapters 4 and 5. His dedication to “computational theology” and his commitment to resolving inconsistencies between *The Java™ Virtual Machine Specification* and *The Java™ Language Specification* have benefited this book tremendously.

*Tim Lindholm
Frank Yellin*
Java Software, Sun Microsystems, Inc

Notes on the Java SE 7 Edition

The third edition of *The Java™ Virtual Machine Specification* incorporates all the changes that have been made to the specification through Java SE 6. Chief among these is the new approach to bytecode verification. In addition, numerous corrections and clarifications that have been made over time. Changes that have been added to support new features of the Java programming language are integrated herein as well.

More people than we can mention here have, over time, contributed to the design and implementation of the Java virtual machine. It’s worth belatedly mentioning some highlights nevertheless.

The excellent performance we see in the JVMs of today would never have been possible without the technological foundation laid by David Ungar and his colleagues at the Self project at Sun Labs. This technology took a convoluted path, from Self on through the Animorphic Smalltalk VM to eventually become Sun’s Hotspot virtual machine. Lars Bak and Urs Hoelzle are the two people who were present through all these stages, and are more responsible than anyone else for the high performance we take for granted in JVMs today.

At the same time, JVMs have also become very small. The KVM, designed for mobile devices, was pioneered by Antero Taivalsaari. The new verification technique specified in this edition was pioneered in the KVM context.

It was Eva Rose who, in her masters thesis, first proposed a radical revision of JVM bytecode verification, in the context of the Java Card™ platform. This led first to an implementation for Java ME CLDC, and eventually to the revision of the Java SE verification process documented here.

Sheng Liang implemented the Java ME CLDC verifier. I was responsible for specifying the verifier, and Antero Taivalsaari led the overall specification of Java ME CLDC. Alessandro Coglio's analysis of Java bytecode verification was the most extensive, realistic and thorough study of the topic, and contributed greatly to this specification.

Wei Tao, together with Frank Yellin, Tim Lindholm and myself, implemented the Prolog verifier that formed the basis for the specification in both Java ME and Java SE. Wei then implemented the specification "for real" in the JVM. Later, Mingyao Yang improved the design and specification, and implemented the final version that ships in Java SE 6.

This specification benefited from the efforts of the JSR 202 expert group: Peter Burka, Alessandro Coglio, Sanghoon Jin, Christian Kemper, Larry Rau, Eva Rose and Mark Stoltz.

My director, Janet Koenig, did everything she possibly could to provide an excellent working environment. Brian Goetz and David Holmes provided valuable feedback and discussion.

Above all, I wish to acknowledge the special contribution of Alex Buckley, my successor at Sun, who did all the hard work to actually get this book out the door. Alex made significant improvements to the text, especially in chapter 4. He reviewed the book as a whole and helped make it more consistent and cohesive. Last but not least, Alex prepared this volume for publication. It is a thankless task for which I thank him nonetheless. I know that future revisions of the core Java specifications are in good hands.

Gilad Bracha
Java SE, Sun Microsystems, Inc

Introduction

1.1 A Bit of History

THE Java™ programming language is a general-purpose object-oriented concurrent language. Its syntax is similar to C and C++, but it omits many of the features that make C and C++ complex, confusing, and unsafe. The Java platform was initially developed to address the problems of building software for networked consumer devices. It was designed to support multiple host architectures and to allow secure delivery of software components. To meet these requirements, compiled code had to survive transport across networks, operate on any client, and assure the client that it was safe to run.

The popularization of the World Wide Web made these attributes much more interesting. Web browsers enabled millions of people to surf the Net and access media-rich content in simple ways. At last there was a medium where what you saw and heard was essentially the same regardless of the machine you were using and whether it was connected to a fast network or a slow modem.

Web enthusiasts soon discovered that the content supported by the Web's HTML document format was too limited. HTML extensions, such as forms, only highlighted those limitations, while making it clear that no browser could include all the features users wanted. Extensibility was the answer.

Sun's HotJava™ browser first showcased the interesting properties of the Java programming language and platform by making it possible to embed programs inside HTML pages. Programs are transparently downloaded into the browser along with the HTML pages in which they appear. Before being accepted by the browser, programs are carefully checked to make sure they are safe. Like HTML pages, compiled programs are network- and host-independent. The programs behave the same way regardless of where they come from or what kind of machine they are being loaded into and run on.

A Web browser incorporating the Java platform is no longer limited to a pre-determined set of capabilities. Visitors to Web pages incorporating dynamic content can be assured that their machines cannot be damaged by that content. Programmers can write a program once, and it will run on any machine supplying a Java runtime environment.

1.2 The Java Virtual Machine

The Java virtual machine is the cornerstone of the Java platform. It is the component of the technology responsible for its hardware- and operating system-independence, the small size of its compiled code, and its ability to protect users from malicious programs.

The Java virtual machine is an abstract computing machine. Like a real computing machine, it has an instruction set and manipulates various memory areas at runtime. It is reasonably common to implement a programming language using a virtual machine; the best-known virtual machine may be the P-Code machine of UCSD Pascal.

The first prototype implementation of the Java virtual machine, done at Sun Microsystems, Inc., emulated the Java virtual machine instruction set in software hosted by a handheld device that resembled a contemporary Personal Digital Assistant (PDA). Oracle's current implementations emulate the Java virtual machine on mobile, desktop and server devices, but the Java virtual machine does not assume any particular implementation technology, host hardware, or host operating system. It is not inherently interpreted, but can just as well be implemented by compiling its instruction set to that of a silicon CPU. It may also be implemented in microcode or directly in silicon.

The Java virtual machine knows nothing of the Java programming language, only of a particular binary format, the `class` file format. A `class` file contains Java virtual machine instructions (or *bytecodes*) and a symbol table, as well as other ancillary information.

For the sake of security, the Java virtual machine imposes strong syntactic and structural constraints on the code in a `class` file. However, any language with functionality that can be expressed in terms of a valid `class` file can be hosted by the Java virtual machine. Attracted by a generally available, machine-independent platform, implementors of other languages can turn to the Java virtual machine as a delivery vehicle for their languages.

1.3 Summary of Chapters

The rest of this book is structured as follows:

- Chapter 2 gives an overview of the Java virtual machine architecture.
- Chapter 3 introduces compilation of code written in the Java programming language into the instruction set of the Java virtual machine.
- Chapter 4 specifies the `class` file format, the hardware- and operating system-independent binary format used to represent compiled classes and interfaces.
- Chapter 5 specifies the start-up of the Java virtual machine and the loading, linking, and initialization of classes and interfaces.
- Chapter 6 specifies the instruction set of the Java virtual machine, presenting the instructions in alphabetical order of opcode mnemonics.
- Chapter 7 gives a table of Java virtual machine opcode mnemonics indexed by opcode value.

In *The Java™ Virtual Machine Specification, Second Edition*, Chapter 2 gave an overview of the Java programming language intended to support the specification of the Java virtual machine, but was not itself a part of that specification.

In this specification, the reader is referred to *The Java™ Language Specification, Third Edition*, by James Gosling, Bill Joy, Guy Steele and Gilad Bracha, for information about the Java programming language. References of the form:

(JLS3 §x.y)

indicate where this is necessary.

For an introduction to the Java programming language, see *The Java™ Programming Language, Fourth Edition*, by Ken Arnold, James Gosling, and David Holmes.

In *The Java™ Virtual Machine Specification, Second Edition*, Chapter 8 detailed the low-level actions that explained the interaction of Java virtual machine threads with a shared main memory. It was adapted from Chapter 17 of *The Java™ Language Specification, First Edition*.

Chapter 17 in *The Java™ Language Specification, Third Edition*, was updated to incorporate *The Java™ Memory Model and Thread Specification* produced by

the JSR-133 Expert Group. The reader is referred to that chapter for information about threads and locks.

1.4 Notation

Throughout this book we refer to classes and interfaces drawn from the Java platform. Whenever we refer to a class or interface using a single identifier *N*, the intended reference is to the class or interface `java.lang.N`. We use the fully qualified name for classes from packages other than `java.lang`.

Whenever we refer to a class or interface that is declared in the package `java` or any of its subpackages, the intended reference is to that class or interface as loaded by the bootstrap class loader (§5.3.1). Whenever we refer to a subpackage of a package named `java`, the intended reference is to that subpackage as determined by the bootstrap class loader.

The use of fonts in this book is as follows:

- A **fixed width** font is used for code examples written in the Java programming language, Java virtual machine data types, exceptions, and errors.
- *Italic* is used for Java virtual machine “assembly language”, its opcodes and operands, as well as items in the Java virtual machine’s runtime data areas. It is also used to introduce new terms and simply for emphasis.

The Structure of the Java Virtual Machine

THIS book specifies an abstract machine. It does not document any particular implementation of the Java virtual machine.

To implement the Java virtual machine correctly, you need only be able to read the `class` file format and correctly perform the operations specified therein. Implementation details that are not part of the Java virtual machine's specification would unnecessarily constrain the creativity of implementors. For example, the memory layout of runtime data areas, the garbage-collection algorithm used, and any internal optimization of the Java virtual machine instructions (for example, translating them into machine code) are left to the discretion of the implementor.

All references to Unicode in this specification are given with respect to *The Unicode Standard, Version 6.0.0*, available at <http://www.unicode.org/>.

2.1 The `class` File Format

Compiled code to be executed by the Java virtual machine is represented using a hardware- and operating system-independent binary format, typically (but not necessarily) stored in a file, known as the `class` file format. The `class` file format precisely defines the representation of a class or interface, including details such as byte ordering that might be taken for granted in a platform-specific object file format.

Chapter 4, “The `class` File Format”, covers the `class` file format in detail.

2.2 Data Types

Like the Java programming language, the Java virtual machine operates on two kinds of types: *primitive types* and *reference types*. There are, correspondingly, two kinds of values that can be stored in variables, passed as arguments, returned by methods, and operated upon: *primitive values* and *reference values*.

The Java virtual machine expects that nearly all type checking is done prior to runtime, typically by a compiler, and does not have to be done by the Java virtual machine itself. Values of primitive types need not be tagged or otherwise be inspectable to determine their types at runtime, or to be distinguished from values of reference types. Instead, the instruction set of the Java virtual machine distinguishes its operand types using instructions intended to operate on values of specific types. For instance, *iadd*, *ladd*, *fadd*, and *dadd* are all Java virtual machine instructions that add two numeric values and produce numeric results, but each is specialized for its operand type: `int`, `long`, `float`, and `double`, respectively. For a summary of type support in the Java virtual machine instruction set, see §2.11.1.

The Java virtual machine contains explicit support for objects. An object is either a dynamically allocated class instance or an array. A reference to an object is considered to have Java virtual machine type `reference`. Values of type `reference` can be thought of as pointers to objects. More than one reference to an object may exist. Objects are always operated on, passed, and tested via values of type `reference`.

2.3 Primitive Types and Values

The primitive data types supported by the Java virtual machine are the *numeric types*, the `boolean` type (§2.3.4),¹ and the `returnAddress` type (§2.3.3). The numeric types consist of the *integral types* (§2.3.1) and the *floating-point types* (§2.3.2). The integral types are:

¹ The first edition of *The Java™ Virtual Machine Specification* did not consider `boolean` to be a Java virtual machine type. However, `boolean` values do have limited support in the Java virtual machine. The second edition clarified the issue by treating `boolean` as a type.

- **byte**, whose values are 8-bit signed two's-complement integers, and whose default value is zero
- **short**, whose values are 16-bit signed two's-complement integers, and whose default value is zero
- **int**, whose values are 32-bit signed two's-complement integers, and whose default value is zero
- **long**, whose values are 64-bit signed two's-complement integers, and whose default value is zero
- **char**, whose values are 16-bit unsigned integers representing Unicode code points in the Basic Multilingual Plane, encoded with UTF-16, and whose default value is the null code point ('\u0000')

The floating-point types are:

- **float**, whose values are elements of the float value set or, where supported, the float-extended-exponent value set, and whose default value is positive zero
- **double**, whose values are elements of the double value set or, where supported, the double-extended-exponent value set, and whose default value is positive zero

The values of the **boolean** type encode the truth values **true** and **false**, and the default value is **false**.

The values of the **returnAddress** type are pointers to the opcodes of Java virtual machine instructions. Of the primitive types only the **returnAddress** type is not directly associated with a Java programming language type.

2.3.1 Integral Types and Values

The values of the integral types of the Java virtual machine are: ~~the same as those for the integral types of the Java programming language~~:

- For **byte**, from -128 to 127 (-2^7 to $2^7 - 1$), inclusive
- For **short**, from -32768 to 32767 (-2^{15} to $2^{15} - 1$), inclusive
- For **int**, from -2147483648 to 2147483647 (-2^{31} to $2^{31} - 1$), inclusive
- For **long**, from -9223372036854775808 to 9223372036854775807 (-2^{63} to $2^{63} - 1$), inclusive

- For `char`, from 0 to 65535 inclusive

2.3.2 Floating-Point Types, Value Sets, and Values

The floating-point types are `float` and `double`, which are conceptually associated with the 32-bit single-precision and 64-bit double-precision format IEEE 754 values and operations as specified in *IEEE Standard for Binary Floating-Point Arithmetic*, ANSI/IEEE Std. 754-1985 (IEEE, New York).

The IEEE 754 standard includes not only positive and negative sign-magnitude numbers, but also positive and negative zeros, positive and negative *infinities*, and a special *Not-a-Number value* (hereafter abbreviated as “NaN”). The NaN value is used to represent the result of certain invalid operations such as dividing zero by zero.

Every implementation of the Java virtual machine is required to support two standard sets of floating-point values, called the *float value set* and the *double value set*. In addition, an implementation of the Java virtual machine may, at its option, support either or both of two extended-exponent floating-point value sets, called the *float-extended-exponent value set* and the *double-extended-exponent value set*. These extended-exponent value sets may, under certain circumstances, be used instead of the standard value sets to represent the values of type `float` or `double`.

The finite nonzero values of any floating-point value set can all be expressed in the form $s \cdot m \cdot 2^{(e - N + 1)}$, where s is $+1$ or -1 , m is a positive integer less than 2^N , and e is an integer between $E_{\min} = -(2^{K-1} - 2)$ and $E_{\max} = 2^{K-1} - 1$, inclusive, and where N and K are parameters that depend on the value set. Some values can be represented in this form in more than one way; for example, supposing that a value v in a value set might be represented in this form using certain values for s , m , and e , then if it happened that m were even and e were less than 2^{K-1} , one could halve m and increase e by 1 to produce a second representation for the same value v . A representation in this form is called *normalized* if $m \geq 2^{N-1}$; otherwise the representation is said to be *denormalized*. If a value in a value set cannot be represented in such a way that $m \geq 2^{N-1}$, then the value is said to be a *denormalized value*, because it has no normalized representation.

The constraints on the parameters N and K (and on the derived parameters E_{\min} and E_{\max}) for the two required and two optional floating-point value sets are summarized in Table 2.1.

Where one or both extended-exponent value sets are supported by an implementation, then for each supported extended-exponent value set there is a specific

Table 2.1 Floating-point value set parameters

Parameter	float	float-extended-exponent	double	double-extended-exponent
N	24	24	53	53
K	8	≥ 11	11	≥ 15
E_{\max}	+127	$\geq +1023$	+1023	$\geq +16383$
E_{\min}	-126	≤ -1022	-1022	≤ -16382

implementation-dependent constant K , whose value is constrained by Table 2.1; this value K in turn dictates the values for E_{\min} and E_{\max} .

Each of the four value sets includes not only the finite nonzero values that are ascribed to it above, but also the five values positive zero, negative zero, positive infinity, negative infinity, and NaN.

Note that the constraints in Table 2.1 are designed so that every element of the float value set is necessarily also an element of the float-extended-exponent value set, the double value set, and the double-extended-exponent value set. Likewise, each element of the double value set is necessarily also an element of the double-extended-exponent value set. Each extended-exponent value set has a larger range of exponent values than the corresponding standard value set, but does not have more precision.

The elements of the float value set are exactly the values that can be represented using the single floating-point format defined in the IEEE 754 standard, except that there is only one NaN value (IEEE 754 specifies $2^{24} - 2$ distinct NaN values). The elements of the double value set are exactly the values that can be represented using the double floating-point format defined in the IEEE 754 standard, except that there is only one NaN value (IEEE 754 specifies $2^{53} - 2$ distinct NaN values). Note, however, that the elements of the float-extended-exponent and double-extended-exponent value sets defined here do *not* correspond to the values that be represented using IEEE 754 single extended and double extended formats, respectively. This specification does not mandate a specific representation for the values of the floating-point value sets except where floating-point values must be represented in the `class` file format (§4.4.4, §4.4.5).

The float, float-extended-exponent, double, and double-extended-exponent value sets are not types. It is always correct for an implementation of the Java virtual machine to use an element of the float value set to represent a value of type `float`; however, it may be permissible in certain contexts for an implementation to use an element of the float-extended-exponent value set instead. Similarly, it is

always correct for an implementation to use an element of the double value set to represent a value of type `double`; however, it may be permissible in certain contexts for an implementation to use an element of the double-extended-exponent value set instead.

Except for NaNs, values of the floating-point value sets are *ordered*. When arranged from smallest to largest, they are negative infinity, negative finite values, positive and negative zero, positive finite values, and positive infinity.

Floating-point positive zero and floating-point negative zero compare as equal, but there are other operations that can distinguish them; for example, dividing 1.0 by 0.0 produces positive infinity, but dividing 1.0 by -0.0 produces negative infinity.

Nan`s` are *unordered*, so numerical comparisons and tests for numerical equality have the value `false` if either or both of their operands are NaN. In particular, a test for numerical equality of a value against itself has the value `false` if and only if the value is NaN. A test for numerical inequality has the value `true` if either operand is NaN.

2.3.3 The `returnAddress` Type and Values

The `returnAddress` type is used by the Java virtual machine's `jsr`, `ret`, and `jsr_w` instructions. The values of the `returnAddress` type are pointers to the opcodes of Java virtual machine instructions. Unlike the numeric primitive types, the `returnAddress` type does not correspond to any Java programming language type and cannot be modified by the running program.

2.3.4 The `boolean` Type

Although the Java virtual machine defines a `boolean` type, it only provides very limited support for it. There are no Java virtual machine instructions solely dedicated to operations on `boolean` values. Instead, expressions in the Java programming language that operate on `boolean` values are compiled to use values of the Java virtual machine `int` data type.

The Java virtual machine does directly support `boolean` arrays. Its `newarray` instruction enables creation of `boolean` arrays. Arrays of type `boolean` are accessed and modified using the byte array instructions `baload` and `bastore`.²

² In Oracle's Java virtual machine implementation, `boolean` arrays in the Java programming language are encoded as Java virtual machine byte arrays, using 8 bits per `boolean` element.

The Java virtual machine encodes `boolean` array components using `1` to represent `true` and `0` to represent `false`. Where Java programming language `boolean` values are mapped by compilers to values of Java virtual machine type `int`, the compilers must use the same encoding.

2.4 Reference Types and Values

There are three kinds of `reference` types: class types, array types, and interface types. Their values are references to dynamically created class instances, arrays, or class instances or arrays that implement interfaces, respectively.

An array type consists of a *component type* with a single dimension (whose length is not given by the type). The component type of an array type may itself be an array type. If, starting from any array type, one considers its component type, and then (if that is also an array type) the component type of that type, and so on, eventually one must reach a component type that is not an array type; this is called the *element type* of the array type. The element type of an array type is necessarily either a primitive type, or a class type, or an interface type.

A `reference` value may also be the special null reference, a reference to no object, which will be denoted here by `null`. The `null` reference initially has no runtime type, but may be cast to any type. The default value of a reference type is `null`.

The Java virtual machine specification does not mandate a concrete value encoding `null`.

2.5 Runtime Data Areas

The Java virtual machine defines various runtime data areas that are used during execution of a program. Some of these data areas are created on Java virtual machine start-up and are destroyed only when the Java virtual machine exits. Other data areas are per thread. Per-thread data areas are created when a thread is created and destroyed when the thread exits.

2.5.1 The pc Register

The Java virtual machine can support many threads of execution at once (JLS3 §17). Each Java virtual machine thread has its own `pc` (program counter) register. At any point, each Java virtual machine thread is executing the code of a single method,

namely the current method (§2.6) for that thread. If that method is not `native`, the `pc` register contains the address of the Java virtual machine instruction currently being executed. If the method currently being executed by the thread is `native`, the value of the Java virtual machine's `pc` register is undefined. The Java virtual machine's `pc` register is wide enough to hold a `returnAddress` or a native pointer on the specific platform.

2.5.2 Java Virtual Machine Stacks

Each Java virtual machine thread has a private *Java virtual machine stack*, created at the same time as the thread.³ A Java virtual machine stack stores frames (§2.6). A Java virtual machine stack is analogous to the stack of a conventional language such as C: it holds local variables and partial results, and plays a part in method invocation and return. Because the Java virtual machine stack is never manipulated directly except to push and pop frames, frames may be heap allocated. The memory for a Java virtual machine stack does not need to be contiguous.

The Java virtual machine specification permits Java virtual machine stacks either to be of a fixed size or to dynamically expand and contract as required by the computation. If the Java virtual machine stacks are of a fixed size, the size of each Java virtual machine stack may be chosen independently when that stack is created. A Java virtual machine implementation may provide the programmer or the user control over the initial size of Java virtual machine stacks, as well as, in the case of dynamically expanding or contracting Java virtual machine stacks, control over the maximum and minimum sizes.

The following exceptional conditions are associated with Java virtual machine stacks:

- If the computation in a thread requires a larger Java virtual machine stack than is permitted, the Java virtual machine throws a `StackOverflowError`.
- If Java virtual machine stacks can be dynamically expanded, and expansion is attempted but insufficient memory can be made available to effect the expansion, or if insufficient memory can be made available to create the initial Java virtual machine stack for a new thread, the Java virtual machine throws an `OutOfMemoryError`.

³ In the first edition of this specification, the Java virtual machine stack was known as the *Java stack*.

2.5.3 Heap

The Java virtual machine has a *heap* that is shared among all Java virtual machine threads. The heap is the runtime data area from which memory for all class instances and arrays is allocated.

The heap is created on virtual machine start-up. Heap storage for objects is reclaimed by an automatic storage management system (known as a *garbage collector*); objects are never explicitly deallocated. The Java virtual machine assumes no particular type of automatic storage management system, and the storage management technique may be chosen according to the implementor's system requirements. The heap may be of a fixed size or may be expanded as required by the computation and may be contracted if a larger heap becomes unnecessary. The memory for the heap does not need to be contiguous.

A Java virtual machine implementation may provide the programmer or the user control over the initial size of the heap, as well as, if the heap can be dynamically expanded or contracted, control over the maximum and minimum heap size.

The following exceptional condition is associated with the heap:

- If a computation requires more heap than can be made available by the automatic storage management system, the Java virtual machine throws an `OutOfMemoryError`.

2.5.4 Method Area

The Java virtual machine has a *method area* that is shared among all Java virtual machine threads. The method area is analogous to the storage area for compiled code of a conventional language or analogous to the “text” segment in an operating system process. It stores per-class structures such as the runtime constant pool, field and method data, and the code for methods and constructors, including the special methods (§2.9) used in class and instance initialization and interface initialization.

The method area is created on virtual machine start-up. Although the method area is logically part of the heap, simple implementations may choose not to either garbage collect or compact it. This version of the Java virtual machine specification does not mandate the location of the method area or the policies used to manage compiled code. The method area may be of a fixed size or may be expanded as required by the computation and may be contracted if a larger method area becomes unnecessary. The memory for the method area does not need to be contiguous.

A Java virtual machine implementation may provide the programmer or the user control over the initial size of the method area, as well as, in the case of a varying-size method area, control over the maximum and minimum method area size.

The following exceptional condition is associated with the method area:

- If memory in the method area cannot be made available to satisfy an allocation request, the Java virtual machine throws an `OutOfMemoryError`.

2.5.5 Runtime Constant Pool

A *runtime constant pool* is a per-class or per-interface runtime representation of the `constant_pool` table in a `class` file (§4.4). It contains several kinds of constants, ranging from numeric literals known at compile time to method and field references that must be resolved at runtime. The runtime constant pool serves a function similar to that of a symbol table for a conventional programming language, although it contains a wider range of data than a typical symbol table.

Each runtime constant pool is allocated from the Java virtual machine’s method area (§2.5.4). The runtime constant pool for a class or interface is constructed when the class or interface is created (§5.3) by the Java virtual machine.

The following exceptional condition is associated with the construction of the runtime constant pool for a class or interface:

- When creating a class or interface, if the construction of the runtime constant pool requires more memory than can be made available in the method area of the Java virtual machine, the Java virtual machine throws an `OutOfMemoryError`.

See Chapter 5, “Loading, Linking, and Initializing,” for information about the construction of the runtime constant pool.

2.5.6 Native Method Stacks

An implementation of the Java virtual machine may use conventional stacks, colloquially called “C stacks,” to support `native` methods, methods written in a language other than the Java programming language. Native method stacks may also be used by the implementation of an interpreter for the Java virtual machine’s instruction set in a language such as C. Java virtual machine implementations that cannot load `native` methods and that do not themselves rely on conventional stacks need

not supply native method stacks. If supplied, native method stacks are typically allocated per thread when each thread is created.

The Java virtual machine specification permits native method stacks either to be of a fixed size or to dynamically expand and contract as required by the computation. If the native method stacks are of a fixed size, the size of each native method stack may be chosen independently when that stack is created. In any case, a Java virtual machine implementation may provide the programmer or the user control over the initial size of the native method stacks. In the case of varying-size native method stacks, it may also make available control over the maximum and minimum method stack sizes.

The following exceptional conditions are associated with native method stacks:

- If the computation in a thread requires a larger native method stack than is permitted, the Java virtual machine throws a `StackOverflowError`.
- If native method stacks can be dynamically expanded and native method stack expansion is attempted but insufficient memory can be made available, or if insufficient memory can be made available to create the initial native method stack for a new thread, the Java virtual machine throws an `OutOfMemoryError`.

2.6 Frames

A *frame* is used to store data and partial results, as well as to perform dynamic linking, return values for methods, and dispatch exceptions.

A new frame is created each time a method is invoked. A frame is destroyed when its method invocation completes, whether that completion is normal or abrupt (it throws an uncaught exception). Frames are allocated from the Java virtual machine stack (§2.5.2) of the thread creating the frame. Each frame has its own array of local variables (§2.6.1), its own operand stack (§2.6.2), and a reference to the runtime constant pool (§2.5.5) of the class of the current method.

The sizes of the local variable array and the operand stack are determined at compile time and are supplied along with the code for the method associated with the frame (§4.7.3). Thus the size of the frame data structure depends only on the implementation of the Java virtual machine, and the memory for these structures can be allocated simultaneously on method invocation.

Only one frame, the frame for the executing method, is active at any point in a given thread of control. This frame is referred to as the *current frame*, and its method is known as the *current method*. The class in which the current method is defined is the *current class*. Operations on local variables and the operand stack are typically with reference to the current frame.

A frame ceases to be current if its method invokes another method or if its method completes. When a method is invoked, a new frame is created and becomes current when control transfers to the new method. On method return, the current frame passes back the result of its method invocation, if any, to the previous frame. The current frame is then discarded as the previous frame becomes the current one.

Note that a frame created by a thread is local to that thread and cannot be referenced by any other thread.

2.6.1 Local Variables

Each frame (§2.6) contains an array of variables known as its *local variables*. The length of the local variable array of a frame is determined at compile time and supplied in the binary representation of a class or interface along with the code for the method associated with the frame (§4.7.3).

A single local variable can hold a value of type `boolean`, `byte`, `char`, `short`, `int`, `float`, `reference`, or `returnAddress`. A pair of local variables can hold a value of type `long` or `double`.

Local variables are addressed by indexing. The index of the first local variable is zero. An integer is considered to be an index into the local variable array if and only if that integer is between zero and one less than the size of the local variable array.

A value of type `long` or type `double` occupies two consecutive local variables. Such a value may only be addressed using the lesser index. For example, a value of type `double` stored in the local variable array at index n actually occupies the local variables with indices n and $n+1$; however, the local variable at index $n+1$ cannot be loaded from. It can be stored into. However, doing so invalidates the contents of local variable n .

The Java virtual machine does not require n to be even. In intuitive terms, values of types `double` and `long` need not be 64-bit aligned in the local variables array. Implementors are free to decide the appropriate way to represent such values using the two local variables reserved for the value.

The Java virtual machine uses local variables to pass parameters on method invocation. On class method invocation any parameters are passed in consecutive local variables starting from local variable *0*. On instance method invocation, local variable *0* is always used to pass a reference to the object on which the instance method is being invoked (*this* in the Java programming language). Any parameters are subsequently passed in consecutive local variables starting from local variable *1*.

2.6.2 Operand Stacks

Each frame (§2.6) contains a last-in-first-out (LIFO) stack known as its *operand stack*. The maximum depth of the operand stack of a frame is determined at compile time and is supplied along with the code for the method associated with the frame (§4.7.3).

Where it is clear by context, we will sometimes refer to the operand stack of the current frame as simply the operand stack.

The operand stack is empty when the frame that contains it is created. The Java virtual machine supplies instructions to load constants or values from local variables or fields onto the operand stack. Other Java virtual machine instructions take operands from the operand stack, operate on them, and push the result back onto the operand stack. The operand stack is also used to prepare parameters to be passed to methods and to receive method results.

For example, the *iadd* instruction adds two `int` values together. It requires that the `int` values to be added be the top two values of the operand stack, pushed there by previous instructions. Both of the `int` values are popped from the operand stack. They are added, and their sum is pushed back onto the operand stack. Subcomputations may be nested on the operand stack, resulting in values that can be used by the encompassing computation.

Each entry on the operand stack can hold a value of any Java virtual machine type, including a value of type `long` or type `double`.

Values from the operand stack must be operated upon in ways appropriate to their types. It is not possible, for example, to push two `int` values and subsequently treat them as a `long` or to push two `float` values and subsequently add them with an *iadd* instruction. A small number of Java virtual machine instructions (the *dup* instructions and *swap*) operate on runtime data areas as raw values without regard to their specific types; these instructions are defined in such a way that they cannot be used to modify or break up individual values. These restric-

tions on operand stack manipulation are enforced through `class` file verification (§4.10).

At any point in time an operand stack has an associated depth, where a value of type `long` or `double` contributes two units to the depth and a value of any other type contributes one unit.

2.6.3 Dynamic Linking

Each frame (§2.6) contains a reference to the runtime constant pool (§2.5.5) for the type of the current method to support *dynamic linking* of the method code. The `class` file code for a method refers to methods to be invoked and variables to be accessed via symbolic references. Dynamic linking translates these symbolic method references into concrete method references, loading classes as necessary to resolve as-yet-undefined symbols, and translates variable accesses into appropriate offsets in storage structures associated with the runtime location of these variables.

This late binding of the methods and variables makes changes in other classes that a method uses less likely to break this code.

2.6.4 Normal Method Invocation Completion

A method invocation *completes normally* if that invocation does not cause an exception (§2.10) to be thrown, either directly from the Java virtual machine or as a result of executing an explicit `throw` statement. If the invocation of the current method completes normally, then a value may be returned to the invoking method. This occurs when the invoked method executes one of the return instructions (§2.11.8), the choice of which must be appropriate for the type of the value being returned (if any).

The current frame (§2.6) is used in this case to restore the state of the invoker, including its local variables and operand stack, with the program counter of the invoker appropriately incremented to skip past the method invocation instruction. Execution then continues normally in the invoking method's frame with the returned value (if any) pushed onto the operand stack of that frame.

2.6.5 Abrupt Method Invocation Completion

A method invocation *completes abruptly* if execution of a Java virtual machine instruction within the method causes the Java virtual machine to throw an exception

| (§2.10), and that exception is not handled within the method. Execution of an *athrow* instruction also causes an exception to be explicitly thrown and, if the exception is not caught by the current method, results in abrupt method invocation completion. A method invocation that completes abruptly never returns a value to its invoker.

2.6.6 Additional Information

A frame may be extended with additional implementation-specific information, such as debugging information.

2.7 Representation of Objects

The Java virtual machine does not mandate any particular internal structure for objects.⁴

2.8 Floating-Point Arithmetic

The Java virtual machine incorporates a subset of the floating-point arithmetic specified in *IEEE Standard for Binary Floating-Point Arithmetic* (ANSI/IEEE Std. 754-1985, New York).

2.8.1 Java Virtual Machine Floating-Point Arithmetic and IEEE 754

The key differences between the floating-point arithmetic supported by the Java virtual machine and the IEEE 754 standard are:

- The floating-point operations of the Java virtual machine do not throw exceptions, trap, or otherwise signal the IEEE 754 exceptional conditions of invalid operation, division by zero, overflow, underflow, or inexact. The Java virtual machine has no signaling NaN value.
- The Java virtual machine does not support IEEE 754 signaling floating-point comparisons.

| ⁴ In some of Oracle's implementations of the Java virtual machine, a reference to a class instance is a pointer to a *handle* that is itself a pair of pointers: one to a table containing the methods of the object and a pointer to the `Class` object that represents the type of the object, and the other to the memory allocated from the heap for the object data.

- The rounding operations of the Java virtual machine always use IEEE 754 round to nearest mode. Inexact results are rounded to the nearest representable value, with ties going to the value with a zero least-significant bit. This is the IEEE 754 default mode. But Java virtual machine instructions that convert values of floating-point types to values of integral types round toward zero. The Java virtual machine does not give any means to change the floating-point rounding mode.
- The Java virtual machine does not support either the IEEE 754 single extended or double extended format, except insofar as the double and double-extended-exponent value sets may be said to support the single extended format. The float-extended-exponent and double-extended-exponent value sets, which may optionally be supported, do not correspond to the values of the IEEE 754 extended formats: the IEEE 754 extended formats require extended precision as well as extended exponent range.

2.8.2 Floating-Point Modes

Every method has a *floating-point mode*, which is either *FP-strict* or *not FP-strict*. The floating-point mode of a method is determined by the setting of the `ACC_STRICT` flag of the `access_flags` item of the `method_info` structure (§4.6) defining the method. A method for which this flag is set is FP-strict; otherwise, the method is not FP-strict.

Note that this mapping of the `ACC_STRICT` flag implies that methods in classes compiled by a compiler in JDK release 1.1 or earlier are effectively not FP-strict.

We will refer to an operand stack as having a given floating-point mode when the method whose invocation created the frame containing the operand stack has that floating-point mode. Similarly, we will refer to a Java virtual machine instruction as having a given floating-point mode when the method containing that instruction has that floating-point mode.

If a float-extended-exponent value set is supported (§2.3.2), values of type `float` on an operand stack that is not FP-strict may range over that value set except where prohibited by value set conversion (§2.8.3). If a double-extended-exponent value set is supported (§2.3.2), values of type `double` on an operand stack that is not FP-strict may range over that value set except where prohibited by value set conversion.

In all other contexts, whether on the operand stack or elsewhere, and regardless of floating-point mode, floating-point values of type `float` and `double` may only range over the float value set and double value set, respectively. In particular, class and instance fields, array elements, local variables, and method parameters may only contain values drawn from the standard value sets.

2.8.3 Value Set Conversion

An implementation of the Java virtual machine that supports an extended floating-point value set is permitted or required, under specified circumstances, to map a value of the associated floating-point type between the extended and the standard value sets. Such a *value set conversion* is not a type conversion, but a mapping between the value sets associated with the same type.

Where value set conversion is indicated, an implementation is permitted to perform one of the following operations on a value:

- If the value is of type `float` and is not an element of the float value set, it maps the value to the nearest element of the float value set.
- If the value is of type `double` and is not an element of the double value set, it maps the value to the nearest element of the double value set.

In addition, where value set conversion is indicated certain operations are required:

- Suppose execution of a Java virtual machine instruction that is not FP-strict causes a value of type `float` to be pushed onto an operand stack that is FP-strict, passed as a parameter, or stored into a local variable, a field, or an element of an array. If the value is not an element of the float value set, it maps the value to the nearest element of the float value set.
- Suppose execution of a Java virtual machine instruction that is not FP-strict causes a value of type `double` to be pushed onto an operand stack that is FP-strict, passed as a parameter, or stored into a local variable, a field, or an element of an array. If the value is not an element of the double value set, it maps the value to the nearest element of the double value set.

Such required value set conversions may occur as a result of passing a parameter of a floating-point type during method invocation, including native method invocation; returning a value of a floating-point type from a method that is not

FP-strict to a method that is FP-strict; or storing a value of a floating-point type into a local variable, a field, or an array in a method that is not FP-strict.

Not all values from an extended-exponent value set can be mapped exactly to a value in the corresponding standard value set. If a value being mapped is too large to be represented exactly (its exponent is greater than that permitted by the standard value set), it is converted to a (positive or negative) infinity of the corresponding type. If a value being mapped is too small to be represented exactly (its exponent is smaller than that permitted by the standard value set), it is rounded to the nearest of a representable denormalized value or zero of the same sign.

Value set conversion preserves infinities and NaNs and cannot change the sign of the value being converted. Value set conversion has no effect on a value that is not of a floating-point type.

2.9 Specially Named Initialization Methods

At the level of the Java virtual machine, every constructor written in the Java programming language (JLS3 §8.8) appears as an *instance initialization method* that has the special name `<init>`. This name is supplied by a compiler. Because the name `<init>` is not a valid identifier, it cannot be used directly in a program written in the Java programming language. Instance initialization methods may be invoked only within the Java virtual machine by the `invokespecial` instruction, and they may be invoked only on uninitialized class instances. An instance initialization method takes on the access permissions (JLS3 §6.6) of the constructor from which it was derived.

A class or interface has at most one *class or interface initialization method* and is initialized (§5.5) by invoking that method. The initialization method of a class or interface is static, takes no arguments, and has the special name `<cinit>`.⁵ This name is supplied by a compiler. Because the name `<cinit>` is not a valid identifier, it cannot be used directly in a program written in the Java programming language. Class and interface initialization methods are invoked implicitly by the Java virtual machine; they are never invoked directly from any Java virtual machine instruction, but are invoked only indirectly as part of the class initialization process.

⁵ Other methods named `<cinit>` in a `class` file are of no consequence. They are not class or interface initialization methods. They cannot be invoked by any Java virtual machine instruction and are never invoked by the Java virtual machine itself.

2.10 Exceptions

An exception in the Java virtual machine is represented by an instance of the class `Throwable` or one of its subclasses. Throwing an exception results in an immediate nonlocal transfer of control from the point where the exception was thrown.

Most exceptions occur synchronously as a result of an action by the thread in which they occur. An asynchronous exception, by contrast, can potentially occur at any point in the execution of a program. The Java virtual machine throws an exception for one of three reasons:

1. An abnormal execution condition was synchronously detected by the Java virtual machine. These exceptions are not thrown at an arbitrary point in the program, but only synchronously after execution of an instruction that either:
 - Specifies the exception as a possible result, such as:
 - When the instruction embodies an operation that violates the semantics of the Java programming language, for example indexing outside the bounds of an array.
 - When an error occurs in loading or linking part of the program.
 - Causes some limit on a resource to be exceeded, for example when too much memory is used.
2. An `athrow` instruction was executed.
3. An asynchronous exception occurred because:
 - The `stop` method of class `Thread` or `ThreadGroup` was invoked, or
 - An internal error occurred in the Java virtual machine implementation.

The `stop` methods may be invoked by one thread to affect another thread or all the threads in a specified thread group. They are asynchronous because they may occur at any point in the execution of the other thread or threads. An internal error is considered asynchronous (§6.3).

A Java virtual machine may permit a small but bounded amount of execution to occur before an asynchronous exception is thrown. This delay is permitted to allow optimized code to detect and throw these exceptions at points where it is practical to handle them while obeying the semantics of the Java programming language.⁶

Exceptions thrown by the Java virtual machine are precise: when the transfer of control takes place, all effects of the instructions executed before the point from

which the exception is thrown must appear to have taken place. No instructions that occur after the point from which the exception is thrown may appear to have been evaluated. If optimized code has speculatively executed some of the instructions which follow the point at which the exception occurs, such code must be prepared to hide this speculative execution from the user-visible state of the program.

Each method in the Java virtual machine may be associated with zero or more exception handlers. An exception handler specifies the range of offsets into the Java virtual machine code implementing the method for which the exception handler is active, describes the type of exception that the exception handler is able to handle, and specifies the location of the code that is to handle that exception. An exception matches an exception handler if the offset of the instruction that caused the exception is in the range of offsets of the exception handler and the exception type is the same class as or a subclass of the class of exception that the exception handler handles. When an exception is thrown, the Java virtual machine searches for a matching exception handler in the current method. If a matching exception handler is found, the system branches to the exception handling code specified by the matched handler.

If no such exception handler is found in the current method, the current method invocation completes abruptly (§2.6.5). On abrupt completion, the operand stack and local variables of the current method invocation are discarded, and its frame is popped, reinstating the frame of the invoking method. The exception is then rethrown in the context of the invoker's frame and so on, continuing up the method invocation chain. If no suitable exception handler is found before the top of the method invocation chain is reached, the execution of the thread in which the exception was thrown is terminated.

The order in which the exception handlers of a method are searched for a match is important. Within a `class` file the exception handlers for each method are stored in a table (§4.7.3). At runtime, when an exception is thrown, the Java virtual machine searches the exception handlers of the current method in the order that they appear in

⁶ A simple implementation might poll for asynchronous exceptions at the point of each control transfer instruction. Since a program has a finite size, this provides a bound on the total delay in detecting an asynchronous exception. Since no asynchronous exception will occur between control transfers, the code generator has some flexibility to reorder computation between control transfers for greater performance. The paper *Polling Efficiently on Stock Hardware* by Marc Feeley, *Proc. 1993 Conference on Functional Programming and Computer Architecture*, Copenhagen, Denmark, pp. 179–187, is recommended as further reading.

the corresponding exception handler table in the `class` file, starting from the beginning of that table.

Note that the Java virtual machine does not enforce nesting of or any ordering of the exception table entries of a method. The exception handling semantics of the Java programming language are implemented only through cooperation with the compiler (§3.12). When `class` files are generated by some other means, the defined search procedure ensures that all Java virtual machines will behave consistently.

2.11 Instruction Set Summary

A Java virtual machine instruction consists of a one-byte *opcode* specifying the operation to be performed, followed by zero or more *operands* supplying arguments or data that are used by the operation. Many instructions have no operands and consist only of an opcode.

Ignoring exceptions, the inner loop of a Java virtual machine interpreter is effectively

```
do {
    atomically calculate pc and fetch opcode at pc;
    if (operands) fetch operands;
    execute the action for the opcode;
} while (there is more to do);
```

The number and size of the operands are determined by the opcode. If an operand is more than one byte in size, then it is stored in *big-endian* order—high-order byte first. For example, an unsigned 16-bit index into the local variables is stored as two unsigned bytes, *byte1* and *byte2*, such that its value is

$$(\text{byte1} \ll 8) | \text{byte2}$$

The bytecode instruction stream is only single-byte aligned. The two exceptions are the *tableswitch* and *lookupswitch* instructions, which are padded to force internal alignment of some of their operands on 4-byte boundaries.

The decision to limit the Java virtual machine opcode to a byte and to forgo data alignment within compiled code reflects a conscious bias in favor of compactness, possibly at the cost of some performance in naive implementations. A one-byte opcode also limits the size of the instruction set. Not assuming data alignment means that immediate data larger than a byte must be constructed from bytes at runtime on many machines.

2.11.1 Types and the Java Virtual Machine

Most of the instructions in the Java virtual machine instruction set encode type information about the operations they perform. For instance, the *iload* instruction loads the contents of a local variable, which must be an `int`, onto the operand stack. The *fload* instruction does the same with a `float` value. The two instructions may have identical implementations, but have distinct opcodes.

For the majority of typed instructions, the instruction type is represented explicitly in the opcode mnemonic by a letter: *i* for an `int` operation, *l* for `long`, *s* for `short`, *b* for `byte`, *c* for `char`, *f* for `float`, *d* for `double`, and *a* for `reference`. Some instructions for which the type is unambiguous do not have a type letter in their mnemonic. For instance, *arraylength* always operates on an object that is an array. Some instructions, such as *goto*, an unconditional control transfer, do not operate on typed operands.

Given the Java virtual machine's one-byte opcode size, encoding types into opcodes places pressure on the design of its instruction set. If each typed instruction supported all of the Java virtual machine's runtime data types, there would be more instructions than could be represented in a byte. Instead, the instruction set of the Java virtual machine provides a reduced level of type support for certain operations. In other words, the instruction set is intentionally not orthogonal. Separate instructions can be used to convert between unsupported and supported data types as necessary.

Table 2.2 summarizes the type support in the instruction set of the Java virtual machine. A specific instruction, with type information, is built by replacing the *T* in the instruction template in the opcode column by the letter in the type column. If the type column for some instruction template and type is blank, then no instruction exists supporting that type of operation. For instance, there is a load instruction for type `int`, *iload*, but there is no load instruction for type `byte`.

Note that most instructions in Table 2.2 do not have forms for the integral types `byte`, `char`, and `short`. None have forms for the `boolean` type. Compilers encode loads of literal values of types `byte` and `short` using Java virtual machine instructions that sign-extend those values to values of type `int` at compile time or runtime. Loads of literal values of types `boolean` and `char` are encoded using instructions that zero-extend the literal to a value of type `int` at compile time or runtime. Likewise, loads from arrays of values of type `boolean`, `byte`, `short`, and `char` are encoded using Java virtual machine instructions that sign-extend or zero-extend the values to values of type `int`. Thus, most opera-

tions on values of actual types `boolean`, `byte`, `char`, and `short` are correctly performed by instructions operating on values of computational type `int`.

Table 2.2 Type support in the Java virtual machine instruction set

opcode	byte	short	int	long	float	double	char	reference
<i>Tpush</i>	<i>bipush</i>	<i>sipush</i>						
<i>Tconst</i>			<i>iconst</i>	<i>lconst</i>	<i>fconst</i>	<i>dconst</i>		<i>aconst</i>
<i>Tload</i>			<i>iload</i>	<i>lload</i>	<i>fload</i>	<i>dload</i>		<i>aload</i>
<i>Tstore</i>			<i>istore</i>	<i>lstore</i>	<i>fstore</i>	<i>dstore</i>		<i>astore</i>
<i>Tinc</i>			<i>iinc</i>					
<i>Taload</i>	<i>baload</i>	<i>saload</i>	<i>iaload</i>	<i>laload</i>	<i>faload</i>	<i>daload</i>	<i>caload</i>	<i>aaload</i>
<i>Tastore</i>	<i>bas-tore</i>	<i>sas-tore</i>	<i>iastore</i>	<i>lastore</i>	<i>fastore</i>	<i>dastore</i>	<i>cas-tore</i>	<i>aastore</i>
<i>Tadd</i>			<i>iadd</i>	<i>ladd</i>	<i>fadd</i>	<i>dadd</i>		
<i>Tsub</i>			<i>isub</i>	<i>lsub</i>	<i>fsub</i>	<i>dsub</i>		
<i>Tmul</i>			<i>imul</i>	<i>lmul</i>	<i>fmul</i>	<i>dmul</i>		
<i>Tdiv</i>			<i>idiv</i>	<i>ldiv</i>	<i>fdiv</i>	<i>ddiv</i>		
<i>Trem</i>			<i>irem</i>	<i>lrem</i>	<i>frem</i>	<i>drem</i>		
<i>Tneg</i>			<i>ineg</i>	<i>lneg</i>	<i>fneg</i>	<i>dneg</i>		
<i>Tshl</i>			<i>ishl</i>	<i>lshl</i>				
<i>Tshr</i>			<i>ishr</i>	<i>lshr</i>				
<i>Tushr</i>			<i>iushr</i>	<i>lushr</i>				
<i>Tand</i>			<i>iand</i>	<i>land</i>				
<i>Tor</i>			<i>ior</i>	<i>lor</i>				
<i>Txor</i>			<i>ixor</i>	<i>lxor</i>				
<i>i2T</i>	<i>i2b</i>	<i>i2s</i>		<i>i2l</i>	<i>i2f</i>	<i>i2d</i>		
<i>l2T</i>			<i>l2i</i>		<i>l2f</i>	<i>l2d</i>		
<i>f2T</i>			<i>f2i</i>	<i>f2l</i>		<i>f2d</i>		
<i>d2T</i>			<i>d2i</i>	<i>d2l</i>	<i>d2f</i>			
<i>Tcmp</i>				<i>lcmp</i>				
<i>Tcmpl</i>					<i>fcmpl</i>	<i>dcmpl</i>		
<i>Tcmpg</i>					<i>fcmpg</i>	<i>dcmpg</i>		
<i>if_TcmpOP</i>			<i>if_icmpOP</i>					<i>if_acmpOP</i>
<i>Treturn</i>			<i>ireturn</i>	<i>lreturn</i>	<i>freturn</i>	<i>dreturn</i>		<i>areturn</i>

The mapping between Java virtual machine actual types and Java virtual machine computational types is summarized by Table 2.3.

Table 2.3 Java virtual machine actual and computational types

Actual Type	Computational Type	Category
<code>boolean</code>	<code>int</code>	category 1
<code>byte</code>	<code>int</code>	category 1
<code>char</code>	<code>int</code>	category 1
<code>short</code>	<code>int</code>	category 1
<code>int</code>	<code>int</code>	category 1
<code>float</code>	<code>float</code>	category 1
<code>reference</code>	<code>reference</code>	category 1
<code>returnAddress</code>	<code>returnAddress</code>	category 1
<code>long</code>	<code>long</code>	category 2
<code>double</code>	<code>double</code>	category 2

Certain Java virtual machine instructions such as *pop* and *swap* operate on the operand stack without regard to type; however, such instructions are constrained to use only on values of certain categories of computational types, also given in Table 2.3.

2.11.2 Load and Store Instructions

The load and store instructions transfer values between the local variables (§2.6.1) and the operand stack (§2.6.2) of a Java virtual machine frame (§2.6):

- Load a local variable onto the operand stack: *iload*, *iload_<n>*, *lload*, *lload_<n>*, *fload*, *fload_<n>*, *dload*, *dload_<n>*, *aload*, *aload_<n>*.
- Store a value from the operand stack into a local variable: *istore*, *istore_<n>*, *lstore*, *lstore_<n>*, *fstore*, *fstore_<n>*, *dstore*, *dstore_<n>*, *astore*, *astore_<n>*.
- Load a constant onto the operand stack: *bipush*, *sipush*, *ldc*, *ldc_w*, *ldc2_w*, *aconst_null*, *iconst_m1*, *iconst_<i>*, *lconst_<l>*, *fconst_<f>*, *dconst_<d>*.

- Gain access to more local variables using a wider index, or to a larger immediate operand: *wide*.

Instructions that access fields of objects and elements of arrays (§2.11.5) also transfer data to and from the operand stack.

Instruction mnemonics shown above with trailing letters between angle brackets (for instance, *iload_<n>*) denote families of instructions (with members *iload_0*, *iload_1*, *iload_2*, and *iload_3* in the case of *iload_<n>*). Such families of instructions are specializations of an additional generic instruction (*iload*) that takes one operand. For the specialized instructions, the operand is implicit and does not need to be stored or fetched. The semantics are otherwise the same (*iload_0* means the same thing as *iload* with the operand *0*). The letter between the angle brackets specifies the type of the implicit operand for that family of instructions: for *<n>*, a nonnegative integer; for *<i>*, an *int*; for *<l>*, a *long*; for *<f>*, a *float*; and for *<d>*, a *double*. Forms for type *int* are used in many cases to perform operations on values of type *byte*, *char*, and *short* (§2.11.1).

This notation for instruction families is used throughout *The Java™ Virtual Machine Specification*.

2.11.3 Arithmetic Instructions

The arithmetic instructions compute a result that is typically a function of two values on the operand stack, pushing the result back on the operand stack. There are two main kinds of arithmetic instructions: those operating on integer values and those operating on floating-point values. Within each of these kinds, the arithmetic instructions are specialized to Java virtual machine numeric types. There is no direct support for integer arithmetic on values of the *byte*, *short*, and *char* types (§2.11.1), or for values of the *boolean* type; those operations are handled by instructions operating on type *int*. Integer and floating-point instructions also differ in their behavior on overflow and divide-by-zero. The arithmetic instructions are as follows:

- Add: *iadd*, *ladd*, *fadd*, *dadd*.
- Subtract: *isub*, *lsub*, *fsub*, *dsub*.
- Multiply: *imul*, *lmul*, *fmul*, *dmul*.
- Divide: *idiv*, *ldiv*, *fdiv*, *ddiv*.
- Remainder: *irem*, *lrem*, *frem*, *drem*.

- Negate: *ineg*, *lneg*, *fneg*, *dneg*.
- Shift: *ishl*, *ishr*, *iushr*, *lshl*, *lshr*, *lushr*.
- Bitwise OR: *ior*, *lor*.
- Bitwise AND: *iand*, *land*.
- Bitwise exclusive OR: *ixor*, *lxor*.
- Local variable increment: *iinc*.
- Comparison: *dcmpg*, *dcmpl*, *fcmpg*, *fcmpl*, *lcmp*.

The semantics of the Java programming language operators on integer and floating-point values (JLS3 §4.2.2, JLS3 §4.2.4) are directly supported by the semantics of the Java virtual machine instruction set.

The Java virtual machine does not indicate overflow during operations on integer data types. The only integer operations that can throw an exception are the integer divide instructions (*idiv* and *ldiv*) and the integer remainder instructions (*irem* and *lrem*), which throw an `ArithmaticException` if the divisor is zero.

Java virtual machine operations on floating-point numbers behave as specified in IEEE 754. In particular, the Java virtual machine requires full support of IEEE 754 *denormalized* floating-point numbers and *gradual underflow*, which make it easier to prove desirable properties of particular numerical algorithms.

The Java virtual machine requires that floating-point arithmetic behave as if every floating-point operator rounded its floating-point result to the result precision. *Inexact* results must be rounded to the representable value nearest to the infinitely precise result; if the two nearest representable values are equally near, the one having a least significant bit of zero is chosen. This is the IEEE 754 standard's default rounding mode, known as *round to nearest* mode.

The Java virtual machine uses the IEEE 754 *round towards zero* mode when converting a floating-point value to an integer. This results in the number being truncated; any bits of the significand that represent the fractional part of the operand and value are discarded. Round towards zero mode chooses as its result the type's value closest to, but no greater in magnitude than, the infinitely precise result.

The Java virtual machine's floating-point operators do not throw runtime exceptions (not to be confused with IEEE 754 floating-point exceptions). An operation that overflows produces a signed infinity, an operation that underflows produces a denormalized value or a signed zero, and an operation that has no mathematically definite result produces NaN. All numeric operations with NaN as an operand produce NaN as a result.

Comparisons on values of type `long` (`lcmp`) perform a signed comparison. Comparisons on values of floating-point types (`dcmpg`, `dcmpl`, `fcmpg`, `fcmpl`) are performed using IEEE 754 nonsignaling comparisons.

2.11.4 Type Conversion Instructions

The type conversion instructions allow conversion between Java virtual machine numeric types. These may be used to implement explicit conversions in user code or to mitigate the lack of orthogonality in the instruction set of the Java virtual machine.

The Java virtual machine directly supports the following widening numeric conversions:

- `int` to `long`, `float`, or `double`
- `long` to `float` or `double`
- `float` to `double`

The widening numeric conversion instructions are `i2l`, `i2f`, `i2d`, `l2f`, `l2d`, and `f2d`. The mnemonics for these opcodes are straightforward given the naming conventions for typed instructions and the punning use of 2 to mean “to.” For instance, the `i2d` instruction converts an `int` value to a `double`. Widening numeric conversions do not lose information about the overall magnitude of a numeric value. Indeed, conversions widening from `int` to `long` and `int` to `double` do not lose any information at all; the numeric value is preserved exactly. Conversions widening from `float` to `double` that are FP-strict (§2.8.2) also preserve the numeric value exactly; however, such conversions that are not FP-strict may lose information about the overall magnitude of the converted value.

Conversion of an `int` or a `long` value to `float`, or of a `long` value to `double`, may lose *precision*, that is, may lose some of the least significant bits of the value; the resulting floating-point value is a correctly rounded version of the integer value, using IEEE 754 round to nearest mode.

A widening numeric conversion of an `int` to a `long` simply sign-extends the two’s-complement representation of the `int` value to fill the wider format. A widening numeric conversion of a `char` to an integral type zero-extends the representation of the `char` value to fill the wider format.

Despite the fact that loss of precision may occur, widening numeric conversions never cause the Java virtual machine to throw a runtime exception (not to be confused with an IEEE 754 floating-point exception).

Note that widening numeric conversions do not exist from integral types `byte`, `char`, and `short` to type `int`. As noted in §2.11.1, values of type `byte`, `char`, and `short` are internally widened to type `int`, making these conversions implicit.

The Java virtual machine also directly supports the following narrowing numeric conversions:

- `int` to `byte`, `short`, or `char`
- `long` to `int`
- `float` to `int` or `long`
- `double` to `int`, `long`, or `float`

The narrowing numeric conversion instructions are `i2b`, `i2c`, `i2s`, `l2i`, `f2i`, `f2l`, `d2i`, `d2l`, and `d2f`. A narrowing numeric conversion can result in a value of different sign, a different order of magnitude, or both; it may thereby lose precision.

A narrowing numeric conversion of an `int` or `long` to an integral type T simply discards all but the N lowest-order bits, where N is the number of bits used to represent type T. This may cause the resulting value not to have the same sign as the input value.

In a narrowing numeric conversion of a floating-point value to an integral type T, where T is either `int` or `long`, the floating-point value is converted as follows:

- If the floating-point value is NaN, the result of the conversion is an `int` or `long` 0.
- Otherwise, if the floating-point value is not an infinity, the floating-point value is rounded to an integer value V using IEEE 754 round towards zero mode. There are two cases:
 - If T is `long` and this integer value can be represented as a `long`, then the result is the `long` value V.
 - If T is of type `int` and this integer value can be represented as an `int`, then the result is the `int` value V.
- Otherwise:

- Either the value must be too small (a negative value of large magnitude or negative infinity), and the result is the smallest representable value of type `int` or `long`.
- Or the value must be too large (a positive value of large magnitude or positive infinity), and the result is the largest representable value of type `int` or `long`.

A narrowing numeric conversion from `double` to `float` behaves in accordance with IEEE 754. The result is correctly rounded using IEEE 754 round to nearest mode. A value too small to be represented as a `float` is converted to a positive or negative zero of type `float`; a value too large to be represented as a `float` is converted to a positive or negative infinity. A `double` NaN is always converted to a `float` NaN.

Despite the fact that overflow, underflow, or loss of precision may occur, narrowing conversions among numeric types never cause the Java virtual machine to throw a runtime exception (not to be confused with an IEEE 754 floating-point exception).

2.11.5 Object Creation and Manipulation

Although both class instances and arrays are objects, the Java virtual machine creates and manipulates class instances and arrays using distinct sets of instructions:

- Create a new class instance: `new`.
- Create a new array: `newarray`, `anewarray`, `multianewarray`.
- Access fields of classes (`static` fields, known as class variables) and fields of class instances (non-`static` fields, known as instance variables): `getfield`, `putfield`, `getstatic`, `putstatic`.
- Load an array component onto the operand stack: `baload`, `caload`, `saload`, `iaload`, `laload`, `faload`, `daload`, `aaload`.
- Store a value from the operand stack as an array component: `bastore`, `castore`, `sastore`, `iastore`, `lastore`, `fastore`, `dastore`, `aastore`.
- Get the length of array: `arraylength`.
- Check properties of class instances or arrays: `instanceof`, `checkcast`.

2.11.6 Operand Stack Management Instructions

A number of instructions are provided for the direct manipulation of the operand stack: *pop*, *pop2*, *dup*, *dup2*, *dup_x1*, *dup2_x1*, *dup_x2*, *dup2_x2*, *swap*.

2.11.7 Control Transfer Instructions

The control transfer instructions conditionally or unconditionally cause the Java virtual machine to continue execution with an instruction other than the one following the control transfer instruction. They are:

- Conditional branch: *ifeq*, *iflt*, *ifle*, *ifne*, *ifgt*, *ifge*, *ifnull*, *ifnonnull*, *if_icmpne*, *if_icmpne*, *if_icmpgt*, *if_icmple*, *if_icmpge*, *if_acmpeq*, *if_acmpne*.
- Compound conditional branch: *tableswitch*, *lookupswitch*.
- Unconditional branch: *goto*, *goto_w*, *jsr*, *jsr_w*, *ret*.

The Java virtual machine has distinct sets of instructions that conditionally branch on comparison with data of `int` and reference types. It also has distinct conditional branch instructions that test for the null reference and thus is not required to specify a concrete value for `null` (§2.4).

Conditional branches on comparisons between data of types `boolean`, `byte`, `char`, and `short` are performed using `int` comparison instructions (§2.11.1). A conditional branch on a comparison between data of types `long`, `float`, or `double` is initiated using an instruction that compares the data and produces an `int` result of the comparison (§2.11.3). A subsequent `int` comparison instruction tests this result and effects the conditional branch. Because of its emphasis on `int` comparisons, the Java virtual machine provides a rich complement of conditional branch instructions for type `int`.

All `int` conditional control transfer instructions perform signed comparisons.

2.11.8 Method Invocation and Return Instructions

The following four instructions invoke methods:

- *invokevirtual* invokes an instance method of an object, dispatching on the (virtual) type of the object. This is the normal method dispatch in the Java programming language.
- *invokeinterface* invokes an interface method, searching the methods implemented by the particular runtime object to find the appropriate method.
- *invokespecial* invokes an instance method requiring special handling, whether an instance initialization method (§2.9), a **private** method, or a superclass method.
- *invokestatic* invokes a class (**static**) method in a named class.

The method return instructions, which are distinguished by return type, are *ireturn* (used to return values of type **boolean**, **byte**, **char**, **short**, or **int**), *lreturn*, *freturn*, *dreturn*, and *areturn*. In addition, the *return* instruction is used to return from methods declared to be **void**, instance initialization methods, and class or interface initialization methods.

2.11.9 Throwing Exceptions

An exception is thrown programmatically using the *athrow* instruction. Exceptions can also be thrown by various Java virtual machine instructions if they detect an abnormal condition.

2.11.10 Synchronization

The Java virtual machine supports synchronization of both methods and sequences of instructions within a method by a single synchronization construct: the *monitor*.

Method-level synchronization is performed implicitly, as part of method invocation and return (§2.11.8). A synchronized method is distinguished in the runtime constant pool's *method_info* structure (§4.6) by the **ACC_SYNCHRONIZED** flag, which is checked by the method invocation instructions. When invoking a method for which **ACC_SYNCHRONIZED** is set, the executing thread enters a monitor, invokes the method itself, and exits the monitor whether the method invocation completes normally or abruptly. During the time the executing thread owns the monitor, no other thread may enter it. If an exception is thrown during invocation of the **synchronized** method and the **synchronized** method does not handle the exception, the monitor for the method is automatically exited before the exception is rethrown out of the **synchronized** method.

Synchronization of sequences of instructions is typically used to encode the `synchronized` block of the Java programming language. The Java virtual machine supplies the `monitorenter` and `monitorexit` instructions to support such language constructs. Proper implementation of `synchronized` blocks requires cooperation from a compiler targeting the Java virtual machine (see Section 3.14, “Synchronization”).

Structured locking is the situation when, during a method invocation, every exit on a given monitor matches a preceding entry on that monitor. Since there is no assurance that all code submitted to the Java virtual machine will perform structured locking, implementations of the Java virtual machine are permitted but not required to enforce both of the following two rules guaranteeing structured locking. Let T be a thread and M be a monitor. Then:

1. The number of monitor entries performed by T on M during a method invocation must equal the number of monitor exits performed by T on M during the method invocation whether the method invocation completes normally or abruptly.
2. At no point during a method invocation may the number of monitor exits performed by T on M since the method invocation exceed the number of monitor entries performed by T on M since the method invocation.

Note that the monitor entry and exit automatically performed by the Java virtual machine when invoking a `synchronized` method are considered to occur during the calling method’s invocation.

2.12 Class Libraries

The Java virtual machine must provide sufficient support for the implementation of the class libraries of the associated platform. Some of the classes in these libraries cannot be implemented without the cooperation of the Java virtual machine.

Classes that might require special support from the Java virtual machine include those that support:

- Reflection, such as the classes in the package `java.lang.reflect` and the class `Class`.
- Loading and creation of a class or interface. The most obvious example is the class `ClassLoader`.

- Linking and initialization of a class or interface. The example classes cited above fall into this category as well.
- Security, such as the classes in the package `java.security` and other classes such as `SecurityManager`.
- Multithreading, such as the class `Thread`.
- Weak references, such as the classes in the package `java.lang.ref`.

The list above is meant to be illustrative rather than comprehensive. An exhaustive list of these classes or of the functionality they provide is beyond the scope of this book. See the specifications of the Java platform class libraries for details.

2.13 Public Design, Private Implementation

Thus far this book has sketched the public view of the Java virtual machine: the `class` file format and the instruction set. These components are vital to the hardware-, operating system-, and implementation-independence of the Java virtual machine. The implementor may prefer to think of them as a means to securely communicate fragments of programs between hosts each implementing the Java platform, rather than as a blueprint to be followed exactly.

It is important to understand where the line between the public design and the private implementation lies. A Java virtual machine implementation must be able to read `class` files and must exactly implement the semantics of the Java virtual machine code therein. One way of doing this is to take this document as a specification and to implement that specification literally. But it is also perfectly feasible and desirable for the implementor to modify or optimize the implementation within the constraints of this specification. So long as the `class` file format can be read and the semantics of its code are maintained, the implementor may implement these semantics in any way. What is “under the hood” is the implementor’s business, as long as the correct external interface is carefully maintained.⁷

⁷ There are some exceptions: debuggers, profilers, and just-in-time code generators can each require access to elements of the Java virtual machine that are normally considered to be “under the hood.” Where appropriate, Oracle works with other Java virtual machine implementors and tools vendors to develop common interfaces to the Java virtual machine for use by such tools, and to promote those interfaces across the industry.

The implementor can use this flexibility to tailor Java virtual machine implementations for high performance, low memory use, or portability. What makes sense in a given implementation depends on the goals of that implementation. The range of implementation options includes the following:

- Translating Java virtual machine code at load time or during execution into the instruction set of another virtual machine.
- Translating Java virtual machine code at load time or during execution into the native instruction set of the host CPU (sometimes referred to as *just-in-time*, or *JIT*, code generation).

The existence of a precisely defined virtual machine and object file format need not significantly restrict the creativity of the implementor. The Java virtual machine is designed to support many different implementations, providing new and interesting solutions while retaining compatibility between implementations.

Compiling for the Java Virtual Machine

THE Java virtual machine is designed to support the Java programming language. Oracle’s JDK software contains both a compiler from source code written in the Java programming language to the instruction set of the Java virtual machine, and a runtime system that implements the Java virtual machine itself. Understanding how one compiler utilizes the Java virtual machine is useful to the prospective compiler writer, as well as to one trying to understand the Java virtual machine itself. The numbered sections in this chapter are not normative.

~~Although this chapter concentrates on compiling source code written in the Java programming language, the Java virtual machine does not assume that the instructions it executes were generated from such code. While there have been a number of efforts aimed at compiling other languages to the Java virtual machine, the current version of the Java virtual machine was not designed to support a wide range of languages. Some languages may be hosted fairly directly by the Java virtual machine. Other languages may be implemented only inefficiently.~~

Note that the term “compiler” is sometimes used when referring to a translator from the instruction set of a Java virtual machine to the instruction set of a specific CPU. One example of such a translator is a just-in-time (JIT) code generator, which generates platform-specific instructions only after Java virtual machine code has been loaded. This chapter does not address issues associated with code generation, only those associated with compiling source code written in the Java programming language to Java virtual machine instructions.

3.1 Format of Examples

This chapter consists mainly of examples of source code together with annotated listings of the Java virtual machine code that the `javac` compiler in Oracle’s JDK release 1.0.2 generates for the examples. The Java virtual machine code is written in the informal “virtual machine assembly language” output by Oracle’s `javap` utility, distributed with the JDK release. You can use `javap` to generate additional examples of compiled methods.

The format of the examples should be familiar to anyone who has read assembly code. Each instruction takes the form

```
<index> <opcode> [<operand1> [<operand2>...]] [<comment>]
```

The `<index>` is the index of the opcode of the instruction in the array that contains the bytes of Java virtual machine code for this method. Alternatively, the `<index>` may be thought of as a byte offset from the beginning of the method. The `<opcode>` is the mnemonic for the instruction’s opcode, and the zero or more `<operandN>` are the operands of the instruction. The optional `<comment>` is given in end-of-line comment syntax:

```
8 bipush 100           // Push int constant 100
```

Some of the material in the comments is emitted by `javap`; the rest is supplied by the authors. The `<index>` prefacing each instruction may be used as the target of a control transfer instruction. For instance, a `goto 8` instruction transfers control to the instruction at index 8. Note that the actual operands of Java virtual machine control transfer instructions are offsets from the addresses of the opcodes of those instructions; these operands are displayed by `javap` (and are shown in this chapter) as more easily read offsets into their methods.

We preface an operand representing a runtime constant pool index with a hash sign and follow the instruction by a comment identifying the runtime constant pool item referenced, as in

```
10 ldc #1           // Push float constant 100.0
```

or

```
9 invokevirtual #4    // Method Example.addTwo(II)I
```

For the purposes of this chapter, we do not worry about specifying details such as operand sizes.

3.2 Use of Constants, Local Variables, and Control Constructs

Java virtual machine code exhibits a set of general characteristics imposed by the Java virtual machine’s design and use of types. In the first example we encounter many of these, and we consider them in some detail.

The `spin` method simply spins around an empty `for` loop 100 times:

```
void spin() {
    int i;
    for (i = 0; i < 100; i++) {
        ;           // Loop body is empty
    }
}
```

A compiler might compile `spin` to

<i>Method void spin()</i>
0 <i>iconst_0</i> <i>// Push int constant 0</i>
1 <i>istore_1</i> <i>// Store into local variable 1 (i=0)</i>
2 <i>goto 8</i> <i>// First time through don't increment</i>
5 <i>iinc 1 1</i> <i>// Increment local variable 1 by 1 (i++)</i>
8 <i>iload_1</i> <i>// Push local variable 1 (i)</i>
9 <i>bipush 100</i> <i>// Push int constant 100</i>
11 <i>if_icmplt 5</i> <i>// Compare and loop if less than (i < 100)</i>
14 <i>return</i> <i>// Return void when done</i>

The Java virtual machine is stack-oriented, with most operations taking one or more operands from the operand stack of the Java virtual machine’s current frame or pushing results back onto the operand stack. A new frame is created each time a method is invoked, and with it is created a new operand stack and set of local variables for use by that method (see Section 2.6, “Frames”). At any one point of the computation, there are thus likely to be many frames and equally many operand stacks per thread of control, corresponding to many nested method invocations. Only the operand stack in the current frame is active.

The instruction set of the Java virtual machine distinguishes operand types by using distinct bytecodes for operations on its various data types. The method `spin` operates only on values of type `int`. The instructions in its compiled code chosen to operate on typed data (`iconst_0`, `istore_1`, `iinc`, `iload_1`, `if_icmplt`) are all specialized for type `int`.

The two constants in `spin`, 0 and 100, are pushed onto the operand stack using two different instructions. The 0 is pushed using an `iconst_0` instruction, one of the family of `iconst_{<i>}` instructions. The 100 is pushed using a `bipush` instruction, which fetches the value it pushes as an immediate operand.

The Java virtual machine frequently takes advantage of the likelihood of certain operands (`int` constants $-1, 0, 1, 2, 3, 4$ and 5 in the case of the `iconst_{<i>}` instructions) by making those operands implicit in the opcode. Because the `iconst_0` instruction knows it is going to push an `int 0`, `iconst_0` does not need to store an operand to tell it what value to push, nor does it need to fetch or decode an operand. Compiling the push of 0 as `bipush 0` would have been correct, but would have made the compiled code for `spin` one byte longer. A simple virtual machine would have also spent additional time fetching and decoding the explicit operand each time around the loop. Use of implicit operands makes compiled code more compact and efficient.

The `int i` in `spin` is stored as Java virtual machine local variable I . Because most Java virtual machine instructions operate on values popped from the operand stack rather than directly on local variables, instructions that transfer values between local variables and the operand stack are common in code compiled for the Java virtual machine. These operations also have special support in the instruction set. In `spin`, values are transferred to and from local variables using the `istore_I` and `iload_I` instructions, each of which implicitly operates on local variable I . The `istore_I` instruction pops an `int` from the operand stack and stores it in local variable I . The `iload_I` instruction pushes the value in local variable I onto the operand stack.

The use (and reuse) of local variables is the responsibility of the compiler writer. The specialized load and store instructions should encourage the compiler writer to reuse local variables as much as is feasible. The resulting code is faster, more compact, and uses less space in the frame.

Certain very frequent operations on local variables are catered to specially by the Java virtual machine. The `iinc` instruction increments the contents of a local variable by a one-byte signed value. The `iinc` instruction in `spin` increments the first local variable (its first operand) by I (its second operand). The `iinc` instruction is very handy when implementing looping constructs.

The `for` loop of `spin` is accomplished mainly by these instructions:

```

5  iinc 1 1      // Increment local 1 by 1 (i++)
8  iload_1       // Push local variable 1 (i)
9  bipush 100    // Push int constant 100
11 if_icmplt 5   // Compare and loop if less than (i < 100)

```

The *bipush* instruction pushes the value *100* onto the operand stack as an *int*, then the *if_icmplt* instruction pops that value off the operand stack and compares it against *i*. If the comparison succeeds (the variable *i* is less than 100), control is transferred to index 5 and the next iteration of the *for* loop begins. Otherwise, control passes to the instruction following the *if_icmplt*.

If the *spin* example had used a data type other than *int* for the loop counter, the compiled code would necessarily change to reflect the different data type. For instance, if instead of an *int* the *spin* example uses a *double*, as shown,

```

void dspin() {
    double i;
    for (i = 0.0; i < 100.0; i++) {
        ;           // Loop body is empty
    }
}

```

the compiled code is

```

Method void dspin()
0  dconst_0      // Push double constant 0.0
1  dstore_1       // Store into local variables 1 and 2
2  goto 9         // First time through don't increment
5  dload_1        // Push local variables 1 and 2
6  dconst_1        // Push double constant 1.0
7  dadd            // Add; there is no dinc instruction
8  dstore_1        // Store result in local variables 1 and 2
9  dload_1        // Push local variables 1 and 2
10 ldc2_w #4      // Push double constant 100.0
13 dcmpg          // There is no if_dcmplt instruction
14 iflt 5         // Compare and loop if less than (i < 100.0)
17 return          // Return void when done

```

The instructions that operate on typed data are now specialized for type *double*. (The *ldc2_w* instruction will be discussed later in this chapter.)

Recall that `double` values occupy two local variables, although they are only accessed using the lesser index of the two local variables. This is also the case for values of type `long`. Again for example,

```
double doubleLocals(double d1, double d2) {
    return d1 + d2;
}
```

becomes

```
Method double doubleLocals(double, double)
  0  dload_1           // First argument in local variables 1 and 2
  1  dload_3           // Second argument in local variables 3 and 4
  2  dadd
  3  dreturn
```

Note that local variables of the local variable pairs used to store `double` values in `doubleLocals` must never be manipulated individually.

The Java virtual machine's opcode size of 1 byte results in its compiled code being very compact. However, 1-byte opcodes also mean that the Java virtual machine instruction set must stay small. As a compromise, the Java virtual machine does not provide equal support for all data types: it is not completely orthogonal (see Table 2.2, “Type support in the Java virtual machine instruction set”).

For example, the comparison of values of type `int` in the `for` statement of example `spin` can be implemented using a single `if_icmplt` instruction; however, there is no single instruction in the Java virtual machine instruction set that performs a conditional branch on values of type `double`. Thus, `dspin` must implement its comparison of values of type `double` using a `dcmpg` instruction followed by an `iflt` instruction.

The Java virtual machine provides the most direct support for data of type `int`. This is partly in anticipation of efficient implementations of the Java virtual machine's operand stacks and local variable arrays. It is also motivated by the frequency of `int` data in typical programs. Other integral types have less direct support. There are no `byte`, `char`, or `short` versions of the store, load, or add instructions, for instance. Here is the `spin` example written using a `short`:

```

void sspin() {
    short i;
    for (i = 0; i < 100; i++) {
        ;      // Loop body is empty
    }
}

```

It must be compiled for the Java virtual machine, as follows, using instructions operating on another type, most likely `int`, converting between `short` and `int` values as necessary to ensure that the results of operations on `short` data stay within the appropriate range:

```

Method void sspin()
0  iconst_0
1  istore_1
2  goto 10
5  iload_1      // The short is treated as though an int
6  iconst_1
7  iadd
8  i2s          // Truncate int to short
9  istore_1
10 iload_1
11 bipush 100
13 if_icmplt 5
16 return

```

The lack of direct support for `byte`, `char`, and `short` types in the Java virtual machine is not particularly painful, because values of those types are internally promoted to `int` (`byte` and `short` are sign-extended to `int`, `char` is zero-extended). Operations on `byte`, `char`, and `short` data can thus be done using `int` instructions. The only additional cost is that of truncating the values of `int` operations to valid ranges.

The `long` and floating-point types have an intermediate level of support in the Java virtual machine, lacking only the full complement of conditional control transfer instructions.

3.3 Arithmetic

The Java virtual machine generally does arithmetic on its operand stack. (The exception is the *iinc* instruction, which directly increments the value of a local variable.) For instance, the `align2grain` method aligns an `int` value to a given power of 2:

```
int align2grain(int i, int grain) {
    return ((i + grain-1) & ~(grain-1));
}
```

Operands for arithmetic operations are popped from the operand stack, and the results of operations are pushed back onto the operand stack. Results of arithmetic subcomputations can thus be made available as operands of their nesting computation. For instance, the calculation of $\sim(\text{grain}-1)$ is handled by these instructions:

```
5 iload_2          // Push grain
6 iconst_1         // Push int constant 1
7 isub             // Subtract; push result
8 iconst_m1        // Push int constant -1
9 ixor             // Do XOR; push result
```

First `grain – 1` is calculated using the contents of local variable 2 and an immediate `int` value 1. These operands are popped from the operand stack and their difference pushed back onto the operand stack. The difference is thus immediately available for use as one operand of the `ixor` instruction. (Recall that $\sim x == -1 \wedge x$.) Similarly, the result of the `ixor` instruction becomes an operand for the subsequent `iand` instruction.

The code for the entire method follows:

```
Method int align2grain(int, int)
0 iload_1
1 iload_2
2 iadd
3 iconst_1
4 isub
5 iload_2
6 iconst_1
```

```

7  isub
8  iconst_m1
9  ixor
10 iand
11 ireturn

```

3.4 Accessing the Runtime Constant Pool

Many numeric constants, as well as objects, fields, and methods, are accessed via the runtime constant pool of the current class. Object access is considered later (§3.8). Data of types `int`, `long`, `float`, and `double`, as well as references to instances of class `String`, are managed using the `ldc`, `ldc_w`, and `ldc2_w` instructions.

The `ldc` and `ldc_w` instructions are used to access values in the runtime constant pool (including instances of class `String`) of types other than `double` and `long`. The `ldc_w` instruction is used in place of `ldc` only when there is a large number of runtime constant pool items and a larger index is needed to access an item. The `ldc2_w` instruction is used to access all values of types `double` and `long`; there is no non-wide variant.

Integral constants of types `byte`, `char`, or `short`, as well as small `int` values, may be compiled using the `bipush`, `sipush`, or `iconst_{i}` instructions, as seen earlier (§3.2). Certain small floating-point constants may be compiled using the `fconst_{f}` and `dconst_{d}` instructions.

In all of these cases, compilation is straightforward. For instance, the constants for

```

void useManyNumeric() {
    int i = 100;
    int j = 1000000;
    long l1 = 1;
    long l2 = 0xffffffff;
    double d = 2.2;
    ...do some calculations...
}

```

are set up as follows:

```

Method void useManyNumeric()
0  bipush 100      //Push a small int with bipush
2  istore_1
3  ldc #1          //Push int constant 1000000; a larger int
                   //value uses ldc
5  istore_2
6  lconst_1         //A tiny long value uses short, fast lconst_1
7  lstore_3
8  ldc2_w #6       //Push long 0xffffffff (that is, an int -1); any
                   //long constant value can be pushed using ldc2_w
11 lstore 5
13 ldc2_w #8       //Push double constant 2.200000; uncommon
                   //double values are also pushed using ldc2_w
16 dstore 7
...do those calculations...

```

3.5 More Control Examples

Compilation of `for` statements was shown in an earlier section (§3.2). Most of the Java programming language’s other control constructs (`if-then-else`, `do`, `while`, `break`, and `continue`) are also compiled in the obvious ways. The compilation of `switch` statements is handled in a separate section (Section 3.10, “Compiling Switches”), as are the compilation of exceptions (Section 3.12, “Throwing and Handling Exceptions”) and the compilation of `finally` clauses (Section 3.13, “Compiling finally”).

As a further example, a `while` loop is compiled in an obvious way, although the specific control transfer instructions made available by the Java virtual machine vary by data type. As usual, there is more support for data of type `int`, for example:

```

void whileInt() {
    int i = 0;
    while (i < 100) {
        i++;
    }
}

```

is compiled to

```

Method void whileInt()
 0  iconst_0
 1  istore_1
 2  goto 8
 5  iinc 1 1
 8  iload_1
 9  bipush 100
11  if_icmplt 5
14  return

```

Note that the test of the `while` statement (implemented using the `if_icmplt` instruction) is at the bottom of the Java virtual machine code for the loop. (This was also the case in the `spin` examples earlier.) The test being at the bottom of the loop forces the use of a `goto` instruction to get to the test prior to the first iteration of the loop. If that test fails, and the loop body is never entered, this extra instruction is wasted. However, `while` loops are typically used when their body is expected to be run, often for many iterations. For subsequent iterations, putting the test at the bottom of the loop saves a Java virtual machine instruction each time around the loop: if the test were at the top of the loop, the loop body would need a trailing `goto` instruction to get back to the top.

Control constructs involving other data types are compiled in similar ways, but must use the instructions available for those data types. This leads to somewhat less efficient code because more Java virtual machine instructions are needed, for example:

```

void whileDouble() {
    double i = 0.0;
    while (i < 100.1) {
        i++;
    }
}

```

is compiled to

```

Method void whileDouble()
 0  dconst_0
 1  dstore_1
 2  goto 9
 5  dload_1

```

```

6  dconst_1
7  dadd
8  dstore_1
9  dload_1
10 ldc2_w #4      // Push double constant 100.1
13 dcmpg          // To do the compare and branch we have to use...
14 iflt 5         // ...two instructions
17 return

```

Each floating-point type has two comparison instructions: *fcmpl* and *fcmpg* for type *float*, and *dcmpl* and *dcmpg* for type *double*. The variants differ only in their treatment of NaN. NaN is unordered, so all floating-point comparisons fail if either of their operands is NaN. The compiler chooses the variant of the comparison instruction for the appropriate type that produces the same result whether the comparison fails on non-NaN values or encounters a NaN.

For instance:

```

int lessThan100(double d) {
    if (d < 100.0) {
        return 1;
    } else {
        return -1;
    }
}

```

compiles to

Method int lessThan100(double)

```

0  dload_1
1  ldc2_w #4      // Push double constant 100.0
4  dcmpg          // Push 1 if d is NaN or d > 100.0;
                  // push 0 if d == 100.0
5  ifge 10         // Branch on 0 or 1
8  iconst_1
9  ireturn
10 iconst_m1
11 ireturn

```

If d is not NaN and is less than 100.0, the *dcmpg* instruction pushes an *int* -1 onto the operand stack, and the *ifge* instruction does not branch. Whether d is greater than 100.0 or is NaN, the *dcmpg* instruction pushes an *int* 1 onto the operand stack, and the *ifge* branches. If d is equal to 100.0, the *dcmpg* instruction pushes an *int* 0 onto the operand stack, and the *ifge* branches.

The *dcmpl* instruction achieves the same effect if the comparison is reversed:

```
int greaterThan100(double d) {
    if (d > 100.0) {
        return 1;
    } else {
        return -1;
    }
}
```

becomes

Method int greaterThan100(double)

0	<i>dload_1</i>	
1	<i>ldc2_w #4</i>	// Push double constant 100.0
4	<i>dcmpl</i>	// Push -1 if d is NaN or $d < 100.0$;
		// push 0 if $d == 100.0$
5	<i>ifle 10</i>	// Branch on 0 or -1
8	<i>iconst_1</i>	
9	<i>ireturn</i>	
10	<i>iconst_m1</i>	
11	<i>ireturn</i>	

Once again, whether the comparison fails on a non-NaN value or because it is passed a NaN, the *dcmpl* instruction pushes an *int* value onto the operand stack that causes the *ifle* to branch. If both of the *dcmp* instructions did not exist, one of the example methods would have had to do more work to detect NaN.

3.6 Receiving Arguments

If n arguments are passed to an instance method, they are received, by convention, in the local variables numbered 1 through n of the frame created for the new method invocation. The arguments are received in the order they were passed. For example:

```
int addTwo(int i, int j) {
    return i + j;
}
```

compiles to

<i>Method int addTwo(int,int)</i>	
0 <i>iload_1</i>	<i>// Push value of local variable 1 (i)</i>
1 <i>iload_2</i>	<i>// Push value of local variable 2 (j)</i>
2 <i>iadd</i>	<i>// Add; leave int result on operand stack</i>
3 <i>ireturn</i>	<i>// Return int result</i>

By convention, an instance method is passed a reference to its instance in local variable 0 . In the Java programming language the instance is accessible via the `this` keyword.

Class (`static`) methods do not have an instance, so for them this use of local variable zero is unnecessary. A class method starts using local variables at index zero. If the `addTwo` method were a class method, its arguments would be passed in a similar way to the first version:

```
static int addTwoStatic(int i, int j) {
    return i + j;
}
```

compiles to

<i>Method int addTwoStatic(int,int)</i>
0 <i>iload_0</i>
1 <i>iload_1</i>
2 <i>iadd</i>
3 <i>ireturn</i>

The only difference is that the method arguments appear starting in local variable 0 rather than 1 .

3.7 Invoking Methods

The normal method invocation for a instance method dispatches on the runtime type of the object. (They are virtual, in C++ terms.) Such an invocation is implemented using the *invokevirtual* instruction, which takes as its argument an index to a runtime constant pool entry giving the internal form of the binary name of the class type of the object, the name of the method to invoke, and that method's descriptor (§4.3.3). To invoke the `addTwo` method, defined earlier as an instance method, we might write

```
int add12and13() {
    return addTwo(12, 13);
}
```

This compiles to

```
Method int add12and13()
0  aload_0           // Push local variable 0 (this)
1  bipush 12        // Push int constant 12
3  bipush 13        // Push int constant 13
5  invokevirtual #4 // Method Example.addtwo(I)I
8  ireturn          // Return int on top of operand stack; it is
                      // the int result of addTwo()
```

The invocation is set up by first pushing a reference to the current instance, `this`, onto the operand stack. The method invocation's arguments, `int` values 12 and 13, are then pushed. When the frame for the `addTwo` method is created, the arguments passed to the method become the initial values of the new frame's local variables. That is, the reference for `this` and the two arguments, pushed onto the operand stack by the invoker, will become the initial values of local variables 0, 1, and 2 of the invoked method.

Finally, `addTwo` is invoked. When it returns, its `int` return value is pushed onto the operand stack of the frame of the invoker, the `add12and13` method. The return value is thus put in place to be immediately returned to the invoker of `add12and13`.

The return from `add12and13` is handled by the *ireturn* instruction of `add12and13`. The *ireturn* instruction takes the `int` value returned by `addTwo`, on the operand stack of the current frame, and pushes it onto the operand stack of the frame of the invoker. It then returns control to the invoker, making the invoker's frame current. The Java virtual machine provides distinct return instructions for

many of its numeric and reference data types, as well as a *return* instruction for methods with no return value. The same set of return instructions is used for all varieties of method invocations.

The operand of the *invokevirtual* instruction (in the example, the runtime constant pool index #4) is not the offset of the method in the class instance. The compiler does not know the internal layout of a class instance. Instead, it generates symbolic references to the methods of an instance, which are stored in the runtime constant pool. Those runtime constant pool items are resolved at runtime to determine the actual method location. The same is true for all other Java virtual machine instructions that access class instances.

Invoking `addTwoStatic`, a class (`static`) variant of `addTwo`, is similar, as shown:

```
int add12and13() {
    return addTwoStatic(12, 13);
}
```

although a different Java virtual machine method invocation instruction is used:

```
Method int add12and13()
0  bipush 12
2  bipush 13
4  invokestatic #3      // Method Example.addTwoStatic(II)I
7  ireturn
```

Compiling an invocation of a class (`static`) method is very much like compiling an invocation of an instance method, except `this` is not passed by the invoker. The method arguments will thus be received beginning with local variable 0 (see Section 3.6, “Receiving Arguments”). The *invokestatic* instruction is always used to invoke class methods.

The *invokespecial* instruction must be used to invoke instance initialization methods (see Section 3.8, “Working with Class Instances”). It is also used when invoking methods in the superclass (`super`) and when invoking `private` methods. For instance, given classes `Near` and `Far` declared as

```
class Near {
    int it;
    public int getItNear() {
        return getIt();
    }
}
```

```

        private int getIt() {
            return it;
        }
    }
    class Far extends Near {
        int getItFar() {
            return super.getItNear();
        }
    }
}

```

the method `Near.getItNear` (which invokes a `private` method) becomes

Method int getItNear()

- 0 `aload_0`
- 1 `invokespecial #5` // Method `Near.getIt()`
- 4 `ireturn`

The method `Far.getItFar` (which invokes a superclass method) becomes

Method int getItFar()

- 0 `aload_0`
- 1 `invokespecial #4` // Method `Near.getItNear()`
- 4 `ireturn`

Note that methods called using the `invokespecial` instruction always pass `this` to the invoked method as its first argument. As usual, it is received in local variable `0`.

3.8 Working with Class Instances

Java virtual machine class instances are created using the Java virtual machine's `new` instruction. Recall that at the level of the Java virtual machine, a constructor appears as a method with the compiler-supplied name `<init>`. This specially named method is known as the instance initialization method (§2.9). Multiple instance initialization methods, corresponding to multiple constructors, may exist for a given class. Once the class instance has been created and its instance variables, including those of the class and all of its superclasses, have been initialized to their default values, an instance initialization method of the new class instance is invoked. For example:

```
Object create() {
    return new Object();
}
```

compiles to

```
Method java.lang.Object create()
0  new #1           // Class java.lang.Object
3  dup
4  invokespecial #4 // Method java.lang.Object.<init>()V
7  areturn
```

Class instances are passed and returned (as reference types) very much like numeric values, although type `reference` has its own complement of instructions, for example:

```
int i;           // An instance variable
MyObj example() {
    MyObj o = new MyObj();
    return silly(o);
}
MyObj silly(MyObj o) {
    if (o != null) {
        return o;
    } else {
        return o;
    }
}
```

becomes

```

Method MyObj example()
0 new #2                      // Class MyObj
3 dup
4 invokespecial #5           // Method MyObj.<init>()V
7 astore_1
8 aload_0
9 aload_1
10 invokevirtual #4
     // Method Example.silly(LMyObj;)LMyObj;
13 areturn

```

```

Method MyObj silly(MyObj)
0 aload_1
1 ifnull 6
4 aload_1
5 areturn
6 aload_1
7 areturn

```

The fields of a class instance (instance variables) are accessed using the *getfield* and *putfield* instructions. If *i* is an instance variable of type *int*, the methods *setIt* and *getIt*, defined as

```

void setIt(int value) {
    i = value;
}
int getIt() {
    return i;
}

```

become

```

Method void setIt(int)
0 aload_0
1 iload_1
2 putfield #4      // Field Example.i I
5 return

```

```
Method int getIt()
0  aload_0
1  getfield #4    //Field Example.i I
4  ireturn
```

As with the operands of method invocation instructions, the operands of the *putfield* and *getfield* instructions (the runtime constant pool index #4) are not the offsets of the fields in the class instance. The compiler generates symbolic references to the fields of an instance, which are stored in the runtime constant pool. Those runtime constant pool items are resolved at runtime to determine the location of the field within the referenced object.

3.9 Arrays

Java virtual machine arrays are also objects. Arrays are created and manipulated using a distinct set of instructions. The *newarray* instruction is used to create an array of a numeric type. The code

```
void createBuffer() {
    int buffer[];
    int bufsz = 100;
    int value = 12;
    buffer = new int[bufsz];
    buffer[10] = value;
    value = buffer[11];
}
```

might be compiled to

```

Method void createBuffer()
0  bipush 100      //Push int constant 100 (bufsz)
2  istore_2        //Store bufsz in local variable 2
3  bipush 12       //Push int constant 12 (value)
5  istore_3        //Store value in local variable 3
6  iload_2         //Push bufsz...
7  newarray int    //...and create new array of int of that length
9  astore_1         //Store new array in buffer
10  aload_1         //Push buffer
11  bipush 10       //Push int constant 10
13  iload_3         //Push value
14  iastore         //Store value at buffer[10]
15  aload_1         //Push buffer
16  bipush 11       //Push int constant 11
18  iload           //Push value at buffer[11]...
19  istore_3        //...and store it in value
20  return

```

The *anewarray* instruction is used to create a one-dimensional array of object references, for example:

```

void createThreadArray() {
    Thread threads[];
    int count = 10;
    threads = new Thread[count];
    threads[0] = new Thread();
}

```

becomes

```

Method void createThreadArray()
0  bipush 10          //Push int constant 10
2  istore_2           //Initialize count to that
3  iload_2            //Push count, used by anewarray
4  anewarray class #1 //Create new array of class Thread
7  astore_1             //Store new array in threads
8  aload_1              //Push value of threads
9  iconst_0             //Push int constant 0
10 new #1               //Create instance of class Thread

```

```

13 dup           // Make duplicate reference...
14 invokespecial #5 // ...to pass to instance initialization method
                     // Method java.lang.Thread.<init>()V
17 aastore        // Store new Thread in array at 0
18 return

```

The *anewarray* instruction can also be used to create the first dimension of a multi-dimensional array. Alternatively, the *multianewarray* instruction can be used to create several dimensions at once. For example, the three-dimensional array:

```

int[][][] create3DArray() {
    int grid[][][];
    grid = new int[10][5][];
    return grid;
}

```

is created by

```

Method int create3DArray() []
0 bipush 10          // Push int 10 (dimension one)
2  iconst_5          // Push int 5 (dimension two)
3  multianewarray #1 dim #2 // Class [[[I, a three
                           // dimensional int array;
                           // only create first two
                           // dimensions
7  astore_1           // Store new array...
8  aload_1             // ...then prepare to return it
9  areturn

```

The first operand of the *multianewarray* instruction is the runtime constant pool index to the array class type to be created. The second is the number of dimensions of that array type to actually create. The *multianewarray* instruction can be used to create all the dimensions of the type, as the code for `create3DArray` shows. Note that the multidimensional array is just an object and so is loaded and returned by an *aload_1* and *areturn* instruction, respectively. For information about array class names, see Section 4.4.1.

All arrays have associated lengths, which are accessed via the *arraylength* instruction.

3.10 Compiling Switches

Compilation of `switch` statements uses the *tableswitch* and *lookupswitch* instructions. The *tableswitch* instruction is used when the cases of the `switch` can be efficiently represented as indices into a table of target offsets. The `default` target of the `switch` is used if the value of the expression of the `switch` falls outside the range of valid indices. For instance,

```
int chooseNear(int i) {
    switch (i) {
        case 0: return 0;
        case 1: return 1;
        case 2: return 2;
        default: return -1;
    }
}
```

compiles to

```
Method int chooseNear(int)
0 iload_1           // Push local variable 1 (argument i)
1 tableswitch 0 to 2: // Valid indices are 0 through 2
    0: 28           // If i is 0, continue at 28
    1: 30           // If i is 1, continue at 30
    2: 32           // If i is 2, continue at 32
    default: 34     // Otherwise, continue at 34
28  iconst_0         // i was 0; push int constant 0...
29  ireturn          // ...and return it
30  iconst_1         // i was 1; push int constant 1...
31  ireturn          // ...and return it
32  iconst_2         // i was 2; push int constant 2...
33  ireturn          // ...and return it
34  iconst_m1        // otherwise push int constant -1...
35  ireturn          // ...and return it
```

The Java virtual machine's *tableswitch* and *lookupswitch* instructions operate only on `int` data. Because operations on `byte`, `char`, or `short` values are internally promoted to `int`, a `switch` whose expression evaluates to one of those types is compiled as though it evaluated to type `int`. If the `chooseNear`

method had been written using type `short`, the same Java virtual machine instructions would have been generated as when using type `int`. Other numeric types must be narrowed to type `int` for use in a `switch`.

Where the cases of the `switch` are sparse, the table representation of the `tableswitch` instruction becomes inefficient in terms of space. The `lookupswitch` instruction may be used instead. The `lookupswitch` instruction pairs `int` keys (the values of the `case` labels) with target offsets in a table. When a `lookupswitch` instruction is executed, the value of the expression of the `switch` is compared against the keys in the table. If one of the keys matches the value of the expression, execution continues at the associated target offset. If no key matches, execution continues at the `default` target. For instance, the compiled code for

```
int chooseFar(int i) {
    switch (i) {
        case -100:    return -1;
        case 0:       return 0;
        case 100:     return 1;
        default:      return -1;
    }
}
```

looks just like the code for `chooseNear`, except for the `lookupswitch` instruction:

```
Method int chooseFar(int)
0 iload_1
1 lookupswitch 3:
    -100: 36
    0: 38
    100: 40
    default:42
36  iconst_m1
37  ireturn
38  iconst_0
39  ireturn
40  iconst_1
41  ireturn
42  iconst_m1
43  ireturn
```

The Java virtual machine specifies that the table of the *lookupswitch* instruction must be sorted by key so that implementations may use searches more efficient than a linear scan. Even so, the *lookupswitch* instruction must search its keys for a match rather than simply perform a bounds check and index into a table like *tableswitch*. Thus, a *tableswitch* instruction is probably more efficient than a *lookupswitch* where space considerations permit a choice.

3.11 Operations on the Operand Stack

The Java virtual machine has a large complement of instructions that manipulate the contents of the operand stack as untyped values. These are useful because of the Java virtual machine's reliance on deft manipulation of its operand stack. For instance,

```
public long nextIndex() {
    return index++;
}

private long index = 0;
```

is compiled to

```
Method long nextIndex()
0  aload_0      // Push this
1  dup          // Make a copy of it
2  getfield #4  // One of the copies of this is consumed
                // pushing long field index,
                // above the original this
5   dup2_x1     // The long on top of the operand stack is
                // inserted into the operand stack below the
                // original this
6   lconst_1     // Push long constant 1
7   ladd         // The index value is incremented...
8   putfield #4  // ...and the result stored back in the field
11  lreturn      // The original value of index is left on
                // top of the operand stack, ready to be returned
```

Note that the Java virtual machine never allows its operand stack manipulation instructions to modify or break up individual values on the operand stack.

3.12 Throwing and Handling Exceptions

Exceptions are thrown from programs using the `throw` keyword. Its compilation is simple:

```
void cantBeZero(int i) throws TestExc {
    if (i == 0) {
        throw new TestExc();
    }
}
```

becomes

```
Method void cantBeZero(int)
0 iload_1           // Push argument 1 (i)
1 ifne 12          // If i==0, allocate instance and throw
4 new #1           // Create instance of TestExc
7 dup              // One reference goes to the constructor
8 invokespecial #7 // Method TestExc.<init>()V
11 athrow           // Second reference is thrown
12 return          // Never get here if we threw TestExc
```

Compilation of `try-catch` constructs is straightforward. For example,

```
void catchOne() {
    try {
        tryItOut();
    } catch (TestExc e) {
        handleExc(e);
    }
}
```

is compiled as

```
Method void catchOne()
0 aload_0           // Beginning of try block
1 invokevirtual #6 // Method Example.tryItOut()V
4 return            // End of try block; normal return
5 astore_1           // Store thrown value in local variable 1
6 aload_0           // Push this
```

```

7  aload_1           // Push thrown value
8  invokevirtual #5 // Invoke handler method:
                     // Example.handleExc(LTestExc;)V
11 return            // Return after handling TestExc
Exception table:
  From To Target    Type
    0   4   5        Class TestExc

```

Looking more closely, the `try` block is compiled just as it would be if the `try` were not present:

```

Method void catchOne()
0  aload_0           // Beginning of try block
1  invokevirtual #4 // Method Example.tryItOut()V
4  return            // End of try block; normal return

```

If no exception is thrown during the execution of the `try` block, it behaves as though the `try` were not there: `tryItOut` is invoked and `catchOne` returns.

Following the `try` block is the Java virtual machine code that implements the single `catch` clause:

```

5  astore_1           // Store thrown value in local variable 1
6  aload_0             // Push this
7  aload_1             // Push thrown value
8  invokevirtual #5 // Invoke handler method:
                     // Example.handleExc(LTestExc;)V
11 return             // Return after handling TestExc
Exception table:
  From To Target    Type
    0   4   5        Class TestExc

```

The invocation of `handleExc`, the contents of the `catch` clause, is also compiled like a normal method invocation. However, the presence of a `catch` clause causes the compiler to generate an exception table entry (§2.10, §4.7.3). The exception table for the `catchOne` method has one entry corresponding to the one argument (an instance of class `TestExc`) that the `catch` clause of `catchOne` can handle. If some value that is an instance of `TestExc` is thrown during execution of the instructions between indices 0 and 4 in `catchOne`, control is transferred to the Java virtual machine code at index 5, which implements the block of the `catch` clause. If the

value that is thrown is not an instance of `TestExc`, the `catch` clause of `catchOne` cannot handle it. Instead, the value is rethrown to the invoker of `catchOne`.

A `try` may have multiple `catch` clauses:

```
void catchTwo() {
    try {
        tryItOut();
    } catch (TestExc1 e) {
        handleExc(e);
    } catch (TestExc2 e) {
        handleExc(e);
    }
}
```

Multiple `catch` clauses of a given `try` statement are compiled by simply appending the Java virtual machine code for each `catch` clause one after the other and adding entries to the exception table, as shown:

Method void catchTwo()

0	<i>aload_0</i>	<i>// Begin try block</i>
1	<i>invokevirtual #5</i>	<i>// Method Example.tryItOut()V</i>
4	<i>return</i>	<i>// End of try block; normal return</i>
5	<i>astore_1</i>	<i>// Beginning of handler for TestExc1;</i> <i>// Store thrown value in local variable 1</i>
6	<i>aload_0</i>	<i>// Push this</i>
7	<i>aload_1</i>	<i>// Push thrown value</i>
8	<i>invokevirtual #7</i>	<i>// Invoke handler method:</i> <i>// Example.handleExc(LTestExc1;)V</i>
11	<i>return</i>	<i>// Return after handling TestExc1</i>
12	<i>astore_1</i>	<i>// Beginning of handler for TestExc2;</i> <i>// Store thrown value in local variable 1</i>
13	<i>aload_0</i>	<i>// Push this</i>
14	<i>aload_1</i>	<i>// Push thrown value</i>
15	<i>invokevirtual #7</i>	<i>// Invoke handler method:</i> <i>// Example.handleExc(LTestExc2;)V</i>
18	<i>return</i>	<i>// Return after handling TestExc2</i>

Exception table:

<i>From</i>	<i>To</i>	<i>Target</i>	<i>Type</i>
-------------	-----------	---------------	-------------

0 4 5	<i>Class TestExc1</i>
0 4 12	<i>Class TestExc2</i>

If during the execution of the `try` clause (between indices *0* and *4*) a value is thrown that matches the parameter of one or more of the `catch` clauses (the value is an instance of one or more of the parameters), the first (innermost) such `catch` clause is selected. Control is transferred to the Java virtual machine code for the block of that `catch` clause. If the value thrown does not match the parameter of any of the `catch` clauses of `catchTwo`, the Java virtual machine rethrows the value without invoking code in any `catch` clause of `catchTwo`.

Nested `try-catch` statements are compiled very much like a `try` statement with multiple `catch` clauses:

```
void nestedCatch() {
    try {
        try {
            tryItOut();
        } catch (TestExc1 e) {
            handleExc1(e);
        }
    } catch (TestExc2 e) {
        handleExc2(e);
    }
}
```

becomes

```
Method void nestedCatch()
0  aload_0           // Begin try block
1  invokevirtual #8   // Method Example.tryItOut()V
4  return             // End of try block; normal return
5  astore_1            // Beginning of handler for TestExc1;
                      // Store thrown value in local variable 1
6  aload_0            // Push this
7  aload_1            // Push thrown value
8  invokevirtual #7   // Invoke handler method:
                      // Example.handleExc1(LTestExc1;)V
11 return              // Return after handling TestExc1
12 astore_1            // Beginning of handler for TestExc2;
```

```

    // Store thrown value in local variable 1
13  aload_0           // Push this
14  aload_1           // Push thrown value
15  invokevirtual #6 // Invoke handler method:
                           // Example.handleExc2(LTestExc2;)V
18  return             // Return after handling TestExc2

Exception table:
  From  To   Target      Type
    0    4    5        Class TestExc1
    0   12   12        Class TestExc2

```

The nesting of `catch` clauses is represented only in the exception table. The Java virtual machine does not enforce nesting of or any ordering of the exception table entries (§2.10). However, because `try`-`catch` constructs are structured, a compiler can always order the entries of the exception handler table such that, for any thrown exception and any program counter value in that method, the first exception handler that matches the thrown exception corresponds to the innermost matching `catch` clause.

For instance, if the invocation of `tryItOut` (at index 1) threw an instance of `TestExc1`, it would be handled by the `catch` clause that invokes `handleExc1`. This is so even though the exception occurs within the bounds of the outer `catch` clause (catching `TestExc2`) and even though that outer `catch` clause might otherwise have been able to handle the thrown value.

As a subtle point, note that the range of a `catch` clause is inclusive on the “from” end and exclusive on the “to” end (§4.7.3). Thus, the exception table entry for the `catch` clause catching `TestExc1` does not cover the `return` instruction at offset 4. However, the exception table entry for the `catch` clause catching `TestExc2` does cover the `return` instruction at offset 11. Return instructions within nested `catch` clauses are included in the range of instructions covered by nesting `catch` clauses.

3.13 Compiling **finally**

Compilation of a **try-finally** statement is similar to that of **try-catch**. Prior to transferring control outside the **try** statement, whether that transfer is normal or abrupt, because an exception has been thrown, the **finally** clause must first be executed. For this simple example

```
void tryFinally() {
    try {
        tryItOut();
    } finally {
        wrapItUp();
    }
}
```

the compiled code is

```
Method void tryFinally()
0  aload_0           // Beginning of try block
1  invokevirtual #6 // Method Example.tryItOut()V
4  jsr 14          // Call finally block
7  return           // End of try block
8  astore_1         // Beginning of handler for any throw
9  jsr 14          // Call finally block
12 aload_1          // Push thrown value
13 athrow          // ...and rethrow the value to the invoker
14 astore_2         // Beginning of finally block
15 aload_0          // Push this
16 invokevirtual #5 // Method Example.wrapItUp()V
19 ret 2            // Return from finally block

Exception table:
  From To Target Type
    0   4   8     any
```

There are four ways for control to pass outside of the **try** statement: by falling through the bottom of that block, by returning, by executing a **break** or **continue** statement, or by raising an exception. If **tryItOut** returns without raising an exception, control is transferred to the **finally** block using a **jsr** instruction. The **jsr 14** instruction at index 4 makes a “subroutine call” to the code for the **finally** block at

index 14 (the `finally` block is compiled as an embedded subroutine). When the `finally` block completes, the `ret 2` instruction returns control to the instruction following the `jsr` instruction at index 4.

In more detail, the subroutine call works as follows: The `jsr` instruction pushes the address of the following instruction (`return` at index 7) onto the operand stack before jumping. The `astore_2` instruction that is the jump target stores the address on the operand stack into local variable 2. The code for the `finally` block (in this case the `aload_0` and `invokevirtual` instructions) is run. Assuming execution of that code completes normally, the `ret` instruction retrieves the address from local variable 2 and resumes execution at that address. The `return` instruction is executed, and `tryFinally` returns normally.

A `try` statement with a `finally` clause is compiled to have a special exception handler, one that can handle any exception thrown within the `try` statement. If `tryItOut` throws an exception, the exception table for `tryFinally` is searched for an appropriate exception handler. The special handler is found, causing execution to continue at index 8. The `astore_1` instruction at index 8 stores the thrown value into local variable 1. The following `jsr` instruction does a subroutine call to the code for the `finally` block. Assuming that code returns normally, the `aload_1` instruction at index 12 pushes the thrown value back onto the operand stack, and the following `athrow` instruction rethrows the value.

Compiling a `try` statement with both a `catch` clause and a `finally` clause is more complex:

```
void tryCatchFinally() {
    try {
        tryItOut();
    } catch (TestExc e) {
        handleExc(e);
    } finally {
        wrapItUp();
    }
}
```

becomes

```
Method void tryCatchFinally()
0  aload_0           // Beginning of try block
1  invokevirtual #4 // Method Example.tryItOut()V
4  goto 16          // Jump to finally block
```

```

7  astore_3           // Beginning of handler for TestExc;
8  aload_0             // Store thrown value in local variable 3
9  aload_3             // Push this
10 invokevirtual #6   // Push thrown value
11 invokevirtual #6   // Invoke handler method:
12 goto 16            // Example.handleExc(LTestExc;)V
13 Huh???1          // Huh???
14 jsr 26              // Call finally block
15 return              // Return after handling TestExc
16 astore_1             // Beginning of handler for exceptions
17 // other than TestExc, or exceptions
18 // thrown while handling TestExc
19 jsr 26              // Call finally block
20 aload_1             // Push thrown value...
21 athrow              // ...and rethrow the value to the invoker
22 astore_2             // Beginning of finally block
23 aload_0             // Push this
24 invokevirtual #5   // Method Example.wrapItUp()V
25 ret 2               // Return from finally block

```

Exception table:

From	To	Target	Type
0	4	7	Class TestExc
0	16	20	any

If the `try` statement completes normally, the `goto` instruction at index 4 jumps to the subroutine call for the `finally` block at index 16. The `finally` block at index 26 is executed, control returns to the `return` instruction at index 19, and `tryCatchFinally` returns normally.

If `tryItOut` throws an instance of `TestExc`, the first (innermost) applicable exception handler in the exception table is chosen to handle the exception. The code for that exception handler, beginning at index 7, passes the thrown value to `handleExc` and on its return makes the same subroutine call to the `finally` block at index 26 as in the normal case. If an exception is not thrown by `handleExc`, `tryCatchFinally` returns normally.

If `tryItOut` throws a value that is not an instance of `TestExc` or if `handleExc` itself throws an exception, the condition is handled by the second entry in the

¹ This `goto` instruction is strictly unnecessary, but is generated by the `javac` compiler of Oracle's JDK release 1.0.2.

exception table, which handles any value thrown between indices *0* and *16*. That exception handler transfers control to index *20*, where the thrown value is first stored in local variable *1*. The code for the `finally` block at index *26* is called as a subroutine. If it returns, the thrown value is retrieved from local variable *1* and rethrown using the `athrow` instruction. If a new value is thrown during execution of the `finally` clause, the `finally` clause aborts, and `tryCatchFinally` returns abruptly, throwing the new value to its invoker.

3.14 Synchronization

Synchronization in the Java virtual machine is implemented by monitor entry and exit, either explicitly (by use of the `monitorenter` and `monitorexit` instructions) or implicitly (by the method invocation and return instructions).

For code written in the Java programming language, perhaps the most common form of synchronization is the `synchronized` method. A `synchronized` method is not normally implemented using `monitorenter` and `monitorexit`. Rather, it is simply distinguished in the runtime constant pool by the `ACC_SYNCHRONIZED` flag, which is checked by the method invocation instructions (see Section 2.11.10, “Synchronization”).

The `monitorenter` and `monitorexit` instructions enable the compilation of `synchronized` statements. For example:

```
void onlyMe(Foo f) {  
    synchronized(f) {  
        doSomething();  
    }  
}
```

is compiled to

```

Method void onlyMe(Foo)
  0  aload_1           // Push f
  1  dup               // Duplicate it on the stack
  2  astore_2          // Store duplicate in local variable 2
  3  monitorenter      // Enter the monitor associated with f
  4  aload_0           // Holding the monitor, pass this and...
  5  invokevirtual #5  // ...call Example.doSomething()V
  8  aload_2           // Push local variable 2 (f)
  9  monitorexit       // Exit the monitor associated with f
 10  goto 18           // Complete the method normally
 13  astore_3          // In case of any throw, end up here
 14  aload_2           // Push local variable 2 (f)
 15  monitorexit       // Be sure to exit the monitor!
 16  aload_3           // Push thrown exception...
 17  athrow             // ...then rethrow the value to the invoker
 18  return             // Return in the normal case

```

Exception table:

From	To	Target	Type
4	10	13	any
13	16	13	any

The compiler ensures that at any method invocation completion, a *monitorexit* instruction will have been executed for each *monitorenter* instruction executed since the method invocation. This is the case whether the method invocation completes normally (§2.6.4) or abruptly (§2.6.5). To enforce proper pairing of *monitorenter* and *monitorexit* instructions on abrupt method invocation completion, the compiler generates exception handlers (§2.10) that will match any exception and whose associated code executes the necessary *monitorexit* instructions.

3.15 Annotations

The representation of annotations in class files is described in §4.7.16 and §4.7.17, which make it clear how to represent annotations on types, fields and methods in the class file format. Package annotations require additional rules, given here.

When the compiler encounters an annotated package declaration that must be made available at runtime, it emits a `class` file that represents an interface whose name is the internal form (§4.2.1) of `package-name.package-info`. The inter-

face has the default access level (“package-private”) and no superinterfaces. The ACC_INTERFACE and ACC_ABSTRACT flags (Table 4.1) of the `ClassFile` structure (§4.1) are set. If the emitted `class` file version number is less than 50.0, then the ACC_SYNTHETIC flag is unset; if the `class` file version number is 50.0 or above, then the ACC_SYNTHETIC flag is set. The only members of the interface are those implied by *The Java Language Specification, Third Edition* (JLS3 §9.2).

The package-level annotations are stored in the `RuntimeVisibleAnnotations` (§4.7.16) and `RuntimeInvisibleAnnotations` (§4.7.17) attributes of the `ClassFile` structure (§4.1) of this interface.

The class File Format

THIS chapter describes the Java virtual machine `class` file format. Each `class` file contains the definition of a single class or interface. Although a class or interface need not have an external representation literally contained in a file (for instance, because the class is generated by a class loader), we will colloquially refer to any valid representation of a class or interface as being in the `class` file format.

A `class` file consists of a stream of 8-bit bytes. All 16-bit, 32-bit, and 64-bit quantities are constructed by reading in two, four, and eight consecutive 8-bit bytes, respectively. Multibyte data items are always stored in big-endian order, where the high bytes come first. In the Java platform, this format is supported by interfaces `java.io.DataInput` and `java.io.DataOutput` and classes such as `java.io.DataInputStream` and `java.io.DataOutputStream`.

This chapter defines its own set of data types representing `class` file data: The types `u1`, `u2`, and `u4` represent an unsigned one-, two-, or four-byte quantity, respectively. In the Java platform, these types may be read by methods such as `readUnsignedByte`, `readUnsignedShort`, and `readInt` of the interface `java.io.DataInput`.

This chapter presents the `class` file format using pseudostructures written in a C-like structure notation. To avoid confusion with the fields of classes and class instances, etc., the contents of the structures describing the `class` file format are referred to as *items*. Successive items are stored in the `class` file sequentially, without padding or alignment.

Tables, consisting of zero or more variable-sized items, are used in several `class` file structures. Although we use C-like array syntax to refer to table items, the fact that tables are streams of varying-sized structures means that it is not possible to translate a table index directly to a byte offset into the table.

Where we refer to a data structure as an array, it consists of zero or more contiguous fixed-sized items and can be indexed like an array.

Note: We use this font for Prolog code and code fragments, and **this** font for Java virtual machine instructions and **class** file structures. Commentary, designed to clarify the specification, is given as indented text between horizontal lines:

Commentary provides intuition, motivation, rationale, examples, etc.

4.1 The ClassFile Structure

A **class** file consists of a single **ClassFile** structure:

```
ClassFile {
    u4 magic;
    u2 minor_version;
    u2 major_version;
    u2 constant_pool_count;
    cp_info constant_pool[constant_pool_count-1];
    u2 access_flags;
    u2 this_class;
    u2 super_class;
    u2 interfaces_count;
    u2 interfaces[interfaces_count];
    u2 fields_count;
    field_info fields[fields_count];
    u2 methods_count;
    method_info methods[methods_count];
    u2 attributes_count;
    attribute_info attributes[attributes_count];
}
```

The items in the **ClassFile** structure are as follows:

magic

The **magic** item supplies the magic number identifying the *class* file format; it has the value 0xCAFEBAE.

minor_version, major_version

The values of the **minor_version** and **major_version** items are the minor and major version numbers of this *class* file.

Together, a major and a minor version number determine the version of the *class* file format. If a *class* file has major version number M and minor version number m, we denote the version of its *class* file format as M.m. Thus, *class* file format versions may be ordered lexicographically, for example, 1.5 < 2.0 < 2.1.

A Java virtual machine implementation can support a *class* file format of version v if and only if v lies in some contiguous range $M_i.0 \leq v \leq M_j.m$. The release level of the Java platform to which a Java virtual machine implementation conforms is responsible for determining the range.¹

constant_pool_count

The value of the **constant_pool_count** item is equal to the number of entries in the **constant_pool** table plus one. A **constant_pool** index is considered valid if it is greater than zero and less than **constant_pool_count**, with the exception for constants of type **long** and **double** noted in §4.4.5.

constant_pool[]

The **constant_pool** is a table of structures (§4.4) representing various string constants, class and interface names, field names, and other constants that are referred to within the *ClassFile* structure and its substructures. The format of each **constant_pool** table entry is indicated by its first “tag” byte.

The **constant_pool** table is indexed from 1 to **constant_pool_count**–1.

¹ Oracle’s Java virtual machine implementation in JDK release 1.0.2 supports *class* file format versions 45.0 through 45.3 inclusive. JDK releases 1.1.X support *class* file format versions in the range 45.0 through 45.65535 inclusive. For $k \geq 2$, implementations of version 1.k of the Java platform support *class* file format versions in the range 45.0 through 44+k.0 inclusive.

access_flags

The value of the `access_flags` item is a mask of flags used to denote access permissions to and properties of this class or interface. The interpretation of each flag, when set, is as shown in Table 4.1.

Table 4.1 Class access and property modifiers

Flag Name	Value	Interpretation
ACC_PUBLIC	0x0001	Declared <code>public</code> ; may be accessed from outside its package.
ACC_FINAL	0x0010	Declared <code>final</code> ; no subclasses allowed.
ACC_SUPER	0x0020	Treat superclass methods specially when invoked by the <code>invokespecial</code> instruction.
ACC_INTERFACE	0x0200	Is an interface, not a class.
ACC_ABSTRACT	0x0400	Declared <code>abstract</code> ; must not be instantiated.
ACC_SYNTHETIC	0x1000	Declared <code>synthetic</code> ; not present in the source code.
ACC_ANNOTATION	0x2000	Declared as an annotation type.
ACC_ENUM	0x4000	Declared as an <code>enum</code> type.

A class may be marked with the ACC_SYNTHETIC flag to indicate that it was generated by the compiler and does not appear in the source code.

The ACC_ENUM flag indicates that this class or its superclass is declared as an enumerated type.

An interface is distinguished by its ACC_INTERFACE flag being set. If its ACC_INTERFACE flag is not set, this class file defines a class, not an interface.

If the ACC_INTERFACE flag of this class file is set, its ACC_ABSTRACT flag must also be set (JLS3 §9.1.1.1). Such a class file must not have its ACC_FINAL, ACC_SUPER or ACC_ENUM flags set.

An annotation type must have its ACC_ANNOTATION flag set. If the ACC_ANNOTATION flag is set, the ACC_INTERFACE flag must

be set as well. If the ACC_INTERFACE flag of this `class` file is not set, it may have any of the other flags in Table 4.1 set, except the ACC_ANNOTATION flag. However, such a `class` file cannot have both its ACC_FINAL and ACC_ABSTRACT flags set (JLS3 §8.1.1.2).

The ACC_SUPER flag indicates which of two alternative semantics is to be expressed by the *invokespecial* instruction if it appears in this class. Compilers to the instruction set of the Java virtual machine should set the ACC_SUPER flag.²

All bits of the `access_flags` item not assigned in Table 4.1 are reserved for future use. They should be set to zero in generated `class` files and should be ignored by Java virtual machine implementations.

`this_class`

The value of the `this_class` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Class_info` (§4.4.1) structure representing the class or interface defined by this `class` file.

`super_class`

For a class, the value of the `super_class` item either must be zero or must be a valid index into the `constant_pool` table. If the value of the `super_class` item is nonzero, the `constant_pool` entry at that index must be a `CONSTANT_Class_info` (§4.4.1) structure representing the direct superclass of the class defined by this `class` file. Neither the direct superclass nor any of its superclasses may have the ACC_FINAL flag set in the `access_flags` item of its `ClassFile` structure.

If the value of the `super_class` item is zero, then this `class` file must represent the class `Object`, the only class or interface without a direct superclass.

For an interface, the value of the `super_class` item must always be a valid index into the `constant_pool` table. The

² The ACC_SUPER flag exists for backward compatibility with code compiled by older compilers for the Java programming language. In Oracle's JDK prior to release 1.0.2, the compiler generated `ClassFile` `access_flags` in which the flag now representing ACC_SUPER had no assigned meaning, and Oracle's Java virtual machine implementation ignored the flag if it was set.

`constant_pool` entry at that index must be a
`CONSTANT_Class_info` structure representing the class `Object`.

`interfaces_count`

The value of the `interfaces_count` item gives the number of direct superinterfaces of this class or interface type.

`interfaces[]`

Each value in the `interfaces` array must be a valid index into the `constant_pool` table. The `constant_pool` entry at each value of `interfaces[i]`, where $0 \leq i < \text{interfaces_count}$, must be a `CONSTANT_Class_info` (§4.4.1) structure representing an interface that is a direct superinterface of this class or interface type, in the left-to-right order given in the source for the type.

`fields_count`

The value of the `fields_count` item gives the number of `field_info` structures in the `fields` table. The `field_info` (§4.5) structures represent all fields, both class variables and instance variables, declared by this class or interface type.

`fields[]`

Each value in the `fields` table must be a `field_info` (§4.5) structure giving a complete description of a field in this class or interface. The `fields` table includes only those fields that are declared by this class or interface. It does not include items representing fields that are inherited from superclasses or superinterfaces.

`methods_count`

The value of the `methods_count` item gives the number of `method_info` structures in the `methods` table.

`methods[]`

Each value in the `methods` table must be a `method_info` (§4.6) structure giving a complete description of a method in this class or interface. If neither of the `ACC_NATIVE` and `ACC_ABSTRACT` flags are set in the `access_flags` item of a `method_info` structure, the Java virtual machine instructions implementing the method are also supplied.

The `method_info` structures represent all methods declared by this class or interface type, including instance methods, class methods, instance initialization methods (§2.9), and any class or interface initialization method (§2.9). The `methods` table does not include items representing methods that are inherited from superclasses or superinterfaces.

`attributes_count`

The value of the `attributes_count` item gives the number of attributes (§4.7) in the `attributes` table of this class.

`attributes[]`

Each value of the `attributes` table must be an `attribute_info` structure (§4.7).

The only attributes defined by this specification as appearing in the `attributes` table of a `ClassFile` structure are the `InnerClasses` (§4.7.6), `EnclosingMethod` (§4.7.7), `Synthetic` (§4.7.8), `Signature` (§4.7.9), `SourceFile` (§4.7.10), `SourceDebugExtension` (§4.7.11), `Deprecated` (§4.7.15), `RuntimeVisibleAnnotations` (§4.7.16) and `RuntimeInvisibleAnnotations` (§4.7.17) attributes.

If a Java virtual machine implementation recognizes `class` files whose version number is 49.0 or above, it must recognize and correctly read `Signature` (§4.7.9), `RuntimeVisibleAnnotations` (§4.7.16), and `RuntimeInvisibleAnnotations` (§4.7.17) attributes found in the `attributes` table of a `ClassFile` structure of a `class` file whose version number is 49.0 or above.

A Java virtual machine implementation is required to silently ignore any or all attributes in the `attributes` table of a `ClassFile` structure that it does not recognize. Attributes not defined in this specification are not allowed to affect the semantics of the `class` file, but only to provide additional descriptive information (§4.7.1).

4.2 The Internal Form of Names

4.2.1 Binary Class and Interface Names

Class and interface names that appear in `class` file structures are always represented in a fully qualified form as *binary names* (JLS3 §13.1). Such names are always represented as `CONSTANT_Utf8_info` (§4.4.7) structures and thus may be drawn, where not further constrained, from the entire Unicode ~~character set~~ codespace. Class and interface names are referenced from those `CONSTANT_NameAndType_info` (§4.4.6) structures which have such names as part of their descriptor (§4.3), and from all `CONSTANT_Class_info` (§4.4.1) structures.

For historical reasons, the syntax of binary names that appear in `class` file structures differs from the syntax of binary names documented in JLS §13.1. In this internal form, the ASCII periods ('.') that normally separate the identifiers that make up the binary name are replaced by ASCII forward slashes ('/'). The identifiers themselves must be unqualified names (§4.2.2).

For example, the normal binary name of class `Thread` is `java.lang.Thread`. In the internal form used in descriptors in the `class` file format, a reference to the name of class `Thread` is implemented using a `CONSTANT_Utf8_info` structure representing the string "java/lang/Thread".

4.2.2 Unqualified Names

Names of methods, fields and local variables are stored as *unqualified names*. Unqualified names must not contain the (Unicode code points corresponding to the) ASCII characters '.', ';', '[', or '/'. Method names are further constrained so that, with the exception of the special method names `<init>` and `<clinit>` (§2.9), they must not contain the (Unicode code points corresponding to the) ASCII characters '<' or '>'.

4.3 Descriptors and Signatures

A *descriptor* is a string representing the type of a field or method. Descriptors are represented in the `class` file format using modified UTF-8 strings (§4.4.7) and thus may be drawn, where not further constrained, from the entire Unicode ~~character set~~ codespace.

A *signature* is a string representing the generic type of a field or method, or generic type information for a class declaration.

4.3.1 Grammar Notation

Descriptors and signatures are specified using a grammar. This grammar is a set of productions that describe how sequences of characters can form syntactically correct descriptors of various types. Terminal symbols of the grammar are shown in **bold fixed-width** font. Nonterminal symbols are shown in *italic* type. The definition of a nonterminal is introduced by the name of the nonterminal being defined, followed by a colon. One or more alternative right-hand sides for the nonterminal then follow on succeeding lines. For example, the production:

FieldType:

BaseType
ObjectType
ArrayType

states that a *FieldType* may represent either a *BaseType*, an *ObjectType* or an *ArrayType*.

A nonterminal symbol on the right-hand side of a production that is followed by an asterisk (*) represents zero or more possibly different values produced from that nonterminal, appended without any intervening space. Similarly, a nonterminal symbol on the right-hand side of a production that is followed by a plus sign (+) represents one or more possibly different values produced from that nonterminal, appended without any intervening space. The production:

MethodDescriptor:

(*ParameterDescriptor**) *ReturnDescriptor*

states that a *MethodDescriptor* represents a left parenthesis, followed by zero or more *ParameterDescriptor* values, followed by a right parenthesis, followed by a *ReturnDescriptor*.

4.3.2 Field Descriptors

A *field descriptor* represents the type of a class, instance, or local variable. It is a series of characters generated by the grammar:

FieldDescriptor:

FieldType

ComponentType:

FieldType

FieldType:

BaseType

ObjectType

ArrayType

BaseType:

B

C

D

F

I

J

S

Z

ObjectType:

L Classname;

ArrayType:

[ComponentType

The characters of *BaseType*, the *L* and ; of *ObjectType*, and the [of *ArrayType* are all ASCII characters. The **Classname** represents a binary class or interface name encoded in internal form (§4.2.1). A type descriptor representing an array type is valid only if it represents a type with 255 or fewer dimensions. The interpretation of the field types is as shown in Table 4.2.

Table 4.2 Interpretation of *BaseType* characters

<i>BaseType Character</i>	<i>Type</i>	<i>Interpretation</i>
B	<code>byte</code>	signed byte
C	<code>char</code>	Unicode character code point in the Basic Multilingual Plane, encoded with UTF-16
D	<code>double</code>	double-precision floating-point value
F	<code>float</code>	single-precision floating-point value
I	<code>int</code>	integer
J	<code>long</code>	long integer

Table 4.2 Interpretation of *BaseType* characters

L Classname;	reference	an instance of class <classname>
S	short	signed short
Z	boolean	true or false
L	reference	one array dimension

For example, the descriptor of an instance variable of type `int` is simply **I**. The descriptor of an instance variable of type `Object` is **Ljava/lang/Object;**. Note that the internal form of the binary name for class `Object` is used. The descriptor of an instance variable that is a multidimensional `double` array,

`double d[][][];`

is

[[[D

4.3.3 Method Descriptors

A *method descriptor* represents the parameters that the method takes and the value that it returns:

MethodDescriptor:

(ParameterDescriptor*) ReturnDescriptor

A *parameter descriptor* represents a parameter passed to a method:

ParameterDescriptor:

FieldType

A *return descriptor* represents the type of the value returned from a method. It is a series of characters generated by the grammar:

ReturnDescriptor:

FieldType

VoidDescriptor

VoidDescriptor:

V

The character **V** indicates that the method returns no value (its return type is `void`).

A method descriptor is valid only if it represents method parameters with a total length of 255 or less, where that length includes the contribution for `this` in the case of instance or interface method invocations. The total length is calculated by summing the contributions of the individual parameters, where a parameter of type `long` or `double` contributes two units to the length and a parameter of any other type contributes one unit.

For example, the method descriptor for the method

```
Object mymethod(int i, double d, Thread t)
```

is

```
(IDLjava/lang/Thread;)Ljava/lang/Object;
```

Note that the internal forms of the binary names of `Thread` and `Object` are used in the method descriptor.

The method descriptor for `mymethod` is the same whether `mymethod` is a class or an instance method. Although an instance method is passed `this`, a reference to the current class instance, in addition to its intended parameters, that fact is not reflected in the method descriptor. (A reference to `this` is not passed to a class method.) The reference to `this` is passed implicitly by the method invocation instructions of the Java virtual machine used to invoke instance methods.

4.3.4 Signatures

Signatures are used to encode Java programming language type information that is not part of the Java virtual machine type system, such as generic type and method declarations and parameterized types. See *The Java Language Specification, Third Edition*, for details about such types.

This kind of type information is needed to support reflection and debugging, and by the Java compiler.

In the following, the terminal symbol **Identifier** is used to denote the name of a type, field, local variable, parameter, method, or type variable, as generated by the Java compiler. Such a name must not contain the characters '.', ';', '[', '/', '<', '>', or ':', but may contain characters that must not appear in a legal identifier in the Java programming language.

A class signature, defined by the production *ClassSignature*, is used to encode type information about a class declaration. It describes any formal type parameters the class might have, and lists its (possibly parameterized) direct superclass and direct superinterfaces, if any.

ClassSignature:

FormalTypeParameters *opt SuperclassSignature SuperinterfaceSignature**

A formal type parameter is described by its name, followed by its class and interface bounds. If the class bound does not specify a type, it is taken to be `Object`.

FormalTypeParameters:

<FormalTypeParameter+>

FormalTypeParameter:

Identifier *ClassBound InterfaceBound**

ClassBound:

: FieldTypeSignature opt

InterfaceBound:

: FieldTypeSignature

SuperclassSignature:

ClassTypeSignature

SuperinterfaceSignature:

ClassTypeSignature

A field type signature, defined by the production *FieldTypeSignature*, encodes the (possibly parameterized) type for a field, parameter or local variable.

FieldTypeSignature:

ClassTypeSignature

ArrayTypeSignature

TypeVariableSignature

A class type signature gives complete type information for a class or interface type. The class type signature must be formulated such that it can be reliably mapped to the binary name of the class it denotes by erasing any type arguments and converting each ‘.’ character in the signature to a ‘\$’ character.

ClassTypeSignature:

L *PackageSpecifieropt SimpleClassTypeSignature ClassTypeSignatureSuffix** ;

PackageSpecifier:

Identifier / *PackageSpecifier**

SimpleClassTypeSignature:

Identifier *TypeArgumentsopt*

ClassTypeSignatureSuffix:

 . *SimpleClassTypeSignature*

TypeVariableSignature:

T Identifier ;

TypeArguments:

 <*TypeArgument*+>

TypeArgument:

WildcardIndicatoropt FieldTypeSignature

 *

WildcardIndicator:

 +

 -

ArrayTypeSignature:

 [*TypeSignature*

TypeSignature:

FieldTypeSignature

BaseType

A method signature, defined by the production *MethodTypeSignature*, encodes the (possibly parameterized) types of the method's formal arguments and of the exceptions it has declared in its throws clause, its (possibly parameterized) return type, and any formal type parameters in the method declaration.

MethodTypeSignature:

FormalTypeParametersopt (TypeSignature) ReturnType ThrowsSignature**

ReturnType:

TypeSignature

VoidDescriptor

ThrowsSignature:

^*ClassTypeSignature*
 ^*TypeVariableSignature*

If the throws clause of a method or constructor does not involve type variables, the *ThrowsSignature* may be elided from the *MethodTypeSignature*.

A Java compiler must output generic signature information for any class, interface, constructor or member whose generic signature in the Java programming language would include references to type variables or parameterized types.

The signature and descriptor (§4.3.3) of a given method or constructor may not correspond exactly, due to compiler-generated artifacts. In particular, the number of *TypeSignatures* that encode formal arguments in *MethodTypeSignature* may be less than the number of *ParameterDescriptors* in *MethodDescriptor*.

Oracle's Java virtual machine implementation does not check the well formedness of the signatures described in this subsection during loading or linking. Instead, these checks are deferred until the signatures are used by reflective methods, as specified in the API of `Class` and members of `java.lang.reflect`. Future versions of a Java virtual machine implementation may be required to perform some or all of these checks during loading or linking.

4.4 The Constant Pool

Java virtual machine instructions do not rely on the runtime layout of classes, interfaces, class instances, or arrays. Instead, instructions refer to symbolic information in the `constant_pool` table.

All `constant_pool` table entries have the following general format:

```
cp_info {  
    u1 tag;  
    u1 info[];  
}
```

Each item in the `constant_pool` table must begin with a 1-byte tag indicating the kind of `cp_info` entry. The contents of the `info` array vary with the value of `tag`.

The valid tags and their values are listed in Table 4.3. Each tag byte must be followed by two or more bytes giving information about the specific constant. The format of the additional information varies with the tag value.

Table 4.3 Constant pool tags

Constant Type	Value
CONSTANT_Class	7
CONSTANT_Fieldref	9
CONSTANT_Methodref	10
CONSTANT_InterfaceMethodref	11
CONSTANT_String	8
CONSTANT_Integer	3
CONSTANT_Float	4
CONSTANT_Long	5
CONSTANT_Double	6
CONSTANT_NameAndType	12
CONSTANT_Utf8	1

4.4.1 The CONSTANT_Class_info Structure

The CONSTANT_Class_info structure is used to represent a class or an interface:

```
CONSTANT_Class_info {
    u1 tag;
    u2 name_index;
}
```

The items of the CONSTANT_Class_info structure are the following:

tag

The tag item has the value CONSTANT_Class (7).

name_index

The value of the name_index item must be a valid index into the constant_pool table. The constant_pool entry at that index must be a CONSTANT_Utf8_info (§4.4.7) structure representing a

valid binary class or interface name encoded in internal form
(\\$4.2.1).

Because arrays are objects, the opcodes *anewarray* and *multianewarray* can reference array “classes” via **CONSTANT_Class_info** (§4.4.1) structures in the **constant_pool** table. For such array classes, the name of the class is the descriptor of the array type.

For example, the class name representing a two-dimensional **int** array type

```
int[] []
```

is

```
[[I
```

The class name representing the type array of class Thread

```
Thread[]
```

is

```
[Ljava/lang/Thread;
```

An array type descriptor is valid only if it represents 255 or fewer dimensions.

4.4.2 The **CONSTANT_Fieldref_info**, **CONSTANT_Methodref_info**, and **CONSTANT_InterfaceMethodref_info** Structures

Fields, methods, and interface methods are represented by similar structures:

```
CONSTANT_Fieldref_info {
    u1 tag;
    u2 class_index;
    u2 name_and_type_index;
}

CONSTANT_Methodref_info {
    u1 tag;
    u2 class_index;
    u2 name_and_type_index;
}

CONSTANT_InterfaceMethodref_info {
    u1 tag;
    u2 class_index;
    u2 name_and_type_index;
}
```

The items of these structures are as follows:

tag

The `tag` item of a `CONSTANT_Fieldref_info` structure has the value `CONSTANT_Fieldref` (9).

The `tag` item of a `CONSTANT_Methodref_info` structure has the value `CONSTANT_Methodref` (10).

The `tag` item of a `CONSTANT_InterfaceMethodref_info` structure has the value `CONSTANT_InterfaceMethodref` (11).

class_index

The value of the `class_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Class_info` (§4.4.1) structure representing a class or interface type that has the field or method as a member.

The `class_index` item of a `CONSTANT_Methodref_info` structure must be a class type, not an interface type. The `class_index` item of a `CONSTANT_InterfaceMethodref_info` structure must be an interface type. The `class_index` item of a `CONSTANT_Fieldref_info` structure may be either a class type or an interface type.

name_and_type_index

The value of the `name_and_type_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_NameAndType_info` (§4.4.6) structure. This `constant_pool` entry indicates the name and descriptor of the field or method. In a `CONSTANT_Fieldref_info` the indicated descriptor must be a field descriptor (§4.3.2). Otherwise, the indicated descriptor must be a method descriptor (§4.3.3).

If the name of the method of a `CONSTANT_Methodref_info` structure begins with a '<' ('\u003c'), then the name must be the special name `<init>`, representing an instance initialization method (§2.9). The return type of such a method must be `void`.

4.4.3 The CONSTANT_String_info Structure

The CONSTANT_String_info structure is used to represent constant objects of the type String:

```
CONSTANT_String_info {
    u1 tag;
    u2 string_index;
}
```

The items of the CONSTANT_String_info structure are as follows:

tag

The tag item of the CONSTANT_String_info structure has the value CONSTANT_String (8).

string_index

The value of the string_index item must be a valid index into the constant_pool table. The constant_pool entry at that index must be a CONSTANT_Utf8_info (§4.4.7) structure representing the sequence of characters Unicode code points to which the String object is to be initialized.

4.4.4 The CONSTANT_Integer_info and CONSTANT_Float_info Structures

The CONSTANT_Integer_info and CONSTANT_Float_info structures represent 4-byte numeric (int and float) constants:

```
CONSTANT_Integer_info {
    u1 tag;
    u4 bytes;
}

CONSTANT_Float_info {
    u1 tag;
    u4 bytes;
}
```

The items of these structures are as follows:

tag

The **tag** item of the **CONSTANT_Integer_info** structure has the value **CONSTANT_Integer** (3).

The **tag** item of the **CONSTANT_Float_info** structure has the value **CONSTANT_Float** (4).

bytes

The **bytes** item of the **CONSTANT_Integer_info** structure represents the value of the **int** constant. The bytes of the value are stored in big-endian (high byte first) order.

The **bytes** item of the **CONSTANT_Float_info** structure represents the value of the **float** constant in IEEE 754 floating-point single format (§2.3.2). The bytes of the single format representation are stored in big-endian (high byte first) order.

The value represented by the **CONSTANT_Float_info** structure is determined as follows. The bytes of the value are first converted into an **int** constant bits. Then:

- If bits is **0x7f800000**, the **float** value will be positive infinity.
- If bits is **0xff800000**, the **float** value will be negative infinity.
- If bits is in the range **0x7f800001** through **0x7fffffff** or in the range **0xff800001** through **0xfffffff**, the **float** value will be NaN.
- In all other cases, let **s**, **e**, and **m** be three values that might be computed from **bits**:

```
int s = ((bits >> 31) == 0) ? 1 : -1;
int e = ((bits >> 23) & 0xff);
int m = (e == 0) ?
    (bits & 0x7fffff) << 1 :
    (bits & 0x7fffff) | 0x800000;
```

Then the **float** value equals the result of the mathematical expression $s \cdot m \cdot 2^{e-150}$.

4.4.5 The CONSTANT_Long_info and CONSTANT_Double_info Structures

The `CONSTANT_Long_info` and `CONSTANT_Double_info` represent 8-byte numeric (`long` and `double`) constants:

```
CONSTANT_Long_info {
    u1 tag;
    u4 high_bytes;
    u4 low_bytes;
}

CONSTANT_Double_info {
    u1 tag;
    u4 high_bytes;
    u4 low_bytes;
}
```

All 8-byte constants take up two entries in the `constant_pool` table of the `class` file. If a `CONSTANT_Long_info` or `CONSTANT_Double_info` structure is the item in the `constant_pool` table at index `n`, then the next usable item in the pool is located at index `n+2`. The `constant_pool` index `n+1` must be valid but is considered unusable.³

The items of these structures are as follows:

`tag`

The `tag` item of the `CONSTANT_Long_info` structure has the value `CONSTANT_Long` (5).

The `tag` item of the `CONSTANT_Double_info` structure has the value `CONSTANT_Double` (6).

`high_bytes, low_bytes`

The unsigned `high_bytes` and `low_bytes` items of the `CONSTANT_Long_info` structure together represent the value of the `long` constant `((long) high_bytes << 32) + low_bytes`, where the bytes of each of `high_bytes` and `low_bytes` are stored in big-endian (high byte first) order.

³ In retrospect, making 8-byte constants take two constant pool entries was a poor choice.

The `high_bytes` and `low_bytes` items of the `CONSTANT_Double_info` structure together represent the `double` value in IEEE 754 floating-point double format (§2.3.2). The bytes of each item are stored in big-endian (high byte first) order.

The value represented by the `CONSTANT_Double_info` structure is determined as follows. The `high_bytes` and `low_bytes` items are converted into the `long` constant bits, which is equal to $((\text{long}) \text{high_bytes} \ll 32) + \text{low_bytes}$. Then:

- If bits is `0x7ff0000000000000L`, the `double` value will be positive infinity.
- If bits is `0xffff000000000000L`, the `double` value will be negative infinity.
- If bits is in the range `0x7ff000000000001L` through `0x7fffffffffffffL` or in the range `0xffff000000000001L` through `0xfffffffffffffL`, the `double` value will be NaN.
- In all other cases, let `s`, `e`, and `m` be three values that might be computed from bits:

```
int s = ((bits >> 63) == 0) ? 1 : -1;
int e = (int)((bits >> 52) & 0x7ffL);
long m = (e == 0) ?
    (bits & 0xfffffffffffffL) << 1 :
    (bits & 0xfffffffffffffL) | 0x10000000000000L;
```

Then the floating-point value equals the `double` value of the mathematical expression $s \cdot m \cdot 2^{e-1075}$.

4.4.6 The `CONSTANT_NameAndType_info` Structure

The `CONSTANT_NameAndType_info` structure is used to represent a field or method, without indicating which class or interface type it belongs to:

```
CONSTANT_NameAndType_info {
    u1 tag;
    u2 name_index;
    u2 descriptor_index;
}
```

The items of the `CONSTANT_NameAndType_info` structure are as follows:

`tag`

The `tag` item of the `CONSTANT_NameAndType_info` structure has the value `CONSTANT_NameAndType` (12).

`name_index`

The value of the `name_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Utf8_info` (§4.4.7) structure representing either the special method name `<init>` (§2.9) or a valid unqualified name (§4.2.2) denoting a field or method.

`descriptor_index`

The value of the `descriptor_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Utf8_info` (§4.4.7) structure representing a valid field descriptor (§4.3.2) or method descriptor (§4.3.3).

4.4.7 The `CONSTANT_Utf8_info` Structure

The `CONSTANT_Utf8_info` structure is used to represent constant string values:

```
CONSTANT_Utf8_info {
    u1 tag;
    u2 length;
    u1 bytes[length];
}
```

The items of the `CONSTANT_Utf8_info` structure are the following:

`tag`

The `tag` item of the `CONSTANT_Utf8_info` structure has the value `CONSTANT_Utf8` (1).

`length`

The value of the `length` item gives the number of bytes in the `bytes` array (not the length of the resulting string). The strings in the `CONSTANT_Utf8_info` structure are not null-terminated.

bytes[]

The **bytes** array contains the bytes of the string. No byte may have the value `(byte)0` or lie in the range `(byte)0xf0-(byte)0xff`.

String content is encoded in *modified UTF-8*. Modified UTF-8 strings are encoded so that **character** code point sequences that contain only non-null ASCII characters can be represented using only 1 byte per **character** code point, but all **Unicode characters** code points in the Unicode codespace can be represented.

Characters Code points in the range '`\u0001`' to '`\u007F`' are represented by a single byte:

<code>0</code>	<i>bits 6-0</i>
----------------	-----------------

The 7 bits of data in the byte give the value of the **character** code point represented.

The null **character** code point ('`\u0000`') and **characters** code points in the range '`\u0080`' to '`\u07FF`' are represented by a pair of bytes x and y:

x: <code>1 1 0</code>	<i>bits 10-6</i>	y: <code>1 0</code>	<i>bits 5-0</i>
---------------------------	------------------	-----------------------	-----------------

The bytes represent the **character** code point with the value:

$$((x \& 0x1f) << 6) + (y \& 0x3f)$$

Characters Code points in the range '`\u0800`' to '`\uFFFF`' are represented by 3 bytes x, y, and z:

x: <code>1 1 1 0</code>	<i>bits 15-12</i>	y: <code>1 0</code>	<i>bits 11-6</i>	z: <code>1 0</code>	<i>bits 5-0</i>
-------------------------------	-------------------	-----------------------	------------------	-----------------------	-----------------

The three bytes represent the **character** code point with the value:

$$((x \& 0xf) << 12) + ((y \& 0x3f) << 6) + (z \& 0x3f)$$

Characters with code points above U+FFFF (so-called *supplementary characters*) are represented by separately encoding the two surrogate code units of their UTF-16 representation. Each of the surrogate code units is represented by three bytes. This means supplementary characters are represented by six bytes, u, v, w, x, y, and z:

u: <code>1 1 1 0 1 1 0 1</code>	v: <code>1 0 1 0</code>	<i>(bits 20-16)-1</i>	w: <code>1 0</code>	<i>bits 15-10</i>
-----------------------------------------------	-------------------------------	-----------------------	-----------------------	-------------------

x:	[1 1 1 0 1 1 0 1]	y: [1 0 1 1 bits 9-6]	z: [1 0 bits 5-0]
----	---------------------------------	-------------------------------	-----------------------

The six bytes represent the character code point with the value:

```
0x10000 + ((v & 0x0f) << 16) +
((w & 0x3f) << 10) + (y & 0x0f) << 6) + (z & 0x3f)
```

The bytes of multibyte characters are stored in the class file in big-endian (high byte first) order.

There are two differences between this format and the “standard” UTF-8 format. First, the null character (char)0 is encoded using the 2-byte format rather than the 1-byte format, so that modified UTF-8 strings never have embedded nulls. Second, only the 1-byte, 2-byte, and 3-byte formats of standard UTF-8 are used. The Java virtual machine does not recognize the four-byte format of standard UTF-8; it uses its own two-times-three-byte format instead.

For more information regarding the standard UTF-8 format, see Section 3.9 *Unicode Encoding Forms of The Unicode Standard, Version 6.0.0*.

4.5 Fields

Each field is described by a `field_info` structure. No two fields in one class file may have the same name and descriptor (§4.3.2).

The structure has the following format:

```
field_info {
    u2 access_flags;
    u2 name_index;
    u2 descriptor_index;
    u2 attributes_count;
    attribute_info attributes[attributes_count];
}
```

The items of the `field_info` structure are as follows:

`access_flags`

The value of the `access_flags` item is a mask of flags used to denote access permission to and properties of this field. The interpretation of each flag, when set, is as shown in Table 4.4.

Table 4.4 Field access and property flags

Flag Name	Value	Interpretation
ACC_PUBLIC	0x0001	Declared <code>public</code> ; may be accessed from outside its package.
ACC_PRIVATE	0x0002	Declared <code>private</code> ; usable only within the defining class.
ACC_PROTECTED	0x0004	Declared <code>protected</code> ; may be accessed within subclasses.
ACC_STATIC	0x0008	Declared <code>static</code> .
ACC_FINAL	0x0010	Declared <code>final</code> ; never directly assigned to after object construction (JLS3 §17.5).
ACC_VOLATILE	0x0040	Declared <code>volatile</code> ; cannot be cached.
ACC_TRANSIENT	0x0080	Declared <code>transient</code> ; not written or read by a persistent object manager.
ACC_SYNTHETIC	0x1000	Declared <code>synthetic</code> ; not present in the source code.
ACC_ENUM	0x4000	Declared as an element of an enum.

A field may be marked with the ACC_SYNTHETIC flag to indicate that it was generated by the compiler and does not appear in the source code.

The ACC_ENUM flag indicates that this field is used to hold an element of an enumerated type.

Fields of classes may set any of the flags in Table 4.4. However, a specific field of a class may have at most one of its ACC_PRIVATE, ACC_PROTECTED, and ACC_PUBLIC flags set (JLS3 §8.3.1) and must not have both its ACC_FINAL and ACC_VOLATILE flags set (JLS3 §8.3.1.4).

All fields of interfaces must have their ACC_PUBLIC, ACC_STATIC, and ACC_FINAL flags set; they may have their ACC_SYNTHETIC flag set and must not have any of the other flags in Table 4.4 set (JLS3 §9.3).

All bits of the `access_flags` item not assigned in Table 4.4 are reserved for future use. They should be set to zero in generated class files and should be ignored by Java virtual machine implementations.

name_index

The value of the **name_index** item must be a valid index into the **constant_pool** table. The **constant_pool** entry at that index must be a **CONSTANT_Utf8_info** (§4.4.7) structure which must represent a valid unqualified name (§4.2.2) denoting a field.

descriptor_index

The value of the **descriptor_index** item must be a valid index into the **constant_pool** table. The **constant_pool** entry at that index must be a **CONSTANT_Utf8_info** (§4.4.7) structure that must represent a valid field descriptor (§4.3.2).

attributes_count

The value of the **attributes_count** item indicates the number of additional attributes (§4.7) of this field.

attributes[]

Each value of the **attributes** table must be an attribute structure (§4.7). A field can have any number of attributes associated with it.

The attributes defined by this specification as appearing in the **attributes** table of a **field_info** structure are **ConstantValue** (§4.7.2), **Synthetic** (§4.7.8), **Signature** (§4.7.9), **Deprecated** (§4.7.15), **RuntimeVisibleAnnotations** (§4.7.16) and **RuntimeInvisibleAnnotations** (§4.7.17).

A Java virtual machine implementation must recognize and correctly read **ConstantValue** (§4.7.2) attributes found in the **attributes** table of a **field_info** structure. If a Java virtual machine implementation recognizes **class** files whose version number is 49.0 or above, it must recognize and correctly read **Signature** (§4.7.9), **RuntimeVisibleAnnotations** (§4.7.16) and **RuntimeInvisibleAnnotations** (§4.7.17) attributes found in the **attributes** table of a **field_info** structure of a **class** file whose version number is 49.0 or above.

A Java virtual machine implementation is required to silently ignore any or all attributes that it does not recognize in the **attributes** table of a **field_info** structure. Attributes not defined in this specification are not allowed to affect the semantics of the **class** file, but only to provide additional descriptive information (§4.7.1).

4.6 Methods

Each method, including each instance initialization method (§2.9) and the class or interface initialization method (§2.9), is described by a `method_info` structure. No two methods in one `class` file may have the same name and descriptor (§4.3.3).

The structure has the following format:

```
method_info {
    u2 access_flags;
    u2 name_index;
    u2 descriptor_index;
    u2 attributes_count;
    attribute_info attributes[attributes_count];
}
```

The items of the `method_info` structure are as follows:

`access_flags`

The value of the `access_flags` item is a mask of flags used to denote access permission to and properties of this method. The interpretation of each flag, when set, is as shown in Table 4.5.

The `ACC_VARARGS` flag indicates that this method takes a variable number of arguments at the source code level. A method declared to take a variable number of arguments must be compiled with the `ACC_VARARGS` flag set to 1. All other methods must be compiled with the `ACC_VARARGS` flag set to 0.

The `ACC_BRIDGE` flag is used to indicate a bridge method generated by the compiler.

A method may be marked with the `ACC_SYNTHETIC` flag to indicate that it was generated by the compiler and does not appear in the source code, unless it is one of the methods named in Section 4.7.8, “The Synthetic Attribute”.

Methods of classes may set any of the flags in Table 4.5. However, a specific method of a class may have at most one of its `ACC_PRIVATE`, `ACC_PROTECTED` and `ACC_PUBLIC` flags set (JLS3 §8.4.3). If a specific method has its `ACC_ABSTRACT` flag set, it must not have any of its `ACC_FINAL`, `ACC_NATIVE`, `ACC_PRIVATE`, `ACC_STATIC`, `ACC_STRICT` or

Table 4.5 Method access and property flags

Flag Name	Value	Interpretation
ACC_PUBLIC	0x0001	Declared <code>public</code> ; may be accessed from outside its package.
ACC_PRIVATE	0x0002	Declared <code>private</code> ; accessible only within the defining class.
ACC_PROTECTED	0x0004	Declared <code>protected</code> ; may be accessed within subclasses.
ACC_STATIC	0x0008	Declared <code>static</code> .
ACC_FINAL	0x0010	Declared <code>final</code> ; must not be overridden.
ACC_SYNCHRONIZED	0x0020	Declared <code>synchronized</code> ; invocation is wrapped by a monitor use.
ACC_BRIDGE	0x0040	A bridge method, generated by the compiler.
ACC_VARARGS	0x0080	Declared with variable number of arguments.
ACC_NATIVE	0x0100	Declared <code>native</code> ; implemented in a language other than Java.
ACC_ABSTRACT	0x0400	Declared <code>abstract</code> ; no implementation is provided.
ACC_STRICT	0x0800	Declared <code>strictfp</code> ; floating-point mode is FP-strict
ACC_SYNTHETIC	0x1000	Declared <code>synthetic</code> ; not present in the source code.

ACC_SYNCHRONIZED flags set (JLS3 §8.4.3.1, JLS3 §8.4.3.3, JLS3 §8.4.3.4).

All interface methods must have their ACC_ABSTRACT and ACC_PUBLIC flags set; they may have their ACC_VARARGS, ACC_BRIDGE and ACC_SYNTHETIC flags set and must not have any of the other flags in Table 4.5 set (JLS3 §9.4).

A specific instance initialization method (§2.9) may have at most one of its ACC_PRIVATE, ACC_PROTECTED, and ACC_PUBLIC

flags set, and may also have its ACC_STRICT, ACC_VARARGS and ACC_SYNTHETIC flags set, but must not have any of the other flags in Table 4.5 set.

Class and interface initialization methods (§2.9) are called implicitly by the Java virtual machine. The value of their `access_flags` item is ignored except for the setting of the ACC_STRICT flag.

All bits of the `access_flags` item not assigned in Table 4.5 are reserved for future use. They should be set to zero in generated `class` files and should be ignored by Java virtual machine implementations.

`name_index`

The value of the `name_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Utf8_info` (§4.4.7) structure representing either one of the special method names (§2.9) `<init>` or `<cinit>`, or a valid unqualified name (§4.2.2) denoting a method.

`descriptor_index`

The value of the `descriptor_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Utf8_info` (§4.4.7) structure representing a valid method descriptor (§4.3.3).

`attributes_count`

The value of the `attributes_count` item indicates the number of additional attributes (§4.7) of this method.

`attributes[]`

Each value of the `attributes` table must be an attribute structure (§4.7). A method can have any number of optional attributes associated with it.

The only attributes defined by this specification as appearing in the `attributes` table of a `method_info` structure are the `Code` (§4.7.3), `Exceptions` (§4.7.5), `Synthetic` (§4.7.8), `Signature` (§4.7.9), `Deprecated` (§4.7.15), `RuntimeVisibleAnnotations` (§4.7.16),

`RuntimeInvisibleAnnotations` (§4.7.17),
`RuntimeVisibleParameterAnnotations` (§4.7.18),
`RuntimeInvisibleParameterAnnotations` (§4.7.19) and
`AnnotationDefault` (§4.7.20) attributes.

A Java virtual machine implementation must recognize and correctly read `Code` (§4.7.3) and `Exceptions` (§4.7.5) attributes found in the `attributes` table of a `method_info` structure. If a Java virtual machine implementation recognizes `class` files whose version number is 49.0 or above, it must recognize and correctly read `Signature` (§4.7.9),
`RuntimeVisibleAnnotations` (§4.7.16),
`RuntimeInvisibleAnnotations` (§4.7.17),
`RuntimeVisibleParameterAnnotations` (§4.7.18),
`RuntimeInvisibleParameterAnnotations` (§4.7.19) and
`AnnotationDefault` (§4.7.20) attributes found in the `attributes` table of a `method_info` structure of a `class` file whose version number is 49.0 or above.

A Java virtual machine implementation is required to silently ignore any or all attributes in the `attributes` table of a `method_info` structure that it does not recognize. Attributes not defined in this specification are not allowed to affect the semantics of the `class` file, but only to provide additional descriptive information (§4.7.1).

4.7 Attributes

Attributes are used in the `ClassFile` (§4.1), `field_info` (§4.5), `method_info` (§4.6) and `Code_attribute` (§4.7.3) structures of the `class` file format. All attributes have the following general format:

```
attribute_info {
    u2 attribute_name_index;
    u4 attribute_length;
    u1 info[attribute_length];
}
```

For all attributes, the `attribute_name_index` must be a valid unsigned 16-bit index into the constant pool of the class. The `constant_pool` entry at `attribute_name_index` must be a `CONSTANT_Utf8_info` (§4.4.7) structure representing the name of the attribute. The value of the `attribute_length` item indicates the length of the subsequent information in bytes. The length does not include the initial six bytes that contain the `attribute_name_index` and `attribute_length` items.

Certain attributes are predefined as part of the `class` file specification. They are listed in Table 4.6, accompanied by the version of the Java Platform, Standard Edition (“Java SE”) and the version of the `class` file format in which each first appeared. Within the context of their use in this specification, that is, in the `attributes` tables of the `class` file structures in which they appear, the names of these predefined attributes are reserved. Of the predefined attributes:

- The `ConstantValue`, `Code` and `Exceptions` attributes must be recognized and correctly read by a `class` file reader for correct interpretation of the `class` file by a Java virtual machine implementation.
- The `InnerClasses`, `EnclosingMethod` and `Synthetic` attributes must be recognized and correctly read by a `class` file reader in order to properly implement the Java platform class libraries (§2.12).
- The `RuntimeVisibleAnnotations`, `RuntimeInvisibleAnnotations`, `RuntimeVisibleParameterAnnotations`, `RuntimeInvisibleParameterAnnotations` and `AnnotationDefault` attributes must be recognized and correctly read by a `class` file reader in order to properly implement the Java platform class libraries (§2.12), if the `class` file’s version number is 49.0

or above and the Java virtual machine implementation recognizes `class` files whose version number is 49.0 or above,

- The `Signature` attribute must be recognized and correctly read by a `class` file reader if the `class` file's version number is 49.0 or above and the Java virtual machine implementation recognizes `class` files whose version number is 49.0 or above.
- The `StackMapTable` attribute must be recognized and correctly read by a `class` file reader if the `class` file's version number is 50.0 or above and the Java virtual machine implementation recognizes `class` files whose version number is 50.0 or above.

Table 4.6 Predefined `class` file attributes

Attribute	Java SE	<code>class</code> file
<code>ConstantValue</code> (§4.7.2)	1.0.2	45.3
<code>Code</code> (§4.7.3)	1.0.2	45.3
<code>StackMapTable</code> (§4.7.4)	1.6	50.0
<code>Exceptions</code> (§4.7.5)	1.0.2	45.3
<code>InnerClasses</code> (§4.7.6)	1.1	45.3
<code>EnclosingMethod</code> (§4.7.7)	1.5	49.0
<code>Synthetic</code> (§4.7.8)	1.1	45.3
<code>Signature</code> (§4.7.9)	1.5	49.0
<code>SourceFile</code> (§4.7.10)	1.0.2	45.3
<code>SourceDebugExtension</code> (§4.7.11)	1.5	49.0
<code>LineNumberTable</code> (§4.7.12)	1.0.2	45.3
<code>LocalVariableTable</code> (§4.7.13)	1.0.2	45.3
<code>LocalVariableTypeTable</code> (§4.7.14)	1.5	49.0
<code>Deprecated</code> (§4.7.15)	1.1	45.3
<code>RuntimeVisibleAnnotations</code> (§4.7.16)	1.5	49.0
<code>RuntimeInvisibleAnnotations</code> (§4.7.17)	1.5	49.0
<code>RuntimeVisibleParameterAnnotations</code> (§4.7.18)	1.5	49.0
<code>RuntimeInvisibleParameterAnnotations</code> (§4.7.19)	1.5	49.0
<code>AnnotationDefault</code> (§4.7.20)	1.5	49.0

Table 4.6 Predefined class file attributes

SourceID (§4.7.21)	1.4	48.0
CompilationID (§4.7.22)	1.4	48.0

Use of the remaining predefined attributes is optional; a `class` file reader may use the information they contain, or otherwise must silently ignore those attributes.

4.7.1 Defining and Naming New Attributes

Compilers are permitted to define and emit `class` files containing new attributes in the `attributes` tables of `class` file structures. Java virtual machine implementations are permitted to recognize and use new attributes found in the `attributes` tables of `class` file structures. However, any attribute not defined as part of this Java virtual machine specification must not affect the semantics of class or interface types. Java virtual machine implementations are required to silently ignore attributes they do not recognize.

For instance, defining a new attribute to support vendor-specific debugging is permitted. Because Java virtual machine implementations are required to ignore attributes they do not recognize, `class` files intended for that particular Java virtual machine implementation will be usable by other implementations even if those implementations cannot make use of the additional debugging information that the `class` files contain.

Java virtual machine implementations are specifically prohibited from throwing an exception or otherwise refusing to use `class` files simply because of the presence of some new attribute. Of course, tools operating on `class` files may not run correctly if given `class` files that do not contain all the attributes they require.

Two attributes that are intended to be distinct, but that happen to use the same attribute name and are of the same length, will conflict on implementations that recognize either attribute. Attributes defined other than in this specification must have names chosen according to the package naming convention defined by *The Java Language Specification* (JLS3 §7.7).

Future versions of this specification may define additional attributes.

4.7.2 The ConstantValue Attribute

The `ConstantValue` attribute is a fixed-length attribute in the `attributes` table of a `field_info` (§4.5) structure. A `ConstantValue` attribute represents the value of a constant field. There can be no more than one `ConstantValue` attribute in the `attributes` table of a given `field_info` structure. If the field is static (that is, the `ACC_STATIC` flag (Table 4.4) in the `access_flags` item of the `field_info` structure is set) then the constant field represented by the `field_info` structure is assigned the value referenced by its `ConstantValue` attribute as part of the initialization of the class or interface declaring the constant field (§5.5). This occurs ~~immediately~~ prior to the invocation of the class or interface initialization method (§2.9) of that class or interface.

If a `field_info` structure representing a non-static field has a `ConstantValue` attribute, then that attribute must silently be ignored. Every Java virtual machine implementation must recognize `ConstantValue` attributes.

The `ConstantValue` attribute has the following format:

```
ConstantValue_attribute {
    u2 attribute_name_index;
    u4 attribute_length;
    u2 constantvalue_index;
}
```

The items of the `ConstantValue_attribute` structure are as follows:

attribute_name_index

The value of the `attribute_name_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Utf8_info` (§4.4.7) structure representing the string "ConstantValue".

attribute_length

The value of the `attribute_length` item of a `ConstantValue_attribute` structure must be 2.

constantvalue_index

The value of the `constantvalue_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index gives the constant value represented by this attribute.

The `constant_pool` entry must be of a type appropriate to the field, as shown by Table 4.7.

Table 4.7 Constant value attribute types

Field Type	Entry Type
<code>long</code>	<code>CONSTANT_Long</code>
<code>float</code>	<code>CONSTANT_Float</code>
<code>double</code>	<code>CONSTANT_Double</code>
<code>int, short, char, byte, boolean</code>	<code>CONSTANT_Integer</code>
<code>String</code>	<code>CONSTANT_String</code>

4.7.3 The Code Attribute

The `Code` attribute is a variable-length attribute in the `attributes` table of a `method_info` (§4.6) structure. A `Code` attribute contains the Java virtual machine instructions and auxiliary information for a single method, instance initialization method (§2.9), or class or interface initialization method (§2.9). Every Java virtual machine implementation must recognize `Code` attributes. If the method is either `native` or `abstract`, its `method_info` structure must not have a `Code` attribute. Otherwise, its `method_info` structure must have exactly one `Code` attribute.

The `Code` attribute has the following format:

```
Code_attribute {
    u2 attribute_name_index;
    u4 attribute_length;
    u2 max_stack;
    u2 max_locals;
    u4 code_length;
    u1 code[code_length];
    u2 exception_table_length;
    {
        u2 start_pc;
        u2 end_pc;
        u2 handler_pc;
        u2 catch_type;
    }   exception_table[exception_table_length];
    u2 attributes_count;
    attribute_info attributes[attributes_count];
```

```
}
```

The items of the `Code_attribute` structure are as follows:

`attribute_name_index`

The value of the `attribute_name_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Utf8_info` (§4.4.7) structure representing the string "Code".

`attribute_length`

The value of the `attribute_length` item indicates the length of the attribute, excluding the initial six bytes.

`max_stack`

The value of the `max_stack` item gives the maximum depth (§2.6.2) of the operand stack of this method at any point during execution of the method.

`max_locals`

The value of the `max_locals` item gives the number of local variables in the local variable array allocated upon invocation of this method, including the local variables used to pass parameters to the method on its invocation.

The greatest local variable index for a value of type `long` or `double` is `max_locals`-2. The greatest local variable index for a value of any other type is `max_locals`-1.

`code_length`

The value of the `code_length` item gives the number of bytes in the `code` array for this method. The value of `code_length` must be greater than zero; the `code` array must not be empty.

`code[]`

The `code` array gives the actual bytes of Java virtual machine code that implement the method.

When the `code` array is read into memory on a byte-addressable machine, if the first byte of the array is aligned on a 4-byte boundary, the *tableswitch* and *lookupswitch* 32-bit offsets will be 4-byte aligned. (Refer to the descriptions of those

instructions for more information on the consequences of `code` array alignment.)

The detailed constraints on the contents of the `code` array are extensive and are given in a separate section (§4.9).

`exception_table_length`

The value of the `exception_table_length` item gives the number of entries in the `exception_table` table.

`exception_table[]`

Each entry in the `exception_table` array describes one exception handler in the `code` array. The order of the handlers in the `exception_table` array is significant. See Section 2.10 for more details.

Each `exception_table` entry contains the following four items:

`start_pc, end_pc`

The values of the two items `start_pc` and `end_pc` indicate the ranges in the `code` array at which the exception handler is active. The value of `start_pc` must be a valid index into the `code` array of the opcode of an instruction. The value of `end_pc` either must be a valid index into the `code` array of the opcode of an instruction or must be equal to `code_length`, the length of the `code` array. The value of `start_pc` must be less than the value of `end_pc`.

The `start_pc` is inclusive and `end_pc` is exclusive; that is, the exception handler must be active while the program counter is within the interval $[start_pc, end_pc]$.⁴

⁴ The fact that `end_pc` is exclusive is a historical mistake in the design of the Java virtual machine: if the Java virtual machine code for a method is exactly 65535 bytes long and ends with an instruction that is 1 byte long, then that instruction cannot be protected by an exception handler. A compiler writer can work around this bug by limiting the maximum size of the generated Java virtual machine code for any method, instance initialization method, or static initializer (the size of any `code` array) to 65534 bytes.

handler_pc

The value of the `handler_pc` item indicates the start of the exception handler. The value of the item must be a valid index into the `code` array and must be the index of the opcode of an instruction.

catch_type

If the value of the `catch_type` item is nonzero, it must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Class_info` (§4.4.1) structure representing a class of exceptions that this exception handler is designated to catch. The exception handler will be called only if the thrown exception is an instance of the given class or one of its subclasses.

If the value of the `catch_type` item is zero, this exception handler is called for all exceptions. This is used to implement `finally` (see Section 3.13, “Compiling finally”).

attributes_count

The value of the `attributes_count` item indicates the number of attributes of the `Code` attribute.

attributes[]

Each value of the `attributes` table must be an attribute structure (§4.7). A `Code` attribute can have any number of optional attributes associated with it.

The only attributes defined by this specification as appearing in the `attributes` table of a `Code` attribute are the `LineNumberTable` (§4.7.12), `LocalVariableTable` (§4.7.13), `LocalVariableTypeTable` (§4.7.14), and `StackMapTable` (§4.7.4) attributes.

If a Java virtual machine implementation recognizes `class` files whose version number is 50.0 or above, it must recognize and correctly read `StackMapTable` (§4.7.4) attributes found in the `attributes` table of a `Code` attribute of a `class` file whose version number is 50.0 or above.

A Java virtual machine implementation is required to silently ignore any or all attributes in the `attributes` table of a `Code`

attribute that it does not recognize. Attributes not defined in this specification are not allowed to affect the semantics of the `class` file, but only to provide additional descriptive information (§4.7.1).

4.7.4 The `StackMapTable` Attribute

The `StackMapTable` attribute is a variable-length attribute in the `attributes` table of a `Code` (§4.7.3) attribute. This attribute is used during the process of verification by typechecking (§4.10.1).

A `StackMapTable` attribute consists of zero or more *stack map frames*. Each stack map frame specifies (either explicitly or implicitly) a bytecode offset, the verification types (§4.10.1) for the local variables, and the verification types for the operand stack.

The type checker deals with and manipulates the expected types of a method's local variables and operand stack. Throughout this section, a *location* refers to either a single local variable or to a single operand stack entry.

We will use the terms *stack map frame* and *type state* interchangeably to describe a mapping from locations in the operand stack and local variables of a method to verification types. We will usually use the term *stack map frame* when such a mapping is provided in the class file, and the term *type state* when the mapping is used by the type checker.

If a method's `Code` attribute does not have a `StackMapTable` attribute, it has an *implicit stack map attribute*. This implicit stack map attribute is equivalent to a `StackMapTable` attribute with `number_of_entries` equal to zero. A method's `Code` attribute may have at most one `StackMapTable` attribute, otherwise a `ClassFormatError` is thrown.

The `StackMapTable` attribute has the following format:

```
StackMapTable_attribute {
    u2 attribute_name_index;
    u4 attribute_length;
    u2 number_of_entries;
    stack_map_frame entries[number_of_entries];
}
```

The items of the `StackMapTable_attribute` structure are as follows:

attribute_name_index

The value of the **attribute_name_index** item must be a valid index into the **constant_pool** table. The **constant_pool** entry at that index must be a **CONSTANT_Utf8_info** (§4.4.7) structure representing the string "StackMapTable".

attribute_length

The value of the **attribute_length** item indicates the length of the attribute, excluding the initial six bytes.

number_of_entries

The value of the **number_of_entries** item gives the number of **stack_map_frame** entries in the **entries** table.

entries

The **entries** array gives the method's **stack_map_frame** structures.

Each **stack_map_frame** structure specifies the type state at a particular bytecode offset. Each frame type specifies (explicitly or implicitly) a value, **offset_delta**, that is used to calculate the actual bytecode offset at which a frame applies. The bytecode offset at which a frame applies is calculated by adding **offset_delta** + 1 to the bytecode offset of the previous frame, unless the previous frame is the initial frame of the method, in which case the bytecode offset is **offset_delta**.

By using an offset delta rather than the actual bytecode offset we ensure, by definition, that stack map frames are in the correctly sorted order. Furthermore, by consistently using the formula **offset_delta** + 1 for all explicit frames, we guarantee the absence of duplicates.

We say that an instruction in the bytecode has a corresponding stack map frame if the instruction starts at offset i in the **code** array of a **Code** attribute, and the **Code** attribute has a **StackMapTable** attribute whose **entries** array has a **stack_map_frame** structure that applies at bytecode offset i .

The **stack_map_frame** structure consists of a one-byte tag followed by zero or more bytes, giving more information, depending upon the tag.

A stack map frame may belong to one of several *frame types*:

```

union stack_map_frame {
    same_frame;
    same_locals_1_stack_item_frame;
    same_locals_1_stack_item_frame_extended;
    chop_frame;
    same_frame_extended;
    append_frame;
    full_frame;
}

```

All frame types, even `full_frame`, rely on the previous frame for some of their semantics. This raises the question of what is the very first frame? The initial frame is implicit, and computed from the method descriptor. See the Prolog code for `methodInitialStackFrame` (§4.10.1.3.3).

The frame type `same_frame` is represented by tags in the range [0-63]. If the frame type is `same_frame`, it means the frame has exactly the same locals as the previous stack map frame and that the number of stack items is zero. The `offset_delta` value for the frame is the value of the tag item, `frame_type`.

```

same_frame {
    u1 frame_type = SAME; /* 0-63 */
}

```

The frame type `same_locals_1_stack_item_frame` is represented by tags in the range [64, 127]. If the `frame_type` is `same_locals_1_stack_item_frame`, it means the frame has exactly the same locals as the previous stack map frame and that the number of stack items is 1. The `offset_delta` value for the frame is the value (`frame_type` - 64). There is a `verification_type_info` following the `frame_type` for the one stack item.

```

same_locals_1_stack_item_frame {
    u1 frame_type = SAME_LOCALS_1_STACK_ITEM; /* 64-127 */
    verification_type_info stack[1];
}

```

Tags in the range [128-246] are reserved for future use.

The frame type `same_locals_1_stack_item_frame_extended` is represented by the tag 247. The frame type `same_locals_1_stack_item_frame_extended` indicates that the frame has exactly the same locals as the previous stack map frame and that the number of stack items is 1. The `offset_delta` value for the frame is given explicitly. There is a `verification_type_info` following the `frame_type` for the one stack item.

```
same_locals_1_stack_item_frame_extended {
    u1 frame_type = SAME_LOCALS_1_STACK_ITEM_EXTENDED;
                                /* 247 */
    u2 offset_delta;
    verification_type_info stack[1];
}
```

The frame type `chop_frame` is represented by tags in the range [248-250]. If the frame type is `chop_frame`, it means that the operand stack is empty and the current locals are the same as the locals in the previous frame, except that the k last locals are absent. The value of k is given by the formula $251 - \text{frame_type}$.

```
chop_frame {
    u1 frame_type = CHOP; /* 248-250 */
    u2 offset_delta;
}
```

The frame type `same_frame_extended` is represented by the tag value 251. If the frame type is `same_frame_extended`, it means the frame has exactly the same locals as the previous stack map frame and that the number of stack items is zero.

```
same_frame_extended {
    u1 frame_type = SAME_FRAME_EXTENDED; /* 251 */
    u2 offset_delta;
}
```

The frame type `append_frame` is represented by tags in the range [252-254]. If the frame type is `append_frame`, it means that the operand stack is empty and the current locals are the same as the locals in the previous frame, except that k additional locals are defined. The value of k is given by the formula `frame_type - 251`.

```
append_frame {
    u1 frame_type = APPEND; /* 252-254 */
    u2 offset_delta;
    verification_type_info locals[frame_type - 251];
}
```

The 0th entry in `locals` represents the type of the first additional local variable. If `locals[M]` represents local variable N, then `locals[M+1]` represents local variable N+1 if `locals[M]` is one of:

- `Top_variable_info`
- `Integer_variable_info`
- `Float_variable_info`
- `Null_variable_info`
- `UninitializedThis_variable_info`
- `Object_variable_info`
- `Uninitialized_variable_info`

Otherwise `locals[M+1]` represents local variable N+2. It is an error if, for any index `i`, `locals[i]` represents a local variable whose index is greater than the maximum number of local variables for the method.

The frame type `full_frame` is represented by the tag value 255.

```
full_frame {
    u1 frame_type = FULL_FRAME; /* 255 */
    u2 offset_delta;
    u2 number_of_locals;
    verification_type_info locals[number_of_locals];
    u2 number_of_stack_items;
    verification_type_info stack[number_of_stack_items];
}
```

The 0th entry in `locals` represents the type of local variable 0. If `locals[M]` represents local variable N, then `locals[M+1]` represents local variable N+1 if `locals[M]` is one of:

- Top_variable_info
- Integer_variable_info
- Float_variable_info
- Null_variable_info
- UninitializedThis_variable_info
- Object_variable_info
- Uninitialized_variable_info

Otherwise `locals[M+1]` represents local variable N+2. It is an error if, for any index `i`, `locals[i]` represents a local variable whose index is greater than the maximum number of local variables for the method.

The 0th entry in `stack` represents the type of the bottom of the stack, and subsequent entries represent types of stack elements closer to the top of the operand stack. We shall refer to the bottom element of the stack as stack element 0, and to subsequent elements as stack element 1, 2 etc. If `stack[M]` represents stack element N, then `stack[M+1]` represents stack element N+1 if `stack[M]` is one of:

- Top_variable_info
- Integer_variable_info
- Float_variable_info
- Null_variable_info
- UninitializedThis_variable_info
- Object_variable_info
- Uninitialized_variable_info

Otherwise, `stack[M+1]` represents stack element N+2. It is an error if, for any index `i`, `stack[i]` represents a stack entry whose index is greater than the maximum operand stack size for the method.

The `verification_type_info` structure consists of a one-byte tag followed by zero or more bytes, giving more information about the tag. Each `verification_type_info` structure specifies the verification type of one or two locations.

```
union verification_type_info {
    Top_variable_info;
    Integer_variable_info;
    Float_variable_info;
    Long_variable_info;
    Double_variable_info;
    Null_variable_info;
    UninitializedThis_variable_info;
    Object_variable_info;
    Uninitialized_variable_info;
}
```

The `Top_variable_info` type indicates that the local variable has the verification type `top` (\top).

```
Top_variable_info {
    u1 tag = ITEM_Top; /* 0 */
}
```

The `Integer_variable_info` type indicates that the location contains the verification type `int`.

```
Integer_variable_info {
    u1 tag = ITEM_Integer; /* 1 */
}
```

The `Float_variable_info` type indicates that the location contains the verification type `float`.

```
Float_variable_info {
    u1 tag = ITEM_Float; /* 2 */
}
```

The `Long_variable_info` type indicates that the location contains the verification type `long`. If the location is a local variable, then:

- It must not be the local variable with the highest index.
- The next higher numbered local variable contains the verification type \top .

If the location is an operand stack entry, then:

- The current location must not be the topmost location of the operand stack.
- The next location closer to the top of the operand stack contains the verification type \top .

This structure gives the contents of two locations in the operand stack or in the local variables.

```
Long_variable_info {
    u1 tag = ITEM_Long; /* 4 */
}
```

The `Double_variable_info` type indicates that the location contains the verification type `double`. If the location is a local variable, then:

- It must not be the local variable with the highest index.
- The next higher numbered local variable contains the verification type \top .

If the location is an operand stack entry, then:

- The current location must not be the topmost location of the operand stack.
- The next location closer to the top of the operand stack contains the verification type \top .

This structure gives the contents of two locations in the operand stack or in the local variables.

```
Double_variable_info {
    u1 tag = ITEM_Double; /* 3 */
}
```

The `Null_variable_info` type indicates that location contains the verification type `null`.

```
Null_variable_info {
    u1 tag = ITEM_Null; /* 5 */
}
```

The `UninitializedThis_variable_info` type indicates that the location contains the verification type `uninitializedThis`.

```
UninitializedThis_variable_info {
    u1 tag = ITEM_UninitializedThis; /* 6 */
}
```

The `Object_variable_info` type indicates that the location contains an instance of the class represented by the `CONSTANT_CLASS_Info` structure (§4.4.1) found in the `constant_pool` table at the index given by `cpool_index`.

```
Object_variable_info {
    u1 tag = ITEM_Object; /* 7 */
    u2 cpool_index;
}
```

The `Uninitialized_variable_info` indicates that the location contains the verification type `uninitialized(offset)`. The `offset` item indicates the offset, in the `code` array of the `Code` attribute that contains this `StackMapTable` attribute, of the `new` instruction that created the object being stored in the location.

```
Uninitialized_variable_info {
    u1 tag = ITEM_Uninitialized /* 8 */
    u2 offset;
}
```

4.7.5 The Exceptions Attribute

The `Exceptions` attribute is a variable-length attribute in the `attributes` table of a `method_info` (§4.6) structure. The `Exceptions` attribute indicates which checked exceptions a method may throw. There may be at most one `Exceptions` attribute in each `method_info` structure.

The `Exceptions` attribute has the following format:

```
Exceptions_attribute {
    u2 attribute_name_index;
    u4 attribute_length;
    u2 number_of_exceptions;
    u2 exception_index_table[number_of_exceptions];
}
```

The items of the `Exceptions_attribute` structure are as follows:

attribute_name_index

The value of the **attribute_name_index** item must be a valid index into the **constant_pool** table. The **constant_pool** entry at that index must be the **CONSTANT_Utf8_info** (§4.4.7) structure representing the string "Exceptions".

attribute_length

The value of the **attribute_length** item indicates the attribute length, excluding the initial six bytes.

number_of_exceptions

The value of the **number_of_exceptions** item indicates the number of entries in the **exception_index_table**.

exception_index_table[]

Each value in the **exception_index_table** array must be a valid index into the **constant_pool** table. The **constant_pool** entry referenced by each table item must be a **CONSTANT_Class_info** (§4.4.1) structure representing a class type that this method is declared to throw.

A method should throw an exception only if at least one of the following three criteria is met:

- The exception is an instance of **RuntimeException** or one of its subclasses.
- The exception is an instance of **Error** or one of its subclasses.
- The exception is an instance of one of the exception classes specified in the **exception_index_table** just described, or one of their subclasses.

These requirements are not enforced in the Java virtual machine; they are enforced only at compile time.

4.7.6 The **InnerClasses** Attribute

The **InnerClasses** attribute⁵ is a variable-length attribute in the **attributes** table of a **ClassFile** (§4.1) structure. If the constant pool of a class or interface C con-

⁵ The **InnerClasses** attribute was introduced in JDK release 1.1 to support nested classes and interfaces.

tains a `CONSTANT_Class_info` entry which represents a class or interface that is not a member of a package, then C's `ClassFile` structure must have exactly one `InnerClasses` attribute in its `attributes` table.

The `InnerClasses` attribute has the following format:

```
InnerClasses_attribute {
    u2 attribute_name_index;
    u4 attribute_length;
    u2 number_of_classes;
    {   u2 inner_class_info_index;
        u2 outer_class_info_index;
        u2 inner_name_index;
        u2 inner_class_access_flags;
    }   classes[number_of_classes];
}
```

The items of the `InnerClasses_attribute` structure are as follows:

`attribute_name_index`

The value of the `attribute_name_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Utf8_info` (§4.4.7) structure representing the string "`InnerClasses`".

`attribute_length`

The value of the `attribute_length` item indicates the length of the attribute, excluding the initial six bytes.

`number_of_classes`

The value of the `number_of_classes` item indicates the number of entries in the `classes` array.

`classes[]`

Every `CONSTANT_Class_info` entry in the `constant_pool` table which represents a class or interface C that is not a package member must have exactly one corresponding entry in the `classes` array.

If a class has members that are classes or interfaces, its `constant_pool` table (and hence its `InnerClasses` attribute) must refer to each such member, even if that member is not otherwise mentioned by the class. These rules imply that a nested

class or interface member will have `InnerClasses` information for each enclosing class and for each immediate member.

Each `classes` array entry contains the following four items:

`inner_class_info_index`

The value of the `inner_class_info_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Class_info` (§4.4.1) structure representing C. The remaining items in the `classes` array entry give information about C.

`outer_class_info_index`

If C is not a member of a class or an interface (that is, if C is a top-level class or interface (JLS3 7.6) or a local class (JLS3 14.3) or an anonymous class (15.9.5)), the value of the `outer_class_info_index` item must be zero. Otherwise, the value of the `outer_class_info_index` item must be a valid index into the `constant_pool` table, and the entry at that index must be a `CONSTANT_Class_info` (§4.4.1) structure representing the class or interface of which C is a member.

`inner_name_index`

If C is anonymous (JLS3 15.9.5), the value of the `inner_name_index` item must be zero. Otherwise, the value of the `inner_name_index` item must be a valid index into the `constant_pool` table, and the entry at that index must be a `CONSTANT_Utf8_info` (§4.4.7) structure that represents the original simple name of C, as given in the source code from which this `class` file was compiled.

`inner_class_access_flags`

The value of the `inner_class_access_flags` item is a mask of flags used to denote access permissions to and properties of class or interface C as declared in the source code from which this `class` file was compiled. It is used by compilers to recover the original information when source code is not available. The flags are shown in Table 4.8.

Table 4.8 Nested class access and property flags

Flag Name	Value	Meaning
ACC_PUBLIC	0x0001	Marked or implicitly <code>public</code> in source.
ACC_PRIVATE	0x0002	Marked <code>private</code> in source.
ACC_PROTECTED	0x0004	Marked <code>protected</code> in source.
ACC_STATIC	0x0008	Marked or implicitly <code>static</code> in source.
ACC_FINAL	0x0010	Marked <code>final</code> in source.
ACC_INTERFACE	0x0200	Was an <code>interface</code> in source.
ACC_ABSTRACT	0x0400	Marked or implicitly <code>abstract</code> in source.
ACC_SYNTHETIC	0x1000	Declared <code>synthetic</code> ; not present in the source code.
ACC_ANNOTATION	0x2000	Declared as an annotation type.
ACC_ENUM	0x4000	Declared as an <code>enum</code> type.

All bits of the `inner_class_access_flags` item not assigned in Table 4.8 are reserved for future use. They should be set to zero in generated `class` files and should be ignored by Java virtual machine implementations.

If a `class` file has a version number that is greater than or equal to 51.0, and has an `InnerClasses` attribute in its `attributes` table, then for all entries in the `classes` array of the `InnerClasses` attribute, the value of the `outer_class_info_index` item must be zero if the value of the `inner_name_index` item is zero.

Oracle's Java virtual machine implementation does not check the consistency of an `InnerClasses` attribute against a `class` file representing a class or interface referenced by the attribute.

4.7.7 The `EnclosingMethod` Attribute

The `EnclosingMethod` attribute is an optional fixed-length attribute in the `attributes` table of a `ClassFile` (§4.1) structure. A class must have an `EnclosingMethod` attribute if and only if it is a local class or an anonymous class. A class may have no more than one `EnclosingMethod` attribute.

The `EnclosingMethod` attribute has the following format:

```
EnclosingMethod_attribute {
    u2 attribute_name_index;
    u4 attribute_length;
    u2 class_index
    u2 method_index;
}
```

The items of the `EnclosingMethod_attribute` structure are as follows:

`attribute_name_index`

The value of the `attribute_name_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Utf8_info` (§4.4.7) structure representing the string "EnclosingMethod".

`attribute_length`

The value of the `attribute_length` item is four.

`class_index`

The value of the `class_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Class_info` (§4.4.1) structure representing the innermost class that encloses the declaration of the current class.

`method_index`

If the current class is not immediately enclosed by a method or constructor, then the value of the `method_index` item must be zero. Otherwise, the value of the `method_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_NameAndType_info` (§4.4.6) structure representing the name and type of a method in the class referenced by the `class_index` attribute above. It is the responsibility of the Java compiler to ensure that the method identified via the `method_index` is indeed the closest lexically enclosing method of the class that contains this `EnclosingMethod` attribute.

4.7.8 The Synthetic Attribute

The `Synthetic` attribute⁶ is a fixed-length attribute in the `attributes` table of a `ClassFile` (§4.1), `field_info` (§4.5) or `method_info` (§4.6) structure. A class member that does not appear in the source code must be marked using a `Synthetic` attribute, or else it must have its `ACC_SYNTHETIC` flag set. The only exceptions to this requirement are compiler-generated methods which are not considered implementation artifacts, namely the instance initialization method representing a default constructor of the Java programming language (§2.9), the class initialization method (§2.9) and the `Enum.values()` and `Enum.valueOf()` methods.

The `Synthetic` attribute has the following format:

```
Synthetic_attribute {
    u2 attribute_name_index;
    u4 attribute_length;
}
```

The items of the `Synthetic_attribute` structure are as follows:

`attribute_name_index`

The value of the `attribute_name_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Utf8_info` (§4.4.7) structure representing the string "Synthetic".

`attribute_length`

The value of the `attribute_length` item is zero.

4.7.9 The Signature Attribute

The `Signature` attribute is an optional fixed-length attribute in the `attributes` table of a `ClassFile` (§4.1), `field_info` (§4.5) or `method_info` (§4.6) structure. The `Signature` attribute records generic signature information for any class, interface, constructor or member whose generic signature in the Java programming language would include references to type variables or parameterized types.

The `Signature` attribute has the following format:

⁶ The `Synthetic` attribute was introduced in JDK release 1.1 to support nested classes and interfaces.

```
Signature_attribute {
    u2 attribute_name_index;
    u4 attribute_length;
    u2 signature_index;
}
```

The items of the `Signature_attribute` structure are as follows:

`attribute_name_index`

The value of the `attribute_name_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Utf8_info` (§4.4.7) structure representing the string "Signature".

`attribute_length`

The value of the `attribute_length` item of a `Signature_attribute` structure must be 2.

`signature_index`

The value of the `signature_index` item must be a valid index into the `constant_pool` table. The constant pool entry at that index must be a `CONSTANT_Utf8_info` (§4.4.7) structure representing either a class signature, if this signature attribute is an attribute of a `ClassFile` structure, a method type signature, if this signature is an attribute of a `method_info` structure, or a field type signature otherwise.

4.7.10 The SourceFile Attribute

The `SourceFile` attribute is an optional fixed-length attribute in the `attributes` table of a `ClassFile` (§4.1) structure. There can be no more than one `SourceFile` attribute in the `attributes` table of a given `ClassFile` structure.

The `SourceFile` attribute has the following format:

```
SourceFile_attribute {
    u2 attribute_name_index;
    u4 attribute_length;
    u2 sourcefile_index;
}
```

The items of the `SourceFile_attribute` structure are as follows:

`attribute_name_index`

The value of the `attribute_name_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Utf8_info` (§4.4.7) structure representing the string "SourceFile".

`attribute_length`

The value of the `attribute_length` item of a `SourceFile_attribute` structure must be 2.

`sourcefile_index`

The value of the `sourcefile_index` item must be a valid index into the `constant_pool` table. The constant pool entry at that index must be a `CONSTANT_Utf8_info` (§4.4.7) structure representing a string.

The string referenced by the `sourcefile_index` item will be interpreted as indicating the name of the source file from which this `class` file was compiled. It will not be interpreted as indicating the name of a directory containing the file or an absolute path name for the file; such platform-specific additional information must be supplied by the runtime interpreter or development tool at the time the file name is actually used.

4.7.11 The SourceDebugExtension Attribute

The `SourceDebugExtension` attribute is an optional attribute in the `attributes` table of a `ClassFile` (§4.1) structure. There can be no more than one `SourceDebugExtension` attribute in the `attributes` table of a given `ClassFile` structure.

The `SourceDebugExtension` attribute has the following format:

```
SourceDebugExtension_attribute {
    u2 attribute_name_index;
    u4 attribute_length;
    u1 debug_extension[attribute_length];
}
```

The items of the `SourceDebugExtension_attribute` structure are as follows:

`attribute_name_index`

The value of the `attribute_name_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Utf8_info` (§4.4.7) structure representing the string "SourceDebugExtension".

`attribute_length`

The value of the `attribute_length` item indicates the length of the attribute, excluding the initial six bytes. The value of the `attribute_length` item is thus the number of bytes in the `debug_extension[]` item.

`debug_extension[]`

The `debug_extension` array holds extended debugging information which has no semantic effect on the Java Virtual Machine. The information is represented using a modified UTF-8 string (§4.4.7) with no terminating zero byte. Note that the `debug_extension` array may denote a string longer than that which can be represented with an instance of class `String`.

4.7.12 The LineNumberTable Attribute

The `LineNumberTable` attribute is an optional variable-length attribute in the `attributes` table of a `Code` (§4.7.3) attribute. It may be used by debuggers to determine which part of the Java virtual machine code array corresponds to a given line number in the original source file. If `LineNumberTable` attributes are present

in the `attributes` table of a given `Code` attribute, then they may appear in any order. Furthermore, multiple `LineNumberTable` attributes may together represent a given line of a source file; that is, `LineNumberTable` attributes need not be one-to-one with source lines.

The `LineNumberTable` attribute has the following format:

```
LineNumberTable_attribute {
    u2 attribute_name_index;
    u4 attribute_length;
    u2 line_number_table_length;
    {   u2 start_pc;
        u2 line_number;
    }   line_number_table[line_number_table_length];
}
```

The items of the `LineNumberTable_attribute` structure are as follows:

`attribute_name_index`

The value of the `attribute_name_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Utf8_info` (§4.4.7) structure representing the string "`LineNumberTable`".

`attribute_length`

The value of the `attribute_length` item indicates the length of the attribute, excluding the initial six bytes.

`line_number_table_length`

The value of the `line_number_table_length` item indicates the number of entries in the `line_number_table` array.

`line_number_table[]`

Each entry in the `line_number_table` array indicates that the line number in the original source file changes at a given point in the `code` array. Each `line_number_table` entry must contain the following two items:

`start_pc`

The value of the `start_pc` item must indicate the index into the `code` array at which the code for a new line in the original source file begins. The value of `start_pc` must be less than

the value of the `code_length` item of the `Code` attribute of which this `LineNumberTable` is an attribute.

`line_number`

The value of the `line_number` item must give the corresponding line number in the original source file.

4.7.13 The `LocalVariableTable` Attribute

The `LocalVariableTable` attribute is an optional variable-length attribute in the `attributes` table of a `Code` (§4.7.3) attribute. It may be used by debuggers to determine the value of a given local variable during the execution of a method. If `LocalVariableTable` attributes are present in the `attributes` table of a given `Code` attribute, then they may appear in any order. There may be no more than one `LocalVariableTable` attribute per local variable in the `Code` attribute.

The `LocalVariableTable` attribute has the following format:

```
LocalVariableTable_attribute {
    u2 attribute_name_index;
    u4 attribute_length;
    u2 local_variable_table_length;
    {
        u2 start_pc;
        u2 length;
        u2 name_index;
        u2 descriptor_index;
        u2 index;
    }   local_variable_table[local_variable_table_length];
}
```

The items of the `LocalVariableTable_attribute` structure are as follows:

`attribute_name_index`

The value of the `attribute_name_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Utf8_info` (§4.4.7) structure representing the string "LocalVariableTable".

`attribute_length`

The value of the `attribute_length` item indicates the length of the attribute, excluding the initial six bytes.

local_variable_table_length

The value of the `local_variable_table_length` item indicates the number of entries in the `local_variable_table` array.

local_variable_table[]

Each entry in the `local_variable_table` array indicates a range of code array offsets within which a local variable has a value. It also indicates the index into the local variable array of the current frame at which that local variable can be found. Each entry must contain the following five items:

start_pc, length

The given local variable must have a value at indices into the code array in the interval `[start_pc, start_pc+length)`, that is, between `start_pc` and `start_pc+length` exclusive. The value of `start_pc` must be a valid index into the code array of this `Code` attribute and must be the index of the opcode of an instruction. The value of `start_pc+length` must either be a valid index into the code array of this `Code` attribute and be the index of the opcode of an instruction, or it must be the first index beyond the end of that code array.

name_index

The value of the `name_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must contain a `CONSTANT_Utf8_info` (§4.4.7) structure representing a valid unqualified name (§4.2.2) denoting a local variable.

descriptor_index

The value of the `descriptor_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must contain a `CONSTANT_Utf8_info` (§4.4.7) structure. That `CONSTANT_Utf8_info` structure must represent a field descriptor (§4.3.2) encoding the type of a local variable in the source program.

`index`

The given local variable must be at `index` in the local variable array of the current frame. If the local variable at `index` is of type `double` or `long`, it occupies both `index` and `index+1`.

4.7.14 The LocalVariableTypeTable Attribute

The `LocalVariableTypeTable` attribute is an optional variable-length attribute in the `attributes` table of a `Code` (§4.7.3) attribute. It may be used by debuggers to determine the value of a given local variable during the execution of a method. If `LocalVariableTypeTable` attributes are present in the `attributes` table of a given `Code` attribute, then they may appear in any order. There may be no more than one `LocalVariableTypeTable` attribute per local variable in the `Code` attribute.

The `LocalVariableTypeTable` attribute differs from the `LocalVariableTable` attribute in that it provides signature information rather than descriptor information. This difference is only significant for variables whose type is a generic reference type. Such variables will appear in both tables, while variables of other types will appear only in `LocalVariableTable`.

The `LocalVariableTypeTable` attribute has the following format:

```
LocalVariableTypeTable_attribute {
    u2 attribute_name_index;
    u4 attribute_length;
    u2 local_variable_type_table_length;
    {
        u2 start_pc;
        u2 length;
        u2 name_index;
        u2 signature_index;
        u2 index;
    } local_variable_type_table[local_variable_type_table_length];
}
```

The items of the `LocalVariableTypeTable_attribute` structure are as follows:

attribute_name_index

The value of the **attribute_name_index** item must be a valid index into the **constant_pool** table. The **constant_pool** entry at that index must be a **CONSTANT_Utf8_info** (§4.4.7) structure representing the string "LocalVariableTypeTable".

attribute_length

The value of the **attribute_length** item indicates the length of the attribute, excluding the initial six bytes.

local_variable_type_table_length

The value of the **local_variable_type_table_length** item indicates the number of entries in the **local_variable_table** array.

local_variable_type_table[]

Each entry in the **local_variable_type_table** array indicates a range of code array offsets within which a local variable has a value. It also indicates the index into the local variable array of the current frame at which that local variable can be found. Each entry must contain the following five items:

start_pc, length

The given local variable must have a value at indices into the code array in the interval [**start_pc**, **start_pc+length**), that is, between **start_pc** and **start_pc+length** exclusive. The value of **start_pc** must be a valid index into the **code** array of this **Code** attribute and must be the index of the opcode of an instruction. The value of **start_pc+length** must either be a valid index into the **code** array of this **Code** attribute and be the index of the opcode of an instruction, or it must be the first index beyond the end of that **code** array.

name_index

The value of the **name_index** item must be a valid index into the **constant_pool** table. The **constant_pool** entry at that index must contain a **CONSTANT_Utf8_info** (§4.4.7)

structure representing a valid unqualified name (§4.2.2) denoting a local variable.

`signature_index`

The value of the `signature_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must contain a `CONSTANT_Utf8_info` (§4.4.7) structure representing a field type signature (§4.3.4) encoding the type of a local variable in the source program.

`index`

The given local variable must be at `index` in the local variable array of the current frame. If the local variable at `index` is of type `double` or `long`, it occupies both `index` and `index+1`.

4.7.15 The Deprecated Attribute

The `Deprecated` attribute⁷ is an optional fixed-length attribute in the `attributes` table of a `ClassFile` (§4.1), `field_info` (§4.5) or `method_info` (§4.6) structure. A class, interface, method, or field may be marked using a `Deprecated` attribute to indicate that the class, interface, method, or field has been superseded. A runtime interpreter or tool that reads the `class` file format, such as a compiler, can use this marking to advise the user that a superceded class, interface, method, or field is being referred to. The presence of a `Deprecated` attribute does not alter the semantics of a class or interface.

The `Deprecated` attribute has the following format:

```
Deprecated_attribute {
    u2 attribute_name_index;
    u4 attribute_length;
}
```

The items of the `Deprecated_attribute` structure are as follows:

⁷ The `Deprecated` attribute was introduced in JDK release 1.1 to support the `@deprecated` tag in documentation comments.

attribute_name_index

The value of the **attribute_name_index** item must be a valid index into the **constant_pool** table. The **constant_pool** entry at that index must be a **CONSTANT_Utf8_info** (§4.4.7) structure representing the string "Deprecated".

attribute_length

The value of the **attribute_length** item is zero.

4.7.16 The **RuntimeVisibleAnnotations** attribute

The **RuntimeVisibleAnnotations** attribute is a variable-length attribute in the **attributes** table of a **ClassFile** (§4.1), **field_info** (§4.5) or **method_info** (§4.6) structure. The **RuntimeVisibleAnnotations** attribute records runtime-visible Java programming language annotations on the corresponding class, field, or method. Each **ClassFile**, **field_info**, and **method_info** structure may contain at most one **RuntimeVisibleAnnotations** attribute, which records all the runtime-visible Java programming language annotations on the corresponding program element. The Java virtual machine must make these annotations available so they can be returned by the appropriate reflective APIs.

The **RuntimeVisibleAnnotations** attribute has the following format:

```
RuntimeVisibleAnnotations_attribute {
    u2 attribute_name_index;
    u4 attribute_length;
    u2 num_annotations;
    annotation annotations[num_annotations];
}
```

The items of the **RuntimeVisibleAnnotations** structure are as follows:

attribute_name_index

The value of the **attribute_name_index** item must be a valid index into the **constant_pool** table. The **constant_pool** entry at that index must be a **CONSTANT_Utf8_info** structure representing the string "RuntimeVisibleAnnotations".

attribute_length

The value of the **attribute_length** item indicates the length of the attribute, excluding the initial six bytes. The value of the

`attribute_length` item is thus dependent on the number of runtime-visible annotations represented by the structure, and their values.

`num_annotations`

The value of the `num_annotations` item gives the number of runtime-visible annotations represented by the structure. Note that a maximum of 65535 runtime-visible Java programming language annotations may be directly attached to a program element.

`annotations`

Each value of the `annotations` table represents a single runtime-visible annotation on a program element. The annotation structure has the following format:

```
annotation {
    u2 type_index;
    u2 num_element_value_pairs;
    {   u2 element_name_index;
        element_value value;
    }   element_value_pairs[num_element_value_pairs]
}
```

The items of the annotation structure are as follows:

`type_index`

The value of the `type_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Utf8_info` structure representing a field descriptor representing the annotation type corresponding to the annotation represented by this annotation structure.

`num_element_value_pairs`

The value of the `num_element_value_pairs` item gives the number of element-value pairs of the annotation represented by this `annotation` structure. Note that a maximum of 65535 element-value pairs may be contained in a single annotation.

`element_value_pairs`

Each value of the `element_value_pairs` table represents a single element-value pair in the annotation represented by this

annotation structure. Each `element_value_pairs` entry contains the following two items:

`element_name_index`

The value of the `element_name_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Utf8_info` structure representing a valid field descriptor (§4.3.2) that denotes the name of the annotation type element represented by this `element_value_pairs` entry.

`value`

The value of the `value` item represents the value of the element-value pair represented by this `element_value_pairs` entry.

4.7.16.1 The `element_value` structure

The `element_value` structure is a discriminated union representing the value of an element-value pair. It is used to represent element values in all attributes that describe annotations (`RuntimeVisibleAnnotations`, `RuntimeInvisibleAnnotations`, `RuntimeVisibleParameterAnnotations`, and `RuntimeInvisibleParameterAnnotations`).

The `element_value` structure has the following format:

```
element_value {
    u1 tag;
    union {
        u2 const_value_index;
        {   u2 type_name_index;
            u2 const_name_index;
        }   enum_const_value;
        u2 class_info_index;
        annotation annotation_value;
        {   u2 num_values;
            element_value values[num_values];
        }   array_value;
    }   value;
}
```

The items of the `element_value` structure are as follows:

tag

The **tag** item indicates the type of this annotation element-value pair. The letters 'B', 'C', 'D', 'F', 'I', 'J', 'S', and 'Z' indicate a primitive type. These letters are interpreted as *BaseType* characters (Table 4.2). The other legal values for **tag** are listed with their interpretations in the table below.

Table 4.9 Interpretation of additional tag values

tag value	Element Type
s	String
e	enum constant
c	class
@	annotation type
[array

value

The **value** item represents the value of this annotation element. This item is a union. The **tag** item, above, determines which item of the union is to be used:

const_value_index

The **const_value_index** item is used if the **tag** item is one of 'B', 'C', 'D', 'F', 'I', 'J', 'S', 'Z', or 's'. The value of the **const_value_index** item must be a valid index into the **constant_pool** table. The **constant_pool** entry at that index must be of the correct entry type for the field type designated by the **tag** item, as specified in Table 4.9.

enum_const_value

The **enum_const_value** item is used if the **tag** item is 'e'. The **enum_const_value** item consists of the following two items:

type_name_index

The value of the **type_name_index** item must be a valid index into the **constant_pool** table. The **constant_pool** entry at that index must be a **CONSTANT_Utf8_info** structure representing a valid

field descriptor (§4.3.2) that denotes the internal form of the binary name (§4.2.1) of the type of the enum constant represented by this `element_value` structure.

`const_name_index`

The value of the `const_name_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Utf8_info` structure representing the simple name of the enum constant represented by this `element_value` structure.

`class_info_index`

The `class_info_index` item is used if the `tag` item is 'c'. The `class_info_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Utf8_info` structure representing the return descriptor (§4.3.3) of the type that is reified by the class represented by this `element_value` structure (e.g., 'V' for `Void.class`, 'Ljava/lang/Object; for `Object`, etc.)

`annotation_value`

The `annotation_value` item is used if the `tag` item is '@'. The `element_value` structure represents a "nested" annotation.

`array_value`

The `array_value` item is used if the `tag` item is '['. The `array_value` item consists of the following two items:

`num_values`

The value of the `num_values` item gives the number of elements in the array-typed value represented by this `element_value` structure. Note that a maximum of 65535 elements are permitted in an array-typed element value.

`values`

Each value of the `values` table gives the value of an element of the array-typed value represented by this `element_value` structure.

4.7.17 The RuntimeInvisibleAnnotations attribute

The `RuntimeInvisibleAnnotations` attribute is similar to the `RuntimeVisibleAnnotations` attribute, except that the annotations represented by a `RuntimeInvisibleAnnotations` attribute must not be made available for return by reflective APIs, unless the Java virtual machine has been instructed to retain these annotations via some implementation-specific mechanism such as a command line flag. In the absence of such instructions, the Java virtual machine ignores this attribute.

The `RuntimeInvisibleAnnotations` attribute is a variable-length attribute in the `attributes` table of a `ClassFile` (§4.1), `field_info` (§4.5) or `method_info` (§4.6) structure. The `RuntimeInvisibleAnnotations` attribute records runtime-invisible Java programming language annotations on the corresponding class, method, or field. Each `ClassFile`, `field_info`, and `method_info` structure may contain at most one `RuntimeInvisibleAnnotations` attribute, which records all the runtime-invisible Java programming language annotations on the corresponding program element.

The `RuntimeInvisibleAnnotations` attribute has the following format:

```
RuntimeInvisibleAnnotations_attribute {
    u2 attribute_name_index;
    u4 attribute_length;
    u2 num_annotations;
    annotation annotations[num_annotations];
}
```

The items of the `RuntimeInvisibleAnnotations` structure are as follows:

`attribute_name_index`

The value of the `attribute_name_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Utf8_info` structure representing the string "RuntimeInvisibleAnnotations".

`attribute_length`

The value of the `attribute_length` item indicates the length of the attribute, excluding the initial six bytes. The value of the `attribute_length` item is thus dependent on the number of

runtime-invisible annotations represented by the structure, and their values.

`num_annotations`

The value of the `num_annotations` item gives the number of runtime-invisible annotations represented by the structure. Note that a maximum of 65535 runtime-invisible Java programming language annotations may be directly attached to a program element.

`annotations`

Each value of the `annotations` table represents a single runtime-invisible annotation on a program element.

4.7.18 The `RuntimeVisibleParameterAnnotations` attribute

The `RuntimeVisibleParameterAnnotations` attribute is a variable-length attribute in the `attributes` table of the `method_info` (§4.6) structure. The `RuntimeVisibleParameterAnnotations` attribute records runtime-visible Java programming language annotations on the parameters of the corresponding method. Each `method_info` structure may contain at most one `RuntimeVisibleParameterAnnotations` attribute, which records all the runtime-visible Java programming language annotations on the parameters of the corresponding method. The Java virtual machine must make these annotations available so they can be returned by the appropriate reflective APIs.

The `RuntimeVisibleParameterAnnotations` attribute has the following format:

```
RuntimeVisibleParameterAnnotations_attribute {
    u2 attribute_name_index;
    u4 attribute_length;
    u1 num_parameters;
    {
        u2 num_annotations;
        annotation annotations[num_annotations];
    } parameter_annotations[num_parameters];
}
```

The items of the `RuntimeVisibleParameterAnnotations` structure are as follows:

attribute_name_index

The value of the **attribute_name_index** item must be a valid index into the **constant_pool** table. The **constant_pool** entry at that index must be a **CONSTANT_Utf8_info** structure representing the string "**RuntimeVisibleParameterAnnotations**".

attribute_length

The value of the **attribute_length** item indicates the length of the attribute, excluding the initial six bytes. The value of the **attribute_length** item is thus dependent on the number of parameters, the number of runtime-visible annotations on each parameter, and their values.

num_parameters

The value of the **num_parameters** item gives the number of parameters of the method represented by the **method_info** structure on which the annotation occurs. (This duplicates information that could be extracted from the method descriptor.)

parameter_annotations

Each value of the **parameter_annotations** table represents all of the runtime-visible annotations on a single parameter. The sequence of values in the table corresponds to the sequence of parameters in the method descriptor. Each **parameter_annotations** entry contains the following two items:

num_annotations

The value of the **num_annotations** item indicates the number of runtime-visible annotations on the parameter corresponding to the sequence number of this **parameter_annotations** element.

annotations

Each value of the **annotations** table represents a single runtime-visible annotation on the parameter corresponding to the sequence number of this **parameter_annotations** element.

4.7.19 The RuntimeInvisibleParameterAnnotations attribute

The `RuntimeInvisibleParameterAnnotations` attribute is similar to the `RuntimeVisibleParameterAnnotations` attribute, except that the annotations represented by a `RuntimeInvisibleParameterAnnotations` attribute must not be made available for return by reflective APIs, unless the Java virtual machine has specifically been instructed to retain these annotations via some implementation-specific mechanism such as a command line flag. In the absence of such instructions, the Java virtual machine ignores this attribute.

The `RuntimeInvisibleParameterAnnotations` attribute is a variable-length attribute in the `attributes` table of a `method_info` (§4.6) structure. The `RuntimeInvisibleParameterAnnotations` attribute records runtime-invisible Java programming language annotations on the parameters of the corresponding method. Each `method_info` structure may contain at most one `RuntimeInvisibleParameterAnnotations` attribute, which records all the runtime-invisible Java programming language annotations on the parameters of the corresponding method.

The `RuntimeInvisibleParameterAnnotations` attribute has the following format:

```
RuntimeInvisibleParameterAnnotations_attribute {
    u2 attribute_name_index;
    u4 attribute_length;
    u1 num_parameters;
    {   u2 num_annotations;
        annotation annotations[num_annotations];
    }   parameter_annotations[num_parameters];
}
```

The items of the `RuntimeInvisibleParameterAnnotations` structure are as follows:

`attribute_name_index`

The value of the `attribute_name_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Utf8_info` structure representing the string "RuntimeInvisibleParameterAnnotations".

attribute_length

The value of the `attribute_length` item indicates the length of the attribute, excluding the initial six bytes. The value of the `attribute_length` item is thus dependent on the number of parameters, the number of runtime-invisible annotations on each parameter, and their values.

num_parameters

The value of the `num_parameters` item gives the number of parameters of the method represented by the `method_info` structure on which the annotation occurs. (This duplicates information that could be extracted from the method descriptor.)

parameter_annotations

Each value of the `parameter_annotations` table represents all of the runtime-invisible annotations on a single parameter. The sequence of values in the table corresponds to the sequence of parameters in the method descriptor. Each `parameter_annotations` entry contains the following two items:

num_annotations

The value of the `num_annotations` item indicates the number of runtime-invisible annotations on the parameter corresponding to the sequence number of this `parameter_annotations` element.

annotations

Each value of the `annotations` table represents a single runtime-invisible annotation on the parameter corresponding to the sequence number of this `parameter_annotations` element.

4.7.20 The `AnnotationDefault` attribute

The `AnnotationDefault` attribute is a variable-length attribute in the `attributes` table of certain `method_info` (§4.6) structures, namely those representing elements of annotation types. The `AnnotationDefault` attribute records the default value for the element represented by the `method_info` structure. Each `method_info` structure representing an element of an annotation type may contain at most one

`AnnotationDefault` attribute. The Java virtual machine must make this default value available so it can be applied by appropriate reflective APIs.

The `AnnotationDefault` attribute has the following format:

```
AnnotationDefault_attribute {
    u2 attribute_name_index;
    u4 attribute_length;
    element_value default_value;
}
```

The items of the `AnnotationDefault` structure are as follows:

`attribute_name_index`

The value of the `attribute_name_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Utf8_info` structure representing the string "`AnnotationDefault`".

`attribute_length`

The value of the `attribute_length` item indicates the length of the attribute, excluding the initial six bytes. The value of the `attribute_length` item is thus dependent on the default value.

`default_value`

The `default_value` item represents the default value of the annotation type element whose default value is represented by this `AnnotationDefault` attribute.

4.7.21 The SourceID Attribute

The `SourceID` attribute is an optional fixed-length attribute in the `attributes` table of a `ClassFile` (§4.1) structure. There can be no more than one `SourceID` attribute in the `attributes` table of a given `ClassFile` structure.

The `SourceID` attribute has the following format:

```
SourceID_attribute {
    u2 attribute_name_index;
    u4 attribute_length;
    u2 source_id_index;
}
```

The items of the `SourceID_attribute` structure are as follows:

`attribute_name_index`

The value of the `attribute_name_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Utf8_info` (§4.4.7) structure representing the string "SourceID".

`attribute_length`

The value of the `attribute_length` item of a `SourceID_attribute` structure must be 8.

`source_id_index`

The value of the `source_id_index` item must be a valid index into the `constant_pool` table. The constant pool entry at that index must be a `CONSTANT_Utf8_info` (§4.4.7) structure representing the last-modified-time of the source file (as reported by the filesystem, in milliseconds since midnight, January 1, 1970 UTC) when the `ClassFile` structure was generated.

4.7.22 The CompilationID Attribute

The `CompilationID` attribute is an optional fixed-length attribute in the attributes table of a `ClassFile` (§4.1) structure. There can be no more than one `CompilationID` attribute in the attributes table of a given `ClassFile` structure.

The `CompilationID` attribute has the following format:

```
CompilationID_attribute {
    u2 attribute_name_index;
    u4 attribute_length;
    u2 compilation_id_index;
}
```

The items of the `SourceID_attribute` structure are as follows:

attribute_name_index

The value of the `attribute_name_index` item must be a valid index into the `constant_pool` table. The `constant_pool` entry at that index must be a `CONSTANT_Utf8_info` (§4.4.7) structure representing the string "CompilationID".

attribute_length

The value of the `attribute_length` item of a `CompilationID_attribute` structure must be 8.

compilation_id_index

The value of the `compilation_id_index` item must be a valid index into the `constant_pool` table. The constant pool entry at that index must be a `CONSTANT_Utf8_info` (§4.4.7) structure representing the value of `System.currentTimeMillis()` when the `ClassFile` structure was generated.

If a `ClassFile` structure that contains both a `CompilationID` attribute and a `SourceID` attribute, then the millisecond value referenced by `compilation_id_index` in the `CompilationID` attribute must be equal to or greater than the millisecond value referenced by `source_id_index` in the `SourceID` attribute.

4.8 Format Checking

When a prospective `class` file is loaded (§5.3) by the Java virtual machine, the Java virtual machine first ensures that the file has the basic format of a `class` file (§4.1). This process is known as *format checking*. The first four bytes must contain the right magic number. All recognized attributes must be of the proper length. The `class` file must not be truncated or have extra bytes at the end. The constant pool must not contain any superficially unrecognizable information.

This check for basic `class` file integrity is necessary for any interpretation of the `class` file contents.

Format checking is distinct from bytecode verification. Both are part of the verification process. Historically, format checking has been confused with bytecode verification, because both are a form of integrity check.

4.9 Constraints on Java Virtual Machine Code

The Java virtual machine code for a method, instance initialization method (§2.9), or class or interface initialization method (§2.9) is stored in the `code` array of the `Code` attribute of a `method_info` structure of a `class` file. This section describes the constraints associated with the contents of the `Code_attribute` structure.

4.9.1 Static Constraints

The *static constraints* on a `class` file are those defining the well-formedness of the file. With the exception of the static constraints on the Java virtual machine code of the `class` file, these constraints have been given in the previous sections. The static constraints on the Java virtual machine code in a `class` file specify how Java virtual machine instructions must be laid out in the `code` array and what the operands of individual instructions must be.

The static constraints on the instructions in the `code` array are as follows:

- The `code` array must not be empty, so the `code_length` item cannot have the value 0.
- The value of the `code_length` item must be less than 65536.

- The opcode of the first instruction in the `code` array begins at index 0.
- Only instances of the instructions documented in Section 6.4 may appear in the `code` array. Instances of instructions using the reserved opcodes (§6.2) or any opcodes not documented in this specification must not appear in the `code` array.
- If the `class` file version number is 51.0 or above, then neither the `jsr` opcode or the `jsr_w` opcode may appear in the `code` array.
- For each instruction in the `code` array except the last, the index of the opcode of the next instruction equals the index of the opcode of the current instruction plus the length of that instruction, including all its operands. The *wide* instruction is treated like any other instruction for these purposes; the opcode specifying the operation that a *wide* instruction is to modify is treated as one of the operands of that *wide* instruction. That opcode must never be directly reachable by the computation.
- The last byte of the last instruction in the `code` array must be the byte at index `code_length - 1`.

The static constraints on the operands of instructions in the `code` array are as follows:

- The target of each jump and branch instruction (`jsr`, `jsr_w`, `goto`, `goto_w`, `ifeq`, `ifne`, `ifle`, `iflt`, `ifge`, `ifgt`, `ifnull`, `ifnonnull`, `if_icmpne`, `if_icmpne`, `if_icmplt`, `if_icmpge`, `if_icmpgt`, `if_acmpne`, `if_acmpne`) must be the opcode of an instruction within this method. The target of a jump or branch instruction must never be the opcode used to specify the operation to be modified by a *wide* instruction; a jump or branch target may be the *wide* instruction itself.
- Each target, including the default, of each *tableswitch* instruction must be the opcode of an instruction within this method. Each *tableswitch* instruction must have a number of entries in its jump table that is consistent with the value of its *low* and *high* jump table operands, and its *low* value must be less than or equal to its *high* value. No target of a *tableswitch* instruction may be the opcode used to specify the operation to be modified by a *wide* instruction; a *tableswitch* target may be a *wide* instruction itself.
- Each target, including the default, of each *lookupswitch* instruction must be the opcode of an instruction within this method. Each *lookupswitch* instruction

must have a number of *match-offset* pairs that is consistent with the value of its *npairs* operand. The *match-offset* pairs must be sorted in increasing numerical order by signed *match* value. No target of a *lookupswitch* instruction may be the opcode used to specify the operation to be modified by a *wide* instruction; a *lookupswitch* target may be a *wide* instruction itself.

- The operand of each *ldc* instruction must be a valid index into the `constant_pool` table. The operands of each *ldc_w* instruction must represent a valid index into the `constant_pool` table. In both cases, the constant pool entry referenced by that index must be of type:
 - `CONSTANT_Integer`, `CONSTANT_Float` or `CONSTANT_String` if the `class` file version number is less than 49.0.
 - `CONSTANT_Integer`, `CONSTANT_Float`, `CONSTANT_String` or `CONSTANT_Class` if the `class` file version number is 49.0 or above.
- The operands of each *ldc2_w* instruction must represent a valid index into the `constant_pool` table. The constant pool entry referenced by that index must be of type `CONSTANT_Long` or `CONSTANT_Double`. In addition, the subsequent constant pool index must also be a valid index into the constant pool, and the constant pool entry at that index must not be used.
- The operands of each *getfield*, *putfield*, *getstatic*, and *putstatic* instruction must represent a valid index into the `constant_pool` table. The constant pool entry referenced by that index must be of type `CONSTANT_Fieldref`.
- The indexbyte operands of each *invokevirtual*, *invokespecial*, and *invokestatic* instruction must represent a valid index into the `constant_pool` table. The constant pool entry referenced by that index must be of type `CONSTANT_Methodref`.
- Only the *invokespecial* instruction is allowed to invoke an instance initialization method (§2.9). No other method whose name begins with the character '<' ('\u003c') may be called by the method invocation instructions. In particular, the class or interface initialization method specially named `<clinit>` is never called explicitly from Java virtual machine instructions, but only implicitly by the Java virtual machine itself.
- The indexbyte operands of each *invokeinterface* instruction must represent a valid index into the `constant_pool` table. The constant pool entry referenced by that index must be of type `CONSTANT_InterfaceMethodref`. The value of the *count* operand of each *invokeinterface*

instruction must reflect the number of local variables necessary to store the arguments to be passed to the interface method, as implied by the descriptor of the `CONSTANT_NameAndType_info` structure referenced by the `CONSTANT_InterfaceMethodref` constant pool entry. The fourth operand byte of each `invokeinterface` instruction must have the value zero.

- The operands of each `instanceof`, `checkcast`, `new`, and `anewarray` instruction and the indexbyte operands of each `multianewarray` instruction must represent a valid index into the `constant_pool` table. The constant pool entry referenced by that index must be of type `CONSTANT_Class`.
- No `anewarray` instruction may be used to create an array of more than 255 dimensions.
- No `new` instruction may reference a `CONSTANT_Class` `constant_pool` table entry representing an array class. The `new` instruction cannot be used to create an array.
- A `multianewarray` instruction must be used only to create an array of a type that has at least as many dimensions as the value of its `dimensions` operand. That is, while a `multianewarray` instruction is not required to create all of the dimensions of the array type referenced by its indexbyte operands, it must not attempt to create more dimensions than are in the array type. The `dimensions` operand of each `multianewarray` instruction must not be zero.
- The `atype` operand of each `newarray` instruction must take one of the values `T_BOOLEAN` (4), `T_CHAR` (5), `T_FLOAT` (6), `T_DOUBLE` (7), `T_BYTE` (8), `T_SHORT` (9), `T_INT` (10), or `T_LONG` (11).
- The index operand of each `iload`, `fload`, `aload`, `istore`, `fstore`, `astore`, `iinc`, and `ret` instruction must be a nonnegative integer no greater than `max_locals`-1.
- The implicit index of each `iload_<n>`, `fload_<n>`, `aload_<n>`, `istore_<n>`, `fstore_<n>`, and `astore_<n>` instruction must be no greater than the value of `max_locals`-1.
- The index operand of each `lload`, `dload`, `lstore`, and `dstore` instruction must be no greater than the value of `max_locals`-2.
- The implicit index of each `lload_<n>`, `dload_<n>`, `lstore_<n>`, and `dstore_<n>` instruction must be no greater than the value of `max_locals`-2.
- The indexbyte operands of each `wide` instruction modifying an `iload`, `fload`, `aload`, `istore`, `fstore`, `astore`, `ret`, or `iinc` instruction must represent a nonnegative integer no greater than `max_locals`-2.

tive integer no greater than `max_locals`-1. The indexbyte operands of each *wide* instruction modifying an *lload*, *dload*, *lstore*, or *dstore* instruction must represent a nonnegative integer no greater than `max_locals`-2.

4.9.2 Structural Constraints

The structural constraints on the `code` array specify constraints on relationships between Java virtual machine instructions. The structural constraints are as follows:

- Each instruction must only be executed with the appropriate type and number of arguments in the operand stack and local variable array, regardless of the execution path that leads to its invocation. An instruction operating on values of type `int` is also permitted to operate on values of type `boolean`, `byte`, `char`, and `short`. (As noted in §2.3.4 and §2.11.1, the Java virtual machine internally converts values of types `boolean`, `byte`, `char`, and `short` to type `int`.)
- If an instruction can be executed along several different execution paths, the operand stack must have the same depth (§2.6.2) prior to the execution of the instruction, regardless of the path taken.
- At no point during execution can the order of the local variable pair holding a value of type `long` or `double` be reversed or the pair split up. At no point can the local variables of such a pair be operated on individually.
- No local variable (or local variable pair, in the case of a value of type `long` or `double`) can be accessed before it is assigned a value.
- At no point during execution can the operand stack grow to a depth (§2.6.2) greater than that implied by the `max_stack` item.
- At no point during execution can more values be popped from the operand stack than it contains.
- Each *invokespecial* instruction must name an instance initialization method (§2.9), a method in the current class, or a method in a superclass of the current class.
If an *invokespecial* instruction names an instance initialization method from a class that is not the current class or a superclass, and the target reference on the operand stack is a class instance created by an earlier *new* instruction, then *invokespecial* must name an instance initialization method from the class of that class instance.

- When the instance initialization method (§2.9) is invoked, an uninitialized class instance must be in an appropriate position on the operand stack. An instance initialization method must never be invoked on an initialized class instance.
- When any instance method is invoked or when any instance variable is accessed, the class instance that contains the instance method or instance variable must already be initialized.
- There must never be an uninitialized class instance on the operand stack or in a local variable when any backwards branch is taken.
- There must never be an uninitialized class instance on the operand stack or in a local variable when a *jsr* or *jsr_w* instruction is executed.
- Each instance initialization method (§2.9), 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 initialization 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.
- The arguments to each method invocation must be method invocation compatible (JLS3 §5.3) with the method descriptor (§4.3.3).
- The type of every class instance that is the target of a method invocation instruction must be assignment compatible (JLS3 §5.2) with the class or interface type specified in the instruction. In addition, the type of the target of an *invokespecial* instruction must be assignment compatible with the current class, unless an instance initialization method is being invoked.
- Each return instruction must match its method's return type. If the method returns a `boolean`, `byte`, `char`, `short`, or `int`, only the *ireturn* instruction may be used. If the method returns a `float`, `long`, or `double`, only an *freturn*, *lreturn*, or *dreturn* instruction, respectively, may be used. If the method returns a `reference` type, it must do so using an *areturn* instruction, and the type of the returned value must be assignment compatible (JLS3 §5.2) with the return descriptor (§4.3.3) of the method. All instance initialization methods, class or interface initialization methods, and methods declared to return `void` must use only the *return* instruction.

- If *getfield* or *putfield* is used to access a **protected** field *of* declared in a superclass that is a member of a different runtime package than the current class, then the type of the class instance being accessed must be the same as or a subclass of the current class. If *invokevirtual* or *invokespecial* is used to access a **protected** method *of* declared in a superclass that is a member of a different runtime package than the current class, then the type of the class instance being accessed must be the same as or a subclass of the current class.
- The type of every class instance accessed by a *getfield* instruction or modified by a *putfield* instruction must be assignment compatible (JLS3 §5.2) with the class type specified in the instruction.
- The type of every value stored by a *putfield* or *putstatic* instruction must be compatible with the descriptor of the field (§4.3.2) of the class instance or class being stored into. If the descriptor type is `boolean`, `byte`, `char`, `short`, or `int`, then the value must be an `int`. If the descriptor type is `float`, `long`, or `double`, then the value must be a `float`, `long`, or `double`, respectively. If the descriptor type is a **reference** type, then the value must be of a type that is assignment compatible (JLS3 §5.2) with the descriptor type.
- The type of every value stored into an array by an *aastore* instruction must be a reference type. The component type of the array being stored into by the *aastore* instruction must also be a reference type.
- Each *athrow* instruction must throw only values that are instances of class `Throwable` or of subclasses of `Throwable`. Each class mentioned in a `catch_type` item of a method's exception table must be `Throwable` or of subclasses of `Throwable`.
- Execution never falls off the bottom of the code array.
- No return address (a value of type `returnAddress`) may be loaded from a local variable.
- The instruction following each *jsr* or *jsr_w* instruction may be returned to only by a single *ret* instruction.
- No *jsr* or *jsr_w* instruction *that is returned to* 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.)

- 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.

4.10 Verification of class Files

Even though any compiler for the Java programming language must only produce class files that satisfy all the static and structural constraints in the previous sections, the Java virtual machine has no guarantee that any file it is asked to load was generated by that compiler or is properly formed. Applications such as web browsers do not download source code, which they then compile; these applications download already-compiled `class` files. The browser needs to determine whether the `class` file was produced by a trustworthy compiler or by an adversary attempting to exploit the virtual machine.

An additional problem with compile-time checking is version skew. A user may have successfully compiled a class, say `PurchaseStockOptions`, to be a subclass of `TradingClass`. But the definition of `TradingClass` might have changed since the time the class was compiled in a way that is not compatible with preexisting binaries. Methods might have been deleted or had their return types or modifiers changed. Fields might have changed types or changed from instance variables to class variables. The access modifiers of a method or variable may have changed from `public` to `private`. For a discussion of these issues, see Chapter 13, “Binary Compatibility,” in the *The Java™ Language Specification*.

Because of these potential problems, the Java virtual machine needs to verify for itself that the desired constraints are satisfied by the `class` files it attempts to incorporate. A Java virtual machine implementation verifies that each `class` file satisfies the necessary constraints at linking time (§5.4).

Linking-time verification enhances the performance of the interpreter. Expensive checks that would otherwise have to be performed to verify constraints at runtime for each interpreted instruction can be eliminated. The Java virtual machine can assume that these checks have already been performed. For example, the Java virtual machine will already know the following:

- There are no operand stack overflows or underflows.
- All local variable uses and stores are valid.
- The arguments to all the Java virtual machine instructions are of valid types.

The verifier also performs verification that can be done without looking at the code array of the `Code` attribute (§4.7.3). The checks performed include the following:

- Ensuring that `final` classes are not subclassed and that `final` methods are not overridden.
- Checking that every class (except `Object`) has a direct superclass.
- Ensuring that the constant pool satisfies the documented static constraints: for example, that each `CONSTANT_Class_info` structure in the constant pool contains in its `name_index` item a valid constant pool index for a `CONSTANT_Utf8_info` structure.
- Checking that all field references and method references in the constant pool have valid names, valid classes, and a valid type descriptor.

Note that these checks do not ensure that the given field or method actually exists in the given class, nor do they check that the type descriptors given refer to real classes. They ensure only that these items are well formed. More detailed checking is performed when the bytecodes themselves are verified, and during resolution.

There are two strategies that Java virtual machines may use for verification. Verification by type checking must be used to verify `class` files whose version number is greater than or equal to 50.0.

Verification by type inference must be supported by all Java virtual machines, except those conforming to the Java ME CLDC and Java Card profiles, in order to verify `class` files whose version number is less than 50.0. Verification on virtual machines supporting the Java ME CLDC and Java Card profiles is governed by their respective specifications.

4.10.1 Verification by Type Checking

A `class` file whose version number is greater than or equal to 50.0 must be verified using the typechecking rules given in this section. If, and only if, a `class` file's version number equals 50.0, then if the typechecking fails, a virtual machine implementation may choose to attempt to perform verification by type inference.

This is a pragmatic adjustment, designed to ease the transition to the new verification discipline. Many tools that manipulate class files may

alter the bytecodes of a method in a manner that requires adjustment of the method's stack map frames. If a tool does not make the necessary adjustments to the stack map frames, typechecking may fail even though the bytecode is in principle valid (and would consequently verify under the old type inference scheme). To allow implementors time to adapt their tools, virtual machines may fall back to the older verification discipline, but only for a limited time.

In cases where typechecking fails but type inference is invoked and succeeds, a certain performance penalty is expected. Such a penalty is unavoidable. It also should serve as a signal to tool vendors that their output needs to be adjusted, and provides vendors with additional incentive to make these adjustments.

If a virtual machine implementation ever attempts to perform verification by type inference on version 50.0 `class` files, it must do so in all cases where verification by typechecking fails.

This means that that a virtual machine cannot choose to resort to type inference in once case and not in another. It must either reject class files that do not verify via typechecking, or else consistently failover to the type inferencing verifier whenever typechecking fails.

The type checker requires a list of stack map frames for each method with a `Code` attribute. The type checker reads the stack map frames for each such method and uses these maps to generate a proof of the type safety of the instructions in the `Code` attribute. The list of stack map frames is given by the `StackMapTable` (§4.7.4) attribute of the `Code` attribute.

The intent is that a stack map frame must appear at the beginning of each basic block in a method. The stack map frame specifies the verification type of each operand stack entry and of each local variable at the start of each basic block.

The type rules that the typechecker enforces are specified by means of Prolog clauses. English language text is used to describe the type rules in an informal way, while the Prolog code provides a formal specification.

Iff the predicate `classIsTypeSafe` is not true, the type checker must throw the exception `VerifyError` to indicate that the `class` file is malformed. Otherwise,

the `class` file has type checked successfully and bytecode verification has completed successfully.

```
classIsTypeSafe(Class) :-
    classClassName(Class, Name),
    classDefiningLoader(Class, L),
    superclassChain(Name, L, Chain),
    Chain \= [],
    classSuperClassName(Class, SuperclassName),
    loadedClass(SuperclassName, L, Superclass),
    class IsNotFinal(Superclass),
    classMethods(Class, Methods),
    checklist(methodIsTypeSafe(Class), Methods).

classIsTypeSafe(Class) :-
    classClassName(Class, ‘java/lang/Object’),
    classDefiningLoader(Class, L),
    isBootstrapClassLoader(L),
    classMethods(Class, Methods),
    checklist(methodIsTypeSafe(Class), Methods).
```

Thus, a class is type safe if all its methods are type safe, and it does not subclass a final class.

The predicate `classIsTypeSafe` assumes that `Class` is a Prolog term representing a binary class that has been successfully parsed and loaded. This specification does not mandate the precise structure of this term, but does require that certain predicates (e.g., `classMethods`) be defined upon it, as specified in Section 4.10.1.3.1.

For example, we assume a predicate `classMethods(Class, Methods)` that, given a term representing a class as described above as its first argument, binds its second argument to a list comprising all

the methods of the class, represented in a convenient form described below.

We also require the existence of a predicate `loadedClass(Name, InitiatingLoader, ClassDefinition)` which asserts that there exists a class named `Name` whose representation (in accordance with this specification) when loaded by the class loader `InitiatingLoader` is `ClassDefinition`. Additional required predicates are discussed in §4.10.1.3.1.

Individual instructions are presented as terms whose functor is the name of the instruction and whose arguments are its parsed operands.

For example, an `aload` instruction is represented as the term `aload(N)`, which includes the index `N` that is the operand of the instruction.

A few instructions have operands that are constant pool entries representing methods or fields. As specified in §4.3.3, methods are represented by `CONSTANT_InterfaceMethodref_info` (for interface methods) or `CONSTANT_Methodref_info` (for other methods) structures in the constant pool. Such structures are represented here as functor applications of the form `imethod(MethodClassName, MethodName, MethodDescriptor)` (for interface methods) or `method (MethodClassName, MethodName, MethodDescriptor)` (for other methods), where `MethodClassName` is the name of the class referenced by the `class_index` item for the structure, and `MethodName` and `MethodDescriptor` correspond to the name and type descriptor referenced by the `name_and_type_index` of the structure.

Similarly, fields are represented by `CONSTANT_Fieldref_info` structures in the class file. These structures are represented here as functor applications of the form `field(FieldClassName, FieldName, FieldDescriptor)` where `FieldClassName` is the name of the class referenced by the `class_index` item in the structure, and `FieldName` and `FieldDescriptor` correspond to the name and type descriptor referenced by the `name_and_type_index` item of the structure. For clarity, we assume that type descriptors are mapped into more readable names: the leading L and trailing ; are dropped from class names, and the base type characters used for primitive types are mapped to the names of those types).

So, a **getfield** instruction whose operand was an index into the constant pool that refers to a field **foo** of type **F** in class **Bar** would be represented as `getfield(field('Bar', 'foo', 'F'))`.

Constant pool entries that refer to constant values, such as **CONSTANT_String**, **CONSTANT_Integer**, **CONSTANT_Float**, **CONSTANT_Long**, **CONSTANT_Double** and **CONSTANT_Class**, are encoded via the functors whose names are **string**, **int**, **float**, **long**, **double** and **classConstant** respectively.

So an **ldc** instruction for loading the integer 91 would be encoded as `ldc(int(91))`.

The instructions as a whole are represented as a list of terms of the form `instruction(Offset, AnInstruction)`.

For example, `instruction(21, aload(1))`.

The order of instructions in this list must be the same as in the class file.

Stack map frames are represented as a list of terms of the form `stackMap(Offset, TypeState)` where **Offset** is an integer indicating the offset of the instruction the frame map applies to, and **TypeState** is the expected incoming type state for that instruction. The order of instructions in this list must be the same as in the class file.

TypeState has the form `frame(LocalStack, OperandStack, Flags)`.

LocalStack is a list of verification types, such that the *N*th element of the list (with 0 based indexing) represents the type of local variable *N*. If any local variable in **LocalStack** has the type **uninitializedThis**, **Flags** is `[flagThisUninit]`, otherwise it is an empty list.

OperandStack is a list of types, such that the first element represents the type of the top of the operand stack, and the elements below the top follow in the appropriate order.

However, note again that types of size 2 are represented by two entries, with the first entry being top and the second one being the type itself.

So, a stack with a `double`, an `int` and a `long` would be represented as [top, double, int, top, long].

Array types are represented by applying the functor `arrayOf` to an argument denoting the component type of the array. Other reference types are represented using the functor class. Hence `class(N, L)` represents the class whose binary name is N as loaded by the loader L.

Thus, L is an initiating loader of the class represented by `class(N, L)`. It may, or may not, be its defining loader.

The type `uninitialized(offset)` is represented by applying the functor `uninitialized` to an argument representing the numerical value of the `offset`. Other verification types are represented by Prolog atoms whose name denotes the verification type in question.

So, the class `Object` would be represented as `class('java/lang/Object', BL)`, where BL is the bootstrap loader. The types `int[]` and `Object[]` would be represented by `arrayOf(int)` and `arrayOf(class('java/lang/Object', BL))` respectively.

Flags is a list which may either be empty or have the single element `flagThisUninit`.

This flag is used in constructors, to mark type states where initialization of `this` has not yet been completed. In such type states, it is illegal to return from the method.

4.10.1.1 The Type Hierarchy

The typechecker enforces a type system based upon a hierarchy of verification types, illustrated in figure 1. Most verifier types have a direct correspondence with Java virtual machine field type descriptors as given in Table 4.2. The only exceptions are the field descriptors B, C, S and Z all of which correspond to the verifier type `int`.

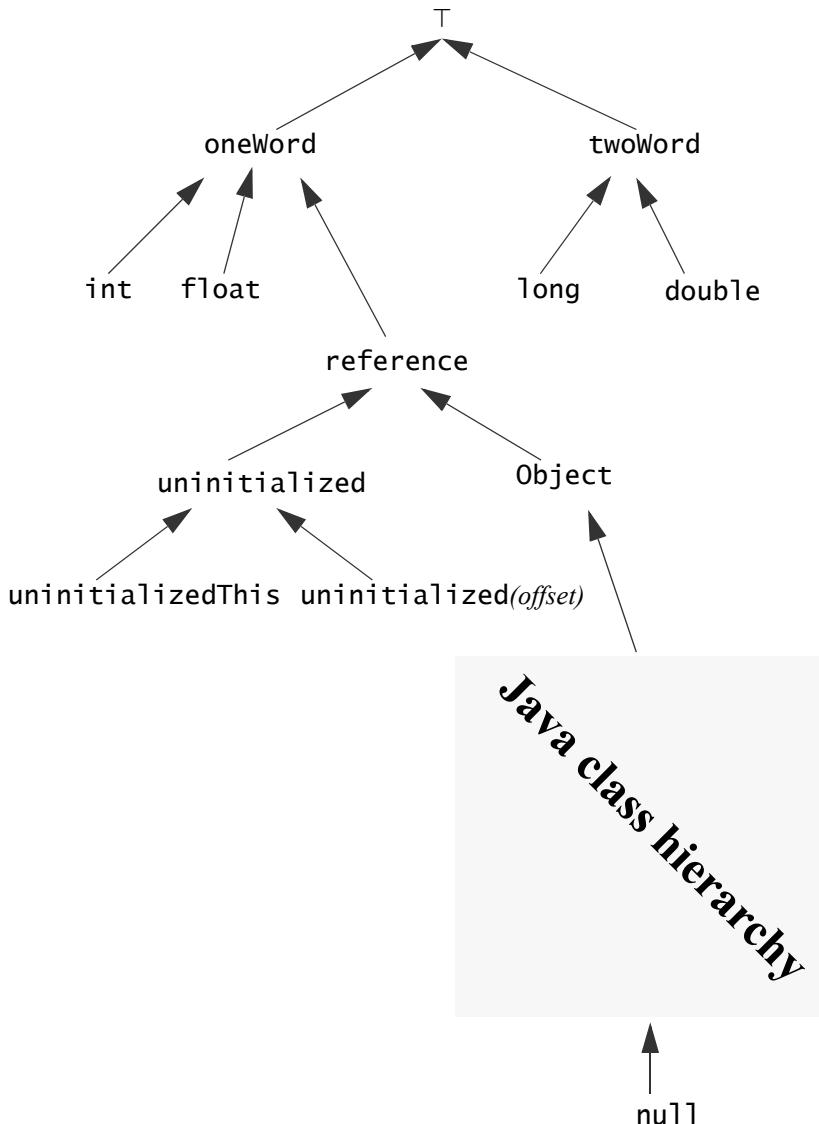


Figure 1: The verification type Hierarchy

4.10.1.2 Subtyping Rules

Subtyping is reflexive.

```
isAssignable(X, X) .
```

```
isAssignable(oneWord, top).
```

```
isAssignable(twoWord, top).
```

```
isAssignable(int, X) :- isAssignable(oneWord, X).
```

```
isAssignable(float, X) :- isAssignable(oneWord, X).
```

```
isAssignable(long, X) :- isAssignable(twoWord, X).
```

```
isAssignable(double, X) :- isAssignable(twoWord, X).
```

```
isAssignable(reference, X) :- isAssignable(oneWord, X).
```

```
isAssignable(class(_, _), X) :- isAssignable(reference, X).
```

```
isAssignable(arrayOf(_), X) :- isAssignable(reference, X).
```

```
isAssignable(uninitialized, X) :- isAssignable(reference, X).
```

```
isAssignable(uninitializedThis, X) :- isAssignable(uninitialized, X).
```

```
isAssignable(uninitialized(_), X) :- isAssignable(uninitialized, X).
```

```
isAssignable(null, class(_, _)).
```

```
isAssignable(null, arrayOf(_)).
```

```
isAssignable(null, X) :-
```

```
    isAssignable(class('java/lang/Object', BL), X),
```

```
    isBootstrapLoader(BL).
```

These subtype rules are not necessarily the most obvious formulation of subtyping. There is a clear split between subtyping rules for reference types in the Java programming language, and rules for the remaining verification types. The split allows us to state general subtyping relations between Java programming language types and other verification types. These relations hold independently of a Java type's position in the class hierarchy, and help to prevent excessive class loading in a Java virtual machine implementation. For example, we do not want to start climbing up the Java class hierarchy in response to a query of the form `class(foo,L) <: twoWord`.

Subtype rules for the reference types in the Java programming language are specified recursively in the obvious way with `isJavaAssignable`. The remaining verification types have subtype rules of the form:

```
isAssignable(v, X) :- isAssignable(the_direct_supertype_of_v, X).
```

That is, `v` is a subtype of `X` if the direct supertype of `v` is a subtype of `X`.

We also have a rule that says subtyping is reflexive, so together these rules cover most verification types that are not reference types in the Java programming language.

```
isAssignable(class(X, Lx), class(Y, Ly)) :-  
    isJavaAssignable(class(X, Lx), class(Y, Ly)).  
  
isAssignable(arrayOf(X), class(Y, L)) :-  
    isJavaAssignable(arrayOf(X), class(Y, L)).  
  
isAssignable(arrayOf(X), arrayOf(Y)) :-  
    isJavaAssignable(arrayOf(X), arrayOf(Y)).
```

For assignments, interfaces are treated like `Object`.

```
isJavaAssignable(class(_, _), class(To, L)) :-  
    loadedClass(To, L, ToClass),  
    classIsInterface(ToClass).  
  
isJavaAssignable(From, To) :-  
    isJavaSubclassOf(From, To).
```

Arrays are subtypes of `Object`.

```
isJavaAssignable(arrayOf(_), class('java/lang/Object', BL)) :-  
    isBootstrapLoader(BL).
```

The intent here is that array types are subtypes of `Cloneable` and
`java.io.Serializable`.

```
isJavaAssignable(arrayOf(_), X) :-  
    isArrayInterface(X).
```

Subtyping between arrays of primitive type is the identity relation.

```
isJavaAssignable(arrayOf(X), arrayOf(Y)) :-  
    atom(X),  
    atom(Y),  
    X = Y.
```

Subtyping between arrays of reference type is covariant.

```
isJavaAssignable(arrayOf(X), arrayOf(Y)) :-  
    compound(X), compound(Y), isJavaAssignable(X, Y).
```

```
isArrayInterface(class('java/lang/Cloneable', BL)) :-  
    isBootstrapLoader(BL).  
isArrayInterface(class('java/io/Serializable', BL)) :-  
    isBootstrapLoader(BL).
```

Subclassing is reflexive.

```
isJavaSubclassOf(class(SubClassName, L),
                 class(SubClassName, L)).  
  

isJavaSubclassOf(class(SubClassName, LSub),
                 class(SuperClassName, LSuper)) :-  

    superclassChain(SubClassName, LSub, Chain),  

    member(class(SuperClassName, L), Chain),  

    loadedClass(SuperClassName, L, Sup),  

    loadedClass(SuperClassName, LSuper, Sup).  
  

sizeOf(X, 2) :- isAssignable(X, twoWord).  

sizeOf(X, 1) :- isAssignable(X, oneWord).  

sizeOf(top, 1).
```

Subtyping is extended pointwise to type states.

The local variable array of a method has a fixed length by construction (in `methodInitialStackFrame`) while the operand stack grows and shrinks. Therefore, we require an explicit check on the length of the operand stacks whose assignability is desired.

```
frameIsAssignable(frame(Locale1, StackMap1, Flags1),
                  frame(Locale2, StackMap2, Flags2)) :-  

    length(StackMap1, StackMapLength),  

    length(StackMap2, StackMapLength),  

    maplist(isAssignable, Locale1, Locale2),  

    maplist(isAssignable, StackMap1, StackMap2),  

    subset(Flags1, Flags2).
```

4.10.1.3 Typechecking Rules

4.10.1.3.1 Accessors

Stipulated Accessors: Throughout this specification, we assume the existence of certain Prolog predicates whose formal definitions are not given in the specification. We list these predicates and describe their expected behavior below.

The principle guiding the determination as to which accessors are fully specified and which are stipulated is that we do not want to over-specify the representation of the class file. Providing specific accessors to the class or method term would force us to completely specify a format for the Prolog term representing the class file.

`parseFieldDescriptor(Descriptor, Type)`

Converts a field descriptor, `Descriptor`, into the corresponding verification type `Type` (see the beginning of Section 4.10.1.1 for the specification of this correspondence).

`parseMethodDescriptor(Descriptor, ArgTypeList, ReturnType)`

Converts a method descriptor, `Descriptor`, into a list of verification types, `ArgTypeList`, corresponding (Section 4.10.1.1) to the method argument types, and a verification type, `ReturnType`, corresponding to the return type.

`parseCodeAttribute(Class, Method, FrameSize, MaxStack,
 ParsedCode, Handlers, StackMap)`

Extracts the instruction stream, `ParsedCode`, of the method `Method` in `Class`, as well as the maximum operand stack size, `MaxStack`, the maximal number of local variables, `FrameSize`, the exception handlers, `Handlers`, and the stack map `StackMap`. The representation of the instruction stream and stack map attribute must be as specified in the beginning of §4.10.1. Each exception handler is represented by a functor application of the form `handler(Start, End, Target, ClassName)` whose arguments are, respectively, the start and end of the range of instructions covered by the handler, the first instruction of the handler code, and the name of the exception class that this handler is designed to handle.

classClassName(Class, ClassName)

Extracts the name, ClassName, of the class Class.

classIsInterface(Class)

True iff the class, Class, is an interface.

classIsNotFinal(Class)

True iff the class, Class, is not a final class.

classSuperClassName(Class, SuperClassName)

Extracts the name, SuperClassName, of the superclass of class Class.

classInterfaces(Class, Interfaces)

Extracts a list, Interfaces, of the direct superinterfaces of the class Class.

classMethods(Class, Methods)

Extracts a list, Methods, of the methods declared in the class Class.

classAttributes(Class, Attributes)

Extracts a list, Attributes, of the attributes of the class Class. Each attribute is represented as a functor application of the form attribute(AttributeName, AttributeContents), where AttributeName is the name of the attribute. The format of the attributes contents is unspecified.

classDefiningLoader(Class, Loader)

Extracts the defining class loader, Loader, of the class Class.

isBootstrapLoader(Loader)

True iff the class loader Loader is the bootstrap class loader.

methodName(Method, Name)

Extracts the name, Name, of the method Method.

methodAccessFlags(Method, AccessFlags)

Extracts the access flags, AccessFlags, of the method Method.

methodDescriptor(Method, Descriptor)

Extracts the descriptor, Descriptor, of the method Method.

methodAttributes(Method, Attributes)

Extracts a list, Attributes, of the attributes of the method Method.

`isNotFinal(Method, Class)`

True iff Method in class Class is not final.

`isProtected(MemberClass, MemberName, MemberDescriptor)`

True iff there is a member named MemberName with descriptor MemberDescriptor in the class MemberClass and it is protected.

`isNotProtected(MemberClass, MemberName, MemberDescriptor)`

True iff there is a member named MemberName with descriptor MemberDescriptor in the class MemberClass and it is not protected.

`samePackageName(Class1, Class2)`

True iff the package names of Class1 and Class2 are the same.

`differentPackageName(Class1, Class2)`

True iff the package names of Class1 and Class2 are different.

Specified Accessors and Utilities: We define accessor and utility rules that extract necessary information from the representation of the class and its methods.

An environment is a six-tuple consisting of:

- a class
 - a method
 - the declared return type of the method
 - the instructions in a method
 - the maximal size of the operand stack
 - a list of exception handlers
-

`maxOperandStackLength(Environment, MaxStack) :-`

`Environment = environment(_Class, _Method, _ReturnType,
_Instructions, MaxStack, _Handlers).`

`exceptionHandlers(Environment, Handlers) :-`

`Environment = environment(_Class, _Method, _ReturnType,
_Instructions, _, Handlers).`

```

thisMethodReturnType(Environment, ReturnType) :-  

    Environment = environment(_Class, _Method, ReturnType,  

                             _Instructions, _, _).  
  

thisClass(Environment, class(ClassName, L)) :-  

    Environment = environment(Class, _Method, _ReturnType,  

                             _Instructions, _, _),  

    classDefiningLoader(Class, L),  

    classClassName(Class, ClassName).  
  

allInstructions(Environment, Instructions) :-  

    Environment = environment(_Class, _Method, _ReturnType,  

                             Instructions, _, _).  
  

offsetStackFrame(Environment, Offset, StackFrame) :-  

    allInstructions(Environment, Instructions),  

    member(stackMap(Offset, StackFrame), Instructions).  
  

currentClassLoader(Environment, Loader) :-  

    thisClass(Environment, class(_, Loader)).  
  

notMember(_, []).  

notMember(X, [A | More]) :- X \= A, notMember(X, More).  
  

sameRuntimePackage(Class1, Class2) :-  

    classDefiningLoader(Class1, L),  

    classDefiningLoader(Class2, L),  

    samePackageName(Class1, Class2).  
  

differentRuntimePackage(Class1, Class2) :-  

    classDefiningLoader(Class1, L1),  

    classDefiningLoader(Class2, L2),  

    L1 \= L2.  

differentRuntimePackage(Class1, Class2) :-  

    differentPackageName(Class1, Class2).

```

4.10.1.3.2 Abstract & Native Methods

Abstract methods and native methods are considered to be type safe if they do not override a final method.

```
methodIsTypeSafe(Class, Method) :-  
    doesNotOverrideFinalMethod(Class, Method),  
    methodAccessFlags(Method, AccessFlags),  
    member(Abstract, AccessFlags).
```

```
methodIsTypeSafe(Class, Method) :-  
    doesNotOverrideFinalMethod(Class, Method),  
    methodAccessFlags(Method, AccessFlags),  
    member(Native, AccessFlags).
```

```
doesNotOverrideFinalMethod(class('java/lang/Object', L), Method) :-  
    isBootstrapLoader(L).
```

```
doesNotOverrideFinalMethod(Class, Method) :-  
    classSuperClassName(Class, SuperclassName),  
    classDefiningLoader(Class, L),  
    loadedClass(SuperclassName, L, Superclass),  
    classMethods(Superclass, MethodList),  
    finalMethodNotOverridden(Method, Superclass, MethodList).
```

```
finalMethodNotOverridden(Method, Superclass, MethodList) :-  
    methodName(Method, Name),  
    methodDescriptor(Method, Descriptor),  
    member(method(_, Name, Descriptor), MethodList),  
    isNotFinal(Method, Superclass).
```

```
finalMethodNotOverridden(Method, Superclass, MethodList) :-  
    methodName(Method, Name),  
    methodDescriptor(Method, Descriptor),  
    notMember(method(_, Name, Descriptor), MethodList),  
    doesNotOverrideFinalMethod(Superclass, Method).
```

4.10.1.3.3 Checking Code

Non-abstract, non-native methods are type correct if they have code and the code is type correct.

```
methodIsTypeSafe(Class, Method) :-  
    doesNotOverrideFinalMethod(Class, Method),  
    methodAccessFlags(Method, AccessFlags),  
    methodAttributes(Method, Attributes),  
    notMember(native, AccessFlags),  
    notMember(abstract, AccessFlags),  
    member(attribute('Code', _), Attributes),  
    methodWithCodeIsTypeSafe(Class, Method).
```

A method with code is type safe if it is possible to merge the code and the stack frames into a single stream such that each stack map precedes the instruction it corresponds to, and the merged stream is type correct.

```
methodWithCodeIsTypeSafe(Class, Method) :-  
    parseCodeAttribute(Class, Method, FrameSize, MaxStack,  
                      ParsedCode, Handlers, StackMap),  
    mergeStackMapAndCode(StackMap, ParsedCode, MergedCode),  
    methodInitialStackFrame(Class, Method, FrameSize, StackFrame,  
                           ReturnType),  
    Environment = environment(Class, Method, ReturnType,  
                               MergedCode, MaxStack, Handlers),  
    handlersAreLegal(Environment),  
    mergedCodeIsTypeSafe(Environment, MergedCode, StackFrame).
```

The initial type state of a method consists of an empty operand stack and local variable types derived from the type of `this` and the arguments, as well as the appropriate flag, depending on whether this is an `<init>` method.

```
methodInitialStackFrame(Class, Method, FrameSize,
                       frame(Locals, [], Flags), ReturnType):-  

    methodDescriptor(Method, Descriptor),
    parseMethodDescriptor(Descriptor, RawArgs, ReturnType),
    expandTypeList(RawArgs, Args),
    methodInitialThisType(Class, Method, ThisList),
    flags(ThisList, Flags),
    append(ThisList, Args, ThisArgs),
    expandToLength(ThisArgs, FrameSize, top, Locals).
```

```
flags([uninitializedThis], [flagThisUninit]).  
flags(X, []) :- X \= [uninitializedThis].
```

```
expandToLength(List, Size, _Filler, List) :- length(List, Size).  
expandToLength(List, Size, Filler, Result) :-  

    length(List, ListLength),
    ListLength < Size,
    Delta is Size - ListLength,
    length(Extra, Delta),
    checklist=(Filler), Extra),
    append(List, Extra, Result).
```

For a static method **this** is irrelevant; the list is empty. For an instance method, we get the type of **this** and put it in a list.

```
methodInitialThisType(_Class, Method, []) :-  
    methodAccessFlags(Method, AccessFlags),  
    member(static, AccessFlags),  
    methodName(Method, MethodName),  
    MethodName \= '<init>' .  
  
methodInitialThisType(Class, Method, [This]) :-  
    methodAccessFlags(Method, AccessFlags),  
    notMember(static, AccessFlags),  
    instanceMethodInitialThisType(Class, Method, This).
```

In the **<init>** method of **Object**, the type of **this** is **Object**. In other **<init>** methods, the type of **this** is **uninitializedThis**. Otherwise, the type of **this** in an instance method is **class(N, L)**, where N is the name of the class containing the method and L is its defining class loader.

```
instanceMethodInitialThisType(Class, Method,  
    class('java/lang/Object', L)) :-  
    className(Method, '<init>'),  
    classDefiningLoader(Class, L),  
    isBootstrapLoader(L),  
    classClassName(Class, 'java/lang/Object').  
  
instanceMethodInitialThisType(Class, Method, uninitializedThis) :-  
    className(Method, '<init>'),  
    classClassName(Class, className),  
    classDefiningLoader(Class, CurrentLoader),  
    superclassChain(className, CurrentLoader, Chain),  
    Chain \= [] .
```

```
instanceMethodInitialThisType(Class, Method, class(ClassName, L)) :-  

    methodName(Method, MethodName),  

    MethodName \= '<init>',  

    classDefiningLoader(Class, L),  

    classClassName(Class, ClassName).
```

Below are the rules for iterating through the code stream. The assumption is that the stream is a well formed mixture of instructions and stack maps, such that the stack map for bytecode index N appears just before instruction N . The rules for building this mixed stream are given later, by the predicate `mergeStackMapAndCode`.

The special marker `afterGoto` is used to indicate an unconditional branch. If we have an unconditional branch at the end of the code, stop.

```
mergedCodeIsTypeSafe(_Environment, [endOfCode(Offset)], afterGoto).
```

After an unconditional branch, if we have a stack map giving the type state for the following instructions, we can proceed and typecheck them using the type state provided by the stack map.

```
mergedCodeIsTypeSafe(Environment,  

    [stackMap(Offset, MapFrame) | MoreCode],  

    afterGoto):-  

    mergedCodeIsTypeSafe(Environment, MoreCode, MapFrame).
```

If we have a stack map and an incoming type state, the type state must be assignable to the one in the stack map. We may then proceed to type check the rest of the stream with the type state given in the stack map.

```
mergedCodeIsTypeSafe(Environment,  

    [stackMap(Offset, MapFrame) | MoreCode],  

    frame(Locals, OperandStack, Flags)) :-  

    frameIsAssignable(frame(Locals, OperandStack, Flags),  

        MapFrame),  

    mergedCodeIsTypeSafe(Environment, MoreCode, MapFrame).
```

It is illegal to have code after an unconditional branch without a stack map frame being provided for it.

```
mergedCodeIsTypeSafe(_Environment,
    [instruction(_,_) | _MoreCode],
    afterGoto) :-  

    write_ln('No stack frame after unconditional branch'),
    fail.
```

A merged code stream is type safe relative to an incoming type state T if it begins with an instruction I that is type safe relative to T, and I satisfies its exception handlers, and the tail of the stream is type safe given the type state following that execution of I.

NextStackFrame indicates what falls through to the following instruction. ExceptionStackFrame indicates what is passed to exception handlers.

```
mergedCodeIsTypeSafe(Environment,
    [instruction(Offset,Parse) | MoreCode],
    frame(Locals, OperandStack, Flags)) :-  

    instructionIsTypeSafe(Parse, Environment, Offset,
        frame(Locals, OperandStack, Flags),
        NextStackFrame, ExceptionStackFrame),
    instructionSatisfiesHandlers(Environment, Offset,
        ExceptionStackFrame),
    mergedCodeIsTypeSafe(Environment, MoreCode,
        NextStackFrame).
```

Branching to a target is type safe if the target has an associated stack frame, Frame, and the current stack frame, StackFrame, is assignable to Frame.

```
targetIsTypeSafe(Environment, StackFrame, Target) :-  

    offsetStackFrame(Environment, Target, Frame),
    frameIsAssignable(StackFrame, Frame).
```

4.10.1.3.4 Combining Streams of Stack Maps and Instructions

Merging an empty **StackMap** and a list of instructions yields the original list of instructions.

```
mergeStackMapAndCode([], CodeList, CodeList).
```

Given a list of stack map frames beginning with the type state for the instruction at Offset, and a list of instructions beginning at Offset, the merged list is the head of the stack frame list, followed by the head of the instruction list, followed by the merge of the tails of the two lists.

```
mergeStackMapAndCode([stackMap(Offset, Map) | RestMap],
                     [instruction(Offset, Parse) | RestCode],
                     [stackMap(Offset, Map), instruction(Offset, Parse) | RestMerge]) :-  

    mergeStackMapAndCode(RestMap, RestCode, RestMerge).
```

Otherwise, given a list of stack frames beginning with the type state for the instruction at OffsetM, and a list of instructions beginning at OffsetP, then, if $\text{OffsetP} < \text{OffsetM}$, the merged list consists of the head of the instruction list, followed by the merge of the stack frame list and the tail of the instruction list.

```
mergeStackMapAndCode([stackMap(OffsetM, Map) | RestMap],
                     [instruction(OffsetP, Parse) | RestCode],
                     [instruction(OffsetP, Parse) | RestMerge]) :-  

    OffsetP < OffsetM,  

    mergeStackMapAndCode([stackMap(OffsetM, Map) | RestMap],
                        RestCode, RestMerge).
```

Otherwise, the merge of the two lists is undefined. Since the instruction list has monotonically increasing offsets, the merge of the two lists is not defined unless every stack map frame offset has a corresponding instruction offset and the stack map frames are in monotonically increasing order.

4.10.1.3.5 Exception Handling

An instruction *satisfies its exception handlers* if it satisfies every exception handler that is applicable to the instruction.

```
instructionSatisfiesHandlers(Environment, Offset, ExceptionStackFrame) :-  
    exceptionHandlers(Environment, Handlers),  
    sublist(isApplicableHandler(Offset), Handlers, ApplicableHandlers),  
    checklist(instructionSatisfiesHandler(Environment,  
                                         ExceptionStackFrame),  
            ApplicableHandlers).
```

An exception handler is *applicable* to an instruction if the offset of the instruction is greater or equal to the start of the handler's range and less than the end of the handler's range.

```
isApplicableHandler(Offset, handler(Start, End, _Target, _ClassName)) :-  
    Offset >= Start,  
    Offset < End.
```

An instruction *satisfies* an exception handler if its incoming type state is StackFrame, and the handler's target (the initial instruction of the handler code) is type safe assuming an incoming type state T. The type state T is derived from StackFrame by replacing the operand stack with a stack whose sole element is the handler's exception class.

```
instructionSatisfiesHandler(Environment, StackFrame, Handler) :-  
    Handler = handler(_, _, Target, _),  
    currentClassLoader(Environment, CurrentLoader),  
    handlerExceptionClass(Handler, ExceptionClass, CurrentLoader),  
    /* The stack consists of just the exception. */  
    StackFrame = frame(Locals, _, Flags),  
    ExcStackFrame = frame(Locals, [ExceptionClass], Flags),  
    operandStackHasLegalLength(Environment, ExcStackFrame),  
    targetIsTypeSafe(Environment, ExcStackFrame, Target).
```

The exception class of a handler is **Throwable** if the handlers class entry is 0, otherwise it is the class named in the handler.

```
handlerExceptionClass(handler(_, _, _, 0),
                      class('java/lang/Throwable', BL), _) :-  

    isBootstrapLoader(BL).  

handlerExceptionClass(handler(_, _, _, Name), class(Name, L), L) :-  

    Name \= 0.
```

An exception handler is legal if its start (Start) is less than its end (End), there exists an instruction whose offset is equal to Start, there exists an instruction whose offset equals End and the handler's exception class is assignable to the class **Throwable**.

```
handlersAreLegal(Environment) :-  

    exceptionHandlers(Environment, Handlers),  

    checklist(handlerIsLegal(Environment), Handlers).  

handlerIsLegal(Environment, Handler) :-  

    Handler = handler(Start, End, Target, _),  

    Start < End,  

    allInstructions(Environment, Instructions),  

    member(instruction(Start, _), Instructions),  

    offsetStackFrame(Environment, Target, _),  

    instructionsIncludeEnd(Instructions, End),  

    currentClassLoader(Environment, CurrentLoader),  

    handlerExceptionClass(Handler, ExceptionClass, CurrentLoader),  

    isBootstrapLoader(BL),  

    isAssignable(ExceptionClass, class('java/lang/Throwable', BL)).  

instructionsIncludeEnd(Instructions, End) :-  

    member(instruction(End, _), Instructions).  

instructionsIncludeEnd(Instructions, End) :-  

    member(endOfCode(End), Instructions).
```

4.10.1.4 Instructions

4.10.1.4.1 Isomorphic Instructions

Many bytecodes have type rules that are completely isomorphic to the rules for other bytecodes. If a bytecode $b1$ is isomorphic to another bytecode $b2$, then the type rule for $b1$ is the same as the type rule for $b2$.

```
instructionIsTypeSafe(Instruction, Environment, Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    instructionHasEquivalentTypeRule(Instruction,  

                                      IsomorphicInstruction),  

    instructionIsTypeSafe(IsomorphicInstruction, Environment, Offset,  

                          StackFrame, NextStackFrame,  

                          ExceptionStackFrame).
```

4.10.1.4.2 Manipulating the Operand Stack

This section defines the rules for legally manipulating the type state's operand stack. Manipulation of the operand stack is complicated by the fact that some types occupy two entries on the stack. The predicates given in this section take this into account, allowing the rest of the specification to abstract from this issue.

```
canPop(frame(Locals, OperandStack, Flags), Types,
       frame(Locals, PoppedOperandStack, Flags)) :-  

    popMatchingList(OperandStack, Types, PoppedOperandStack).
```

```
popMatchingList(OperandStack, [], OperandStack).  

popMatchingList(OperandStack, [P | Rest], NewOperandStack) :-  

    popMatchingType(OperandStack, P, TempOperandStack,  

                    _ActualType),  

    popMatchingList(TempOperandStack, Rest, NewOperandStack).
```

Pop an individual type off the stack. More precisely, if the logical top of the stack is some subtype of the specified type, Type, then pop it. If a type occupies two stack slots, the logical top of stack type is really the type just below the top, and the top of stack is the unusable type **top**.

```
popMatchingType([ActualType | OperandStack],
               Type, OperandStack, ActualType) :-
    sizeOf(Type, 1),
    isAssignable(ActualType, Type).

popMatchingType([top, ActualType | OperandStack],
               Type, OperandStack, ActualType) :-
    sizeOf(Type, 2),
    isAssignable(ActualType, Type).
```

Push a logical type onto the stack. The exact behavior varies with the size of the type. If the pushed type is of size 1, we just push it onto the stack. If the pushed type is of size 2, we push it, and then push **top**.

```
pushOperandStack(OperandStack, 'void', OperandStack).
pushOperandStack(OperandStack, Type, [Type | OperandStack]) :-
    sizeOf(Type, 1).
pushOperandStack(OperandStack, Type, [top, Type | OperandStack]) :-
    sizeOf(Type, 2).
```

The length of the operand stack must not exceed the declared maximum stack length.

```
operandStackHasLegalLength(Environment, OperandStack) :-
    length(OperandStack, Length),
    maxOperandStackLength(Environment, MaxStack),
    Length =< MaxStack.
```

Category 1 types occupy a single stack slot. Popping a logical type of category 1, Type, off the stack is possible if the top of the stack is Type and Type is not **top** (otherwise it could denote the upper half of a category 2 type). The result is the incoming stack, with the top slot popped off.

`popCategory1([Type | Rest], Type, Rest) :-`

```
Type \= top,  
sizeOf(Type, 1).
```

Category 2 types occupy two stack slots. Popping a logical type of category 2, Type, off the stack is possible if the top of the stack is type **top**, and the slot directly below it is Type. The result is the incoming stack, with the top 2 slots popped off.

`popCategory2([top, Type | Rest], Type, Rest) :-`

```
sizeOf(Type, 2).
```

`canSafelyPush(Environment, InputOperandStack, Type,
OutputOperandStack) :-`

```
pushOperandStack(InputOperandStack, Type, OutputOperandStack),  
operandStackHasLegalLength(Environment, OutputOperandStack).
```

`canSafelyPushList(Environment, InputOperandStack, Types,
OutputOperandStack) :-`

```
canPushList(InputOperandStack, Types, OutputOperandStack),  
operandStackHasLegalLength(Environment, OutputOperandStack).
```

`canPushList(InputOperandStack, [Type | Rest], OutputOperandStack) :-`

```
pushOperandStack(InputOperandStack, Type, InterimOperandStack),  
canPushList(InterimOperandStack, Rest, OutputOperandStack).
```

`canPushList(InputOperandStack, [], InputOperandStack).`

4.10.1.4.3 Loads

All load instructions are variations on a common pattern, varying the type of the value that the instruction loads.

Loading a value of type Type from local variable Index is type safe, if the type of that local variable is ActualType, ActualType is assignable to Type, and pushing ActualType onto the incoming operand stack is a valid type transition that yields a new type state NextStackFrame. After execution of the load instruction, the type state will be NextStackFrame.

```
loadIsTypeSafe(Environment, Index, Type, StackFrame, NextStackFrame) :-  
    StackFrame = frame(Locals, _OperandStack, _Flags),  
    nth0(Index, Locals, ActualType),  
    isAssignable(ActualType, Type),  
    validTypeTransition(Environment, [], ActualType, StackFrame,  
        NextStackFrame).
```

4.10.1.4.4 Stores

All store instructions are variations on a common pattern, varying the type of the value that the instruction stores.

In general, a store instruction is type safe if the local variable it references is of a type that is a supertype of Type, and the top of the operand stack is of a subtype of Type, where Type is the type the instruction is designed to store.

More precisely, the store is type safe if one can pop a type ActualType that “matches” Type (i.e., is a subtype of Type) off the operand stack, and then legally assign that type the local variable LIndex.

```
storeIsTypeSafe(_Environment, Index, Type,  
    frame(Locals, OperandStack, Flags),  
    frame(NextLocals, NextOperandStack, Flags)) :-  
    popMatchingType(OperandStack, Type,  
        NextOperandStack, ActualType),  
    modifyLocalVariable(Index, ActualType, Locals, NextLocals).
```

Given local variables Locals, modifying Index to have type Type results in the local variable list NewLocals. The modifications are somewhat involved, because some values (and their corresponding types) occupy two local variables. Hence, modifying LN may require modifying LN+1 (because the type will occupy both the N and N+1 slots) or LN-1 (because local N used to be the upper half of the two word value/type starting at local N-1, and so local N-1 must be invalidated), or both. This is described further below. We start at L0 and count up.

`modifyLocalVariable(Index, Type, Locals, NewLocals) :-`

`modifyLocalVariable(0, Index, Type, Locals, NewLocals).`

Given the suffix of the local variable list starting at index I, LocalsRest, modifying local variable Index to have type Type results in the local variable list suffix NewLocalsRest.

If $I < \text{Index}-1$, just copy the input to the output and recurse forward. If $I = \text{Index}-1$, the type of local I may change. This can occur if L_I has a type of size 2. Once we set L_{I+1} to the new type (and the corresponding value), the type/value of L_I will be invalidated, as its upper half will be trashed. Then we recurse forward.

When we find the variable, and it only occupies one word, we change it to Type and we're done. When we find the variable, and it occupies two words, we change its type to Type and the next word to **top**.

`modifyLocalVariable(I, Index, Type, [Locals1 | LocalsRest],
[Locals1 | NextLocalsRest]) :-`

`I < Index - 1,`

`I1 is I + 1,`

`modifyLocalVariable(I1, Index, Type, LocalsRest, NextLocalsRest).`

`modifyLocalVariable(I, Index, Type, [Locals1 | LocalsRest],
[NextLocals1 | NextLocalsRest]) :-`

`I =:= Index - 1,`

`modifyPreIndexVariable(Locals1, NextLocals1),`

`modifyLocalVariable(Index, Index, Type, LocalsRest,
NextLocalsRest).`

```

modifyLocalVariable(Index, Index, Type, [_ | LocalsRest],
                    [Type | LocalsRest] ) :-  

    sizeOf(Type, 1).  
  

modifyLocalVariable(Index, Index, Type, [_, _ | LocalsRest],
                    [Type, top | LocalsRest]) :-  

    sizeOf(Type, 2).

```

We refer to a local whose index immediately precedes a local whose type will be modified as a *pre-index variable*. The future type of a pre-index variable of type InputType is Result. If the type, Value, of the pre-index local is of size 1, it doesn't change. If the type of the pre-index local, Value, is 2, we need to mark the lower half of its two word value as unusable, by setting its type to **top**.

```

modifyPreIndexVariable(Type, Type) :- sizeOf(Type, 1).  

modifyPreIndexVariable(Type, top) :- sizeOf(Type, 2).

```

Given a list of types, this clause produces a list where every type of size 2 has been substituted by two entries: one for itself, and one **top** entry. The result then corresponds to the representation of the list as 32 bit words in the Java virtual machine.

```

expandTypeList([], []).  

expandTypeList([Item | List], [Item | Result]) :-  

    sizeOf(Item, 1),  

    expandTypeList(List, Result).  
  

expandTypeList([Item | List], [Item, top | Result]) :-  

    sizeOf(Item, 2),  

    expandTypeList(List, Result).

```

4.10.1.4.5 List of all Instructions

In general, the type rule for an instruction is given relative to an environment Environment that defines the class and method in which the instruction occurs, and the offset Offset within the method at which the instruction occurs. The rule states that if the incoming type state StackFrame fulfills certain requirements, then:

- The instruction is type safe.
- It is provable that the type state after the instruction completes normally has a particular form given by NextStackFrame, and that the type state after the instruction completes abruptly is given by ExceptionStackFrame.

The natural language description of the rule is intended to be readable, intuitive and concise. As such, the description avoids repeating all the contextual assumptions given above. In particular:

- We do not explicitly mention the environment.
- When we speak of the operand stack or local variables in the following, we are referring to the operand stack and local variable components of a type state: either the incoming type state or the outgoing one.
- The type state after the instruction completes abruptly is almost always identical to the incoming type state. We only discuss the type state after the instruction completes abruptly when that is not the case.
- We speak of popping and pushing types onto the operand stack. We do not explicitly discuss issues of stack underflow or overflow, but assume that these operations can be completed successfully. The formal rules for operand stack manipulation ensure that the necessary checks are made.
- Similarly, the text discusses only the manipulation of logical types. In practice, some types take more than one word. We abstract from these representation details in our discussion, but the logical rules that manipulate data do not.

Any ambiguities can be resolved by referring to the formal Prolog rules.

aaload:

An `aaload` instruction is type safe iff one can validly replace types matching `int` and an array type with component type `ComponentType` where `ComponentType` is a subtype of `Object`, with `ComponentType` yielding the outgoing type state.

```
instructionIsTypeSafe(aaload, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    nth1OperandStackIs(2, StackFrame, ArrayType),  

    arrayComponentType(ArrayType, ComponentType),  

    isBootstrapLoader(BL),  

    validTypeTransition(Environment,  

                        [int, arrayOf(class('java/lang/Object', BL))],  

                        ComponentType, StackFrame, NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

The component type of an array of X is X. We define the component type of `null` to be `null`.

```
arrayComponentType(arrayOf(X), X).  

arrayComponentType(null, null).
```

aastore:

An `aastore` instruction is type safe iff one can validly pop types matching `Object`, `int`, and an array of `Object` off the incoming operand stack yielding the outgoing type state.

```
instructionIsTypeSafe(aastore, _Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    isBootstrapLoader(BL),  

    canPop(StackFrame, [class('java/lang/Object', BL), int,  

                      arrayOf(class('java/lang/Object', BL))], NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

aconst_null:

An **aconst_null** instruction is type safe if one can validly push the type **null** onto the incoming operand stack yielding the outgoing type state.

```
instructionIsTypeSafe(aconst_null, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    validTypeTransition(Environment, [], null, StackFrame,
                         NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

aload:

An **aload** instruction with operand Index is type safe and yields an outgoing type state NextStackFrame, if a load instruction with operand Index and type **reference** is type safe and yields an outgoing type state NextStackFrame.

```
instructionIsTypeSafe(aload(Index), Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    loadIsTypeSafe(Environment, Index, reference, StackFrame,
                   NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

aload_<n>:

The instructions **aload_<n>**, for $0 \leq n \leq 3$, are typesafe iff the equivalent **aload** instruction is type safe.

```
instructionHasEquivalentTypeRule(aload_0,aload(0)).  

instructionHasEquivalentTypeRule(aload_1,aload(1)).  

instructionHasEquivalentTypeRule(aload_2,aload(2)).  

instructionHasEquivalentTypeRule(aload_3,aload(3)).
```

anewarray:

An **anewarray** instruction with operand CP is type safe iff CP refers to a constant pool entry denoting either a class type or an array type, and one can legally replace a type matching **int** on the incoming operand stack with an array with component type CP yielding the outgoing type state.

```
instructionIsTypeSafe(anewarray(CP), Environment, _Offset,
                      StackFrame, NextStackFrame,
                      ExceptionStackFrame) :-  

    (CP = class(_, _) ; CP = arrayOf(_)),  

    validTypeTransition(Environment, [int], arrayOf(CP),
                         StackFrame, NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

areturn:

An **areturn** instruction is type safe iff the enclosing method has a declared return type, ReturnType, that is a reference type, and one can validly pop a type matching ReturnType off the incoming operand stack.

```
instructionIsTypeSafe(areturn, Environment, _Offset, StackFrame,
                      afterGoto, ExceptionStackFrame) :-  

    thisMethodReturnType(Environment, ReturnType),  

    isAssignable(ReturnType, reference),  

    canPop(StackFrame, [ReturnType], _PoppedStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

arraylength:

An **arraylength** instruction is type safe iff one can validly replace an array type on the incoming operand stack with the type **int** yielding the outgoing type state.

```
instructionIsTypeSafe(arraylength, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    nth1OperandStackIs(1, StackFrame, ArrayType),  

    arrayComponentType(ArrayType, _),  

    validTypeTransition(Environment, [top], int, StackFrame,
                         NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

astore:

An **astore** instruction with operand Index is type safe and yields an outgoing type state NextStackFrame, if a store instruction with operand Index and type **reference** is type safe and yields an outgoing type state NextStackFrame.

```
instructionIsTypeSafe(astore(Index), Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    storeIsTypeSafe(Environment, Index, reference, StackFrame,
                    NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

astore_<n>:

The instructions **astore_<n>**, for $0 \leq n \leq 3$, are typesafe iff the equivalent **astore** instruction is type safe.

```
instructionHasEquivalentTypeRule(astore_0, astore(0)).  

instructionHasEquivalentTypeRule(astore_1, astore(1)).  

instructionHasEquivalentTypeRule(astore_2, astore(2)).  

instructionHasEquivalentTypeRule(astore_3, astore(3)).
```

athrow:

An **athrow** instruction is type safe iff the top of the operand stack matches **Throwable**.

```
instructionIsTypeSafe(athrow, _Environment, _Offset, StackFrame,
                     afterGoto, ExceptionStackFrame) :-  

    isBootstrapLoader(BL),  

    canPop(StackFrame, [class('java/lang/Throwable', BL)],
           _PoppedStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

baload:

A **baload** instruction is type safe iff one can validly replace types matching **int** and a small array type on the incoming operand stack with **int** yielding the outgoing type state.

```
instructionIsTypeSafe(baload, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :  

    nth1OperandStackIs(2, StackFrame, Array),
    isSmallArray(Array),
    validTypeTransition(Environment, [int, top], int, StackFrame,
                        NextStackFrame),
    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

An array type is a *small array type* if it is an array of **byte**, an array of **boolean**, or a subtype thereof (**null**).

```
isSmallArray(arrayOf(byte)).
isSmallArray(arrayOf(boolean)).
isSmallArray(null).
```

bastore:

A **bastore** instruction is type safe iff one can validly pop types matching **int**, **int** and a small array type off the incoming operand stack yielding the outgoing type state.

```
instructionIsTypeSafe(bastore, _Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    nth1OperandStackIs(3, StackFrame, Array),  

    isSmallArray(Array),  

    canPop(StackFrame, [int, int, top], NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

bipush:

A **bipush** instruction is type safe iff the equivalent **sipush** instruction is type safe

```
instructionHasEquivalentTypeRule(bipush(Value), sipush(Value)).
```

caload:

A **caload** instruction is type safe iff one can validly replace types matching **int** and array of **char** on the incoming operand stack with **int** yielding the outgoing type state.

```
instructionIsTypeSafe(caload, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    validTypeTransition(Environment, [int, arrayOf(char)], int,  

                        StackFrame, NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

castore:

A **castore** instruction is type safe iff one can validly pop types matching **int**, **int** and array of **char** off the incoming operand stack yielding the outgoing type state.

```
instructionIsTypeSafe(castore, _Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    canPop(StackFrame, [int, int, arrayOf(char)], NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

checkcast:

A **checkcast** instruction with operand CP is type safe iff CP refers to a constant pool entry denoting either a class or an array, and one can validly replace the type **Object** on top of the incoming operand stack with the type denoted by CP yielding the outgoing type state.

```
instructionIsTypeSafe(checkcast(CP), Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    (CP = class(_, _) ; CP = arrayOf(_)),  

    isBootstrapLoader(BL),  

    validTypeTransition(Environment, [class('java/lang/Object', BL)], CP,  

                        StackFrame, NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

d2f:

A **d2f** instruction is type safe if one can validly pop **double** off the incoming operand stack and replace it with **float**, yielding the outgoing type state.

```
instructionIsTypeSafe(d2f, Environment, _Offset, StackFrame,  
                      NextStackFrame, ExceptionStackFrame) :-  
    validTypeTransition(Environment, [double], float, StackFrame,  
                        NextStackFrame),  
    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

d2i:

A **d2i** instruction is type safe if one can validly pop **double** off the incoming operand stack and replace it with **int**, yielding the outgoing type state.

```
instructionIsTypeSafe(d2i, Environment, _Offset, StackFrame,  
                      NextStackFrame, ExceptionStackFrame) :-  
    validTypeTransition(Environment, [double], int,  
                        StackFrame, NextStackFrame),  
    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

d2l:

A **d2l** instruction is type safe if one can validly pop **double** off the incoming operand stack and replace it with **long**, yielding the outgoing type state.

```
instructionIsTypeSafe(d2l, Environment, _Offset, StackFrame,  
                      NextStackFrame, ExceptionStackFrame) :-  
    validTypeTransition(Environment, [double], long,  
                        StackFrame, NextStackFrame),  
    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

dadd:

A **dadd** instruction is type safe iff one can validly replace types matching **double** and **double** on the incoming operand stack with **double** yielding the outgoing type state.

```
instructionIsTypeSafe(dadd, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    validTypeTransition(Environment, [double, double], double,  

                        StackFrame, NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

daload:

A **daload** instruction is type safe iff one can validly replace types matching **int** and array of **double** on the incoming operand stack with **double** yielding the outgoing type state.

```
instructionIsTypeSafe(daload, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    validTypeTransition(Environment, [int, arrayOf(double)], double,  

                        StackFrame, NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

dastore:

A **dastore** instruction is type safe iff one can validly pop types matching **double**, **int** and array of **double** off the incoming operand stack yielding the outgoing type state.

```
instructionIsTypeSafe(dastore, _Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    canPop(StackFrame, [double, int, arrayOf(double)],  

           NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

dcmp<op>:

A **dcm_{pg}** instruction is type safe iff one can validly replace types matching **double** and **double** on the incoming operand stack with **int** yielding the outgoing type state.

```
instructionIsTypeSafe(dcmpg, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    validTypeTransition(Environment, [double, double], int,  

                        StackFrame, NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

A **dcm_{pl}** instruction is type safe iff the equivalent **dcm_{pg}** instruction is type safe.

instructionHasEquivalentTypeRule(dcm_{pl}, dcm_{pg}).

dconst_<d>:

A **dconst_0** instruction is type safe if one can validly push the type **double** onto the incoming operand stack yielding the outgoing type state.

```
instructionIsTypeSafe(dconst_0, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    validTypeTransition(Environment, [], double,  

                        StackFrame, NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

A **dconst_1** instruction is type safe iff the equivalent **dconst_0** instruction is type safe.

instructionHasEquivalentTypeRule(dconst_1, dconst_0).

ddiv:

A **ddiv** instruction is type safe iff the equivalent **dadd** instruction is type safe.

instructionHasEquivalentTypeRule(ddiv, dadd).

dload:

A **dload** instruction with operand Index is type safe and yields an outgoing type state NextStackFrame, if a load instruction with operand Index and type **double** is type safe and yields an outgoing type state NextStackFrame.

instructionIsTypeSafe(dload(Index), Environment, _Offset, StackFrame,
NextStackFrame, ExceptionStackFrame) :-

 loadIsTypeSafe(Environment, Index, double, StackFrame,
 NextStackFrame),

 exceptionStackFrame(StackFrame, ExceptionStackFrame).

dload_<n>:

The instructions **dload_<n>**, for $0 \leq n \leq 3$, are typesafe iff the equivalent **dload** instruction is type safe.

instructionHasEquivalentTypeRule(dload_0,dload(0)).

instructionHasEquivalentTypeRule(dload_1,dload(1)).

instructionHasEquivalentTypeRule(dload_2,dload(2)).

instructionHasEquivalentTypeRule(dload_3,dload(3)).

dmul:

A **dmul** instruction is type safe iff the equivalent **dadd** instruction is type safe.

instructionHasEquivalentTypeRule(dmul, dadd).

dneg:

A **dneg** instruction is type safe iff there is a type matching **double** on the incoming operand stack. The **dneg** instruction does not alter the type state.

```
instructionIsTypeSafe(dneg, Environment, _Offset, StackFrame,  
                      NextStackFrame, ExceptionStackFrame) :-  
    validTypeTransition(Environment, [double], double, StackFrame,  
                        NextStackFrame),  
    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

drem:

A **drem** instruction is type safe iff the equivalent **dadd** instruction is type safe.

```
instructionHasEquivalentTypeRule(drem, dadd).
```

dreturn:

A **dreturn** instruction is type safe if the enclosing method has a declared return type of **double**, and one can validly pop a type matching **double** off the incoming operand stack.

```
instructionIsTypeSafe(dreturn, Environment, _Offset, StackFrame,  
                      afterGoto, ExceptionStackFrame) :-  
    thisMethodReturnType(Environment, double),  
    canPop(StackFrame, [double], _PoppedStackFrame),  
    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

dstore:

A **dstore** instruction with operand Index is type safe and yields an outgoing type state NextStackFrame, if a store instruction with operand Index and type **double** is type safe and yields an outgoing type state NextStackFrame.

```
instructionIsTypeSafe(dstore(Index), Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    storeIsTypeSafe(Environment, Index, double, StackFrame,  

                     NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

dstore_<n>:

The instructions **dstore_<n>**, for $0 \leq n \leq 3$, are type safe iff the equivalent **dstore** instruction is type safe.

```
instructionHasEquivalentTypeRule(dstore_0,dstore(0)).  

instructionHasEquivalentTypeRule(dstore_1,dstore(1)).  

instructionHasEquivalentTypeRule(dstore_2,dstore(2)).  

instructionHasEquivalentTypeRule(dstore_3,dstore(3)).
```

dsub:

A **dsub** instruction is type safe iff the equivalent **dadd** instruction is type safe.

```
instructionHasEquivalentTypeRule(dsub, dadd).
```

dup:

A **dup** instruction is type safe iff one can validly replace a category 1 type, Type, with the types Type, Type, yielding the outgoing type state.

```
instructionIsTypeSafe(dup, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    StackFrame = frame(Locale, InputOperandStack, Flags),  

    popCategory1(InputOperandStack, Type, _),  

    canSafelyPush(Environment, InputOperandStack, Type,  

                  OutputOperandStack),  

    NextStackFrame = frame(Locale, OutputOperandStack, Flags),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

dup_x1:

A **dup_x1** instruction is type safe iff one can validly replace two category 1 types, Type1, and Type2, on the incoming operand stack with the types Type1, Type2, Type1, yielding the outgoing type state.

```
instructionIsTypeSafe(dup_x1, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    StackFrame = frame(Locale, InputOperandStack, Flags),  

    popCategory1(InputOperandStack, Type1, Stack1),  

    popCategory1(Stack1, Type2, Rest),  

    canSafelyPushList(Environment, Rest, [Type1, Type2, Type1],  

                      OutputOperandStack),  

    NextStackFrame = frame(Locale, OutputOperandStack, Flags),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

dup_x2:

A **dup_x2** instruction is type safe iff it is a type safe form of the **dup_x2** instruction.

```
instructionIsTypeSafe(dup_x2, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    StackFrame = frame(Locale, InputOperandStack, Flags),  

    dup_x2SomeFormIsTypeSafe(Environment, InputOperandStack,  

                             OutputOperandStack),  

    NextStackFrame = frame(Locale, OutputOperandStack, Flags),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

A **dup_x2** instruction is *a type safe form of the dup_x2 instruction* iff it is a type safe form 1 **dup_x2** instruction or a type safe form 2 **dup_x2** instruction.

```
dup_x2SomeFormIsTypeSafe(Environment, InputOperandStack,
                         OutputOperandStack) :-  

    dup_x2Form1IsTypeSafe(Environment, InputOperandStack,  

                          OutputOperandStack).  

dup_x2SomeFormIsTypeSafe(Environment, InputOperandStack,
                         OutputOperandStack) :-  

    dup_x2Form2IsTypeSafe(Environment, InputOperandStack,  

                          OutputOperandStack).
```

A **dup_x2** instruction is a *type safe form 1 dup_x2 instruction* iff one can validly replace three category 1 types, Type1, Type2, Type3 on the incoming operand stack with the types Type1, Type2, Type3, Type1, yielding the outgoing type state.

```
dup_x2Form1IsTypeSafe(Environment, InputOperandStack,
                      OutputOperandStack) :-  

    popCategory1(InputOperandStack, Type1, Stack1),  

    popCategory1(Stack1, Type2, Stack2),  

    popCategory1(Stack2, Type3, Rest),  

    canSafelyPushList(Environment, Rest,  

                       [Type1, Type3, Type2, Type1],  

                       OutputOperandStack).
```

A **dup_x2** instruction is a *type safe form 2 dup_x2 instruction* iff one can validly replace a category 1 type, Type1, and a category 2 type, Type2, on the incoming operand stack with the types Type1, Type2, Type1, yielding the outgoing type state.

```
dup_x2Form2IsTypeSafe(Environment, InputOperandStack,
                      OutputOperandStack) :-  

    popCategory1(InputOperandStack, Type1, Stack1),  

    popCategory2(Stack1, Type2, Rest),  

    canSafelyPushList(Environment, Rest,  

                       [Type1, Type2, Type1],  

                       OutputOperandStack).
```

dup2:

A **dup2** instruction is type safe iff it is a type safe form of the **dup2** instruction.

```
instructionIsTypeSafe(dup2, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    StackFrame = frame(Locale, InputOperandStack, Flags),  

    dup2SomeFormIsTypeSafe(Environment, InputOperandStack,  

                           OutputOperandStack),  

    NextStackFrame = frame(Locale, OutputOperandStack, Flags),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

A **dup2** instruction is *a type safe form of the dup2 instruction* iff it is a type safe form 1 **dup2** instruction or a type safe form 2 **dup2** instruction.

```
dup2SomeFormIsTypeSafe(Environment, InputOperandStack,
                       OutputOperandStack) :-  

    dup2Form1IsTypeSafe(Environment, InputOperandStack,  

                        OutputOperandStack).  

dup2SomeFormIsTypeSafe(Environment, InputOperandStack,
                       OutputOperandStack) :-  

    dup2Form2IsTypeSafe(Environment, InputOperandStack,  

                        OutputOperandStack).
```

A **dup2** instruction is *a type safe form 1 dup2 instruction* iff one can validly replace two category 1 types, Type1 and Type2 on the incoming operand stack with the types Type1, Type2, Type1, Type2, yielding the outgoing type state.

```
dup2Form1IsTypeSafe(Environment, InputOperandStack,  
                      OutputOperandStack):-  
    popCategory1(InputOperandStack, Type1, TempStack),  
    popCategory1(TempStack, Type2, _),  
    canSafelyPushList(Environment, InputOperandStack,  
                      [Type1, Type2], OutputOperandStack).
```

A **dup2** instruction is *a type safe form 2 dup2 instruction* iff one can validly replace a category 2 type, Type on the incoming operand stack with the types Type, Type, yielding the outgoing type state.

```
dup2Form2IsTypeSafe(Environment, InputOperandStack,  
                      OutputOperandStack):-  
    popCategory2(InputOperandStack, Type, _),  
    canSafelyPush(Environment, InputOperandStack,  
                  Type, OutputOperandStack).
```

dup2_x1:

A **dup2_x1** instruction is type safe iff it is a type safe form of the **dup2_x1** instruction.

```
instructionIsTypeSafe(dup2_x1, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    StackFrame = frame(Locale, InputOperandStack, Flags),  

    dup2_x1SomeFormIsTypeSafe(Environment, InputOperandStack,  

                               OutputOperandStack),  

    NextStackFrame = frame(Locale, OutputOperandStack, Flags),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

A **dup2_x1** instruction is *a type safe form of the dup2_x1 instruction* iff it is a type safe form 1 **dup2_x1** instruction or a type safe form 2 **dup_x2** instruction.

```
dup2_x1SomeFormIsTypeSafe(Environment, InputOperandStack,
                           OutputOperandStack) :-  

    dup2_x1Form1IsTypeSafe(Environment, InputOperandStack,  

                           OutputOperandStack).  

dup2_x1SomeFormIsTypeSafe(Environment, InputOperandStack,
                           OutputOperandStack) :-  

    dup2_x1Form2IsTypeSafe(Environment, InputOperandStack,  

                           OutputOperandStack).
```

A **dup2_x1** instruction is *a type safe form 1 dup2_x1 instruction* iff one can validly replace three category 1 types, Type1, Type2, Type3, on the incoming operand stack with the types Type1, Type2, Type3, Type1, Type2, yielding the outgoing type state.

```
dup2_x1Form1IsTypeSafe(Environment, InputOperandStack,
                      OutputOperandStack) :-  

    popCategory1(InputOperandStack, Type1, Stack1),  

    popCategory1(Stack1, Type2, Stack2),  

    popCategory1(Stack2, Type3, Rest),  

    canSafelyPushList(Environment, Rest,  

                      [Type2, Type1, Type3, Type2, Type1],  

                      OutputOperandStack).
```

A **dup2_x1** instruction is *a type safe form 2 dup2_x1 instruction* iff one can validly replace a category 2 type, Type1, and a category 1 type, Type2, on the incoming operand stack with the types Type1, Type2, Type1, yielding the outgoing type state.

```
dup2_x1Form2IsTypeSafe(Environment, InputOperandStack,
                      OutputOperandStack) :-  

    popCategory2(InputOperandStack, Type1, Stack1),  

    popCategory1(Stack1, Type2, Rest),  

    canSafelyPushList(Environment, Rest,  

                      [Type1, Type2, Type1],  

                      OutputOperandStack).
```

dup2_x2:

A **dup2_x2** instruction is type safe iff it is a type safe form of the **dup2_x2** instruction.

```
instructionIsTypeSafe(dup2_x2, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    StackFrame = frame(Locale, InputOperandStack, Flags),  

    dup2_x2SomeFormIsTypeSafe(Environment, InputOperandStack,  

                               OutputOperandStack),  

    NextStackFrame = frame(Locale, OutputOperandStack, Flags),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

A **dup2_x2** instruction is *a type safe form of the dup2_x2 instruction* iff one of the following holds:

- it is a type safe form 1 **dup2_x2** instruction.
- it is a type safe form 2 **dup2_x2** instruction.
- it is a type safe form 3 **dup2_x2** instruction.
- it is a type safe form 4 **dup2_x2** instruction.

```
dup2_x2SomeFormIsTypeSafe(Environment, InputOperandStack,
                           OutputOperandStack) :-  

    dup2_x2Form1IsTypeSafe(Environment, InputOperandStack,  

                           OutputOperandStack).  

dup2_x2SomeFormIsTypeSafe(Environment, InputOperandStack,
                           OutputOperandStack) :-  

    dup2_x2Form2IsTypeSafe(Environment, InputOperandStack,  

                           OutputOperandStack).  

dup2_x2SomeFormIsTypeSafe(Environment, InputOperandStack,
                           OutputOperandStack) :-  

    dup2_x2Form3IsTypeSafe(Environment, InputOperandStack,  

                           OutputOperandStack).
```

```
dup2_x2SomeFormIsTypeSafe(Environment, InputOperandStack,
                           OutputOperandStack) :-  

    dup2_x2Form4IsTypeSafe(Environment, InputOperandStack,
                           OutputOperandStack).
```

A **dup2_x2** instruction is a *type safe form 1 dup2_x2 instruction* iff one can validly replace four category 1 types, Type1, Type2, Type3, Type4, on the incoming operand stack with the types Type1, Type2, Type3, Type4, Type1, Type2, yielding the outgoing type state.

```
dup2_x2Form1IsTypeSafe(Environment, InputOperandStack,
                        OutputOperandStack) :-  

    popCategory1(InputOperandStack, Type1, Stack1),  

    popCategory1(Stack1, Type2, Stack2),  

    popCategory1(Stack2, Type3, Stack3),  

    popCategory1(Stack3, Type4, Rest),  

    canSafelyPushList(Environment, Rest,  

                      [Type2, Type1, Type4, Type3, Type2, Type1],  

                      OutputOperandStack).
```

A **dup2_x2** instruction is a *type safe form 2 dup2_x2 instruction* iff one can validly replace a category 2 type, Type1, and two category 1 types, Type2, Type3, on the incoming operand stack with the types Type1, Type2, Type3, Type1, yielding the outgoing type state.

```
dup2_x2Form2IsTypeSafe(Environment, InputOperandStack,
                        OutputOperandStack) :-  

    popCategory2(InputOperandStack, Type1, Stack1),  

    popCategory1(Stack1, Type2, Stack2),  

    popCategory1(Stack2, Type3, Rest),  

    canSafelyPushList(Environment, Rest,  

                      [Type1, Type3, Type2, Type1],  

                      OutputOperandStack).
```

A **dup2_x2** instruction is *a type safe form 3 dup2_x2 instruction* iff one can validly replace two category 1 types, Type1, Type2, and a category 2 type, Type3, on the incoming operand stack with the types Type1, Type2, Type3, Type1, Type2, yielding the outgoing type state.

```
dup2_x2Form3IsTypeSafe(Environment, InputOperandStack,
                      OutputOperandStack) :-  

    popCategory1(InputOperandStack, Type1, Stack1),  

    popCategory1(Stack1, Type2, Stack2),  

    popCategory2(Stack2, Type3, Rest),  

    canSafelyPushList(Environment, Rest,  

                      [Type2, Type1, Type3, Type2, Type1],  

                      OutputOperandStack).
```

A **dup2_x2** instruction is *a type safe form 4 dup2_x2 instruction* iff one can validly replace two category 2 types, Type1, Type2, on the incoming operand stack with the types Type1, Type2, Type1, yielding the outgoing type state.

```
dup2_x2Form4IsTypeSafe(Environment, InputOperandStack,
                      OutputOperandStack) :-  

    popCategory2(InputOperandStack, Type1, Stack1),  

    popCategory2(Stack1, Type2, Rest),  

    canSafelyPushList(Environment, Rest,  

                      [Type1, Type2, Type1],  

                      OutputOperandStack).
```

f2d:

An **f2d** instruction is type safe if one can validly pop **float** off the incoming operand stack and replace it with **double**, yielding the outgoing type state.

```
instructionIsTypeSafe(f2d, Environment, _Offset, StackFrame,  
                      NextStackFrame, ExceptionStackFrame) :-  
    validTypeTransition(Environment, [float], double,  
                        StackFrame, NextStackFrame),  
    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

f2i:

An **f2i** instruction is type safe if one can validly pop **float** off the incoming operand stack and replace it with **int**, yielding the outgoing type state.

```
instructionIsTypeSafe(f2i, Environment, _Offset, StackFrame,  
                      NextStackFrame, ExceptionStackFrame) :-  
    validTypeTransition(Environment, [float], int,  
                        StackFrame, NextStackFrame),  
    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

f2l:

An **f2l** instruction is type safe if one can validly pop **float** off the incoming operand stack and replace it with **long**, yielding the outgoing type state.

```
instructionIsTypeSafe(f2l, Environment, _Offset, StackFrame,  
                      NextStackFrame, ExceptionStackFrame) :-  
    validTypeTransition(Environment, [float], long,  
                        StackFrame, NextStackFrame),  
    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

fadd:

An **fadd** instruction is type safe iff one can validly replace types matching **float** and **float** on the incoming operand stack with **float** yielding the outgoing type state.

```
instructionIsTypeSafe(fadd, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    validTypeTransition(Environment, [float, float], float,  

                        StackFrame, NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

faload:

An **faload** instruction is type safe iff one can validly replace types matching **int** and array of **float** on the incoming operand stack with **float** yielding the outgoing type state.

```
instructionIsTypeSafe(faload, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    validTypeTransition(Environment, [int, arrayOf(float)], float,  

                        StackFrame, NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

fastore:

An **fastore** instruction is type safe iff one can validly pop types matching **float**, **int** and array of **float** off the incoming operand stack yielding the outgoing type state.

```
instructionIsTypeSafe(fastore, _Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    canPop(StackFrame, [float, int, arrayOf(float)], NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

fcmp<op>:

An **fcmpg** instruction is type safe iff one can validly replace types matching **float** and **float** on the incoming operand stack with **int** yielding the outgoing type state.

```
instructionIsTypeSafe(fcmpg, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    validTypeTransition(Environment, [float, float], int,  

                        StackFrame, NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

An **fcmpl** instruction is type safe iff the equivalent **fcmpg** instruction is type safe.

```
instructionHasEquivalentTypeRule(fcmpl, fcmpg).
```

fconst_<f>:

An **fconst_0** instruction is type safe if one can validly push the type **float** onto the incoming operand stack yielding the outgoing type state.

```
instructionIsTypeSafe(fconst_0, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    validTypeTransition(Environment, [], float,  

                        StackFrame, NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

The rules for the other variants of **fconst** are equivalent:

```
instructionHasEquivalentTypeRule(fconst_1, fconst_0).  

instructionHasEquivalentTypeRule(fconst_2, fconst_0).
```

fdiv:

An **fdiv** instruction is type safe iff the equivalent **fadd** instruction is type safe.

instructionHasEquivalentTypeRule(fdiv, fadd).

fload:

An **fload** instruction with operand Index is type safe and yields an outgoing type state NextStackFrame, if a load instruction with operand Index and type **float** is type safe and yields an outgoing type state NextStackFrame.

instructionIsTypeSafe(fload(Index), Environment, _Offset, StackFrame,
NextStackFrame, ExceptionStackFrame) :-

loadIsTypeSafe(Environment, Index, float, StackFrame,
NextStackFrame),
exceptionStackFrame(StackFrame, ExceptionStackFrame).

fload_<n>:

The instructions **fload_<n>**, for $0 \leq n \leq 3$, are typesafe iff the equivalent **fload** instruction is type safe.

instructionHasEquivalentTypeRule(fload_0,fload(0)).

instructionHasEquivalentTypeRule(fload_1,fload(1)).

instructionHasEquivalentTypeRule(fload_2,fload(2)).

instructionHasEquivalentTypeRule(fload_3,fload(3)).

fmul:

An **fmul** instruction is type safe iff the equivalent **fadd** instruction is type safe.

instructionHasEquivalentTypeRule(fmul, fadd).

fneg:

An **fneg** instruction is type safe iff there is a type matching **float** on the incoming operand stack. The **fneg** instruction does not alter the type state.

```
instructionIsTypeSafe(fneg, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    validTypeTransition(Environment, [float], float, StackFrame,
                         NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

frem:

An **frem** instruction is type safe iff the equivalent **fadd** instruction is type safe.

```
instructionHasEquivalentTypeRule(frem, fadd).
```

freturn:

An **freturn** instruction is type safe if the enclosing method has a declared return type of **float**, and one can validly pop a type matching **float** off the incoming operand stack.

```
instructionIsTypeSafe(freturn, Environment, _Offset, StackFrame,
                      afterGoto, ExceptionStackFrame) :-  

    thisMethodReturnType(Environment, float),  

    canPop(StackFrame, [float], _PoppedStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

fstore:

An **fstore** instruction with operand Index is type safe and yields an outgoing type state NextStackFrame, if a store instruction with operand Index and type **float** is type safe and yields an outgoing type state NextStackFrame.

```
instructionIsTypeSafe(fstore(Index), Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    storeIsTypeSafe(Environment, Index, float, StackFrame,
                     NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

fstore_<n>:

The instructions **fstore_<n>**, for $0 \leq n \leq 3$, are typesafe iff the equivalent **fstore** instruction is type safe.

```
instructionHasEquivalentTypeRule(fstore_0,fstore(0)).  

instructionHasEquivalentTypeRule(fstore_1,fstore(1)).  

instructionHasEquivalentTypeRule(fstore_2,fstore(2)).  

instructionHasEquivalentTypeRule(fstore_3,fstore(3)).
```

fsub:

An **fsub** instruction is type safe iff the equivalent **fadd** instruction is type safe.

```
instructionHasEquivalentTypeRule(fsub, fadd).
```

getfield:

A **getfield** instruction with operand CP is type safe iff CP refers to a constant pool entry denoting a field whose declared type is FieldType, declared in a class FieldClass, and one can validly replace a type matching FieldClass with type FieldType on the incoming operand stack yielding the outgoing type state. FieldClass must not be an array type. Protected fields are subject to additional checks.

```
instructionIsTypeSafe(getfield(CP), Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    CP = field(FieldClass, FieldName, FieldDescriptor),  

    parseFieldDescriptor(FieldDescriptor, FieldType),  

    passesProtectedCheck(Environment, FieldClass, FieldName,  

                          FieldDescriptor, StackFrame),  

    validTypeTransition(Environment, [class(FieldClass)], FieldType,  

                        StackFrame, NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

The protected check applies only to members of superclasses of the current class. Other cases will be caught by the access checking done at resolution time. If the name of a class is not the name of any superclass, it cannot be a superclass, and so it can safely be ignored.

```
passesProtectedCheck(Environment, MemberClassName,  

                      MemberName, MemberDescriptor, StackFrame) :-  

    thisClass(Environment, class(ClassName, Loader)),  

    superclassChain(ClassName, Loader, Chain),  

    notMember(class(MemberClassName, _), Chain).
```

Using a superclass member that is not protected is trivially correct.

If the MemberClassName is the same as the name of a superclass, the class being resolved may indeed be a superclass. In this case, if no superclass named MemberClassName in a different runtime package has a protected member named MemberName with descriptor MemberDescriptor, the the protected check need not apply.

This is because the actual class being resolved will either be one of these superclasses, in which case we know that it is either in the same runtime package, and the access is legal; or the member in question is not protected and the check does not apply; or it will be a subclass, in which case the check would succeed anyway; or it will be some other class in the same runtime package ,in which case the access is legal and the check need not take place; or the verifier need not flag this as a problem, since it will be caught anyway because resolution will per force fail.

```
passesProtectedCheck(Environment, MemberClassName,
                     MemberName, MemberDescriptor, StackFrame) :-  
    thisClass(Environment, class(ClassName, Loader)),  
    superclassChain(ClassName, Loader, Chain),  
    member(class(MemberClassName, _), Chain),  
    classesInOtherPkgWithProtectedMember(  
        class(ClassName, Loader), MemberName,  
        MemberDescriptor, MemberClassName, Chain, []).
```

If there does exist a protected superclass member in a different runtime package, then load MemberClassName; if the member in question is not protected, the check does not apply.

```
passesProtectedCheck(Environment, MemberClassName,
                      MemberName, MemberDescriptor,
                      frame(_Locals, [Target | Rest], _Flags)) :-  
    thisClass(Environment, class(ClassName, Loader)),  
    superclassChain(ClassName, Loader, Chain),  
    member(class(MemberClassName, _), Chain),  
    classesInOtherPkgWIthProtectedMember(  
        class(ClassName, Loader), MemberName,  
        MemberDescriptor, MemberClassName, Chain, List),  
    List /= [],  
    loadedClass(MemberClassName, Loader,  
               ReferencedClass),  
    isNotProtected(ReferencedClass, MemberName,  
                  MemberDescriptor).
```

Otherwise, use of a member of an object of type Target requires that Target be assignable to the type of the current class.

```

passesProtectedCheck(Environment, MemberClassName,
                     MemberName, MemberDescriptor,
                     frame(_Locals, [Target | Rest], _Flags)) :-  

    thisClass(Environment, class(ClassName, CurrentLoader)),  

    superclassChain(ClassName, CurrentLoader, Chain),  

    member(class(MemberClassName, _), Chain),  

    classesInOtherPkgWithProtectedMember(  

        class(ClassName, CurrentLoader),  

        MemberName, MemberDescriptor, MemberClassName,  

        Chain, List),  

    List /= [],  

    loadedClass(MemberClassName, CurrentLoader,  

               ReferencedClass),  

    isProtected(ReferencedClass, MemberName, MemberDescriptor),  

    isAssignable(Target, class(ClassName, CurrentLoader)).  
  

superclassChain(Class, L, [class(SuperclassName, Ls) | Rest]) :-  

    loadedClass(Class, L, Class),  

    classSuperclassName(Class, SuperclassName),  

    classDefiningLoader(Class, Ls),  

    superclassChain(SuperclassName, Ls, Rest).  
  

superclassChain('java/lang/Object', L, []) :-  

    loadedClass('java/lang/Object', L, Class),  

    classDefiningLoader(Class, BL),  

    isBootstrapLoader(BL).

```

The predicate classesInOtherPkgWithProtectedMember(Class, MemberName, MemberDescriptor, MemberClassName, Chain, List) is true if List is the set of classes in Chain with name MemberClassName that are in a different runtime package than Class which have a protected member named MemberName with descriptor MemberDescriptor.

```

classesInOtherPkgWithProtectedMember(_, _, _, _, [], []).

classesInOtherPkgWithProtectedMember(Class, MemberName,
                                     MemberDescriptor, MemberClassName,
                                     [class(MemberClassName, L) | Tail],
                                     [class(MemberClassName, L) | T]) :-  

    differentRuntimePackage(Class, class(MemberClassName, L)),
    loadedClass(MemberClassName, L, Super),
    isProtected(Super, MemberName, MemberDescriptor),
    classesInOtherPkgWithProtectedMember(Class, MemberName,
                                         MemberDescriptor, MemberClassName, Tail, T).  
  

classesInOtherPkgWithProtectedMember(Class, MemberName,
                                     MemberDescriptor, MemberClassName,
                                     [class(MemberClassName, L) | Tail], T) :-  

    differentRuntimePackage(Class, class(MemberClassName, L)),
    loadedClass(MemberClassName, L, Super),
    isNotProtected(Super, MemberName, MemberDescriptor).
    classesInOtherPkgWithProtectedMember(Class, MemberName,
                                         MemberDescriptor, MemberClassName, Tail, T).  
  

classesInOtherPkgWithProtectedMember(Class, MemberName,
                                     MemberDescriptor, MemberClassName,
                                     [class(MemberClassName, L) | Tail], T) :-  

    sameRuntimePackage(Class, class(MemberClassName, L)),
    classesInOtherPkgWithProtectedMember(Class, MemberName,
                                         MemberDescriptor, MemberClassName, Tail, T).

```

getstatic:

A **getstatic** instruction with operand CP is type safe iff CP refers to a constant pool entry denoting a field whose declared type is FieldType, and one can validly push FieldType on the incoming operand stack yielding the outgoing type state.

instructionIsTypeSafe(getstatic(CP), Environment, _Offset, StackFrame,
NextStackFrame, ExceptionStackFrame) :-

```
CP = field(_FieldClass, _FieldName, FieldDescriptor),
parseFieldDescriptor(FieldDescriptor, FieldType),
validTypeTransition(Environment, [], FieldType, StackFrame,
NextStackFrame),
exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

goto:

A **goto** instruction is type safe iff its target operand is a valid branch target.

instructionIsTypeSafe(goto(Target), Environment, _Offset, StackFrame,
afterGoto, ExceptionStackFrame) :-

```
targetIsTypeSafe(Environment, StackFrame, Target),
exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

goto_w:

A **goto_w** instruction is type safe iff the equivalent **goto** instruction is type safe.

instructionHasEquivalentTypeRule(goto_w(Target), goto(Target)).

i2b:

An **i2b** instruction is type safe iff the equivalent **ineg** instruction is type safe.

instructionHasEquivalentTypeRule(i2b, ineg).

i2c:

An **i2c** instruction is type safe iff the equivalent **ineg** instruction is type safe.

instructionHasEquivalentTypeRule(i2c, ineg).

i2d:

An **i2d** instruction is type safe if one can validly pop **int** off the incoming operand stack and replace it with **double**, yielding the outgoing type state.

instructionIsTypeSafe(i2d, Environment, _Offset, StackFrame,
NextStackFrame, ExceptionStackFrame) :-
 validTypeTransition(Environment, [int], double,
 StackFrame, NextStackFrame),
 exceptionStackFrame(StackFrame, ExceptionStackFrame).

i2f:

An **i2f** instruction is type safe if one can validly pop **int** off the incoming operand stack and replace it with **float**, yielding the outgoing type state.

instructionIsTypeSafe(i2f, Environment, _Offset, StackFrame,
NextStackFrame, ExceptionStackFrame) :-
 validTypeTransition(Environment, [int], float,
 StackFrame, NextStackFrame),
 exceptionStackFrame(StackFrame, ExceptionStackFrame).

i2l:

An **i2l** instruction is type safe if one can validly pop **int** off the incoming operand stack and replace it with **long**, yielding the outgoing type state.

```
instructionIsTypeSafe(i2l, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    validTypeTransition(Environment, [int], long,  

                        StackFrame, NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

i2s:

An **i2s** instruction is type safe iff the equivalent **ineg** instruction is type safe.

```
instructionHasEquivalentTypeRule(i2s, ineg).
```

iadd:

An **iadd** instruction is type safe iff one can validly replace types matching **int** and **int** on the incoming operand stack with **int** yielding the outgoing type state.

```
instructionIsTypeSafe(iadd, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    validTypeTransition(Environment, [int, int], int, StackFrame,  

                        NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

iaload:

An **iaload** instruction is type safe iff one can validly replace types matching **int** and array of **int** on the incoming operand stack with **int** yielding the outgoing type state.

```
instructionIsTypeSafe(iaload, Environment, _Offset, StackFrame,  
                      NextStackFrame, ExceptionStackFrame) :-  
    validTypeTransition(Environment, [int, arrayOf(int)], int,  
                        StackFrame, NextStackFrame),  
    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

iand:

An **iand** instruction is type safe iff the equivalent **iadd** instruction is type safe.

```
instructionHasEquivalentTypeRule(iand, iadd).
```

iastore:

An **iastore** instruction is type safe iff one can validly pop types matching **int**, **int** and array of **int** off the incoming operand stack yielding the outgoing type state.

```
instructionIsTypeSafe(iastore, _Environment, _Offset, StackFrame,  
                      NextStackFrame, ExceptionStackFrame) :-  
    canPop(StackFrame, [int, int, arrayOf(int)], NextStackFrame),  
    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

if_acmp<cond>:

An **if_acmpeq** instruction is type safe iff one can validly pop types matching **reference** and **reference** on the incoming operand stack yielding the outgoing type state NextStackFrame, and the operand of the instruction, Target, is a valid branch target assuming an incoming type state of NextStackFrame.

```
instructionIsTypeSafe(if_acmpeq(Target), Environment, _Offset,
                      StackFrame, NextStackFrame,
                      ExceptionStackFrame) :-  

    canPop(StackFrame, [reference, reference], NextStackFrame),  

    targetIsTypeSafe(Environment, NextStackFrame, Target),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

The rule for **if_acmp_ne** is identical.

```
instructionHasEquivalentTypeRule(if_acmpne(Target),
                                 if_acmpeq(Target)).
```

if_icmp<cond>:

An **if_icmpeq** instruction is type safe iff one can validly pop types matching **int** and **int** on the incoming operand stack yielding the outgoing type state NextStackFrame, and the operand of the instruction, Target, is a valid branch target assuming an incoming type state of NextStackFrame.

```
instructionIsTypeSafe(if_icmpeq(Target), Environment, _Offset,
                      StackFrame, NextStackFrame,
                      ExceptionStackFrame) :-  

    canPop(StackFrame, [int, int], NextStackFrame),  

    targetIsTypeSafe(Environment, NextStackFrame, Target),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

The rules for all other variants of the ***if_icmp*** instruction are identical

instructionHasEquivalentTypeRule(if_icmpge(Target),	if_icmpeq(Target)).
instructionHasEquivalentTypeRule(if_icmpgt(Target),	if_icmpeq(Target)).
instructionHasEquivalentTypeRule(if_icmple(Target),	if_icmpeq(Target)).
instructionHasEquivalentTypeRule(if_icmplt(Target),	if_icmpeq(Target)).
instructionHasEquivalentTypeRule(if_icmpne(Target),	if_icmpeq(Target)).

***if_<cond>*:**

An ***if_eq*** instruction is type safe iff one can validly pop a type matching ***int*** off the incoming operand stack yielding the outgoing type state NextStackFrame, and the operand of the instruction, Target, is a valid branch target assuming an incoming type state of NextStackFrame.

```
instructionIsTypeSafe(ifeq(Target), Environment, _Offset, StackFrame,
                     NextStackFrame, ExceptionStackFrame) :-  

    canPop(StackFrame, [int], NextStackFrame),  

    targetIsTypeSafe(Environment, NextStackFrame, Target),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

The rules for all other variations of the ***if<cond>*** instruction are identical

instructionHasEquivalentTypeRule(ifge(Target),	ifeq(Target)).
instructionHasEquivalentTypeRule(ifgt(Target),	ifeq(Target)).
instructionHasEquivalentTypeRule(ifle(Target),	ifeq(Target)).
instructionHasEquivalentTypeRule(iflt(Target),	ifeq(Target)).
instructionHasEquivalentTypeRule(ifne(Target),	ifeq(Target)).

ifnonnull:

An **ifnonnull** instruction is type safe iff one can validly pop a type matching **reference** off the incoming operand stack yielding the outgoing type state NextStackFrame, and the operand of the instruction, Target, is a valid branch target assuming an incoming type state of NextStackFrame.

```
instructionIsTypeSafe(ifnonnull(Target), Environment, _Offset,
                      StackFrame, NextStackFrame,
                      ExceptionStackFrame) :-  

    canPop(StackFrame, [reference], NextStackFrame),  

    targetIsTypeSafe(Environment, NextStackFrame, Target),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

ifnull:

An **ifnull** instruction is type safe iff the equivalent **ifnonnull** instruction is type safe.

```
instructionHasEquivalentTypeRule(ifnull(Target), ifnonnull(Target)).
```

iinc:

An **iinc** instruction with first operand Index is type safe iff LIndex has type **int**. The **iinc** instruction does not change the type state.

```
instructionIsTypeSafe(iinc(Index, _Value), _Environment, _Offset,
                      StackFrame, StackFrame, ExceptionStackFrame) :-  

    StackFrame = frame(Locals, _OperandStack, _Flags),  

    nth0(Index, Locals, int),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

iload:

An **iload** instruction with operand Index is type safe and yields an outgoing type state NextStackFrame, if a load instruction with operand Index and type **int** is type safe and yields an outgoing type state NextStackFrame.

```
instructionIsTypeSafe(iload(Index), Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    loadIsTypeSafe(Environment, Index, int, StackFrame,  

                   NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

iload_<n>:

The instructions **iload_<n>**, for $0 \leq n \leq 3$, are typesafe iff the equivalent **iload** instruction is type safe.

```
instructionHasEquivalentTypeRule(iload_0, iload(0)).  

instructionHasEquivalentTypeRule(iload_1, iload(1)).  

instructionHasEquivalentTypeRule(iload_2, iload(2)).  

instructionHasEquivalentTypeRule(iload_3, iload(3)).
```

imul:

An **imul** instruction is type safe iff the equivalent **iadd** instruction is type safe.

```
instructionHasEquivalentTypeRule(imul, iadd).
```

ineg:

An **ineg** instruction is type safe iff there is a type matching **int** on the incoming operand stack. The **ineg** instruction does not alter the type state.

```
instructionIsTypeSafe(ineg, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    validTypeTransition(Environment, [int], int, StackFrame,
                        NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

instanceof:

An **instanceof** instruction with operand CP is type safe iff CP refers to a constant pool entry denoting either a class or an array, and one can validly replace the type **Object** on top of the incoming operand stack with type **int** yielding the outgoing type state.

```
instructionIsTypeSafe(instanceof(CP), Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    (CP = class(_, _) ; CP = arrayOf(_)),  

    isBootstrapLoader(BL),  

    validTypeTransition(Environment, [class('java/lang/Object')], BL], int,
                        StackFrame, NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

invokeinterface:

An **invokeinterface** instruction is type safe iff all of the following conditions hold:

- Its first operand, CP, refers to a constant pool entry denoting an interface method named MethodName with descriptor Descriptor that is a member of an interface MethodClassName.
- MethodName is not `<init>`.
- MethodName is not `<clinit>`.
- Its second operand, Count, is a valid count operand (see below).
- One can validly replace types matching the type MethodClassName and the argument types given in Descriptor on the incoming operand stack with the return type given in Descriptor, yielding the outgoing type state.

```
instructionIsTypeSafe(invokewithinterface(CP, Count, 0), Environment,
                      _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    CP = imethod(MethodClassName, MethodName, Descriptor),
    MethodName \= '<init>',
    MethodName \= '<clinit>',
    parseMethodDescriptor(Descriptor, OperandArgList, ReturnType),
    currentClassLoader(Environment, L),
    reverse([class(MethodClassName, L) | OperandArgList],
            StackArgList),
    canPop(StackFrame, StackArgList, TempFrame),
    validTypeTransition(Environment, [], ReturnType, TempFrame,
                        NextStackFrame),
    countIsValid(Count, StackFrame, TempFrame),
    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

The count operand of an `invokeinterface` instruction is valid if it equals the size of the arguments to the instruction. This is equal to the difference between the size of InputFrame and OutputFrame.

`countIsValid(Count, InputFrame, OutputFrame) :-`

```
InputFrame = frame(_Locals1, OperandStack1, _Flags1),
OutputFrame = frame(_Locals2, OperandStack2, _Flags2),
length(OperandStack1, Length1),
length(OperandStack2, Length2),
Count := Length1 - Length2.
```

invokespecial:

An `invokespecial` instruction is type safe iff all of the following conditions hold:

- Its first operand, CP, refers to a constant pool entry denoting a method named `MethodName` with descriptor `Descriptor` that is a member of a class `MethodClassName`.

Either

- `MethodName` is not `<init>`.
 - `MethodName` is not `<cinit>`.
 - One can validly replace types matching the current class and the argument types given in `Descriptor` on the incoming operand stack with the return type given in `Descriptor`, yielding the outgoing type state.
 - One can validly replace types matching the class `MethodClassName` and the argument types given in `Descriptor` on the incoming operand stack with the return type given in `Descriptor`.
-

```
instructionIsTypeSafe(invokespecial(CP), Environment, _Offset,
                      StackFrame, NextStackFrame,
                      ExceptionStackFrame) :-  
  
    CP = method(MethodClassName, MethodName, Descriptor),  
    MethodName \= '<init>',  
    MethodName \= '<clinit>',  
    parseMethodDescriptor(Descriptor, OperandArgList, ReturnType),  
    thisClass(Environment, CurrentClass),  
    reverse([CurrentClass | OperandArgList], StackArgList),  
    validTypeTransition(Environment, StackArgList, ReturnType,  
                        StackFrame, NextStackFrame),  
    currentClassLoader(Environment, L),  
    reverse([class(MethodClassName, L) | OperandArgList],
           StackArgList2),  
    validTypeTransition(Environment, StackArgList2, ReturnType,  
                        StackFrame, _ResultStackFrame),  
    isAssignable(class(CurrentClassName, L),  
                class(MethodClassName, L)).  
  
exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

Or

- MethodName is `<init>`.
 - Descriptor specifies a `void` return type.
 - One can validly pop types matching the argument types given in Descriptor and an uninitialized type, `UninitializedArg`, off the incoming operand stack, yielding `OperandStack`.
 - The outgoing type state is derived from the incoming type state by first replacing the incoming operand stack with `OperandStack` and then replacing all instances of `UninitializedArg` with the type of instance being initialized.
-

```
instructionIsTypeSafe(invokespecial(CP), Environment, _Offset,
                      StackFrame, NextStackFrame,
                      ExceptionStackFrame) :-  

    CP = method(MethodClassName, '<init>', Descriptor),
    parseMethodDescriptor(Descriptor, OperandArgList, void),
    reverse(OperandArgList, StackArgList),
    canPop(StackFrame, StackArgList, TempFrame),
    TempFrame = frame(Locals, FullOperandStack, Flags),
    FullOperandStack = [UninitializedArg | OperandStack],
    currentClassLoader(Environment, CurrentLoader),
    rewrittenUninitializedType(UninitializedArg, Environment,
                                class(MethodClassName, CurrentLoader), This),
    rewrittenInitializationFlags(UninitializedArg, Flags, NextFlags),
    substitute(UninitializedArg, This, OperandStack,
               NextOperandStack),
    substitute(UninitializedArg, This, Locals,
               NextLocals),
    NextStackFrame = frame(NextLocals, NextOperandStack,
                           NextFlags),
    ExceptionStackFrame = frame(NextLocals, [], Flags),
    passesProtectedCheck(Environment, MethodClassName, '<init>',
                          Descriptor, NextStackFrame).
```



Special rule for **invokespecial** of an **<init>** method.

This rule is the sole motivation for passing back a distinct exception stack frame. The concern is that **invokespecial** can cause a superclass **<init>** method to be invoked, and that invocation could fail, leaving **this** uninitialized. This situation cannot be created using source code in the Java programming language, but can be created by programming in bytecode directly.

The original frame holds an uninitialized object in a local and has flag **uninitializedThis**. Normal termination of **invokespecial** initializes the uninitialized object and turns off the **uninitializedThis** flag. But if the invocation of an **<init>** method throws an exception, the uninitialized object might be left in a partially initialized state, and needs to be made permanently unusable. This is represented by an exception frame containing the broken object (the new value of the local) and the **uninitializedThis** flag (the old flag). There is no way to get from an apparently-initialized object bearing the **uninitializedThis** flag to a properly initialized object, so the object is permanently unusable. If not for this case, the exception stack frame could be the same as the input stack frame.

```
rewrittenUninitializedType(uninitializedThis, Environment,  
                           _MethodClass, This) :-  
    thisClass(Environment, This).
```

```
rewrittenUninitializedType(uninitialized(Address), Environment,  
                           MethodClass, MethodClass) :-  
    allInstructions(Environment, Instructions),  
    member(instruction(Address, new(MethodClass)), Instructions).
```

Computes what type the uninitialized argument's type needs to be rewritten to.

There are 2 cases.

If we are initializing an object within its constructor, its type is initially **uninitializedThis**. This type will be rewritten to the type of the class of the <**init**> method.

The second case arises from initialization of an object created by **new**. The uninitialized arg type is rewritten to MethodClass, the type of the method holder of <**init**>. We check whether there really is a **new** instruction at Address.

rewrittenInitializationFlags(uninitializedThis, _Flags, []).

rewrittenInitializationFlags(uninitialized(_), Flags, Flags).

substitute(_Old, _New, [], []).

substitute(Old, New, [Old | FromRest], [New | ToRest]) :-

substitute(Old, New, FromRest, ToRest).

substitute(Old, New, [From1 | FromRest], [From1 | ToRest]) :-

From1 $\setminus=$ Old,

substitute(Old, New, FromRest, ToRest).

invokestatic:

An `invokestatic` instruction is type safe iff all of the following conditions hold:

- Its first operand, CP, refers to a constant pool entry denoting a method named MethodName with descriptor Descriptor.
 - MethodName is not `<clinit>`.
 - One can validly replace types matching the argument types given in Descriptor on the incoming operand stack with the return type given in Descriptor, yielding the outgoing type state.
-

```
instructionIsTypeSafe(invokespecial(CP), Environment, _Offset,
                      StackFrame, NextStackFrame,
                      ExceptionStackFrame) :-  
  
    CP = method(_MethodName, MethodName, Descriptor),  
    MethodName \= '<clinit>',  
    parseMethodDescriptor(Descriptor, OperandArgList, ReturnType),  
    reverse(OperandArgList, StackArgList),  
    validTypeTransition(Environment, StackArgList, ReturnType,  
                        StackFrame, NextStackFrame),  
    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

invokevirtual:

An `invokevirtual` instruction is type safe iff all of the following conditions hold:

- Its first operand, CP, refers to a constant pool entry denoting a method named `MethodName` with descriptor `Descriptor` that is a member of an class `MethodClassName`.
 - `MethodName` is not `<init>`.
 - `MethodName` is not `<clinit>`.
 - One can validly replace types matching the class `MethodClassName` and the argument types given in `Descriptor` on the incoming operand stack with the return type given in `Descriptor`, yielding the outgoing type state.
 - If the method is protected, the usage conforms to the special rules governing access to protected members.
-

```
instructionIsTypeSafe(invokeresult(CP), Environment, _Offset,
                      StackFrame, NextStackFrame,
                      ExceptionStackFrame) :-  

    CP = method(MethodClassName, MethodName, Descriptor),
    MethodName \= '<init>',
    MethodName \= '<clinit>',
    parseMethodDescriptor(Descriptor, OperandArgList, ReturnType),
    reverse(OperandArgList, ArgList),
    currentClassLoader(Environment, L),
    reverse([class(MethodClassName, L) | OperandArgList],
            StackArgList),
    validTypeTransition(Environment, StackArgList, ReturnType,
                        StackFrame, NextStackFrame),
    canPop(StackFrame, ArgList, PoppedFrame),
    passesProtectedCheck(Environment, MethodClassName,
                          MethodName, Descriptor, PoppedFrame),
    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

ior:

An **ior** instruction is type safe iff the equivalent **iadd** instruction is type safe.

instructionHasEquivalentTypeRule(ior, iadd).

irem:

An **irem** instruction is type safe iff the equivalent **iadd** instruction is type safe.

instructionHasEquivalentTypeRule(irem, iadd).

ireturn:

An **ireturn** instruction is type safe if the enclosing method has a declared return type of **int**, and one can validly pop a type matching **int** off the incoming operand stack.

instructionIsTypeSafe(ireturn, Environment, _Offset, StackFrame,
 afterGoto, ExceptionStackFrame) :-
 thisMethodReturnType(Environment, int),
 canPop(StackFrame, [int], _PoppedStackFrame),
 exceptionStackFrame(StackFrame, ExceptionStackFrame).

ishl:

An **ishl** instruction is type safe iff the equivalent **iadd** instruction is type safe.

instructionHasEquivalentTypeRule(ishl, iadd).

ishr:

An **ishr** instruction is type safe iff the equivalent **iadd** instruction is type safe.

`instructionHasEquivalentTypeRule(ishr, iadd).`

istore:

An **istore** instruction with operand Index is type safe and yields an outgoing type state NextStackFrame, if a store instruction with operand Index and type **int** is type safe and yields an outgoing type state NextStackFrame.

`instructionIsTypeSafe(istore(Index), Environment, _Offset, StackFrame,
NextStackFrame, ExceptionStackFrame) :-`

`storeIsTypeSafe(Environment, Index, int, StackFrame,
 NextStackFrame),`

`exceptionStackFrame(StackFrame, ExceptionStackFrame).`

istore_<n>:

The instructions **istore_<n>**, for $0 \leq n \leq 3$, are typesafe iff the equivalent **istore** instruction is type safe.

`instructionHasEquivalentTypeRule(istore_0,istore(0)).`

`instructionHasEquivalentTypeRule(istore_1,istore(1)).`

`instructionHasEquivalentTypeRule(istore_2,istore(2)).`

`instructionHasEquivalentTypeRule(istore_3,istore(3)).`

isub:

An **isub** instruction is type safe iff the equivalent **iadd** instruction is type safe.

`instructionHasEquivalentTypeRule(isub, iadd).`

iushr:

An **iushr** instruction is type safe iff the equivalent **iadd** instruction is type safe.

`instructionHasEquivalentTypeRule(iushr, iadd).`

ixor:

An **ixor** instruction is type safe iff the equivalent **iadd** instruction is type safe.

`instructionHasEquivalentTypeRule(ixor, iadd).`

l2d:

An **l2d** instruction is type safe if one can validly pop **long** off the incoming operand stack and replace it with **double**, yielding the outgoing type state.

```
instructionIsTypeSafe(l2d, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    validTypeTransition(Environment, [long], double, StackFrame,
                        NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

l2f:

An **l2f** instruction is type safe if one can validly pop **long** off the incoming operand stack and replace it with **float**, yielding the outgoing type state.

```
instructionIsTypeSafe(l2f, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    validTypeTransition(Environment, [long], float, StackFrame,
                        NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

l2i:

An **l2i** instruction is type safe if one can validly pop **long** off the incoming operand stack and replace it with **int**, yielding the outgoing type state.

```
instructionIsTypeSafe(l2i, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    validTypeTransition(Environment, [long], int, StackFrame,
                        NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

ladd:

An **ladd** instruction is type safe iff one can validly replace types matching **long** and **long** on the incoming operand stack with **long** yielding the outgoing type state.

```
instructionIsTypeSafe(ladd, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    validTypeTransition(Environment, [long, long], long, StackFrame,
                        NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

laload:

An **laload** instruction is type safe iff one can validly replace types matching **int** and array of **long** on the incoming operand stack with **long** yielding the outgoing type state.

```
instructionIsTypeSafe(laload, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    validTypeTransition(Environment, [int, arrayOf(long)], long,
                        StackFrame, NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

land:

An **l_and** instruction is type safe iff the equivalent **l_add** instruction is type safe.

instructionHasEquivalentTypeRule(land, ladd).

lastore:

A **l_ast_or_e** instruction is type safe iff one can validly pop types matching **long**, **int** and array of **long** off the incoming operand stack yielding the outgoing type state.

instructionIsTypeSafe(lastore, _Environment, _Offset, StackFrame,
 NextStackFrame, ExceptionStackFrame) :-
 canPop(StackFrame, [long, int, arrayOf(long)], NextStackFrame),
 exceptionStackFrame(StackFrame, ExceptionStackFrame).

lcmp:

A **l_cmp** instruction is type safe iff one can validly replace types matching **long** and **long** on the incoming operand stack with **int** yielding the outgoing type state.

instructionIsTypeSafe(lcmp, Environment, _Offset, StackFrame,
 NextStackFrame, ExceptionStackFrame) :-
 validTypeTransition(Environment, [long, long], int, StackFrame,
 NextStackFrame),
 exceptionStackFrame(StackFrame, ExceptionStackFrame).

lconst_<l>:

An `lconst_0` instruction is type safe if one can validly push the type `long` onto the incoming operand stack yielding the outgoing type state.

```
instructionIsTypeSafe(lconst_0, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    validTypeTransition(Environment, [], long, StackFrame,
                        NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

An `lconst_1` instruction is type safe iff the equivalent `lconst_0` instruction is type safe.

```
instructionHasEquivalentTypeRule(lconst_1, lconst_0).
```

ldc:

An `ldc` instruction with operand CP is type safe iff CP refers to a constant pool entry denoting an entity of type Type, where Type is either `int`, `float`, `String` or `Class` and one can validly push Type onto the incoming operand stack yielding the outgoing type state.

```
instructionIsTypeSafe(ldc(CP), Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    functor(CP, Tag, _),  

    isBootstrapLoader(BL),  

    member([Tag, Type], [  

        [int, int],  

        [float, float],  

        [string, class('java/lang/String', BL)],  

        [classConst, class('java/lang/Class', BL)]  

    ]),  

    validTypeTransition(Environment, [], Type, StackFrame,
                        NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

ldc_w:

An **ldc_w** instruction is type safe iff the equivalent **ldc** instruction is type safe.

instructionHasEquivalentTypeRule(ldc_w(CP), ldc(CP))

ldc2_w:

An **ldc2_w** instruction with operand CP is type safe iff CP refers to a constant pool entry denoting an entity of type Tag, where Tag is either **long** or **double**, and one can validly push Tag onto the incoming operand stack yielding the outgoing type state.

instructionIsTypeSafe(ldc2_w(CP), Environment, _Offset, StackFrame,
NextStackFrame, ExceptionStackFrame) :-

 functor(CP, Tag, _),
 member(Tag, [long, double]),
 validTypeTransition(Environment, [], Tag, StackFrame,
 NextStackFrame),
 exceptionStackFrame(StackFrame, ExceptionStackFrame).

ldiv:

An **ldiv** instruction is type safe iff the equivalent **ladd** instruction is type safe.

instructionHasEquivalentTypeRule(ldiv, ladd).

lload:

An **lload** instruction with operand Index is type safe and yields an outgoing type state NextStackFrame, if a load instruction with operand Index and type **long** is type safe and yields an outgoing type state NextStackFrame.

```
instructionIsTypeSafe(lload(Index), Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    loadIsTypeSafe(Environment, Index, long, StackFrame,  

                    NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

lload_<n>:

The instructions **lload_<n>**, for $0 \leq n \leq 3$, are typesafe iff the equivalent **lload** instruction is type safe.

```
instructionHasEquivalentTypeRule(lload_0,lload(0)).  

instructionHasEquivalentTypeRule(lload_1,lload(1)).  

instructionHasEquivalentTypeRule(lload_2,lload(2)).  

instructionHasEquivalentTypeRule(lload_3,lload(3)).
```

lmul:

An **lmul** instruction is type safe iff the equivalent **ladd** instruction is type safe.

```
instructionHasEquivalentTypeRule(lmul, ladd).
```

lneg:

An **lneg** instruction is type safe iff there is a type matching **long** on the incoming operand stack. The **lneg** instruction does not alter the type state.

```
instructionIsTypeSafe(lneg, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    validTypeTransition(Environment, [long], long, StackFrame,
                         NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

lookupswitch:

A **lookupswitch** instruction is type safe if its keys are sorted, one can validly pop **int** off the incoming operand stack yielding a new type state **BranchStackFrame**, and all of the instructions targets are valid branch targets assuming **BranchStackFrame** as their incoming type state.

```
instructionIsTypeSafe(lookupswitch(Targets, Keys), Environment, _,  

                      StackFrame, afterGoto, ExceptionStackFrame) :-  

    sort(Keys, Keys),  

    canPop(StackFrame, [int], BranchStackFrame),  

    checklist(targetIsTypeSafe(Environment, BranchStackFrame),  

             Targets),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

lor:

An **lor** instruction is type safe iff the equivalent **ladd** instruction is type safe.

```
instructionHasEquivalentTypeRule(lor, ladd).
```

lrem:

An `lrem` instruction is type safe iff the equivalent `ladd` instruction is type safe.

`instructionHasEquivalentTypeRule(lrem, ladd).`

lreturn:

An `lreturn` instruction is type safe if the enclosing method has a declared return type of `long`, and one can validly pop a type matching `long` off the incoming operand stack.

`instructionIsTypeSafe(lreturn, Environment, _Offset, StackFrame,
afterGoto, ExceptionStackFrame) :-`

`thisMethodReturnType(Environment, long),
canPop(StackFrame, [long], _PoppedStackFrame),
exceptionStackFrame(StackFrame, ExceptionStackFrame).`

lshl:

An `lshl` instruction is type safe if one can validly replace the types `int` and `long` on the incoming operand stack with the type `long` yielding the outgoing type state.

`instructionIsTypeSafe(lshl, Environment, _Offset, StackFrame,
NextStackFrame, ExceptionStackFrame) :-`

`validTypeTransition(Environment, [int, long], long, StackFrame,
NextStackFrame),
exceptionStackFrame(StackFrame, ExceptionStackFrame).`

lshr:

An `lshr` instruction is type safe iff the equivalent `lshl` instruction is type safe.

`instructionHasEquivalentTypeRule(lshr, lshl).`

lstore:

An **lstore** instruction with operand Index is type safe and yields an outgoing type state NextStackFrame, if a store instruction with operand Index and type **long** is type safe and yields an outgoing type state NextStackFrame.

```
instructionIsTypeSafe(lstore(Index), Environment, _Offset, StackFrame,  
NextStackFrame, ExceptionStackFrame) :-  
    storeIsTypeSafe(Environment, Index, long, StackFrame,  
    NextStackFrame),  
    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

lstore_<n>:

The instructions **lstore_<n>**, for $0 \leq n \leq 3$, are typesafe iff the equivalent **lstore** instruction is type safe.

```
instructionHasEquivalentTypeRule(lstore_0,lstore(0)).  
instructionHasEquivalentTypeRule(lstore_1,lstore(1)).  
instructionHasEquivalentTypeRule(lstore_2,lstore(2)).  
instructionHasEquivalentTypeRule(lstore_3,lstore(3)).
```

lsub:

An **lsub** instruction is type safe iff the equivalent **ladd** instruction is type safe.

```
instructionHasEquivalentTypeRule(lsub, ladd).
```

lushr:

An **lushr** instruction is type safe iff the equivalent **lshl** instruction is type safe.

`instructionHasEquivalentTypeRule(lushr, lshl).`

lxor:

An **lxor** instruction is type safe iff the equivalent **ladd** instruction is type safe.

`instructionHasEquivalentTypeRule(lxor, ladd).`

monitorenter:

A **monitorenter** instruction is type safe iff one can validly pop a type matching **reference** off the incoming operand stack yielding the outgoing type state.

```
instructionIsTypeSafe(monitorenter, _Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-
    canPop(StackFrame, [reference], NextStackFrame),
    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

monitorexit:

A **monitorexit** instruction is type safe iff the equivalent **monitorenter** instruction is type safe.

`instructionHasEquivalentTypeRule(monitorexit, monitorenter).`

multinewarray:

A **multinewarray** instruction with operands CP and Dim is type safe iff CP refers to a constant pool entry denoting an array type whose dimension is greater or equal to Dim, Dim is strictly positive, and one can validly replace Dim **int** types on the incoming operand stack with the type denoted by CP yielding the outgoing type state.

```
instructionIsTypeSafe(multianewarray(CP, Dim), Environment, _Offset,
                      StackFrame, NextStackFrame,
                      ExceptionStackFrame) :-  

    CP = arrayOf(_),
    classDimension(CP, Dimension),
    Dimension >= Dim,
    Dim > 0,
    /* Make a list of Dim ints */
    findall(int, between(1, Dim, _), IntList),
    validTypeTransition(Environment, IntList, CP, StackFrame,
                        NextStackFrame),
    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

The dimension of an array type whose component type is also an array type is 1 more than the dimension of its component type.

```
classDimension(arrayOf(X), Dimension) :-  

    classDimension(X, Dimension1),
    Dimension is Dimension1 + 1.  

classDimension(_, Dimension) :- Dimension = 0.
```

new:

A **new** instruction with operand CP at offset Offset is type safe iff CP refers to a constant pool entry denoting a class type, the type **uninitialized(Offset)** does not appear in the incoming operand stack, and one can validly push **uninitialized(Offset)** onto the incoming operand stack and replace **uninitialized(Offset)** with **top** in the incoming local variables yielding the outgoing type state.

```
instructionIsTypeSafe(new(CP), Environment, Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    StackFrame = frame(Locals, OperandStack, Flags),  

    CP = class(_, _),  

    NewItem = uninitialized(Offset),  

    notMember(NewItem, OperandStack),  

    substitute(NewItem, top, Locals, NewLocals),  

    validTypeTransition(Environment, [], NewItem,  

                        frame(NewLocals, OperandStack, Flags),  

                        NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

newarray:

A **newarray** instruction with operand TypeCode is type safe iff TypeCode corresponds to the primitive type ElementType, and one can validly replace the type **int** on the incoming operand stack with the type ‘array of ElementType’, yielding the outgoing type state.

```
instructionIsTypeSafe(newarray(TypeCode), Environment, _Offset,
                      StackFrame, NextStackFrame,
                      ExceptionStackFrame) :-  

    primitiveArrayInfo(TypeCode, _TypeChar, ElementType,
                       _VerifierType),  

    validTypeTransition(Environment, [int], arrayOf(ElementType),
                        StackFrame, NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

The correspondence between type codes and primitive types is specified by the following predicate:

```
primitiveArrayInfo(4, 0'Z, boolean, int).
primitiveArrayInfo(5, 0'C, char, int).
primitiveArrayInfo(6, 0'F, float, float).
primitiveArrayInfo(7, 0'D, double, double).
primitiveArrayInfo(8, 0'B, byte, int).
primitiveArrayInfo(9, 0'S, short, int).
primitiveArrayInfo(10, 0'I, int, int).
primitiveArrayInfo(11, 0'J, long, long).
```

nop:

A **nop** instruction is always type safe. The **nop** instruction does not affect the type state.

```
instructionIsTypeSafe(nop, _Environment, _Offset, StackFrame,
                      StackFrame, ExceptionStackFrame) :-
    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

pop:

A **pop** instruction is type safe iff one can validly pop a category 1 type off the incoming operand stack yielding the outgoing type state.

```
instructionIsTypeSafe(pop, _Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-
    StackFrame = frame(Locals, [Type | Rest], Flags),
    Type \= top,
    sizeOf(Type, 1),
    NextStackFrame = frame(Locals, Rest, Flags),
    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

pop2:

A **pop2** instruction is type safe iff it is a type safe form of the **pop2** instruction.

```
instructionIsTypeSafe(pop2, _Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    StackFrame = frame(Locals, InputOperandStack, Flags),  

    pop2SomeFormIsTypeSafe(InputOperandStack,  

                           OutputOperandStack),  

    NextStackFrame = frame(Locals, OutputOperandStack, Flags),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

A **pop2** instruction is *a type safe form of the pop2 instruction* iff it is a type safe form 1 **pop2** instruction or a type safe form 2 **pop2** instruction.

```
pop2SomeFormIsTypeSafe(InputOperandStack, OutputOperandStack) :-  

    pop2Form1IsTypeSafe(InputOperandStack, OutputOperandStack).  

pop2SomeFormIsTypeSafe(InputOperandStack, OutputOperandStack) :-  

    pop2Form2IsTypeSafe(InputOperandStack, OutputOperandStack).
```

A **pop2** instruction is *a type safe form 1 pop2 instruction* iff one can validly pop two types of size 1 off the incoming operand stack yielding the outgoing type state.

```
pop2Form1IsTypeSafe([Type1, Type2 | Rest], Rest) :-  

    sizeOf(Type1, 1),  

    sizeOf(Type2, 1).
```

A **pop2** instruction is *a type safe form 2 pop2 instruction* iff one can validly pop a type of size 2 off the incoming operand stack yielding the outgoing type state.

```
pop2Form2IsTypeSafe([top, Type | Rest], Rest) :- sizeOf(Type, 2).
```

putfield:

A **putfield** instruction with operand CP is type safe iff CP refers to a constant pool entry denoting a field whose declared type is FieldType, declared in a class FieldClass, and one can validly pop types matching FieldType and FieldClass off the incoming operand stack yielding the outgoing type state.

instructionIsTypeSafe(putfield(CP), Environment, _Offset, StackFrame,
NextStackFrame, ExceptionStackFrame) :-

```
CP = field(FieldClass, FieldName, FieldDescriptor),
parseFieldDescriptor(FieldDescriptor, FieldType),
canPop(StackFrame, [FieldType], PoppedFrame),
passesProtectedCheck(Environment, FieldClass, FieldName,
FieldDescriptor, PoppedFrame),
currentClassLoader(Environment, CurrentLoader),
canPop(StackFrame, [FieldType, class(FieldClass, CurrentLoader)],
NextStackFrame),
exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

putstatic:

A **putstatic** instruction with operand CP is type safe iff CP refers to a constant pool entry denoting a field whose declared type is FieldType, and one can validly pop a type matching FieldType off the incoming operand stack yielding the outgoing type state.

instructionIsTypeSafe(putstatic(CP), _Environment, _Offset, StackFrame,
NextStackFrame, ExceptionStackFrame) :-

```
CP = field(_FieldClass, _FieldName, FieldDescriptor),
parseFieldDescriptor(FieldDescriptor, FieldType),
canPop(StackFrame, [FieldType], NextStackFrame),
exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

return:

A **return** instruction is type safe if the enclosing method declares a **void** return type, and either:

- The enclosing method is not an <**init**> method, or
- **this** has already been completely initialized at the point where the instruction occurs.

```
instructionIsTypeSafe(return, Environment, _Offset, StackFrame,
                      afterGoto, ExceptionStackFrame) :-  

    thisMethodReturnType(Environment, void),  

    StackFrame = frame(_Locals, _OperandStack, Flags),  

    notMember(flagThisUninit, Flags),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

saload:

An **saload** instruction is type safe iff one can validly replace types matching **int** and array of **short** on the incoming operand stack with **int** yielding the outgoing type state.

```
instructionIsTypeSafe(saload, Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  

    validTypeTransition(Environment, [int, arrayOf(short)], int,
                        StackFrame, NextStackFrame),  

    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

sastore:

An **sastore** instruction is type safe iff one can validly pop types matching **int**, **int** and array of **short** off the incoming operand stack yielding the outgoing type state.

```
instructionIsTypeSafe(sastore, _Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  
    canPop(StackFrame, [int, int, arrayOf(short)], NextStackFrame),  
    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

sipush:

An **sipush** instruction is type safe iff one can validly push the type **int** onto the incoming operand stack yielding the outgoing type state.

```
instructionIsTypeSafe(sipush(_Value), Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  
    validTypeTransition(Environment, [], int, StackFrame,  
                        NextStackFrame),  
    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

swap:

A **swap** instruction is type safe iff one can validly replace two category 1 types, Type1 and Type2, on the incoming operand stack with the types Type2 and Type1 yielding the outgoing type state.

```
instructionIsTypeSafe(swap, _Environment, _Offset, StackFrame,
                      NextStackFrame, ExceptionStackFrame) :-  
    StackFrame = frame(_Locals, [Type1, Type2 | Rest], _Flags),  
    sizeOf(Type1, 1),  
    sizeOf(Type2, 1),  
    NextStackFrame = frame(_Locals, [Type2, Type1 | Rest], _Flags),  
    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

tableswitch:

A **tableswitch** instruction is type safe if its keys are sorted, one can validly pop **int** off the incoming operand stack yielding a new type state BranchStackFrame, and all of the instructions targets are valid branch targets assuming BranchStackFrame as their incoming type state.

```
instructionIsTypeSafe(tableswitch(Targets, Keys), Environment, _Offset,
                      StackFrame, afterGoto, ExceptionStackFrame) :-  
    sort(Keys, Keys),  
    canPop(StackFrame, [int], BranchStackFrame),  
    checklist(targetIsTypeSafe(Environment, BranchStackFrame),  
             Targets),  
    exceptionStackFrame(StackFrame, ExceptionStackFrame).
```

wide:

The **wide** instructions follow the same rules as the instructions they widen.

```
instructionHasEquivalentTypeRule(wide(WidenedInstruction),
                                 WidenedInstruction).
```

The type state after an instruction completes abruptly is the same as the incoming type state, except that the operand stack is empty.

`exceptionStackFrame(StackFrame, ExceptionStackFrame) :-`

`StackFrame = frame(Locals, _OperandStack, Flags),`

`ExceptionStackFrame = frame(Locals, [], Flags).`

Most of the type rules in this specification depend on the notion of a valid type transition.

A type transition is valid if one can pop a list of expected types off the incoming type state's operand stack and replace them with an expected result type, resulting in a new valid type state. In particular, the size of the operand stack in the new type state must not exceed its maximum declared size.

`validTypeTransition(Environment, ExpectedTypesOnStack, ResultType,`
`frame(Locals, InputOperandStack, Flags),`
`frame(Locals, NextOperandStack, Flags)) :-`

`popMatchingList(InputOperandStack, ExpectedTypesOnStack,`
`InterimOperandStack),`

`pushOperandStack(InterimOperandStack, ResultType,`
`NextOperandStack),`

`operandStackHasLegalLength(Environment, NextOperandStack).`

Access Ith element of the operand stack from a type state.

`nth1OperandStackIs(I, frame(_Locals, OperandStack, _Flags),`
`Element) :-`

`nth1(I, OperandStack, Element).`

4.10.2 Verification by Type Inference

A `class` file that does not contain a `StackMapTable` attribute (which necessarily has a version number of 49.0 or below) must be verified using type inference.

4.10.2.1 The Process of Verification by Type Inference

During linking, the verifier checks the `code` array of the `Code` attribute for each method of the `class` file by performing data-flow analysis on each method. The verifier ensures that at any given point in the program, no matter what code path is taken to reach that point, the following is true:

- The operand stack is always the same size and contains the same types of values.
- No local variable is accessed unless it is known to contain a value of an appropriate type.
- Methods are invoked with the appropriate arguments.
- Fields are assigned only using values of appropriate types.
- All opcodes have appropriate type arguments on the operand stack and in the local variable array.
- There is never an uninitialized class instance in a local variable in code protected by an exception handler. However, an uninitialized 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.

For details of the data-flow analysis, see Section 4.10.2.2, “The Bytecode Verifier.”

For efficiency reasons, certain tests that could in principle be performed by the verifier are delayed until the first time the code for the method is actually invoked. In so doing, the verifier avoids loading `class` files unless it has to.

For example, if a method invokes another method that returns an instance of class A, and that instance is assigned only to a field of the same type, the verifier does not bother to check if the class A actually exists. However, if it is assigned to a field of the type B, the definitions of both A and B must be loaded in to ensure that A is a subclass of B.

4.10.2.2 The Bytecode Verifier

This section looks at the verification of Java virtual machine code by type inference in more detail.

The code for each method is verified independently. First, the bytes that make up the code are broken up into a sequence of instructions, and the index into the `code` array of the start of each instruction is placed in an array. The verifier then goes through the code a second time and parses the instructions. During this pass a data structure is built to hold information about each Java virtual machine instruction in the method. The operands, if any, of each instruction are checked to make sure they are valid. For instance:

- Branches must be within the bounds of the `code` array for the method.
- The targets of all control-flow instructions are each the start of an instruction. In the case of a *wide* instruction, the *wide* opcode is considered the start of the instruction, and the opcode giving the operation modified by that *wide* instruction is not considered to start an instruction. Branches into the middle of an instruction are disallowed.
- No instruction can access or modify a local variable at an index greater than or equal to the number of local variables that its method indicates it allocates.
- All references to the constant pool must be to an entry of the appropriate type. For example: the instruction *getfield* must reference a field.
- The code does not end in the middle of an instruction.
- Execution cannot fall off the end of the code.
- For each exception handler, the starting and ending point of code protected by the handler must be at the beginning of an instruction or, in the case of the ending point, immediately past the end of the code. The starting point must be before the ending point. The exception handler code must start at a valid instruction, and it must not start at an opcode being modified by the *wide* instruction.

For each instruction of the method, the verifier records the contents of the operand stack and the contents of the local variable array prior to the execution of that instruction. For the operand stack, it needs to know the stack height and the type of each value on it. For each local variable, it needs to know either the type of the contents of that local variable or that the local variable contains an unusable or

unknown value (it might be uninitialized). The bytecode verifier does not need to distinguish between the integral types (e.g., `byte`, `short`, `char`) when determining the value types on the operand stack.

Next, a data-flow analyzer is initialized. For the first instruction of the method, the local variables that represent parameters initially contain values of the types indicated by the method's type descriptor; the operand stack is empty. All other local variables contain an illegal value. For the other instructions, which have not been examined yet, no information is available regarding the operand stack or local variables.

Finally, the data-flow analyzer is run. For each instruction, a “changed” bit indicates whether this instruction needs to be looked at. Initially, the “changed” bit is set only for the first instruction. The data-flow analyzer executes the following loop:

1. Select a virtual machine instruction whose “changed” bit is set. If no instruction remains whose “changed” bit is set, the method has successfully been verified. Otherwise, turn off the “changed” bit of the selected instruction.
2. Model the effect of the instruction on the operand stack and local variable array by doing the following:
 - If the instruction uses values from the operand stack, ensure that there are a sufficient number of values on the stack and that the top values on the stack are of an appropriate type. Otherwise, verification fails.
 - If the instruction uses a local variable, ensure that the specified local variable contains a value of the appropriate type. Otherwise, verification fails.
 - If the instruction pushes values onto the operand stack, ensure that there is sufficient room on the operand stack for the new values. Add the indicated types to the top of the modeled operand stack.
 - If the instruction modifies a local variable, record that the local variable now contains the new type.
3. Determine the instructions that can follow the current instruction. Successor instructions can be one of the following:

- The next instruction, if the current instruction is not an unconditional control transfer instruction (for instance *goto*, *return*, or *athrow*). Verification fails if it is possible to “fall off” the last instruction of the method.
 - The target(s) of a conditional or unconditional branch or switch.
 - Any exception handlers for this instruction.
4. Merge the state of the operand stack and local variable array at the end of the execution of the current instruction into each of the successor instructions. In the special case of control transfer to an exception handler, the operand stack is set to contain a single object of the exception type indicated by the exception handler information. There must be sufficient room on the operand stack for this single value, as if an instruction had pushed it.
- If this is the first time the successor instruction has been visited, record that the operand stack and local variable values calculated in steps 2 and 3 are the state of the operand stack and local variable array prior to executing the successor instruction. Set the “changed” bit for the successor instruction.
 - If the successor instruction has been seen before, merge the operand stack and local variable values calculated in steps 2 and 3 into the values already there. Set the “changed” bit if there is any modification to the values.
5. Continue at step 1.

To merge two operand stacks, the number of values on each stack must be identical. The types of values on the stacks must also be identical, except that differently typed **reference** values may appear at corresponding places on the two stacks. In this case, the merged operand stack contains a **reference** to an instance of the first common superclass of the two types. Such a reference type always exists because the type **Object** is a superclass of all class and interface types. If the operand stacks cannot be merged, verification of the method fails.

To merge two local variable array states, corresponding pairs of local variables are compared. If the two types are not identical, then unless both contain **reference** values, the verifier records that the local variable contains an unusable value. If both of the pair of local variables contain **reference** values, the merged

state contains a reference to an instance of the first common superclass of the two types.

If the data-flow analyzer runs on a method without reporting a verification failure, then the method has been successfully verified by the `class` file verifier.

Certain instructions and data types complicate the data-flow analyzer. We now examine each of these in more detail.

4.10.2.3 Values of Types `long` and `double`

Values of the `long` and `double` types are treated specially by the verification process.

Whenever a value of type `long` or `double` is moved into a local variable at index n , index $n + 1$ is specially marked to indicate that it has been reserved by the value at index n and must not be used as a local variable index. Any value previously at index $n + 1$ becomes unusable.

Whenever a value is moved to a local variable at index n , the index $n - 1$ is examined to see if it is the index of a value of type `long` or `double`. If so, the local variable at index $n - 1$ is changed to indicate that it now contains an unusable value. Since the local variable at index n has been overwritten, the local variable at index $n - 1$ cannot represent a value of type `long` or `double`.

Dealing with values of types `long` or `double` on the operand stack is simpler; the verifier treats them as single values on the stack. For example, the verification code for the `dadd` opcode (add two `double` values) checks that the top two items on the stack are both of type `double`. When calculating operand stack length, values of type `long` and `double` have length two.

Untyped instructions that manipulate the operand stack must treat values of type `double` and `long` as atomic (indivisible). For example, the verifier reports a failure if the top value on the stack is a `double` and it encounters an instruction such as `pop` or `dup`. The instructions `pop2` or `dup2` must be used instead.

4.10.2.4 Instance Initialization Methods and Newly Created Objects

Creating a new class instance is a multistep process. The statement

```
...
new myClass(i, j, k);
...
```

can be implemented by the following:

```

...
new #I           // Allocate uninitialized space for myClass
dup             // Duplicate object on the operand stack
iload_1         // Push i
iload_2         // Push j
iload_3         // Push k
invokepecial #5 // Invoke myClass.<init>
...

```

This instruction sequence leaves the newly created and initialized object on top of the operand stack. (Additional examples of compilation to the instruction set of the Java virtual machine are given in Chapter 3, “Compiling for the Java Virtual Machine.”)

The instance initialization method (§2.9) for class `myClass` sees the new uninitialized object as its `this` argument in local variable 0. Before that method invokes another instance initialization method of `myClass` or its direct superclass on `this`, the only operation the method can perform on `this` is assigning fields declared within `myClass`.

When doing dataflow analysis on instance methods, the verifier initializes local variable 0 to contain an object of the current class, or, for instance initialization methods, local variable 0 contains a special type indicating an uninitialized object. After an appropriate instance initialization method is invoked (from the current class or the current superclass) on this object, all occurrences of this special type on the verifier’s model of the operand stack and in the local variable array are replaced by the current class type. The verifier rejects code that uses the new object before it has been initialized or that initializes the object more than once. In addition, it ensures that every normal return of the method has invoked an instance initialization method either in the class of this method or in the direct superclass.

Similarly, a special type is created and pushed on the verifier’s model of the operand stack as the result of the Java virtual machine instruction `new`. The special type indicates the instruction by which the class instance was created and the type of the uninitialized class instance created. When an instance initialization method *declared in the class of the uninitialized class instance* is invoked on that class instance, all occurrences of the special type are replaced by the intended type of

the class instance. This change in type may propagate to subsequent instructions as the dataflow analysis proceeds.

The instruction number needs to be stored as part of the special type, as there may be multiple not-yet-initialized instances of a class in existence on the operand stack at one time. For example, the Java virtual machine instruction sequence that implements

```
new InputStream(new Foo(), new InputStream("foo"))
```

may have two uninitialized instances of `InputStream` on the operand stack at once. When an instance initialization method is invoked on a class instance, only those occurrences of the special type on the operand stack or in the local variable array that are the *same object* as the class instance are replaced.

A valid instruction sequence must not have an uninitialized object on the operand stack or in a local variable ~~during a backwards branch at the target of a backwards branch if the special type of the uninitialized object is merged with a special type other than itself~~, or in a local variable in code protected by an exception handler or a `finally` clause. Otherwise, a devious piece of code might fool the verifier into thinking it had initialized a class instance when it had, in fact, initialized a class instance created in a previous pass through a loop.

4.10.2.5 Exceptions and `finally`

To implement the `try-finally` construct, Oracle's compiler for the Java programming language (before Java SE 6) uses the exception-handling facilities together with two special instructions: `jsr` (“jump to subroutine”) and `ret` (“return from subroutine”). The `finally` clause is compiled as a subroutine within the Java virtual machine code for its method, much like the code for an exception handler. When a `jsr` instruction that invokes the subroutine is executed, it pushes its return address, the address of the instruction after the `jsr` that is being executed, onto the operand stack as a value of type `returnAddress`. The code for the subroutine stores the return address in a local variable. At the end of the subroutine, a `ret` instruction fetches the return address from the local variable and transfers control to the instruction at the return address.

Control can be transferred to the `finally` clause (the `finally` subroutine can be invoked) in several different ways. If the `try` clause completes normally, the `finally` subroutine is invoked via a `jsr` instruction before evaluating the next expression. A `break` or `continue` inside the `try` clause that transfers control

outside the `try` clause executes a *jsr* to the code for the `finally` clause first. If the `try` clause executes a `return`, the compiled code does the following:

1. Saves the return value (if any) in a local variable.
2. Executes a *jsr* to the code for the `finally` clause.
3. Upon return from the `finally` clause, returns the value saved in the local variable.

The compiler sets up a special exception handler, which catches any exception thrown by the `try` clause. If an exception is thrown in the `try` clause, this exception handler does the following:

1. Saves the exception in a local variable.
2. Executes a *jsr* to the `finally` clause.
3. Upon return from the `finally` clause, rethrows the exception.

For more information about the implementation of the `try-finally` construct, see Section 3.13, “Compiling finally.”

The code for the `finally` clause presents a special problem to the verifier. Usually, if a particular instruction can be reached via multiple paths and a particular local variable contains incompatible values through those multiple paths, then the local variable becomes unusable. However, a `finally` clause might be called from several different places, yielding several different circumstances:

- The invocation from the exception handler may have a certain local variable that contains an exception.
- The invocation to implement `return` may have some local variable that contains the return value.
- The invocation from the bottom of the `try` clause may have an indeterminate value in that same local variable.

The code for the `finally` clause itself might pass verification, but after completing the updating all the successors of the `ret` instruction, the verifier would note that the local variable that the exception handler expects to hold an exception, or that the return code expects to hold a return value, now contains an indeterminate value.

Verifying code that contains a `finally` clause is complicated. The basic idea is the following:

- Each instruction keeps track of the list of *jsr* targets needed to reach that instruction. For most code, this list is empty. For instructions inside code for the `finally` clause, it is of length one. For multiply nested `finally` code (extremely rare!), it may be longer than one.
- For each instruction and each *jsr* needed to reach that instruction, a bit vector is maintained of all local variables accessed or modified since the execution of the *jsr* instruction.
- When executing the *ret* instruction, which implements a return from a subroutine, there must be only one possible subroutine from which the instruction can be returning. Two different subroutines cannot “merge” their execution to a single *ret* instruction.
- To perform the data-flow analysis on a *ret* instruction, a special procedure is used. Since the verifier knows the subroutine from which the instruction must be returning, it can find all the *jsr* instructions that call the subroutine and merge the state of the operand stack and local variable array at the time of the *ret* instruction into the operand stack and local variable array of the instructions following the *jsr*. Merging uses a special set of values for local variables:
 - For any local variable that the bit vector (constructed above) indicates has been accessed or modified by the subroutine, use the type of the local variable at the time of the *ret*.
 - For other local variables, use the type of the local variable before the *jsr* instruction.

4.11 Limitations of the Java Virtual Machine

The following limitations of the Java virtual machine are implicit in the `class` file format:

- The per-class or per-interface constant pool is limited to 65535 entries by the 16-bit `constant_pool_count` field of the `ClassFile` structure (§4.1). This acts as an internal limit on the total complexity of a single class or interface.
- The greatest number of local variables in the local variables array of a frame created upon invocation of a method is limited to 65535 by the size of the `max_locals` item of the `Code` attribute (§4.7.3) giving the code of the method, and by the 16-bit local variable indexing of the Java virtual machine instruction set. Note that values of type `long` and `double` are each considered to reserve two local variables and contribute two units toward the `max_locals` value, so use of local variables of those types further reduces this limit.
- The number of fields that may be declared by a class or interface is limited to 65535 by the size of the `fields_count` item of the `ClassFile` structure (§4.1). Note that the value of the `fields_count` item of the `ClassFile` structure does not include fields that are inherited from superclasses or superinterfaces.
- The number of methods that may be declared by a class or interface is limited to 65535 by the size of the `methods_count` item of the `ClassFile` structure (§4.1). Note that the value of the `methods_count` item of the `ClassFile` structure does not include methods that are inherited from superclasses or superinterfaces.
- The number of direct superinterfaces of a class or interface is limited to 65535 by the size of the `interfaces_count` item of the `ClassFile` structure (§4.1).
- The size of an operand stack in a frame (§2.6) is limited to 65535 values by the `max_stack` field of the `Code` attribute (§4.7.3). Note that values of type `long` and `double` are each considered to contribute two units toward the `max_stack` value, so use of values of these types on the operand stack further reduces this limit.
- The number of dimensions in an array is limited to 255 by the size of the `dimensions` opcode of the `multianewarray` instruction and by the constraints imposed on the `multianewarray`, `anewarray`, and `newarray` instructions by §4.9.1 and §4.9.2.
- The number of method parameters is limited to 255 by the definition of a method descriptor (§4.3.3), where the limit includes one unit for `this` in the case of instance or interface method invocations. Note that a method descriptor is defined in terms of a notion of method parameter length in which a parameter

of type `long` or `double` contributes two units to the length, so parameters of these types further reduce the limit.

- The length of field and method names, field and method descriptors, and other constant string values (including those referenced by `ConstantValue` (§4.7.2) attributes) is limited to 65535 characters by the 16-bit unsigned `length` item of the `CONSTANT_Utf8_info` structure (§4.4.7). Note that the limit is on the number of bytes in the encoding and not on the number of encoded characters. UTF-8 encodes some characters using two or three bytes. Thus, strings incorporating multibyte characters are further constrained.

Loading, Linking, and Initializing

THE Java virtual machine dynamically loads, links and initializes classes and interfaces. Loading is the process of finding the binary representation of a class or interface type with a particular name and *creating* a class or interface from that binary representation. Linking is the process of taking a class or interface and combining it into the runtime state of the Java virtual machine so that it can be executed. Initialization of a class or interface consists of executing the class or interface initialization method `<clinit>` (§2.9).

In this chapter, Section 5.1 describes how the Java virtual machine derives symbolic references from the binary representation of a class or interface. Section 5.2 explains how the processes of loading, linking, and initialization are first initiated by the Java virtual machine. Section 5.3 specifies how binary representations of classes and interfaces are loaded by class loaders and how classes and interfaces are created. Linking is described in Section 5.4. Section 5.5 details how classes and interfaces are initialized. Section 5.6 introduces the notion of binding native methods. Finally, Section 5.7 describes when a Java virtual machine exits.

5.1 The Runtime Constant Pool

The Java virtual machine maintains a per-type constant pool (§2.5.5), a runtime data structure that serves many of the purposes of the symbol table of a conventional programming language implementation.

The `constant_pool` table (§4.4) in the binary representation of a class or interface is used to construct the runtime constant pool upon class or interface creation (§5.3). All references in the runtime constant pool are initially symbolic.

The symbolic references in the runtime constant pool are derived from structures in the binary representation of the class or interface as follows:

- A symbolic reference to a class or interface is derived from a `CONSTANT_Class_info` structure (§4.4.1) in the binary representation of a class or interface. Such a reference gives the name of the class or interface in the form returned by the `Class.getName` method, that is:
 - For a nonarray class or an interface, the name is the binary name (§4.2.1) of the class or interface.
 - For an array class of M dimensions, the name begins with M occurrences of the ASCII "[" character followed by a representation of the element type:
 - If the element type is a primitive type, it is represented by the corresponding field descriptor (§4.3.2).
 - Otherwise, if the element type is a reference type, it is represented by the ASCII "L" character followed by the binary name (§4.2.1) of the element type followed by the ASCII ";" character.
- Whenever this chapter refers to the name of a class or interface, it should be understood to be in the form returned by the `Class.getName` method.
- A symbolic reference to a field of a class or an interface is derived from a `CONSTANT_Fieldref_info` structure (§4.4.2) in the binary representation of a class or interface. Such a reference gives the name and descriptor of the field, as well as a symbolic reference to the class or interface in which the field is to be found.
- A symbolic reference to a method of a class is derived from a `CONSTANT_Methodref_info` structure (§4.4.2) in the binary representation of a class or interface. Such a reference gives the name and descriptor of the method, as well as a symbolic reference to the class in which the method is to be found.
- A symbolic reference to a method of an interface is derived from a `CONSTANT_InterfaceMethodref_info` structure (§4.4.2) in the binary representation of a class or interface. Such a reference gives the name and descriptor of the interface method, as well as a symbolic reference to the interface in which the method is to be found.

In addition, certain non-reference runtime values are derived from items found in the `constant_pool` table:

- A string literal (JLS3 §3.10.5) is derived from a `CONSTANT_String_info` structure (§4.4.3) in the binary representation of a class or interface. The `CONSTANT_String_info` structure gives the sequence of Unicode `characters`-code points constituting the string literal.
- The Java programming language requires that identical string literals (that is, literals that contain the same sequence of `characters`-code points) must refer to the same instance of class `String` (JLS3 §3.10.5). In addition, if the method `String.intern` is called on any string, the result is a reference to the same class instance that would be returned if that string appeared as a literal. Thus,

```
("a" + "b" + "c").intern() == "abc"
```

must have the value `true`.

- To derive a string literal, the Java virtual machine examines the sequence of `characters`-code points given by the `CONSTANT_String_info` structure.
 - If the method `String.intern` has previously been called on an instance of class `String` containing a sequence of Unicode `characters`-code points identical to that given by the `CONSTANT_String_info` structure, then the result of string literal derivation is a reference to that same instance of class `String`.
 - Otherwise, a new instance of class `String` is created containing the sequence of Unicode `characters`-code points given by the `CONSTANT_String_info` structure; that class instance is the result of string literal derivation. Finally, the `intern` method of the new `String` instance is invoked.
- Runtime constant values are derived from `CONSTANT_Integer_info`, `CONSTANT_Float_info`, `CONSTANT_Long_info`, or `CONSTANT_Double_info` structures (§4.4.4, §4.4.5) in the binary representation of a class or interface. Note that `CONSTANT_Float_info` structures represent values in IEEE 754 single format and `CONSTANT_Double_info` structures represent values in IEEE 754 double format (§4.4.4, §4.4.5). The runtime constant values derived from these structures must thus be values that can be represented using IEEE 754 single and double formats, respectively.

The remaining structures in the `constant_pool` table of the binary representation of a class or interface, the `CONSTANT_NameAndType_info` (§4.4.6) and `CONSTANT_Utf8_info` (§4.4.7) structures are only used indirectly when deriving symbolic references to classes, interfaces, methods, and fields, and when deriving string literals.

5.2 Virtual Machine Start-up

The Java virtual machine starts up by creating an initial class, which is specified in an implementation-dependent manner, using the bootstrap class loader (§5.3.1). The Java virtual machine then links the initial class, initializes it, and invokes the public class method `void main(String[])`. The invocation of this method drives all further execution. Execution of the Java virtual machine instructions constituting the `main` method may cause linking (and consequently creation) of additional classes and interfaces, as well as invocation of additional methods.

In an implementation of the Java virtual machine, the initial class could be provided as a command line argument. Alternatively, the implementation could provide an initial class that sets up a class loader which in turn loads an application. Other choices of the initial class are possible so long as they are consistent with the specification given in the previous paragraph.

5.3 Creation and Loading

Creation of a class or interface C denoted by the name N consists of the construction in the method area of the Java virtual machine (§2.5.4) of an implementation-specific internal representation of C. Class or interface creation is triggered by another class or interface D, which references C through its runtime constant pool. Class or interface creation may also be triggered by D invoking methods in certain Java class libraries (§2.12) such as reflection.

If C is not an array class, it is created by loading a binary representation of C (see Chapter 4, “The class File Format”) using a class loader. Array classes do not have an external binary representation; they are created by the Java virtual machine rather than by a class loader.

There are two kinds of class loaders: the bootstrap class loader supplied by the Java virtual machine, and user-defined class loaders. Every user-defined class loader is an instance of a subclass of the abstract class `ClassLoader`. Applications

employ user-defined class loaders in order to extend the manner in which the Java virtual machine dynamically loads and thereby creates classes. User-defined class loaders can be used to create classes that originate from user-defined sources. For example, a class could be downloaded across a network, generated on the fly, or extracted from an encrypted file. If a user-defined classloader prefetches binary representations of classes and interfaces, or loads a group of related classes together, then it must reflect loading errors only at points in the program where they could have arisen without prefetching or group loading.

A class loader L may create C by defining it directly or by delegating to another class loader. If L creates C directly, we say that L *defines* C or, equivalently, that L is the *defining loader* of C.

When one class loader delegates to another class loader, the loader that initiates the loading is not necessarily the same loader that completes the loading and defines the class. If L creates C, either by defining it directly or by delegation, we say that L *initiates* loading of C or, equivalently, that L is an *initiating loader* of C.

At runtime, a class or interface is determined not by its name alone, but by a pair: its binary name (§4.2.1) and its defining class loader. Each such class or interface belongs to a single *runtime package*. The runtime package of a class or interface is determined by the package name and defining class loader of the class or interface.

The Java virtual machine uses one of three procedures to create class or interface C denoted by N:

- If N denotes a nonarray class or an interface, one of the two following methods is used to load and thereby create C :
 - If D was defined by the bootstrap class loader, then the bootstrap class loader initiates loading of C (§5.3.1).
 - If D was defined by a user-defined class loader, then that same user-defined class loader initiates loading of C (§5.3.2).
- Otherwise N denotes an array class. An array class is created directly by the Java virtual machine (§5.3.3), not by a class loader. However, the defining class loader of D is used in the process of creating array class C.

If an error occurs during class loading, then an instance of a subclass of `LinkageError` must be thrown at a point in the program that (directly or indirectly) uses the class or interface being loaded.

If the Java virtual machine ever attempts to load a class C during verification (§5.4.1) or resolution (§5.4.3) (but not initialization (§5.5)), and the class loader that is used to initiate loading of C throws an instance of `ClassNotFoundException`, then the Java virtual machine must throw an instance of `NoClassDefFoundError` whose cause is the instance of `ClassNotFoundException`.

(A subtlety here is that recursive class loading to load superclasses is performed as part of resolution (§5.3.5, step 3). Therefore, a `ClassNotFoundException` that results from a class loader failing to load a superclass must be wrapped in a `NoClassDefFoundError`.)

We will sometimes represent a class or interface using the notation $\langle N, L_d \rangle$, where N denotes the name of the class or interface and L_d denotes the defining loader of the class or interface. We will also represent a class or interface using the notation N^{L_i} , where N denotes the name of the class or interface and L_i denotes an initiating loader of the class or interface.

5.3.1 Loading Using the Bootstrap Class Loader

The following steps are used to load and thereby create the nonarray class or interface C denoted by N using the bootstrap class loader.

First, the Java virtual machine determines whether the bootstrap class loader has already been recorded as an initiating loader of a class or interface denoted by N. If so, this class or interface is C, and no class creation is necessary.

Otherwise, the Java virtual machine passes the argument N to an invocation of a method on the bootstrap class loader to search for a purported representation of C in a platform-dependent manner. Typically, a class or interface will be represented using a file in a hierarchical file system, and the name of the class or interface will be encoded in the pathname of the file.

Note that there is no guarantee that a purported representation found is valid or is a representation of C. This phase of loading must detect the following error:

- If no purported representation of C is found, loading throws an instance of `NoClassDefFoundError` `ClassNotFoundException`.

Then the Java virtual machine attempts to derive a class denoted by N using the bootstrap class loader from the purported representation using the algorithm found in Section 5.3.5. That class is C.

5.3.2 Loading Using a User-defined Class Loader

The following steps are used to load and thereby create the nonarray class or interface C denoted by N using a user-defined class loader L.

First, the Java virtual machine determines whether L has already been recorded as an initiating loader of a class or interface denoted by N. If so, this class or interface is C, and no class creation is necessary.

Otherwise, the Java virtual machine invokes `loadClass(N)` on L.¹ The value returned by the invocation is the created class or interface C. The Java virtual machine then records that L is an initiating loader of C (§5.3.4). The remainder of this section describes this process in more detail.

When the `loadClass` method of the class loader L is invoked with the name N of a class or interface C to be loaded, L must perform one of the following two operations in order to load C :

1. The class loader L can create an array of bytes representing C as the bytes of a `ClassFile` structure (§4.1); it then must invoke the method `defineClass` of class `ClassLoader`. Invoking `defineClass` causes the Java virtual machine to derive a class or interface denoted by N using L from the array of bytes using the algorithm found in Section 5.3.5.
2. The class loader L can delegate the loading of C to some other class loader L'. This is accomplished by passing the argument N directly or indirectly to an invocation of a method on L' (typically the `loadClass` method). The result of the invocation is C.

In either (1) or (2), if the class loader L is unable to load a class or interface denoted by N for any reason, it must throw an instance of `ClassNotFoundException`.

¹ Since JDK release 1.1, Oracle's Java virtual machine implementation has invoked the `loadClass` method of a class loader in order to cause it to load a class or interface. The argument to `loadClass` is the name of the class or interface to be loaded. There is also a two-argument version of the `loadClass` method, where the second argument is a `boolean` that indicates whether the class or interface is to be linked or not. Only the two-argument version was supplied in JDK release 1.0.2, and Oracle's Java virtual machine implementation relied on it to link the loaded class or interface. From JDK release 1.1 onward, Oracle's Java virtual machine implementation links the class or interface directly, without relying on the class loader.

5.3.3 Creating Array Classes

The following steps are used to create the array class C denoted by N using class loader L. Class loader L may be either the bootstrap class loader or a user-defined class loader.

If L has already been recorded as an initiating loader of an array class with the same component type as N, that class is C, and no array class creation is necessary. Otherwise, the following steps are performed to create C:

1. If the component type is a reference type, the algorithm of this section (§5.3) is applied recursively using class loader L in order to load and thereby create the component type of C.
2. The Java virtual machine creates a new array class with the indicated component type and number of dimensions. If the component type is a reference type, C is marked as having been defined by the defining class loader of the component type. Otherwise, C is marked as having been defined by the bootstrap class loader. In any case, the Java virtual machine then records that L is an initiating loader for C (§5.3.4). If the component type is a reference type, the accessibility of the array class is determined by the accessibility of its component type. Otherwise, the accessibility of the array class is `public`.

5.3.4 Loading Constraints

Ensuring type safe linkage in the presence of class loaders requires special care. It is possible that when two different class loaders initiate loading of a class or interface denoted by N, the name N may denote a different class or interface in each loader.

When a class or interface C = <N1, L1> makes a symbolic reference to a field or method of another class or interface D = <N2, L2>, the symbolic reference includes a descriptor specifying the type of the field, or the return and argument types of the method. It is essential that any type name N mentioned in the field or method descriptor denote the same class or interface when loaded by L1 and when loaded by L2.

To ensure this, the Java virtual machine imposes *loading constraints* of the form $N^{L1} = N^{L2}$ during preparation (§5.4.2) and resolution (§5.4.3). To enforce these constraints, the Java virtual machine will, at certain prescribed times (see §5.3.1, §5.3.2, §5.3.3, and §5.3.5), record that a particular loader is an initiating loader of a particular class. After recording that a loader is an initiating loader of a class, the Java virtual machine must immediately check to see if any loading constraints are violated. If so, the record is retracted, the Java virtual machine throws

a `LinkageError`, and the loading operation that caused the recording to take place fails.

Similarly, after imposing a loading constraint (see §5.4.2, §5.4.3.2, §5.4.3.3, and §5.4.3.4), the Java virtual machine must immediately check to see if any loading constraints are violated. If so, the newly imposed loading constraint is retracted, the Java virtual machine throws a `LinkageError`, and the operation that caused the constraint to be imposed (either resolution or preparation, as the case may be) fails.

The situations described here are the only times at which the Java virtual machine checks whether any loading constraints have been violated. A loading constraint is *violated* if, and only if, all the following four conditions hold:

- There exists a loader L such that L has been recorded by the Java virtual machine as an initiating loader of a class C named N.
- There exists a loader L' such that L' has been recorded by the Java virtual machine as an initiating loader of a class C' named N.
- The equivalence relation defined by the (transitive closure of the) set of imposed constraints implies $N^L = N^{L'}$.
- $C \neq C'$.

A full discussion of class loaders and type safety is beyond the scope of this specification. For a more comprehensive discussion, readers are referred to *Dynamic Class Loading in the Java Virtual Machine* by Sheng Liang and Gilad Bracha (Proceedings of the 1998 ACM SIGPLAN Conference on Object-Oriented Programming Systems, Languages and Applications).

5.3.5 Deriving a Class from a `class` File Representation

The following steps are used to derive a `Class` object for the nonarray class or interface C denoted by N using loader L from a purported representation in `class` file format.

1. First, the Java virtual machine determines whether it has already recorded that L is an initiating loader of a class or interface denoted by N. If so, this creation attempt is invalid and loading throws a `LinkageError`.

2. Otherwise, the Java virtual machine attempts to parse the purported representation. However, the purported representation may not in fact be a valid representation of C.

This phase of loading must detect the following errors:

- If the purported representation is not a `ClassFile` structure (§4.1, §4.8), loading throws an instance of `ClassFormatError`.
 - Otherwise, if the purported representation is not of a supported major or minor version (§4.1), loading throws an instance of `UnsupportedClassVersionError`.¹
 - Otherwise, if the purported representation does not actually represent a class named N, loading throws an instance of `NoClassDefFoundError` or an instance of one of its subclasses.
3. If C has a direct superclass, the symbolic reference from C to its direct superclass is resolved using the algorithm of Section 5.4.3.1. Note that if C is an interface it must have `Object` as its direct superclass, which must already have been loaded. Only `Object` has no direct superclass.
- Any exceptions that can be thrown due to class or interface resolution can be thrown as a result of this phase of loading. In addition, this phase of loading must detect the following errors:
- If the class or interface named as the direct superclass of C is in fact an interface, loading throws an `IncompatibleClassChangeError`.
 - Otherwise, if any of the superclasses of C is C itself, loading throws a `ClassCircularityError`.
4. If C has any direct superinterfaces, the symbolic references from C to its direct superinterfaces are resolved using the algorithm of Section 5.4.3.1.

Any exceptions that can be thrown due to class or interface resolution can be thrown as a result of this phase of loading. In addition, this phase of loading must detect the following errors:

¹ `UnsupportedClassVersionError`, a subclass of `ClassFormatError`, was introduced to enable easy identification of a `ClassFormatError` caused by an attempt to load a class whose representation uses an unsupported version of the class file format. In JDK release 1.1 and earlier, an instance of `NoClassDefFoundError` or `ClassFormatError` was thrown in case of an unsupported version, depending on whether the class was being loaded by the system class loader or a user-defined class loader.

- If any of the classes or interfaces named as direct superinterfaces of C is not in fact an interface, loading throws an `IncompatibleClassChangeError`.
 - Otherwise, if any of the superinterfaces of C is C itself, loading throws a `ClassCircularityError`.
5. The Java virtual machine marks C as having L as its defining class loader and records that L is an initiating loader of C (§5.3.4).

5.4 Linking

Linking a class or interface involves verifying and preparing that class or interface, its direct superclass, its direct superinterfaces, and its element type (if it is an array type), if necessary. Resolution of symbolic references in the class or interface is an optional part of linking.

This specification allows an implementation flexibility as to when linking activities (and, because of recursion, loading) take place, provided that all of the following properties are maintained:

- A class or interface is completely loaded before it is linked.
- A class or interface is completely verified and prepared before it is initialized.
- Errors detected during linkage are thrown at a point in the program where some action is taken by the program that might, directly or indirectly, require linkage to the class or interface involved in the error.

For example, a Java virtual machine implementation may choose to resolve each symbolic reference in a class or interface individually when it is used (“lazy” or “late” resolution), or to resolve them all at once when the class is being verified (“eager” or “static” resolution). This means that the resolution process may continue, in some implementations, after a class or interface has been initialized. Whichever strategy is followed, any error detected during resolution must be thrown at a point in the program that (directly or indirectly) uses a symbolic reference to the class or interface.

Because linking involves the allocation of new data structures, it may fail with an `OutOfMemoryError`.

5.4.1 Verification

Verification (§4.10) ensures that the binary representation of a class or interface is structurally correct (§4.9). Verification may cause additional classes and interfaces to be loaded (§5.3) but need not cause them to be verified or prepared.

If the binary representation of a class or interface does not satisfy the static or structural constraints listed in Section 4.9, “Constraints on Java Virtual Machine Code,” then a `VerifyError` must be thrown at the point in the program that caused the class or interface to be verified.

If an attempt by the Java virtual machine to verify a class or interface fails because an error is thrown that is an instance of `LinkageError` (or a subclass),

then subsequent attempts to verify the class or interface always fail with the same error that was thrown as a result of the initial verification attempt.

5.4.2 Preparation

Preparation involves creating the static fields for a class or interface and initializing such fields to their default values (§2.3, §2.4). This does not require the execution of any Java virtual machine code; explicit initializers for static fields are executed as part of initialization (§5.5), not preparation.

During preparation of a class or interface C, the Java virtual machine also imposes loading constraints (§5.3.4). Let L₁ be the defining loader of C. For each method m declared in C that overrides (§5.4.3.5) a method declared in a superclass or superinterface <D, L₂>, the Java virtual machine imposes the following loading constraints:

~~Let T₀ be the name of the type returned by m.~~

~~Let T₁, ..., T_n be the names of the argument types of m.~~

Given that the return type of m is T_r, and

Given that the formal parameter types of m are T_{f1}, ..., T_{fn}, then:

If T_r not an array type, let T₀ be T_r; otherwise, let T₀ be the element type (§2.4) of T_r.

For i = 1 to n: If T_{fi} is not an array type, let T_i be T_{fi}; otherwise, let T_i be the element type (§2.4) of T_{fi}.

Then T_i^{L₁} = T_i^{L₂} for i = 0 to n (§5.3.4).

Furthermore, if C implements a method m declared in a superinterface <I, L₃> of C, but C does not itself declare the method m, then let <D, L₂>, be the superclass of C that declares the implementation of method m inherited by C. The Java virtual machine imposes the following constraints:

~~Let T₀ be the name of the type returned by m.~~

~~Let T₁, ..., T_n be the names of the argument types of m.~~

Given that the return type of m is T_r, and

Given that the formal parameter types of m are T_{f1}, ..., T_{fn}, then:

If T_r not an array type, let T₀ be T_r; otherwise, let T₀ be the element type (§2.4) of T_r.

For i = 1 to n: If T_{fi} is not an array type, let T_i be T_{fi}; otherwise, let T_i be the element type (§2.4) of T_{fi}.

Then T_i^{L₂} = T_i^{L₃} for i = 0 to n (§5.3.4).

Preparation may occur at any time following creation but must be completed prior to initialization.

5.4.3 Resolution

Resolution is the process of dynamically determining concrete values from symbolic references in the runtime constant pool.

Resolution can be attempted on a symbolic reference that has already been resolved. An attempt to resolve a symbolic reference that has already successfully been resolved always succeeds trivially and always results in the same entity produced by the initial resolution of that reference.

If an error occurs during resolution of a symbolic reference, then an instance of `IncompatibleClassChangeError` (or a subclass) must be thrown at a point in the program that (directly or indirectly) uses the symbolic reference.

If an attempt by the Java virtual machine to resolve a symbolic reference fails because an error is thrown that is an instance of `LinkageError` (or a subclass), then subsequent attempts to resolve the reference always fail with the same error that was thrown as a result of the initial resolution attempt.

The Java virtual machine instructions `anewarray`, `checkcast`, `getfield`, `getstatic`, `instanceof`, `invokeinterface`, `invokespecial`, `invokestatic`, `invokevirtual`, `multianewarray`, `new`, `putfield`, and `putstatic` make symbolic references to the runtime constant pool. Execution of any of these instructions requires resolution of its symbolic reference.

Certain of these instructions require additional linking checks when resolving symbolic references. For instance, in order for a `getfield` instruction to successfully resolve the symbolic reference to the field on which it operates, it must not only complete the field resolution steps given in Section 5.4.3.2 but also check that the field is not `static`. If it is a `static` field, a linking exception must be thrown.

Linking exceptions generated by checks that are specific to the execution of a particular Java virtual machine instruction are given in the description of that instruction and are not covered in this general discussion of resolution. Note that such exceptions, although described as part of the execution of Java virtual machine instructions rather than resolution, are still properly considered failures of resolution.

The following sections describe the process of resolving a symbolic reference in the runtime constant pool (§5.1) of a class or interface D. Details of resolution differ with the kind of symbolic reference to be resolved.

5.4.3.1 Class and Interface Resolution

To resolve an unresolved symbolic reference from D to a class or interface C denoted by N, the following steps are performed:

1. The defining class loader of D is used to create a class or interface denoted by N. This class or interface is C. Any exception that can be thrown as a result of failure of class or interface creation can thus be thrown as a result of failure of class and interface resolution. The details of the process are given in Section 5.3.
2. If C is an array class and its element type is a reference type, then the symbolic reference to the class or interface representing the element type is resolved by invoking the algorithm in Section 5.4.3.1 recursively.
3. Finally, access permissions to C are checked:
 - If C is not accessible (§5.4.4) to D, class or interface resolution throws an `IllegalAccessError`.

This condition can occur, for example, if C is a class that was originally declared to be `public` but was changed to be `non-public` after D was compiled.

If steps 1 and 2 succeed but step 3 fails, C is still valid and usable. Nevertheless, resolution fails, and D is prohibited from accessing C.

5.4.3.2 Field Resolution

To resolve an unresolved symbolic reference from D to a field in a class or interface C, the symbolic reference to C given by the field reference must first be resolved (§5.4.3.1). Therefore, any exception that can be thrown as a result of failure of resolution of a class or interface reference can be thrown as a result of failure of field resolution. If the reference to C can be successfully resolved, an exception relating to the failure of resolution of the field reference itself can be thrown.

When resolving a field reference, field resolution first attempts to look up the referenced field in C and its superclasses:

1. If C declares a field with the name and descriptor specified by the field reference, field lookup succeeds. The declared field is the result of the field lookup.
2. Otherwise, field lookup is applied recursively to the direct superinterfaces of the specified class or interface C.
3. Otherwise, if C has a superclass S, field lookup is applied recursively to S.

4. Otherwise, field lookup fails.

If field lookup fails, field resolution throws a `NoSuchFieldError`. Otherwise, if field lookup succeeds but the referenced field is not accessible (§5.4.4) to D, field resolution throws an `IllegalAccessException`.

Otherwise, let $\langle E, L_1 \rangle$ be the class or interface in which the referenced field is actually declared and let L_2 be the defining loader of D. Given that the type of the referenced field is T_f , let T be T_f if T_f is not an array type, and let T be the element type (§2.4) of T_f otherwise. Let T be the name of the type of the referenced field. The Java virtual machine must impose the loading constraint that $T^{L_1} = T^{L_2}$ (§5.3.4).

5.4.3.3 Method Resolution

To resolve an unresolved symbolic reference from D to a method in a class C, the symbolic reference to C given by the method reference is first resolved (§5.4.3.1). Therefore, any exceptions that can be thrown due to resolution of a class reference can be thrown as a result of method resolution. If the reference to C can be successfully resolved, exceptions relating to the resolution of the method reference itself can be thrown.

When resolving a method reference:

1. Method resolution checks whether C is a class or an interface.
 - If C is an interface, method resolution throws an `IncompatibleClassChangeError`.
2. Method resolution attempts to look up the referenced method in C and its superclasses:
 - If C declares a method with the name and descriptor specified by the method reference, method lookup succeeds.
 - Otherwise, if C has a superclass, step 2 of method lookup is recursively invoked on the direct superclass of C.
3. Otherwise, method lookup attempts to locate the referenced method in any of the superinterfaces of the specified class C.
 - If any superinterface of C declares a method with the name and descriptor specified by the method reference, method lookup succeeds.
 - Otherwise, method lookup fails.

If method lookup fails, method resolution throws a `NoSuchMethodError`. If method lookup succeeds and the method is `abstract`, but C is not `abstract`, method resolution throws an `AbstractMethodError`. Otherwise, if the referenced method is not accessible (§5.4.4) to D, method resolution throws an `IllegalAccessError`.

Otherwise, let $\langle E, L_1 \rangle$ be the class or interface in which the referenced method m is actually declared, and let L₂ be the defining loader of D.

~~Let T₀ be the name of the type returned by the referenced method.~~

~~Let T₁, ..., T_n be the names of the argument types of the referenced method.~~

Given that the return type of m is T_r, and

Given that the formal parameter types of m are T_{f1}, ..., T_{fn}, then:

If T_r not an array type, let T₀ be T_r; otherwise, let T₀ be the element type (§2.4) of T_r.

For i = 1 to n: If T_{fi} is not an array type, let T_i be T_{fi}; otherwise, let T_i be the element type (§2.4) of T_{fi}.

The Java virtual machine must impose the loading constraints $T_i^{L_1} = T_i^{L_2}$ for i = 0 to n (§5.3.4).

5.4.3.4 Interface Method Resolution

To resolve an unresolved symbolic reference from D to an interface method in an interface C, the symbolic reference to C given by the interface method reference is first resolved (§5.4.3.1). Therefore, any exceptions that can be thrown as a result of failure of resolution of an interface reference can be thrown as a result of failure of interface method resolution. If the reference to C can be successfully resolved, exceptions relating to the resolution of the interface method reference itself can be thrown.

When resolving an interface method reference:

- If C is not an interface, interface method resolution throws an `IncompatibleClassChangeError`.
- Otherwise, if the referenced method does not have the same name and descriptor as a method in C or in one of the superinterfaces of C, or in class `Object`, interface method resolution throws a `NoSuchMethodError`.

Otherwise, let $\langle E, L_1 \rangle$ be the class or interface in which the referenced interface method m is actually declared, and let L₂ be the defining loader of D.

~~Let T₀ be the name of the type returned by the referenced method.~~

~~Let T_1, \dots, T_n be the names of the argument types of the referenced method.~~

Given that the return type of m is T_r , and

Given that the formal parameter types of m are T_{f1}, \dots, T_{fn} , then:

If T_r not an array type, let T_0 be T_r ; otherwise, let T_0 be the element type (§2.4) of T_r .

For $i = 1$ to n : If T_{fi} is not an array type, let T_i be T_{fi} ; otherwise, let T_i be the element type (§2.4) of T_{fi} .

The Java virtual machine must impose the loading constraints $T_i^{L1} = T_i^{L2}$ for $i = 0$ to n (§5.3.4).

5.4.3.5 Method overriding

An instance method m_1 declared in class C overrides another instance method m_2 declared in class A iff all of the following are true:

- C is a subclass of A .
- m_2 has the same name and descriptor as m_1 .
- Either:
 - m_2 is marked ACC_PUBLIC; or is marked ACC_PROTECTED; or is marked neither ACC_PUBLIC nor ACC_PROTECTED nor ACC_PRIVATE and belongs to the same runtime package as C , or
 - m_1 overrides a method m_3 , m_3 distinct from m_1 , m_3 distinct from m_2 , such that m_3 overrides m_2 .

5.4.4 Access Control

A class or interface C is *accessible* to a class or interface D if and only if either of the following conditions are true:

- C is `public`.
- C and D are members of the same runtime package (§5.3).

A field or method R is *accessible* to a class or interface D if and only if any of the following conditions is true:

- R is `public`.
 - R is `protected` and is declared in a class C, and D is either a subclass of C or C itself. Furthermore, if R is not `static`, then the symbolic reference to R must contain a symbolic reference to a class T, such that T is either a subclass of D, a superclass of D or D itself.
- |
- R is either `protected` or has default access (that is, neither `public` nor `protected` nor `private`), and is declared by a class in the same runtime package as D.
 - R is `private` and is declared in D.

This discussion of access control omits a related restriction on the target of a `protected` field access or method invocation (the target must be of class D or a subtype of D). That requirement is checked as part of the verification process (§5.4.1); it is not part of link-time access control.

5.5 Initialization

Initialization of a class or interface consists of executing its class or interface initialization method (§2.9). A class or interface may be initialized only as a result of:

- The execution of any one of the Java virtual machine instructions `new`, `getstatic`, `putstatic`, or `invokestatic` that references the class or interface. All of these instructions reference a class directly or indirectly through either a field reference or a method reference. Upon execution of a `new` instruction, the referenced class or interface is initialized if it has not been initialized already. Upon execution of a `getstatic`, `putstatic`, or `invokestatic` instruction, the class or interface that declared the resolved field or method is initialized if it has not been initialized already.
- Invocation of certain reflective methods in the class library (§2.12), for example, in class `Class` or in package `java.lang.reflect`.
- The initialization of one of its subclasses.
- Its designation as the initial class at Java virtual machine start-up (§5.2).

Prior to initialization, a class or interface must be linked, that is, verified, prepared, and optionally resolved.

Because the Java virtual machine is multithreaded, initialization of a class or interface requires careful synchronization, since some other thread may be trying to initialize the same class or interface at the same time. There is also the possibility that initialization of a class or interface may be requested recursively as part of the initialization of that class or interface. The implementation of the Java virtual machine is responsible for taking care of synchronization and recursive initialization by using the following procedure. It assumes that the `Class` object has already been verified and prepared, and that the `Class` object contains state that indicates one of four situations:

- This `Class` object is verified and prepared but not initialized.
- This `Class` object is being initialized by some particular thread.
- This `Class` object is fully initialized and ready for use.
- This `Class` object is in an erroneous state, perhaps because initialization was attempted and failed.

For each class or interface `C`, there is a unique initialization lock `LC`. The mapping from `C` to `LC` is left to the discretion of the Java virtual machine implementation. The procedure for initializing `C` is then as follows:

1. Synchronize on the initialization lock, `LC`, for `C`. This involves waiting until the current thread can acquire `LC`.
2. If the `Class` object for `C` indicates that initialization is in progress for `C` by some other thread, then release `LC` and block the current thread until informed that the in-progress initialization has completed, at which time repeat this procedure.
3. If the `Class` object for `C` indicates that initialization is in progress for `C` by the current thread, then this must be a recursive request for initialization. Release `LC` and complete normally.
4. If the `Class` object for `C` indicates that `C` has already been initialized, then no further action is required. Release `LC` and complete normally.
5. If the `Class` object for `C` is in an erroneous state, then initialization is not possible. Release `LC` and throw a `NoClassDefFoundError`.
6. Otherwise, record the fact that initialization of the `Class` object for `C` is in progress by the current thread, and release `LC`. Then, initialize each `final`

`static` field of C with the constant value in its `ConstantValue` attribute (§4.7.2), in the order the fields appear in the `ClassFile`.

7. Next, if C is a class rather than an interface, and its superclass SC has not yet been initialized, then recursively perform this entire procedure for SC. If necessary, verify and prepare SC first. If the initialization of SC completes abruptly because of a thrown exception, then acquire LC, label the Class object for C as erroneous, notify all waiting threads, release LC, and complete abruptly, throwing the same exception that resulted from initializing SC.
8. Next, determine whether assertions are enabled for C by querying its defining class loader.
9. Next, execute the class or interface initialization method of C.
10. If the execution of the class or interface initialization method completes normally, then acquire LC, label the Class object for C as fully initialized, notify all waiting threads, release LC, and complete this procedure normally.
11. Otherwise, the class or interface initialization method must have completed abruptly by throwing some exception E. If the class of E is not Error or one of its subclasses, then create a new instance of the class `ExceptionInInitializerError` with E as the argument, and use this object in place of E in the following step. If a new instance of `ExceptionInInitializerError` cannot be created because an `OutOfMemoryError` occurs, then use an `OutOfMemoryError` object in place of E in the following step.
12. Acquire LC, label the Class object for C as erroneous, notify all waiting threads, release LC, and complete this procedure abruptly with reason E or its replacement as determined in the previous step.

An implementation may optimize this procedure by eliding the lock acquisition in step 1 (and release in step 4/5) when it can determine that the initialization of the class has already completed, provided that, in terms of the memory model, all *happens-before* orderings (JLS3 §17.4.5) that would exist if the lock were acquired, still exist when the optimization is performed.

5.6 Binding Native Method Implementations

Binding is the process by which a function written in a language other than the Java programming language and implementing a `native` method is integrated into the Java virtual machine so that it can be executed. Although this process is traditionally

referred to as linking, the term binding is used in the specification to avoid confusion with linking of classes or interfaces by the Java virtual machine.

5.7 Virtual Machine Exit

The Java virtual machine terminates all its activity and exits when either:

- All threads that are not daemon threads terminate.
- Some thread invokes the `exit` method of class `Runtime` or class `System`, and the `exit` operation is permitted by the security manager.

The Java Virtual Machine Instruction Set

A Java virtual machine instruction consists of an opcode specifying the operation to be performed, followed by zero or more operands embodying values to be operated upon. This chapter gives details about the format of each Java virtual machine instruction and the operation it performs.

6.1 Assumptions: The Meaning of “Must”

The description of each instruction is always given in the context of Java virtual machine code that satisfies the static and structural constraints of Chapter 4, “The class File Format.” In the description of individual Java virtual machine instructions, we frequently state that some situation “must” or “must not” be the case: “The *value2* must be of type `int`.” The constraints of Chapter 4 guarantee that all such expectations will in fact be met. If some constraint (a “must” or “must not”) in an instruction description is not satisfied at runtime, the behavior of the Java virtual machine is undefined.

The Java virtual machine checks that Java virtual machine code satisfies the static and structural constraints at link time using a `class` file verifier (see Section 4.10, “Verification of class Files”). Thus, a Java virtual machine will only attempt to execute code from valid `class` files. Performing verification at link time is attractive in that the checks are performed just once, substantially reducing the amount of work that must be done at runtime. Other implementation strategies are possible, provided that they comply with *The Java Language Specification* and *The Java Virtual Machine Specification*.

6.2 Reserved Opcodes

In addition to the opcodes of the instructions specified later in this chapter, which are used in `class` files (see Chapter 4, “The class File Format”), three opcodes are reserved for internal use by a Java virtual machine implementation. If the instruction set of the Java virtual machine is extended in the future, these reserved opcodes are guaranteed not to be used.

Two of the reserved opcodes, numbers 254 (0xfe) and 255 (0xff), have the mnemonics *impdep1* and *impdep2*, respectively. These instructions are intended to provide “back doors” or traps to implementation-specific functionality implemented in software and hardware, respectively. The third reserved opcode, number 202 (0xca), has the mnemonic *breakpoint* and is intended to be used by debuggers to implement breakpoints.

Although these opcodes have been reserved, they may be used only inside a Java virtual machine implementation. They cannot appear in valid `class` files. Tools such as debuggers or JIT code generators (§2.13) that might directly interact with Java virtual machine code that has been already loaded and executed may encounter these opcodes. Such tools should attempt to behave gracefully if they encounter any of these reserved instructions.

6.3 Virtual Machine Errors

A Java virtual machine implementation throws an object that is an instance of a subclass of the class `VirtualMachineError` when an internal error or resource limitation prevents it from implementing the semantics of the Java programming language. This specification cannot predict where internal errors or resource limitations may be encountered and does not mandate precisely when they can be reported. Thus, any of the `VirtualMachineError` subclasses defined below may be thrown at any time during the operation of the Java virtual machine:

- `InternalError`: An internal error has occurred in the Java virtual machine implementation because of a fault in the software implementing the virtual machine, a fault in the underlying host system software, or a fault in the hardware. This error is delivered asynchronously (§2.10) when it is detected and may occur at any point in a program.

- **OutOfMemoryError:** The Java virtual machine implementation has run out of either virtual or physical memory, and the automatic storage manager was unable to reclaim enough memory to satisfy an object creation request.
- **StackOverflowError:** The Java virtual machine implementation has run out of stack space for a thread, typically because the thread is doing an unbounded number of recursive invocations as a result of a fault in the executing program.
- **UnknownError:** An exception or error has occurred, but the Java virtual machine implementation is unable to report the actual exception or error.

6.4 Format of Instruction Descriptions

Java virtual machine instructions are represented in this chapter by entries of the form shown in Figure 6.1, in alphabetical order and each beginning on a new page.

Each cell in the instruction format diagram represents a single 8-bit byte. The instruction's *mnemonic* is its name. Its opcode is its numeric representation and is given in both decimal and hexadecimal forms. Only the numeric representation is actually present in the Java virtual machine code in a `class` file.

Keep in mind that there are “operands” generated at compile time and embedded within Java virtual machine instructions, as well as “operands” calculated at runtime and supplied on the operand stack. Although they are supplied from several different areas, all these operands represent the same thing: values to be operated upon by the Java virtual machine instruction being executed. By implicitly taking many of its operands from its operand stack, rather than representing them explicitly in its compiled code as additional operand bytes, register numbers, etc., the Java virtual machine’s code stays compact.

Some instructions are presented as members of a family of related instructions sharing a single description, format, and operand stack diagram. As such, a family of instructions includes several opcodes and opcode mnemonics; only the family mnemonic appears in the instruction format diagram, and a separate forms line lists all member mnemonics and opcodes. For example, the **Forms** line for the *lconst_<l>* family of instructions, giving mnemonic and opcode information for the two instructions in that family (*lconst_0* and *lconst_1*), is

Forms *lconst_0* = 9 (0x9)
 lconst_1 = 10 (0xa)

<i>mnemonic</i>	<i>mnemonic</i>				
Operation	Short description of the instruction				
Format	<table border="1"> <tr><td><i>mnemonic</i></td></tr> <tr><td><i>operand1</i></td></tr> <tr><td><i>operand2</i></td></tr> <tr><td>...</td></tr> </table>	<i>mnemonic</i>	<i>operand1</i>	<i>operand2</i>	...
<i>mnemonic</i>					
<i>operand1</i>					
<i>operand2</i>					
...					
	Operation				
Forms	<i>mnemonic</i> = opcode				
Operand Stack	$\dots, value_1, value_2 \Rightarrow \dots, value_3$				
Description	A longer description detailing constraints on operand stack contents or constant pool entries, the operation performed, the type of the results, etc.				
Linking Exceptions	If any linking exceptions may be thrown by the execution of this instruction, they are set off one to a line, in the order in which they must be thrown.				
Runtime Exceptions	If any runtime exceptions can be thrown by the execution of an instruction, they are set off one to a line, in the order in which they must be thrown.				
	Other than the linking and runtime exceptions, if any, listed for an instruction, that instruction must not throw any runtime exceptions except for instances of <code>VirtualMachineError</code> or its subclasses.				
Notes	Comments not strictly part of the specification of an instruction are set aside as notes at the end of the description.				

Figure 6.1 An example instruction page

In the description of the Java virtual machine instructions, the effect of an instruction's execution on the operand stack (§2.6.2) of the current frame (§2.6) is represented textually, with the stack growing from left to right and each value represented separately. Thus,

Operand	$\dots, value1, value2 \Rightarrow$
Stack	$\dots, result$

shows an operation that begins by having *value2* on top of the operand stack with *value1* just beneath it. As a result of the execution of the instruction, *value1* and *value2* are popped from the operand stack and replaced by *result* value, which has been calculated by the instruction. The remainder of the operand stack, represented by an ellipsis (...), is unaffected by the instruction's execution.

Values of types `long` and `double` are represented by a single entry on the operand stack.¹

¹ In the first edition of this specification, values on the operand stack of types `long` and `double` were each represented in the stack diagram by two entries.

aaload***aaload***

Operation Load reference from array

Format

<i>aaload</i>

Forms *aaload* = 50 (0x32)

Operand ..., *arrayref*, *index* ⇒
Stack ..., *value*

Description The *arrayref* must be of type **reference** and must refer to an array whose components are of type **reference**. The *index* must be of type **int**. Both *arrayref* and *index* are popped from the operand stack. The reference *value* in the component of the array at *index* is retrieved and pushed onto the operand stack.

Runtime Exceptions If *arrayref* is **null**, *aaload* throws a **NullPointerException**. Otherwise, if *index* is not within the bounds of the array referenced by *arrayref*, the *aaload* instruction throws an **ArrayIndexOutOfBoundsException**.

aastore***aastore***

Operation Store into **reference** array

Format

aastore

Forms *aastore* = 83 (0x53)

Operand ..., *arrayref*, *index*, *value* ⇒
Stack ...

Description The *arrayref* must be of type **reference** and must refer to an array whose components are of type **reference**. The *index* must be of type **int** and *value* must be of type **reference**. The *arrayref*, *index*, and *value* are popped from the operand stack. The **reference** *value* is stored as the component of the array at *index*.

At runtime, the type of *value* must be compatible with the type of the components of the array referenced by *arrayref*. Specifically, assignment of a value of reference type S (source) to an array component of reference type T (target) is allowed only if:

- If S is a class type, then:
 - If T is a class type, then S must be the same class as T, or S must be a subclass of T;
 - If T is an interface type, S must implement interface T.
- If S is an interface type, then:
 - If T is a class type, then T must be **Object**.
 - If T is an interface type, then T must be the same interface as S or a superinterface of S.

aastore* (cont.)**aastore* (cont.)**

- If S is an array type, namely, the type SC[], that is, an array of components of type SC, then:
 - If T is a class type, then T must be `Object`.
 - If T is an array type TC[], that is, an array of components of type TC, then one of the following must be true:
 - TC and SC are the same primitive type.
 - TC and SC are reference types, and type SC is assignable to TC by these runtime rules.
 - If T is an interface type, T must be one of the interfaces implemented by arrays (JLS3 §4.10.3).

Runtime Exceptions

If *arrayref* is `null`, *aastore* throws a `NullPointerException`.

Otherwise, if *index* is not within the bounds of the array referenced by *arrayref*, the *aastore* instruction throws an `ArrayIndexOutOfBoundsException`.

Otherwise, if *arrayref* is not `null` and the actual type of *value* is not assignment compatible (JLS3 §5.2) with the actual type of the components of the array, *aastore* throws an `ArrayStoreException`.

aconst_null***aconst_null***

Operation Push `null`

Format

<i>aconst_null</i>

Forms *aconst_null* = 1 (0x1)

Operand ... \Rightarrow

Stack ..., *null*

Description Push the `null` object reference onto the operand stack.

Notes The Java virtual machine does not mandate a concrete value for `null`.

aload***aload***

Operation Load reference from local variable

Format

<i>aload</i>
<i>index</i>

Forms *aload* = 25 (0x19)

Operand ... \Rightarrow

Stack ..., *objectref*

Description The *index* is an unsigned byte that must be an index into the local variable array of the current frame (§2.6). The local variable at *index* must contain a reference. The *objectref* in the local variable at *index* is pushed onto the operand stack.

Notes The *aload* instruction cannot be used to load a value of type **return-Address** from a local variable onto the operand stack. This asymmetry with the *astore* instruction is intentional.

The *aload* opcode can be used in conjunction with the *wide* instruction to access a local variable using a two-byte unsigned index.

aload_<n>***aload_<n>***

Operation Load reference from local variable

Format

<i>aload_<n></i>

Forms

aload_0 = 42 (0x2a)
aload_1 = 43 (0x2b)
aload_2 = 44 (0x2c)
aload_3 = 45 (0x2d)

Operand

... \Rightarrow

Stack

..., *objectref*

Description The *<n>* must be an index into the local variable array of the current frame (§2.6). The local variable at *<n>* must contain a reference. The *objectref* in the local variable at *index* is pushed onto the operand stack.

Notes

An *aload_<n>* instruction cannot be used to load a value of type *returnAddress* from a local variable onto the operand stack. This asymmetry with the corresponding *astore_<n>* instruction is intentional. Each of the *aload_<n>* instructions is the same as *aload* with an *index* of *<n>*, except that the operand *<n>* is implicit.

*anewarray**anewarray*

Operation Create new array of reference

Format

<i>anewarray</i>
<i>indexbyte1</i>
<i>indexbyte2</i>

Forms *anewarray* = 189 (0xbd)

Operand ..., *count* \Rightarrow

Stack ..., *arrayref*

Description The *count* must be of type `int`. It is popped off the operand stack. The *count* represents the number of components of the array to be created. The unsigned *indexbyte1* and *indexbyte2* are used to construct an index into the runtime constant pool of the current class (§2.6), where the value of the index is $(\text{indexbyte1} \ll 8) | \text{indexbyte2}$. The runtime constant pool item at that index must be a symbolic reference to a class, array, or interface type. The named class, array, or interface type is resolved (§5.4.3.1). A new array with components of that type, of length *count*, is allocated from the garbage-collected heap, and a reference *arrayref* to this new array object is pushed onto the operand stack. All components of the new array are initialized to `null`, the default value for reference types (§2.4).

Linking Exceptions During resolution of the symbolic reference to the class, array, or interface type, any of the exceptions documented in §5.4.3.1 can be thrown.

Runtime Exception Otherwise, if *count* is less than zero, the *anewarray* instruction throws a `NegativeArraySizeException`.

Notes The *anewarray* instruction is used to create a single dimension of an array of object references or part of a multidimensional array.

areturn***areturn***

Operation Return reference from method

Format

<i>areturn</i>

Forms *areturn* = 176 (0xb0)

Operand ..., *objectref* ⇒
Stack [empty]

Description The *objectref* must be of type `reference` and must refer to an object of a type that is assignment compatible (JLS3 §5.2) with the type represented by the return descriptor (§4.3.3) of the current method. If the current method is a `synchronized` method, the monitor entered or reentered on invocation of the method is updated and possibly exited as if by execution of a `monitorexit` instruction in the current thread. If no exception is thrown, *objectref* is popped from the operand stack of the current frame (§2.6) and pushed onto the operand stack of the frame of the invoker. Any other values on the operand stack of the current method are discarded.

The interpreter then reinstates the frame of the invoker and returns control to the invoker.

Runtime Exceptions If the virtual machine implementation does not enforce the rules on structured locking described in §2.11.10, then if the current method is a `synchronized` method and the current thread is not the owner of the monitor entered or reentered on invocation of the method, *areturn* throws an `IllegalMonitorStateException`. This can happen, for example, if a `synchronized` method contains a `monitorexit` instruction, but no `monitorenter` instruction, on the object on which the method is synchronized.

Otherwise, if the virtual machine implementation enforces the rules on structured locking described in §2.11.10 and if the first of those rules is violated during invocation of the current method, then *areturn* throws an `IllegalMonitorStateException`.

arraylength***arraylength***

Operation Get length of array

Format

<i>arraylength</i>

Forms *arraylength* = 190 (0xbe)

Operand ..., *arrayref* \Rightarrow

Stack ..., *length*

Description The *arrayref* must be of type **reference** and must refer to an array. It is popped from the operand stack. The *length* of the array it references is determined. That *length* is pushed onto the operand stack as an **int**.

Runtime Exception If the *arrayref* is **null**, the *arraylength* instruction throws a **NullPointerException**.

astore***astore***

Operation Store reference into local variable

Format

<i>astore</i>
<i>index</i>

Forms *astore* = 58 (0x3a)

Operand ..., *objectref* \Rightarrow

Stack ...

Description The *index* is an unsigned byte that must be an index into the local variable array of the current frame (§2.6). The *objectref* on the top of the operand stack must be of type `returnAddress` or of type `reference`. It is popped from the operand stack, and the value of the local variable at *index* is set to *objectref*.

Notes

The *astore* instruction is used with an *objectref* of type `return-Address` when implementing the `finally` clause of the Java programming language (see §3.13, “Compiling finally”). The *aload* instruction cannot be used to load a value of type `returnAddress` from a local variable onto the operand stack. This asymmetry with the *astore* instruction is intentional.

The *astore* opcode can be used in conjunction with the `wide` instruction to access a local variable using a two-byte unsigned index.

astore_<n>***astore_<n>***

Operation Store reference into local variable

Format

<i>astore_<n></i>

Forms *astore_0* = 75 (0x4b)
astore_1 = 76 (0x4c)
astore_2 = 77 (0x4d)
astore_3 = 78 (0x4e)

Operand ..., *objectref* ⇒

Stack ...

Description The *<n>* must be an index into the local variable array of the current frame (§2.6). The *objectref* on the top of the operand stack must be of type `returnAddress` or of type `reference`. It is popped from the operand stack, and the value of the local variable at *<n>* is set to *objectref*.

Notes An *astore_<n>* instruction is used with an *objectref* of type `returnAddress` when implementing the `finally` clauses of the Java programming language (see §3.13, “Compiling finally”). An *aload_<n>* instruction cannot be used to load a value of type `returnAddress` from a local variable onto the operand stack. This asymmetry with the corresponding *astore_<n>* instruction is intentional.

Each of the *astore_<n>* instructions is the same as *astore* with an *index* of *<n>*, except that the operand *<n>* is implicit.

athrow***athrow***

Operation Throw exception or error

Format

<i>athrow</i>

Forms *athrow* = 191 (0xbf)

Operand ..., *objectref* ⇒
Stack *objectref*

Description The *objectref* must be of type `reference` and must refer to an object that is an instance of class `Throwable` or of a subclass of `Throwable`. It is popped from the operand stack. The *objectref* is then thrown by searching the current method (§2.6) for the first exception handler that matches the class of *objectref*, as given by the algorithm in §2.10.

If an exception handler that matches *objectref* is found, it contains the location of the code intended to handle this exception. The `pc` register is reset to that location, the operand stack of the current frame is cleared, *objectref* is pushed back onto the operand stack, and execution continues.

If no matching exception handler is found in the current frame, that frame is popped. If the current frame represents an invocation of a `synchronized` method, the monitor entered or reentered on invocation of the method is exited as if by execution of a `monitorexit` instruction. Finally, the frame of its invoker is reinstated, if such a frame exists, and the *objectref* is rethrown. If no such frame exists, the current thread exits.

Runtime Exceptions If *objectref* is `null`, *athrow* throws a `NullPointerException` instead of *objectref*.

athrow* (cont.)**athrow* (cont.)**

Otherwise, if the virtual machine implementation does not enforce the rules on structured locking described in §2.11.10, then if the method of the current frame is a `synchronized` method and the current thread is not the owner of the monitor entered or reentered on invocation of the method, *athrow* throws an `IllegalMonitorStateException` instead of the object previously being thrown. This can happen, for example, if an abruptly completing `synchronized` method contains a `monitorexit` instruction, but no `monitorenter` instruction, on the object on which the method is synchronized.

Otherwise, if the virtual machine implementation enforces the rules on structured locking described in §2.11.10 and if the first of those rules is violated during invocation of the current method, then *athrow* throws an `IllegalMonitorStateException` instead of the object previously being thrown.

Notes

The operand stack diagram for the *athrow* instruction may be misleading: If a handler for this exception is matched in the current method, the *athrow* instruction discards all the values on the operand stack, then pushes the thrown object onto the operand stack. However, if no handler is matched in the current method and the exception is thrown farther up the method invocation chain, then the operand stack of the method (if any) that handles the exception is cleared and `objectref` is pushed onto that empty operand stack. All intervening frames from the method that threw the exception up to, but not including, the method that handles the exception are discarded.

baload***baload***

Operation Load `byte` or `boolean` from array

Format

<i>baload</i>

Forms *baload* = 51 (0x33)

Operand ..., *arrayref*, *index* \Rightarrow

Stack ..., *value*

Description The *arrayref* must be of type `reference` and must refer to an array whose components are of type `byte` or of type `boolean`. The *index* must be of type `int`. Both *arrayref* and *index* are popped from the operand stack. The `byte` *value* in the component of the array at *index* is retrieved, sign-extended to an `int` *value*, and pushed onto the top of the operand stack.

Runtime Exceptions If *arrayref* is `null`, *baload* throws a `NullPointerException`.

Otherwise, if *index* is not within the bounds of the array referenced by *arrayref*, the *baload* instruction throws an `ArrayIndexOutOfBoundsException`.

Notes The *baload* instruction is used to load values from both `byte` and `boolean` arrays. In Oracle's implementation of the Java virtual machine, `boolean` arrays (arrays of type `T_BOOLEAN`; see §2.2 and the description of the *newarray* instruction in this chapter) are implemented as arrays of 8-bit values. Other implementations may implement packed `boolean` arrays; the *baload* instruction of such implementations must be used to access those arrays.

bastore***bastore***

Operation Store into byte or boolean array

Format

<i>bastore</i>

Forms *bastore* = 84 (0x54)

Operand ..., *arrayref*, *index*, *value* ⇒
Stack ...

Description The *arrayref* must be of type `reference` and must refer to an array whose components are of type `byte` or of type `boolean`. The *index* and the *value* must both be of type `int`. The *arrayref*, *index*, and *value* are popped from the operand stack. The `int` *value* is truncated to a `byte` and stored as the component of the array indexed by *index*.

Runtime Exceptions If *arrayref* is `null`, *bastore* throws a `NullPointerException`.

Otherwise, if *index* is not within the bounds of the array referenced by *arrayref*, the *bastore* instruction throws an `ArrayIndexOutOfBoundsException`.

Notes The *bastore* instruction is used to store values into both `byte` and `boolean` arrays. In Oracle's implementation of the Java virtual machine, `boolean` arrays (arrays of type `T_BOOLEAN`; see §2.2 and the description of the `newarray` instruction in this chapter) are implemented as arrays of 8-bit values. Other implementations may implement packed `boolean` arrays; in such implementations the *bastore* instruction must be able to store `boolean` values into packed `boolean` arrays as well as `byte` values into `byte` arrays.

bipush***bipush***

Operation Push byte

Format

<i>bipush</i>
<i>byte</i>

Forms $bipush = 16 \text{ (0x10)}$

Operand $\dots \Rightarrow$

Stack $\dots, value$

Description The immediate *byte* is sign-extended to an `int` *value*. That *value* is pushed onto the operand stack.

caload***caload***

Operation Load char from array

Format

<i>caload</i>

Forms *caload* = 52 (0x34)

Operand ..., *arrayref*, *index* ⇒
Stack ..., *value*

Description The *arrayref* must be of type `reference` and must refer to an array whose components are of type `char`. The *index* must be of type `int`. Both *arrayref* and *index* are popped from the operand stack. The component of the array at *index* is retrieved and zero-extended to an `int` *value*. That *value* is pushed onto the operand stack.

Runtime Exceptions If *arrayref* is `null`, *caload* throws a `NullPointerException`. Otherwise, if *index* is not within the bounds of the array referenced by *arrayref*, the *caload* instruction throws an `ArrayIndexOutOfBoundsException`.

castore***castore***

Operation Store into char array

Format

<i>castore</i>

Forms *castore* = 85 (0x55)

Operand ..., *arrayref*, *index*, *value* ⇒
Stack ...

Description The *arrayref* must be of type reference and must refer to an array whose components are of type char. The *index* and the *value* must both be of type int. The *arrayref*, *index*, and *value* are popped from the operand stack. The int *value* is truncated to a char and stored as the component of the array indexed by *index*.

Runtime Exceptions If *arrayref* is null, *castore* throws a NullPointerException. Otherwise, if *index* is not within the bounds of the array referenced by *arrayref*, the *castore* instruction throws an ArrayIndexOutOfBoundsException.

checkcast***checkcast***

Operation Check whether object is of given type

Format

<i>checkcast</i>
<i>indexbyte1</i>
<i>indexbyte2</i>

Forms *checkcast* = 192 (0xc0)

Operand ..., *objectref* \Rightarrow

Stack ..., *objectref*

Description The *objectref* must be of type `reference`. The unsigned *indexbyte1* and *indexbyte2* are used to construct an index into the runtime constant pool of the current class (§2.6), where the value of the index is (*indexbyte1* \ll 8) | *indexbyte2*. The runtime constant pool item at the index must be a symbolic reference to a class, array, or interface type.

If *objectref* is `null`, then the operand stack is unchanged.

Otherwise, the named class, array, or interface type is resolved (§5.4.3.1). If *objectref* can be cast to the resolved class, array, or interface type, the operand stack is unchanged; otherwise, the *checkcast* instruction throws a `ClassCastException`.

The following rules are used to determine whether an *objectref* that is not `null` can be cast to the resolved type: if S is the class of the object referred to by *objectref* and T is the resolved class, array, or interface type, *checkcast* determines whether *objectref* can be cast to type T as follows:

- If S is an ordinary (nonarray) class, then:
 - If T is a class type, then S must be the same class as T, or a subclass of T.
 - If T is an interface type, then S must implement interface T.

checkcast* (cont.)**checkcast* (cont.)**

- If S is an interface type, then:
 - If T is a class type, then T must be `Object`.
 - If T is an interface type, then T must be the same interface as S or a superinterface of S.
- If S is a class representing the array type SC[], that is, an array of components of type SC, then:
 - If T is a class type, then T must be `Object`.
 - If T is an array type TC[], that is, an array of components of type TC, then one of the following must be true:
 - TC and SC are the same primitive type.
 - TC and SC are reference types, and type SC can be cast to TC by recursive application of these rules.
 - If T is an interface type, T must be one of the interfaces implemented by arrays (JLS3 §4.10.3).

Linking Exceptions	During resolution of the symbolic reference to the class, array, or interface type, any of the exceptions documented in §5.4.3.1 can be thrown.
Runtime Exception	Otherwise, if <i>objectref</i> cannot be cast to the resolved class, array, or interface type, the <i>checkcast</i> instruction throws a <code>ClassCastException</code> .
Notes	The <i>checkcast</i> instruction is very similar to the <i>instanceof</i> instruction. It differs in its treatment of <code>null</code> , its behavior when its test fails (<i>checkcast</i> throws an exception, <i>instanceof</i> pushes a result code), and its effect on the operand stack.

d2f***d2f*****Operation** Convert **double** to **float****Format*****d2f*****Forms** ***d2f*** = 144 (0x90)**Operand** ..., *value* \Rightarrow **Stack** ..., *result*

Description The *value* on the top of the operand stack must be of type **double**. It is popped from the operand stack and undergoes value set conversion (§2.8.3) resulting in *value'*. Then *value'* is converted to a **float** *result* using IEEE 754 round to nearest mode. The *result* is pushed onto the operand stack.

Where an ***d2f*** instruction is FP-strict (§2.8.2), the result of the conversion is always rounded to the nearest representable value in the float value set (§2.3.2).

Where an ***d2f*** instruction is not FP-strict, the result of the conversion may be taken from the float-extended-exponent value set (§2.3.2); it is not necessarily rounded to the nearest representable value in the float value set.

A finite *value'* too small to be represented as a **float** is converted to a zero of the same sign; a finite *value'* too large to be represented as a **float** is converted to an infinity of the same sign. A **double** NaN is converted to a **float** NaN.

Notes

The ***d2f*** instruction performs a narrowing primitive conversion (JLS3 §5.1.3). It may lose information about the overall magnitude of *value'* and may also lose precision.

d2i***d2i*****Operation** Convert `double` to `int`**Format*****d2i*****Forms** $d2i = 142 \text{ (0x8e)}$ **Operand** $\dots, value \Rightarrow$ **Stack** $\dots, result$

Description The *value* on the top of the operand stack must be of type `double`. It is popped from the operand stack and undergoes value set conversion (§2.8.3) resulting in *value'*. Then *value'* is converted to an `int`. The *result* is pushed onto the operand stack:

- If the *value'* is NaN, the *result* of the conversion is an `int` 0.
- Otherwise, if the *value'* is not an infinity, it is rounded to an integer value *V*, rounding towards zero using IEEE 754 round towards zero mode. If this integer value *V* can be represented as an `int`, then the *result* is the `int` value *V*.
- Otherwise, either the *value'* must be too small (a negative value of large magnitude or negative infinity), and the *result* is the smallest representable value of type `int`, or the *value'* must be too large (a positive value of large magnitude or positive infinity), and the *result* is the largest representable value of type `int`.

Notes

The *d2i* instruction performs a narrowing primitive conversion (JLS3 §5.1.3). It may lose information about the overall magnitude of *value'* and may also lose precision.

d2l***d2l*****Operation** Convert `double` to `long`**Format*****d2l*****Forms** $d2l = 143 \text{ (0x8f)}$ **Operand** $\dots, value \Rightarrow$ **Stack** $\dots, result$

Description The *value* on the top of the operand stack must be of type `double`. It is popped from the operand stack and undergoes value set conversion (§2.8.3) resulting in *value'*. Then *value'* is converted to a `long`. The *result* is pushed onto the operand stack:

- If the *value'* is NaN, the *result* of the conversion is a `long` 0.
- Otherwise, if the *value'* is not an infinity, it is rounded to an integer value *V*, rounding towards zero using IEEE 754 round towards zero mode. If this integer value *V* can be represented as a `long`, then the *result* is the `long` value *V*.
- Otherwise, either the *value'* must be too small (a negative value of large magnitude or negative infinity), and the *result* is the smallest representable value of type `long`, or the *value'* must be too large (a positive value of large magnitude or positive infinity), and the *result* is the largest representable value of type `long`.

Notes

The *d2l* instruction performs a narrowing primitive conversion (JLS3 §5.1.3). It may lose information about the overall magnitude of *value'* and may also lose precision.

dadd***dadd*****Operation** Add double**Format**

<i>dadd</i>

Forms *dadd* = 99 (0x63)**Operand** ..., *value1*, *value2* \Rightarrow **Stack** ..., *result***Description** Both *value1* and *value2* must be of type double. The values are popped from the operand stack and undergo value set conversion (§2.8.3), resulting in *value1'* and *value2'*. The double *result* is *value1' + value2'*. The *result* is pushed onto the operand stack.

The result of a *dadd* instruction is governed by the rules of IEEE arithmetic:

- If either *value1'* or *value2'* is NaN, the result is NaN.
- The sum of two infinities of opposite sign is NaN.
- The sum of two infinities of the same sign is the infinity of that sign.
- The sum of an infinity and any finite value is equal to the infinity.
- The sum of two zeroes of opposite sign is positive zero.
- The sum of two zeroes of the same sign is the zero of that sign.
- The sum of a zero and a nonzero finite value is equal to the nonzero value.
- The sum of two nonzero finite values of the same magnitude and opposite sign is positive zero.

dadd (*cont.*)***dadd*** (*cont.*)

- In the remaining cases, where neither operand is an infinity, a zero, or NaN and the values have the same sign or have different magnitudes, the sum is computed and rounded to the nearest representable value using IEEE 754 round to nearest mode. If the magnitude is too large to represent as a `double`, we say the operation overflows; the result is then an infinity of appropriate sign. If the magnitude is too small to represent as a `double`, we say the operation underflows; the result is then a zero of appropriate sign.

The Java virtual machine requires support of gradual underflow as defined by IEEE 754. Despite the fact that overflow, underflow, or loss of precision may occur, execution of a *dadd* instruction never throws a run-time exception.

daload***daload***

Operation Load `double` from array

Format

daload

Forms *daload* = 49 (0x31)

Operand ..., *arrayref*, *index* ⇒

Stack ..., *value*

Description The *arrayref* must be of type `reference` and must refer to an array whose components are of type `double`. The *index* must be of type `int`. Both *arrayref* and *index* are popped from the operand stack. The `double` *value* in the component of the array at *index* is retrieved and pushed onto the operand stack.

Runtime Exceptions If *arrayref* is `null`, *daload* throws a `NullPointerException`.

Otherwise, if *index* is not within the bounds of the array referenced by *arrayref*, the *daload* instruction throws an `ArrayIndexOutOfBoundsException`.

dastore***dastore***

Operation Store into `double` array

Format

<i>dastore</i>

Forms *dastore* = 82 (0x52)

Operand ..., *arrayref*, *index*, *value* ⇒
Stack ...

Description The *arrayref* must be of type `reference` and must refer to an array whose components are of type `double`. The *index* must be of type `int`, and *value* must be of type `double`. The *arrayref*, *index*, and *value* are popped from the operand stack. The `double` *value* undergoes value set conversion (§2.8.3), resulting in *value'*, which is stored as the component of the array indexed by *index*.

Runtime Exceptions If *arrayref* is `null`, *dastore* throws a `NullPointerException`. Otherwise, if *index* is not within the bounds of the array referenced by *arrayref*, the *dastore* instruction throws an `ArrayIndexOutOfBoundsException`.

dcmp<op>***dcmp<op>***

Operation Compare `double`

Format

dcmp<op>

Forms

dcmpg = 152 (0x98)

dcmpl = 151 (0x97)

Operand

..., *value1*, *value2* \Rightarrow

Stack

..., *result*

Description Both *value1* and *value2* must be of type `double`. The values are popped from the operand stack and undergo value set conversion (§2.8.3), resulting in *value1'* and *value2'*. A floating-point comparison is performed:

- If *value1'* is greater than *value2'*, the `int` value *1* is pushed onto the operand stack.
- Otherwise, if *value1'* is equal to *value2'*, the `int` value *0* is pushed onto the operand stack.
- Otherwise, if *value1'* is less than *value2'*, the `int` value *-1* is pushed onto the operand stack.
- Otherwise, at least one of *value1'* or *value2'* is NaN. The *dcmpg* instruction pushes the `int` value *1* onto the operand stack and the *dcmpl* instruction pushes the `int` value *-1* onto the operand stack.

Floating-point comparison is performed in accordance with IEEE 754. All values other than NaN are ordered, with negative infinity less than all finite values and positive infinity greater than all finite values. Positive zero and negative zero are considered equal.

dcmp<op> (*cont.*)***dcmp<op>*** (*cont.*)**Notes**

The *dcmpl* and *dcmpg* instructions differ only in their treatment of a comparison involving NaN. NaN is unordered, so any **double** comparison fails if either or both of its operands are NaN. With both *dcmpl* and *dcmpg* available, any **double** comparison may be compiled to push the same *result* onto the operand stack whether the comparison fails on non-NaN values or fails because it encountered a NaN. For more information, see §3.5, “More Control Examples.”

dconst_<d>***dconst_<d>***

Operation Push double

Format

dconst_<d>

Forms *dconst_0* = 14 (0xe)

dconst_1 = 15 (0xf)

Operand ... \Rightarrow

Stack ..., <*d*>

Description Push the double constant <*d*> (0.0 or 1.0) onto the operand stack.

ddiv ***ddiv***

Operation Divide `double`

Format

<i>ddiv</i>

Forms $ddiv = 111 \text{ (0x6f)}$

Operand $\dots, value1, value2 \Rightarrow$
Stack $\dots, result$

Description Both *value1* and *value2* must be of type `double`. The values are popped from the operand stack and undergo value set conversion (§2.8.3), resulting in *value1'* and *value2'*. The `double` *result* is *value1' / value2'*. The *result* is pushed onto the operand stack.

The result of a *ddiv* instruction is governed by the rules of IEEE arithmetic:

- If either *value1'* or *value2'* is NaN, the result is NaN.
- If neither *value1'* nor *value2'* is NaN, the sign of the result is positive if both values have the same sign, negative if the values have different signs.
- Division of an infinity by an infinity results in NaN.
- Division of an infinity by a finite value results in a signed infinity, with the sign-producing rule just given.
- Division of a finite value by an infinity results in a signed zero, with the sign-producing rule just given.
- Division of a zero by a zero results in NaN; division of zero by any other finite value results in a signed zero, with the sign-producing rule just given.
- Division of a nonzero finite value by a zero results in a signed infinity, with the sign-producing rule just given.

ddiv (*cont.*)

ddiv (*cont.*)

- In the remaining cases, where neither operand is an infinity, a zero, or NaN, the quotient is computed and rounded to the nearest double using IEEE 754 round to nearest mode. If the magnitude is too large to represent as a double, we say the operation overflows; the result is then an infinity of appropriate sign. If the magnitude is too small to represent as a double, we say the operation underflows; the result is then a zero of appropriate sign.

The Java virtual machine requires support of gradual underflow as defined by IEEE 754. Despite the fact that overflow, underflow, division by zero, or loss of precision may occur, execution of a *ddiv* instruction never throws a runtime exception.

dload***dload***

Operation Load `double` from local variable

Format

<i>dload</i>
<i>index</i>

Forms $dload = 24 \text{ (0x18)}$

Operand $\dots \Rightarrow$

Stack $\dots, value$

Description The *index* is an unsigned byte. Both *index* and *index + 1* must be indices into the local variable array of the current frame (§2.6). The local variable at *index* must contain a `double`. The *value* of the local variable at *index* is pushed onto the operand stack.

Notes The *dload* opcode can be used in conjunction with the *wide* instruction to access a local variable using a two-byte unsigned index.

dload_<n>***dload_<n>***

Operation Load `double` from local variable

Format

dload_<n>

Forms

dload_0 = 38 (0x26)
dload_1 = 39 (0x27)
dload_2 = 40 (0x28)
dload_3 = 41 (0x29)

Operand ... \Rightarrow

Stack ..., *value*

Description Both $<n>$ and $<n> + 1$ must be indices into the local variable array of the current frame (§2.6). The local variable at $<n>$ must contain a `double`. The *value* of the local variable at $<n>$ is pushed onto the operand stack.

Notes

Each of the *dload_<n>* instructions is the same as *dload* with an *index* of $<n>$, except that the operand $<n>$ is implicit.

dmul***dmul***

Operation Multiply `double`

Format

<i>dmul</i>

Forms $dmul = 107 \ (0x6b)$

Operand $\dots, value1, value2 \Rightarrow$
Stack $\dots, result$

Description Both $value1$ and $value2$ must be of type `double`. The values are popped from the operand stack and undergo value set conversion (§2.8.3), resulting in $value1'$ and $value2'$. The `double` $result$ is $value1' * value2'$. The $result$ is pushed onto the operand stack.

The result of a *dmul* instruction is governed by the rules of IEEE arithmetic:

- If either $value1'$ or $value2'$ is NaN, the result is NaN.
- If neither $value1'$ nor $value2'$ is NaN, the sign of the result is positive if both values have the same sign and negative if the values have different signs.
- Multiplication of an infinity by a zero results in NaN.
- Multiplication of an infinity by a finite value results in a signed infinity, with the sign-producing rule just given.
- In the remaining cases, where neither an infinity nor NaN is involved, the product is computed and rounded to the nearest representable value using IEEE 754 round to nearest mode. If the magnitude is too large to represent as a `double`, we say the operation overflows; the result is then an infinity of appropriate sign. If the magnitude is too small to represent as a `double`, we say the operation underflows; the result is then a zero of appropriate sign.

dmul (*cont.*)

dmul (*cont.*)

The Java virtual machine requires support of gradual underflow as defined by IEEE 754. Despite the fact that overflow, underflow, or loss of precision may occur, execution of a *dmul* instruction never throws a runtime exception.

dneg***dneg***

Operation Negate double

Format

<i>dneg</i>

Forms *dneg* = 119 (0x77)

Operand ..., *value* \Rightarrow

Stack ..., *result*

Description The *value* must be of type `double`. It is popped from the operand stack and undergoes value set conversion (§2.8.3), resulting in *value'*. The `double` *result* is the arithmetic negation of *value'*. The *result* is pushed onto the operand stack.

For `double` values, negation is not the same as subtraction from zero. If *x* is `+0.0`, then `0.0 - x` equals `+0.0`, but `-x` equals `-0.0`. Unary minus merely inverts the sign of a `double`.

Special cases of interest:

- If the operand is NaN, the result is NaN (recall that NaN has no sign).
- If the operand is an infinity, the result is the infinity of opposite sign.
- If the operand is a zero, the result is the zero of opposite sign.

drem***drem***

Operation Remainder `double`

Format

<i>drem</i>

Forms *drem* = 115 (0x73)

Operand ... , *value1*, *value2* \Rightarrow
Stack ... , *result*

Description Both *value1* and *value2* must be of type `double`. The values are popped from the operand stack and undergo value set conversion (§2.8.3), resulting in *value1'* and *value2'*. The *result* is calculated and pushed onto the operand stack as a `double`.

The result of a *drem* instruction is not the same as that of the so-called remainder operation defined by IEEE 754. The IEEE 754 “remainder” operation computes the remainder from a rounding division, not a truncating division, and so its behavior is *not* analogous to that of the usual integer remainder operator. Instead, the Java virtual machine defines *drem* to behave in a manner analogous to that of the Java virtual machine integer remainder instructions (*irem* and *lrem*); this may be compared with the C library function *fmod*.

The result of a *drem* instruction is governed by these rules:

- If either *value1'* or *value2'* is NaN, the result is NaN.
- If neither *value1'* nor *value2'* is NaN, the sign of the result equals the sign of the dividend.
- If the dividend is an infinity or the divisor is a zero or both, the result is NaN.
- If the dividend is finite and the divisor is an infinity, the result equals the dividend.

drem (*cont.*)***drem*** (*cont.*)

- If the dividend is a zero and the divisor is finite, the result equals the dividend.
- In the remaining cases, where neither operand is an infinity, a zero, or NaN, the floating-point remainder *result* from a dividend *value1*' and a divisor *value2*' is defined by the mathematical relation $result = value1' - (value2' * q)$, where *q* is an integer that is negative only if *value1' / value2'* is negative, and positive only if *value1' / value2'* is positive, and whose magnitude is as large as possible without exceeding the magnitude of the true mathematical quotient of *value1'* and *value2'*.

Despite the fact that division by zero may occur, evaluation of a *drem* instruction never throws a runtime exception. Overflow, underflow, or loss of precision cannot occur.

Notes

The IEEE 754 remainder operation may be computed by the library routine `Math.IEEEremainder`.

dreturn***dreturn***

Operation Return `double` from method

Format

<i>dreturn</i>

Forms *dreturn* = 175 (0xaf)

Operand ... , *value* \Rightarrow
Stack [empty]

Description The current method must have return type `double`. The *value* must be of type `double`. If the current method is a `synchronized` method, the monitor entered or reentered on invocation of the method is updated and possibly exited as if by execution of a `monitorexit` instruction in the current thread. If no exception is thrown, *value* is popped from the operand stack of the current frame (§2.6) and undergoes value set conversion (§2.8.3), resulting in *value'*. The *value'* is pushed onto the operand stack of the frame of the invoker. Any other values on the operand stack of the current method are discarded.

The interpreter then returns control to the invoker of the method, reinstating the frame of the invoker.

Runtime Exceptions If the virtual machine implementation does not enforce the rules on structured locking described in §2.11.10, then if the current method is a `synchronized` method and the current thread is not the owner of the monitor entered or reentered on invocation of the method, *dreturn* throws an `IllegalMonitorStateException`. This can happen, for example, if a `synchronized` method contains a `monitorexit` instruction, but no `monitorenter` instruction, on the object on which the method is synchronized.

Otherwise, if the virtual machine implementation enforces the rules on structured locking described in §2.11.10 and if the first of those rules is violated during invocation of the current method, then *dreturn* throws an `IllegalMonitorStateException`.

dstore***dstore***

Operation Store `double` into local variable

Format

<i>dstore</i>
<i>index</i>

Forms $dstore = 57 \text{ (0x39)}$

Operand $\dots, value \Rightarrow$

Stack \dots

Description The *index* is an unsigned byte. Both *index* and *index + 1* must be indices into the local variable array of the current frame (§2.6). The *value* on the top of the operand stack must be of type `double`. It is popped from the operand stack and undergoes value set conversion (§2.8.3), resulting in *value'*. The local variables at *index* and *index + 1* are set to *value'*.

Notes The *dstore* opcode can be used in conjunction with the *wide* instruction to access a local variable using a two-byte unsigned index.

dstore_<n>***dstore_<n>***

Operation Store `double` into local variable

Format

dstore_<n>

Forms

dstore_0 = 71 (0x47)
dstore_1 = 72 (0x48)
dstore_2 = 73 (0x49)
dstore_3 = 74 (0x4a)

Operand ..., *value* \Rightarrow

Stack ...

Description Both $<n>$ and $<n> + 1$ must be indices into the local variable array of the current frame (§2.6). The *value* on the top of the operand stack must be of type `double`. It is popped from the operand stack and undergoes value set conversion (§2.8.3), resulting in *value'*. The local variables at $<n>$ and $<n> + 1$ are set to *value'*.

Notes Each of the *dstore_<n>* instructions is the same as *dstore* with an *index* of $<n>$, except that the operand $<n>$ is implicit.

dsub***dsub***

Operation Subtract `double`

Format

<i>dsub</i>

Forms *dsub* = 103 (0x67)

Operand ..., *value1*, *value2* \Rightarrow

Stack ..., *result*

Description Both *value1* and *value2* must be of type `double`. The values are popped from the operand stack and undergo value set conversion (§2.8.3), resulting in *value1'* and *value2'*. The `double` *result* is *value1'* – *value2'*. The *result* is pushed onto the operand stack.

For `double` subtraction, it is always the case that $a - b$ produces the same result as $a + (-b)$. However, for the *dsub* instruction, subtraction from zero is not the same as negation, because if x is $+0.0$, then $0.0 - x$ equals $+0.0$, but $-x$ equals -0.0 .

The Java virtual machine requires support of gradual underflow as defined by IEEE 754. Despite the fact that overflow, underflow, or loss of precision may occur, execution of a *dsub* instruction never throws a run-time exception.

dup***dup***

Operation Duplicate the top operand stack value

Format

<i>dup</i>

Forms *dup* = 89 (0x59)

Operand ..., *value* \Rightarrow

Stack ..., *value*, *value*

Description Duplicate the top value on the operand stack and push the duplicated value onto the operand stack.

The *dup* instruction must not be used unless *value* is a value of a category 1 computational type (§2.11.1).

dup_x1***dup_x1***

Operation Duplicate the top operand stack value and insert two values down

Format

dup_x1

Forms *dup_x1* = 90 (0x5a)

Operand Stack $\dots, value2, value1 \Rightarrow \dots, value1, value2, value1$

Description Duplicate the top value on the operand stack and insert the duplicated value two values down in the operand stack.

The *dup_x1* instruction must not be used unless both *value1* and *value2* are values of a category 1 computational type (§2.11.1).

dup_x2***dup_x2***

Operation Duplicate the top operand stack value and insert two or three values down

Format

dup_x2

Forms $dup_x2 = 91 \ (0x5b)$

Operand Form 1:

Stack

$\dots, value3, value2, value1 \Rightarrow$
 $\dots, value1, value3, value2, value1$

where *value1*, *value2*, and *value3* are all values of a category 1 computational type (§2.11.1).

Form 2:

$\dots, value2, value1 \Rightarrow$
 $\dots, value1, value2, value1$

where *value1* is a value of a category 1 computational type and *value2* is a value of a category 2 computational type (§2.11.1).

Description Duplicate the top value on the operand stack and insert the duplicated value two or three values down in the operand stack.

dup2***dup2***

Operation Duplicate the top one or two operand stack values

Format

<i>dup2</i>

Forms *dup2* = 92 (0x5c)

Operand Form 1:

Stack

$\dots, value_2, value_1 \Rightarrow$
 $\dots, value_2, value_1, value_2, value_1$

where both *value1* and *value2* are values of a category 1 computational type (§2.11.1).

Form 2:

$\dots, value \Rightarrow$
 $\dots, value, value$

where *value* is a value of a category 2 computational type (§2.11.1).

Description Duplicate the top one or two values on the operand stack and push the duplicated value or values back onto the operand stack in the original order.

dup2_x1***dup2_x1***

Operation Duplicate the top one or two operand stack values and insert two or three values down

Format

<i>dup2_x1</i>

Forms $dup2_x1 = 93 \ (0x5d)$

Operand Form 1:

Stack

$\dots, value3, value2, value1 \Rightarrow$
 $\dots, value2, value1, value3, value2, value1$

where *value1*, *value2*, and *value3* are all values of a category 1 computational type (§2.11.1).

Form 2:

$\dots, value2, value1 \Rightarrow$
 $\dots, value1, value2, value1$

where *value1* is a value of a category 2 computational type and *value2* is a value of a category 1 computational type (§2.11.1).

Description Duplicate the top one or two values on the operand stack and insert the duplicated values, in the original order, one value beneath the original value or values in the operand stack.

dup2_x2***dup2_x2***

Operation Duplicate the top one or two operand stack values and insert two, three, or four values down

Format

<i>dup2_x2</i>

Forms $dup2_x2 = 94 \ (0x5e)$

**Operand
Stack**

Form 1:

$\dots, value4, value3, value2, value1 \Rightarrow$
 $\dots, value2, value1, value4, value3, value2, value1$

where *value1*, *value2*, *value3*, and *value4* are all values of a category 1 computational type (§2.11.1).

Form 2:

$\dots, value3, value2, value1 \Rightarrow$
 $\dots, value1, value3, value2, value1$

where *value1* is a value of a category 2 computational type and *value2* and *value3* are both values of a category 1 computational type (§2.11.1).

Form 3:

$\dots, value3, value2, value1 \Rightarrow$
 $\dots, value2, value1, value3, value2, value1$

where *value1* and *value2* are both values of a category 1 computational type and *value3* is a value of a category 2 computational type (§2.11.1).

Form 4:

$\dots, value2, value1 \Rightarrow$
 $\dots, value1, value2, value1$

where *value1* and *value2* are both values of a category 2 computational type (§2.11.1).

dup2_x2 (cont.)

dup2_x2 (cont.)

Description Duplicate the top one or two values on the operand stack and insert the duplicated values, in the original order, into the operand stack.

f2d***f2d*****Operation** Convert float to double**Format*****f2d*****Forms** $f2d = 141 \text{ (0x8d)}$ **Operand** $\dots, value \Rightarrow$ **Stack** $\dots, result$ **Description** The *value* on the top of the operand stack must be of type float. It is popped from the operand stack and undergoes value set conversion (§2.8.3), resulting in *value'*. Then *value'* is converted to a double *result*. This *result* is pushed onto the operand stack.**Notes** Where an *f2d* instruction is FP-strict (§2.8.2) it performs a widening primitive conversion (JLS3 §5.1.2). Because all values of the float value set (§2.3.2) are exactly representable by values of the double value set (§2.3.2), such a conversion is exact.

Where an *f2d* instruction is not FP-strict, the result of the conversion may be taken from the double-extended-exponent value set; it is not necessarily rounded to the nearest representable value in the double value set. However, if the operand *value* is taken from the float-extended-exponent value set and the target result is constrained to the double value set, rounding of *value* may be required.

f2i***f2i*****Operation** Convert `float` to `int`**Format**

<i>f2i</i>

Forms *f2i* = 139 (0x8b)**Operand** ..., *value* \Rightarrow **Stack** ..., *result*

Description The *value* on the top of the operand stack must be of type `float`. It is popped from the operand stack and undergoes value set conversion (§2.8.3), resulting in *value'*. Then *value'* is converted to an `int` *result*. This *result* is pushed onto the operand stack:

- If the *value'* is NaN, the *result* of the conversion is an `int` 0.
- Otherwise, if the *value'* is not an infinity, it is rounded to an integer value *V*, rounding towards zero using IEEE 754 round towards zero mode. If this integer value *V* can be represented as an `int`, then the *result* is the `int` value *V*.
- Otherwise, either the *value'* must be too small (a negative value of large magnitude or negative infinity), and the *result* is the smallest representable value of type `int`, or the *value'* must be too large (a positive value of large magnitude or positive infinity), and the *result* is the largest representable value of type `int`.

Notes

The *f2i* instruction performs a narrowing primitive conversion (JLS3 §5.1.3). It may lose information about the overall magnitude of *value'* and may also lose precision.

f2l***f2l*****Operation** Convert float to long**Format*****f2l*****Forms** $f2l = 140 \text{ (0x8c)}$ **Operand** $\dots, value \Rightarrow$ **Stack** $\dots, result$

Description The *value* on the top of the operand stack must be of type float. It is popped from the operand stack and undergoes value set conversion (§2.8.3), resulting in *value'*. Then *value'* is converted to a long *result*. This *result* is pushed onto the operand stack:

- If the *value'* is NaN, the *result* of the conversion is a long 0.
- Otherwise, if the *value'* is not an infinity, it is rounded to an integer value *V*, rounding towards zero using IEEE 754 round towards zero mode. If this integer value *V* can be represented as a long, then the *result* is the long value *V*.
- Otherwise, either the *value'* must be too small (a negative value of large magnitude or negative infinity), and the *result* is the smallest representable value of type long, or the *value'* must be too large (a positive value of large magnitude or positive infinity), and the *result* is the largest representable value of type long.

Notes

The *f2l* instruction performs a narrowing primitive conversion (JLS3 §5.1.3). It may lose information about the overall magnitude of *value'* and may also lose precision.

fadd**fadd****Operation** Add float**Format**

<i>fadd</i>

Forms *fadd* = 98 (0x62)**Operand** ..., *value1*, *value2* \Rightarrow **Stack** ..., *result***Description** Both *value1* and *value2* must be of type float. The values are popped from the operand stack and undergo value set conversion (§2.8.3), resulting in *value1'* and *value2'*. The float *result* is *value1'* + *value2'*. The *result* is pushed onto the operand stack.

The result of an *fadd* instruction is governed by the rules of IEEE arithmetic:

- If either *value1'* or *value2'* is NaN, the result is NaN.
- The sum of two infinities of opposite sign is NaN.
- The sum of two infinities of the same sign is the infinity of that sign.
- The sum of an infinity and any finite value is equal to the infinity.
- The sum of two zeroes of opposite sign is positive zero.
- The sum of two zeroes of the same sign is the zero of that sign.
- The sum of a zero and a nonzero finite value is equal to the nonzero value.
- The sum of two nonzero finite values of the same magnitude and opposite sign is positive zero.

fadd (*cont.*)

fadd (*cont.*)

- In the remaining cases, where neither operand is an infinity, a zero, or NaN and the values have the same sign or have different magnitudes, the sum is computed and rounded to the nearest representable value using IEEE 754 round to nearest mode. If the magnitude is too large to represent as a float, we say the operation overflows; the result is then an infinity of appropriate sign. If the magnitude is too small to represent as a float, we say the operation underflows; the result is then a zero of appropriate sign.

The Java virtual machine requires support of gradual underflow as defined by IEEE 754. Despite the fact that overflow, underflow, or loss of precision may occur, execution of an *fadd* instruction never throws a run-time exception.

faload***faload***

Operation Load float from array

Format

<i>faload</i>

Forms *faload* = 48 (0x30)

Operand ..., *arrayref*, *index* \Rightarrow

Stack ..., *value*

Description The *arrayref* must be of type reference and must refer to an array whose components are of type float. The *index* must be of type int. Both *arrayref* and *index* are popped from the operand stack. The float *value* in the component of the array at *index* is retrieved and pushed onto the operand stack.

Runtime Exceptions If *arrayref* is null, *faload* throws a NullPointerException.

Otherwise, if *index* is not within the bounds of the array referenced by *arrayref*, the *faload* instruction throws an ArrayIndexOutOfBoundsException.

fastore ***fastore***

Operation Store into **float** array

Format

<i>fastore</i>

Forms *fastore* = 81 (0x51)

Operand ..., *arrayref*, *index*, *value* ⇒
Stack ...

Description The *arrayref* must be of type **reference** and must refer to an array whose components are of type **float**. The *index* must be of type **int**, and the *value* must be of type **float**. The *arrayref*, *index*, and *value* are popped from the operand stack. The **float** *value* undergoes value set conversion (§2.8.3), resulting in *value'*, and *value'* is stored as the component of the array indexed by *index*.

Runtime Exceptions If *arrayref* is **null**, *fastore* throws a **NullPointerException**. Otherwise, if *index* is not within the bounds of the array referenced by *arrayref*, the *fastore* instruction throws an **ArrayIndexOutOfBoundsException**.

fcmp<op>***fcmp<op>*****Operation** Compare float**Format***fcmp<op>***Forms***fcmpg* = 150 (0x96)*fcmpl* = 149 (0x95)**Operand***..., value1, value2* \Rightarrow **Stack***..., result***Description** Both *value1* and *value2* must be of type float. The values are popped from the operand stack and undergo value set conversion (§2.8.3), resulting in *value1'* and *value2'*. A floating-point comparison is performed:

- If *value1'* is greater than *value2'*, the int value 1 is pushed onto the operand stack.
- Otherwise, if *value1'* is equal to *value2'*, the int value 0 is pushed onto the operand stack.
- Otherwise, if *value1'* is less than *value2'*, the int value -1 is pushed onto the operand stack.
- Otherwise, at least one of *value1'* or *value2'* is NaN. The *fcmpg* instruction pushes the int value 1 onto the operand stack and the *fcmpl* instruction pushes the int value -1 onto the operand stack.

Floating-point comparison is performed in accordance with IEEE 754. All values other than NaN are ordered, with negative infinity less than all finite values and positive infinity greater than all finite values. Positive zero and negative zero are considered equal.

fcmp<op> (*cont.*)

fcmp<op> (*cont.*)

Notes

The *fcmpg* and *fcmpl* instructions differ only in their treatment of a comparison involving NaN. NaN is unordered, so any `float` comparison fails if either or both of its operands are NaN. With both *fcmpg* and *fcmpl* available, any `float` comparison may be compiled to push the same *result* onto the operand stack whether the comparison fails on non-NaN values or fails because it encountered a NaN. For more information, see §3.5, “More Control Examples.”

fconst_<f>

fconst_<f>

Operation Push float

Format

fconst_<f>

Forms *fconst_0 = 11 (0xb)*

fconst_1 = 12 (0xc)

fconst_2 = 13 (0xd)

Operand ... \Rightarrow

Stack ..., *<f>*

Description Push the float constant *<f>* (0.0, 1.0, or 2.0) onto the operand stack.

fdiv***fdiv*****Operation** Divide float**Format**

<i>fdiv</i>

Forms *fdiv* = 110 (0x6e)**Operand** ..., *value1*, *value2* ⇒
Stack ..., *result***Description** Both *value1* and *value2* must be of type float. The values are popped from the operand stack and undergo value set conversion (§2.8.3), resulting in *value1'* and *value2'*. The float *result* is *value1'* / *value2'*. The *result* is pushed onto the operand stack.The result of an *fdiv* instruction is governed by the rules of IEEE arithmetic:

- If either *value1'* or *value2'* is NaN, the result is NaN.
- If neither *value1'* nor *value2'* is NaN, the sign of the result is positive if both values have the same sign, negative if the values have different signs.
- Division of an infinity by an infinity results in NaN.
- Division of an infinity by a finite value results in a signed infinity, with the sign-producing rule just given.
- Division of a finite value by an infinity results in a signed zero, with the sign-producing rule just given.
- Division of a zero by a zero results in NaN; division of zero by any other finite value results in a signed zero, with the sign-producing rule just given.
- Division of a nonzero finite value by a zero results in a signed infinity, with the sign-producing rule just given.

fdiv (*cont.*)

fdiv (*cont.*)

- In the remaining cases, where neither operand is an infinity, a zero, or NaN, the quotient is computed and rounded to the nearest float using IEEE 754 round to nearest mode. If the magnitude is too large to represent as a float, we say the operation overflows; the result is then an infinity of appropriate sign. If the magnitude is too small to represent as a float, we say the operation underflows; the result is then a zero of appropriate sign.

The Java virtual machine requires support of gradual underflow as defined by IEEE 754. Despite the fact that overflow, underflow, division by zero, or loss of precision may occur, execution of an *fdiv* instruction never throws a runtime exception.

fload***fload***

Operation Load **float** from local variable

Format

<i>fload</i>
<i>index</i>

Forms $fload = 23 \text{ (0x17)}$

Operand $\dots \Rightarrow$

Stack $\dots, value$

Description The *index* is an unsigned byte that must be an index into the local variable array of the current frame (§2.6). The local variable at *index* must contain a **float**. The *value* of the local variable at *index* is pushed onto the operand stack.

Notes The *fload* opcode can be used in conjunction with the *wide* instruction to access a local variable using a two-byte unsigned index.

fload_<n>

fload_<n>

Operation Load float from local variable

Format

fload_<n>

Forms *fload_0 = 34 (0x22)*

fload_1 = 35 (0x23)

fload_2 = 36 (0x24)

fload_3 = 37 (0x25)

Operand ... \Rightarrow

Stack ..., *value*

Description The *<n>* must be an index into the local variable array of the current frame (§2.6). The local variable at *<n>* must contain a float. The *value* of the local variable at *<n>* is pushed onto the operand stack.

Notes Each of the *fload_<n>* instructions is the same as *fload* with an *index* of *<n>*, except that the operand *<n>* is implicit.

fmul***fmul***

Operation Multiply **float**

Format

<i>fmul</i>

Forms *fmul* = 106 (0x6a)

Operand ..., *value1*, *value2* \Rightarrow
Stack ..., *result*

Description Both *value1* and *value2* must be of type **float**. The values are popped from the operand stack and undergo value set conversion (§2.8.3), resulting in *value1'* and *value2'*. The **float** *result* is *value1' * value2'*. The *result* is pushed onto the operand stack.

The result of an *fmul* instruction is governed by the rules of IEEE arithmetic:

- If either *value1'* or *value2'* is NaN, the result is NaN.
- If neither *value1'* nor *value2'* is NaN, the sign of the result is positive if both values have the same sign, and negative if the values have different signs.
- Multiplication of an infinity by a zero results in NaN.
- Multiplication of an infinity by a finite value results in a signed infinity, with the sign-producing rule just given.
- In the remaining cases, where neither an infinity nor NaN is involved, the product is computed and rounded to the nearest representable value using IEEE 754 round to nearest mode. If the magnitude is too large to represent as a **float**, we say the operation overflows; the result is then an infinity of appropriate sign. If the magnitude is too small to represent as a **float**, we say the operation underflows; the result is then a zero of appropriate sign.

fmul (*cont.*)

fmul (*cont.*)

The Java virtual machine requires support of gradual underflow as defined by IEEE 754. Despite the fact that overflow, underflow, or loss of precision may occur, execution of an *fmul* instruction never throws a runtime exception.

fneg**fneg**

Operation Negate **float**

Format

<i>fneg</i>

Forms *fneg* = 118 (0x76)

Operand ..., *value* \Rightarrow

Stack ..., *result*

Description The *value* must be of type **float**. It is popped from the operand stack and undergoes value set conversion (§2.8.3), resulting in *value'*. The **float result** is the arithmetic negation of *value'*. This *result* is pushed onto the operand stack.

For **float** values, negation is not the same as subtraction from zero. If *x* is +0.0, then $0.0 - x$ equals +0.0, but $-x$ equals -0.0. Unary minus merely inverts the sign of a **float**.

Special cases of interest:

- If the operand is NaN, the result is NaN (recall that NaN has no sign).
- If the operand is an infinity, the result is the infinity of opposite sign.
- If the operand is a zero, the result is the zero of opposite sign.

frem***frem***

Operation Remainder **float**

Format

<i>frem</i>

Forms *frem* = 114 (0x72)

Operand ..., *value1*, *value2* \Rightarrow

Stack ..., *result*

Description Both *value1* and *value2* must be of type **float**. The values are popped from the operand stack and undergo value set conversion (§2.8.3), resulting in *value1'* and *value2'*. The *result* is calculated and pushed onto the operand stack as a **float**.

The *result* of an *frem* instruction is not the same as that of the so-called remainder operation defined by IEEE 754. The IEEE 754 “remainder” operation computes the remainder from a rounding division, not a truncating division, and so its behavior is *not* analogous to that of the usual integer remainder operator. Instead, the Java virtual machine defines *frem* to behave in a manner analogous to that of the Java virtual machine integer remainder instructions (*irem* and *lrem*); this may be compared with the C library function *fmod*.

The result of an *frem* instruction is governed by these rules:

- If either *value1'* or *value2'* is NaN, the result is NaN.
- If neither *value1'* nor *value2'* is NaN, the sign of the result equals the sign of the dividend.
- If the dividend is an infinity or the divisor is a zero or both, the result is NaN.
- If the dividend is finite and the divisor is an infinity, the result equals the dividend.

frem (*cont.*)**frem** (*cont.*)

- If the dividend is a zero and the divisor is finite, the result equals the dividend.
- In the remaining cases, where neither operand is an infinity, a zero, or NaN, the floating-point remainder *result* from a dividend *value1*' and a divisor *value2*' is defined by the mathematical relation $result = value1' - (value2' * q)$, where *q* is an integer that is negative only if *value1' / value2'* is negative and positive only if *value1' / value2'* is positive, and whose magnitude is as large as possible without exceeding the magnitude of the true mathematical quotient of *value1'* and *value2'*.

Despite the fact that division by zero may occur, evaluation of an *frem* instruction never throws a runtime exception. Overflow, underflow, or loss of precision cannot occur.

Notes

The IEEE 754 remainder operation may be computed by the library routine `Math.IEEEremainder`.

freturn**freturn**

Operation Return float from method

Format

<i>freturn</i>

Forms *freturn* = 174 (0xae)

Operand ..., *value* \Rightarrow

Stack [empty]

Description The current method must have return type float. The *value* must be of type float. If the current method is a synchronized method, the monitor entered or reentered on invocation of the method is updated and possibly exited as if by execution of a *monitorexit* instruction in the current thread. If no exception is thrown, *value* is popped from the operand stack of the current frame (§2.6) and undergoes value set conversion (§2.8.3), resulting in *value'*. The *value'* is pushed onto the operand stack of the frame of the invoker. Any other values on the operand stack of the current method are discarded.

The interpreter then returns control to the invoker of the method, reinstating the frame of the invoker.

Runtime Exceptions If the virtual machine implementation does not enforce the rules on structured locking described in §2.11.10, then if the current method is a synchronized method and the current thread is not the owner of the monitor entered or reentered on invocation of the method, *freturn* throws an `IllegalMonitorStateException`. This can happen, for example, if a synchronized method contains a *monitorexit* instruction, but no *monitorenter* instruction, on the object on which the method is synchronized.

Otherwise, if the virtual machine implementation enforces the rules on structured locking described in §2.11.10 and if the first of those rules is violated during invocation of the current method, then *freturn* throws an `IllegalMonitorStateException`.

fstore***fstore***

Operation Store **float** into local variable

Format

<i>fstore</i>
<i>index</i>

Forms $fstore = 56 \ (0x38)$

Operand $\dots, value \Rightarrow$

Stack \dots

Description The *index* is an unsigned byte that must be an index into the local variable array of the current frame (§2.6). The *value* on the top of the operand stack must be of type **float**. It is popped from the operand stack and undergoes value set conversion (§2.8.3), resulting in *value'*. The value of the local variable at *index* is set to *value'*.

Notes The *fstore* opcode can be used in conjunction with the *wide* instruction to access a local variable using a two-byte unsigned index.

fstore_<n>***fstore_<n>***

Operation Store **float** into local variable

Format

<i>fstore_<n></i>

Forms *fstore_0* = 67 (0x43)

fstore_1 = 68 (0x44)

fstore_2 = 69 (0x45)

fstore_3 = 70 (0x46)

Operand ..., *value* \Rightarrow

Stack ...

Description The *<n>* must be an index into the local variable array of the current frame (§2.6). The *value* on the top of the operand stack must be of type **float**. It is popped from the operand stack and undergoes value set conversion (§2.8.3), resulting in *value'*. The value of the local variable at *<n>* is set to *value'*.

Notes Each of the *fstore_<n>* is the same as *fstore* with an *index* of *<n>*, except that the operand *<n>* is implicit.

fsub***fsub***

Operation Subtract **float**

Format

<i>fsub</i>

Forms $fsub = 102 \ (0x66)$

Operand $\dots, value1, value2 \Rightarrow$

Stack $\dots, result$

Description Both *value1* and *value2* must be of type **float**. The values are popped from the operand stack and undergo value set conversion (§2.8.3), resulting in *value1'* and *value2'*. The **float** *result* is $value1' - value2'$. The *result* is pushed onto the operand stack.

For **float** subtraction, it is always the case that $a-b$ produces the same result as $a+(-b)$. However, for the *fsub* instruction, subtraction from zero is not the same as negation, because if *x* is $+0.0$, then $0.0-x$ equals $+0.0$, but $-x$ equals -0.0 .

The Java virtual machine requires support of gradual underflow as defined by IEEE 754. Despite the fact that overflow, underflow, or loss of precision may occur, execution of an *fsub* instruction never throws a runtime exception.

getfield***getfield***

Operation Fetch field from object

Format

<i>getfield</i>
<i>indexbyte1</i>
<i>indexbyte2</i>

Forms $\text{getfield} = 180 \text{ (0xb4)}$

Operand $\dots, \text{objectref} \Rightarrow$

Stack \dots, value

Description The *objectref*, which must be of type `reference`, is popped from the operand stack. The unsigned *indexbyte1* and *indexbyte2* are used to construct an index into the runtime constant pool of the current class (§2.6), where the value of the index is $(\text{indexbyte1} \ll 8) | \text{indexbyte2}$. The runtime constant pool item at that index must be a symbolic reference to a field (§5.1), which gives the name and descriptor of the field as well as a symbolic reference to the class in which the field is to be found. The referenced field is resolved (§5.4.3.2). The *value* of the referenced field in *objectref* is fetched and pushed onto the operand stack.

The type of *objectref* must not be an array type. If the field is `protected` (§4.6), and it is a member of a superclass of the current class, and the field is not declared in the same runtime package (§5.3) as the current class, then the class of *objectref* must be either the current class or a subclass of the current class.

Linking Exceptions During resolution of the symbolic reference to the field, any of the errors pertaining to field resolution documented in §5.4.3.2 can be thrown.

Otherwise, if the resolved field is a `static` field, *getfield* throws an `IncompatibleClassChangeError`.

getfield* (cont.)**getfield* (cont.)**

Runtime Exception Otherwise, if *objectref* is `null`, the *getfield* instruction throws a `NullPointerException`.

Notes The *getfield* instruction cannot be used to access the `length` field of an array. The `arraylength` instruction is used instead.

getstatic***getstatic***

Operation Get `static` field from class

Format

<i>getstatic</i>
<i>indexbyte1</i>
<i>indexbyte2</i>

Forms $getstatic = 178 \text{ (0xb2)}$

Operand \dots, \Rightarrow

Stack $\dots, value$

Description The unsigned *indexbyte1* and *indexbyte2* are used to construct an index into the runtime constant pool of the current class (§2.6), where the value of the index is $(indexbyte1 \ll 8) | indexbyte2$. The runtime constant pool item at that index must be a symbolic reference to a field (§5.1), which gives the name and descriptor of the field as well as a symbolic reference to the class or interface in which the field is to be found. The referenced field is resolved (§5.4.3.2).

On successful resolution of the field, the class or interface that declared the resolved field is initialized (§5.5) if that class or interface has not already been initialized.

The *value* of the class or interface field is fetched and pushed onto the operand stack.

Linking Exceptions During resolution of the symbolic reference to the class or interface field, any of the exceptions pertaining to field resolution documented in Section 5.4.3.2 can be thrown.

Otherwise, if the resolved field is not a `static` (class) field or an interface field, *getstatic* throws an `IncompatibleClassChangeError`.

Runtime Exception Otherwise, if execution of this *getstatic* instruction causes initialization of the referenced class or interface, *getstatic* may throw an `Error` as detailed in Section 5.5.

goto***goto***

Operation Branch always

Format

<i>goto</i>
<i>branchbyte1</i>
<i>branchbyte2</i>

Forms $goto = 167 (0xa7)$

Operand No change
Stack

Description The unsigned bytes *branchbyte1* and *branchbyte2* are used to construct a signed 16-bit *branchoffset*, where *branchoffset* is $(branchbyte1 \ll 8) | branchbyte2$. Execution proceeds at that offset from the address of the opcode of this *goto* instruction. The target address must be that of an opcode of an instruction within the method that contains this *goto* instruction.

goto_w***goto_w***

Operation Branch always (wide index)

Format

<i>goto_w</i>
<i>branchbyte1</i>
<i>branchbyte2</i>
<i>branchbyte3</i>
<i>branchbyte4</i>

Forms $goto_w = 200 \ (0xc8)$

Operand No change
Stack

Description The unsigned bytes *branchbyte1*, *branchbyte2*, *branchbyte3*, and *branchbyte4* are used to construct a signed 32-bit *branchoffset*, where *branchoffset* is $(branchbyte1 \ll 24) | (branchbyte2 \ll 16) | (branchbyte3 \ll 8) | branchbyte4$. Execution proceeds at that offset from the address of the opcode of this *goto_w* instruction. The target address must be that of an opcode of an instruction within the method that contains this *goto_w* instruction.

Notes Although the *goto_w* instruction takes a 4-byte branch offset, other factors limit the size of a method to 65535 bytes (§4.11). This limit may be raised in a future release of the Java virtual machine.

i2b***i2b*****Operation** Convert `int` to `byte`**Format*****i2b*****Forms** $i2b = 145 \text{ (0x91)}$ **Operand** $\dots, value \Rightarrow$ **Stack** $\dots, result$ **Description** The *value* on the top of the operand stack must be of type `int`. It is popped from the operand stack, truncated to a `byte`, then sign-extended to an `int` *result*. That *result* is pushed onto the operand stack.**Notes** The *i2b* instruction performs a narrowing primitive conversion (JLS3 §5.1.3). It may lose information about the overall magnitude of *value*. The *result* may also not have the same sign as *value*.

i2c***i2c*****Operation** Convert `int` to `char`**Format**

<i>i2c</i>

Forms $i2c = 146 \text{ (0x92)}$ **Operand** $\dots, value \Rightarrow$ **Stack** $\dots, result$ **Description** The *value* on the top of the operand stack must be of type `int`. It is popped from the operand stack, truncated to `char`, then zero-extended to an `int` *result*. That *result* is pushed onto the operand stack.**Notes** The *i2c* instruction performs a narrowing primitive conversion (JLS3 §5.1.3). It may lose information about the overall magnitude of *value*. The *result* (which is always positive) may also not have the same sign as *value*.

i2d***i2d***

Operation Convert `int` to `double`

Format

i2d

Forms *i2d* = 135 (0x87)

Operand ..., *value* \Rightarrow

Stack ..., *result*

Description The *value* on the top of the operand stack must be of type `int`. It is popped from the operand stack and converted to a `double` *result*. The *result* is pushed onto the operand stack.

Notes The *i2d* instruction performs a widening primitive conversion (JLS3 §5.1.2). Because all values of type `int` are exactly representable by type `double`, the conversion is exact.

i2f***i2f***

Operation Convert `int` to `float`

Format

<i>i2f</i>

Forms $i2f = 134$ (0x86)

Operand $\dots, value \Rightarrow$

Stack $\dots, result$

Description The *value* on the top of the operand stack must be of type `int`. It is popped from the operand stack and converted to the `float` *result* using IEEE 754 round to nearest mode. The *result* is pushed onto the operand stack.

Notes The *i2f* instruction performs a widening primitive conversion (JLS3 §5.1.2), but may result in a loss of precision because values of type `float` have only 24 significand bits.

i2l***i2l*****Operation** Convert `int` to `long`**Format*****i2l*****Forms** $i2l = 133 \text{ (0x85)}$ **Operand** $\dots, value \Rightarrow$ **Stack** $\dots, result$ **Description** The *value* on the top of the operand stack must be of type `int`. It is popped from the operand stack and sign-extended to a `long` *result*. That *result* is pushed onto the operand stack.**Notes** The *i2l* instruction performs a widening primitive conversion (JLS3 §5.1.2). Because all values of type `int` are exactly representable by type `long`, the conversion is exact.

i2s***i2s*****Operation** Convert `int` to `short`**Format**

<i>i2s</i>

Forms $i2s = 147 \text{ (0x93)}$ **Operand** $\dots, value \Rightarrow$ **Stack** $\dots, result$ **Description** The *value* on the top of the operand stack must be of type `int`. It is popped from the operand stack, truncated to a `short`, then sign-extended to an `int` *result*. That *result* is pushed onto the operand stack.**Notes** The *i2s* instruction performs a narrowing primitive conversion (JLS3 §5.1.3). It may lose information about the overall magnitude of *value*. The *result* may also not have the same sign as *value*.

iadd***iadd***

Operation Add `int`

Format

<i>iadd</i>

Forms *iadd* = 96 (0x60)

Operand $\dots, value1, value2 \Rightarrow$

Stack $\dots, result$

Description Both *value1* and *value2* must be of type `int`. The values are popped from the operand stack. The `int` *result* is *value1* + *value2*. The *result* is pushed onto the operand stack.

The result is the 32 low-order bits of the true mathematical result in a sufficiently wide two's-complement format, represented as a value of type `int`. If overflow occurs, then the sign of the result may not be the same as the sign of the mathematical sum of the two values.

Despite the fact that overflow may occur, execution of an *iadd* instruction never throws a runtime exception.

iaload***iaload***

Operation Load `int` from array

Format

iaload

Forms *iaload* = 46 (0x2e)

Operand ..., *arrayref*, *index* \Rightarrow

Stack ..., *value*

Description The *arrayref* must be of type `reference` and must refer to an array whose components are of type `int`. The *index* must be of type `int`. Both *arrayref* and *index* are popped from the operand stack. The `int` *value* in the component of the array at *index* is retrieved and pushed onto the operand stack.

Runtime Exceptions If *arrayref* is `null`, *iaload* throws a `NullPointerException`.

Otherwise, if *index* is not within the bounds of the array referenced by *arrayref*, the *iaload* instruction throws an `ArrayIndexOutOfBoundsException`.

iand***iand*****Operation** Boolean AND `int`**Format**

<i>iand</i>

Forms *iand* = 126 (0x7e)**Operand** ..., *value1*, *value2* \Rightarrow **Stack** ..., *result***Description** Both *value1* and *value2* must be of type `int`. They are popped from the operand stack. An `int` *result* is calculated by taking the bitwise AND (conjunction) of *value1* and *value2*. The *result* is pushed onto the operand stack.

iastore***iastore***

Operation Store into `int` array

Format

<i>iastore</i>

Forms *iastore* = 79 (0x4f)

Operand ..., *arrayref*, *index*, *value* ⇒
Stack ...

Description The *arrayref* must be of type `reference` and must refer to an array whose components are of type `int`. Both *index* and *value* must be of type `int`. The *arrayref*, *index*, and *value* are popped from the operand stack. The `int` *value* is stored as the component of the array indexed by *index*.

Runtime Exceptions If *arrayref* is `null`, *iastore* throws a `NullPointerException`. Otherwise, if *index* is not within the bounds of the array referenced by *arrayref*, the *iastore* instruction throws an `ArrayIndexOutOfBoundsException`.

iconst_<i>***iconst_<i>***

Operation Push `int` constant

Format

iconst_<i>

Forms *iconst_m* = 2 (0x2)

iconst_0 = 3 (0x3)

iconst_1 = 4 (0x4)

iconst_2 = 5 (0x5)

iconst_3 = 6 (0x6)

iconst_4 = 7 (0x7)

iconst_5 = 8 (0x8)

Operand ... \Rightarrow

Stack ..., *<i>*

Description Push the `int` constant *<i>* (-1, 0, 1, 2, 3, 4 or 5) onto the operand stack.

Notes Each of this family of instructions is equivalent to *bipush <i>* for the respective value of *<i>*, except that the operand *<i>* is implicit.

idiv***idiv*****Operation** Divide `int`**Format**

<i>idiv</i>

Forms *idiv* = 108 (0x6c)**Operand** ..., *value1*, *value2* \Rightarrow **Stack** ..., *result***Description** Both *value1* and *value2* must be of type `int`. The values are popped from the operand stack. The `int` *result* is the value of the Java programming language expression *value1* / *value2*. The *result* is pushed onto the operand stack.

An `int` division rounds towards 0; that is, the quotient produced for `int` values in n/d is an `int` value q whose magnitude is as large as possible while satisfying $|d \cdot q| \leq |n|$. Moreover, q is positive when $|n| \geq |d|$ and n and d have the same sign, but q is negative when $|n| \geq |d|$ and n and d have opposite signs.

There is one special case that does not satisfy this rule: if the dividend is the negative integer of largest possible magnitude for the `int` type, and the divisor is -1 , then overflow occurs, and the result is equal to the dividend. Despite the overflow, no exception is thrown in this case.

Runtime Exception If the value of the divisor in an `int` division is 0, *idiv* throws an `ArithmeticalException`.

*if_acmp<cond>**if_acmp<cond>*

Operation Branch if `reference` comparison succeeds

Format

<i>if_acmp<cond></i>
<i>branchbyte1</i>
<i>branchbyte2</i>

Forms

if_acmp eq = 165 (0xa5)

if_acmp ne = 166 (0xa6)

Operand

..., *value1*, *value2* ⇒

Stack

...

Description Both *value1* and *value2* must be of type `reference`. They are both popped from the operand stack and compared. The results of the comparison are as follows:

- *eq* succeeds if and only if *value1* = *value2*
- *ne* succeeds if and only if *value1* ≠ *value2*

If the comparison succeeds, the unsigned *branchbyte1* and *branchbyte2* are used to construct a signed 16-bit offset, where the offset is calculated to be (*branchbyte1* << 8) | *branchbyte2*. Execution then proceeds at that offset from the address of the opcode of this *if_acmp<cond>* instruction. The target address must be that of an opcode of an instruction within the method that contains this *if_acmp<cond>* instruction.

Otherwise, if the comparison fails, execution proceeds at the address of the instruction following this *if_acmp<cond>* instruction.

if_icmp<cond>***if_icmp<cond>***

Operation Branch if `int` comparison succeeds

Format

<i>if_icmp<cond></i>
<i>branchbyte1</i>
<i>branchbyte2</i>

Forms

- if_icmpeq* = 159 (0x9f)
- if_icmpne* = 160 (0xa0)
- if_icmplt* = 161 (0xa1)
- if_icmpge* = 162 (0xa2)
- if_icmpgt* = 163 (0xa3)
- if_icmple* = 164 (0xa4)

Operand

..., value1, value2 \Rightarrow

Stack

...

Description

Both *value1* and *value2* must be of type `int`. They are both popped from the operand stack and compared. All comparisons are signed. The results of the comparison are as follows:

- *eq* succeeds if and only if *value1* = *value2*
- *ne* succeeds if and only if *value1* \neq *value2*
- *lt* succeeds if and only if *value1* < *value2*
- *le* succeeds if and only if *value1* \leq *value2*
- *gt* succeeds if and only if *value1* > *value2*
- *ge* succeeds if and only if *value1* \geq *value2*

if_icmp<cond> (cont.)

if_icmp<cond> (cont.)

If the comparison succeeds, the unsigned *branchbyte1* and *branchbyte2* are used to construct a signed 16-bit offset, where the offset is calculated to be $(\text{branchbyte1} \ll 8) | \text{branchbyte2}$. Execution then proceeds at that offset from the address of the opcode of this *if_icmp<cond>* instruction. The target address must be that of an opcode of an instruction within the method that contains this *if_icmp<cond>* instruction.

Otherwise, execution proceeds at the address of the instruction following this *if_icmp<cond>* instruction.

if<cond>***if<cond>***

Operation Branch if `int` comparison with zero succeeds

Format

<i>if<cond></i>
<i>branchbyte1</i>
<i>branchbyte2</i>

Forms

- ifeq* = 153 (0x99)
- ifne* = 154 (0x9a)
- iflt* = 155 (0x9b)
- ifge* = 156 (0x9c)
- ifgt* = 157 (0x9d)
- ifle* = 158 (0x9e)

Operand ..., *value* \Rightarrow

Stack ...

Description The *value* must be of type `int`. It is popped from the operand stack and compared against zero. All comparisons are signed. The results of the comparisons are as follows:

- *eq* succeeds if and only if *value* = 0
- *ne* succeeds if and only if *value* \neq 0
- *lt* succeeds if and only if *value* < 0
- *le* succeeds if and only if *value* \leq 0
- *gt* succeeds if and only if *value* > 0
- *ge* succeeds if and only if *value* \geq 0

if<cond> (cont.)

if<cond> (cont.)

If the comparison succeeds, the unsigned *branchbyte1* and *branchbyte2* are used to construct a signed 16-bit offset, where the offset is calculated to be $(\text{branchbyte1} \ll 8) \mid \text{branchbyte2}$. Execution then proceeds at that offset from the address of the opcode of this *if<cond>* instruction. The target address must be that of an opcode of an instruction within the method that contains this *if<cond>* instruction.

Otherwise, execution proceeds at the address of the instruction following this *if<cond>* instruction.

ifnonnull***ifnonnull***

Operation Branch if `reference` not `null`

Format

<i>ifnonnull</i>
<i>branchbyte1</i>
<i>branchbyte2</i>

Forms *ifnonnull* = 199 (0xc7)

Operand ..., *value* \Rightarrow

Stack ...

Description The *value* must be of type `reference`. It is popped from the operand stack. If *value* is not `null`, the unsigned *branchbyte1* and *branchbyte2* are used to construct a signed 16-bit offset, where the offset is calculated to be $(\text{branchbyte1} \ll 8) | \text{branchbyte2}$. Execution then proceeds at that offset from the address of the opcode of this *ifnonnull* instruction. The target address must be that of an opcode of an instruction within the method that contains this *ifnonnull* instruction.

Otherwise, execution proceeds at the address of the instruction following this *ifnonnull* instruction.

ifnull***ifnull***

Operation Branch if **reference** is **null**

Format

<i>ifnull</i>
<i>branchbyte1</i>
<i>branchbyte2</i>

Forms $ifnull = 198 \text{ (0xc6)}$

Operand $\dots, value \Rightarrow$

Stack \dots

Description The *value* must of type **reference**. It is popped from the operand stack. If *value* is **null**, the unsigned *branchbyte1* and *branchbyte2* are used to construct a signed 16-bit offset, where the offset is calculated to be $(branchbyte1 \ll 8) | branchbyte2$. Execution then proceeds at that offset from the address of the opcode of this *ifnull* instruction. The target address must be that of an opcode of an instruction within the method that contains this *ifnull* instruction.

Otherwise, execution proceeds at the address of the instruction following this *ifnull* instruction.

iinc***iinc***

Operation Increment local variable by constant

Format

<i>iinc</i>
<i>index</i>
<i>const</i>

Forms *iinc* = 132 (0x84)

Operand Stack No change

Description The *index* is an unsigned byte that must be an index into the local variable array of the current frame (§2.6). The *const* is an immediate signed byte. The local variable at *index* must contain an `int`. The value *const* is first sign-extended to an `int`, and then the local variable at *index* is incremented by that amount.

Notes The *iinc* opcode can be used in conjunction with the *wide* instruction to access a local variable using a two-byte unsigned index and to increment it by a two-byte immediate signed value.

iload***iload***

Operation Load `int` from local variable

Format

<i>iload</i>
<i>index</i>

Forms *iload* = 21 (0x15)

Operand ... \Rightarrow

Stack ..., *value*

Description The *index* is an unsigned byte that must be an index into the local variable array of the current frame (§2.6). The local variable at *index* must contain an `int`. The *value* of the local variable at *index* is pushed onto the operand stack.

Notes The *iload* opcode can be used in conjunction with the *wide* instruction to access a local variable using a two-byte unsigned index.

iload_<n>***iload_<n>***

Operation Load `int` from local variable

Format

iload_<n>

Forms

iload_0 = 26 (0x1a)

iload_1 = 27 (0x1b)

iload_2 = 28 (0x1c)

iload_3 = 29 (0x1d)

Operand

... \Rightarrow

Stack

..., *value*

Description The *<n>* must be an index into the local variable array of the current frame (§2.6). The local variable at *<n>* must contain an `int`. The *value* of the local variable at *<n>* is pushed onto the operand stack.

Notes

Each of the *iload_<n>* instructions is the same as *iload* with an *index* of *<n>*, except that the operand *<n>* is implicit.

imul***imul***

Operation *Multiply int*

Format

<i>imul</i>

Forms *imul* = 104 (0x68)

Operand ... , *value1*, *value2* \Rightarrow
Stack ... , *result*

Description Both *value1* and *value2* must be of type `int`. The values are popped from the operand stack. The `int` *result* is *value1* * *value2*. The *result* is pushed onto the operand stack.

The result is the 32 low-order bits of the true mathematical result in a sufficiently wide two's-complement format, represented as a value of type `int`. If overflow occurs, then the sign of the result may not be the same as the sign of the mathematical sum of the two values.

Despite the fact that overflow may occur, execution of an *imul* instruction never throws a runtime exception.

ineg***ineg***

Operation Negate `int`

Format

<i>ineg</i>

Forms *ineg* = 116 (0x74)

Operand ..., *value* \Rightarrow

Stack ..., *result*

Description The *value* must be of type `int`. It is popped from the operand stack. The `int` *result* is the arithmetic negation of *value*, $-value$. The *result* is pushed onto the operand stack.

For `int` values, negation is the same as subtraction from zero. Because the Java virtual machine uses two's-complement representation for integers and the range of two's-complement values is not symmetric, the negation of the maximum negative `int` results in that same maximum negative number. Despite the fact that overflow has occurred, no exception is thrown.

For all `int` values x , $-x$ equals $(\sim x) + 1$.

*instanceof**instanceof*

Operation Determine if object is of given type

Format

<i>instanceof</i>
<i>indexbyte1</i>
<i>indexbyte2</i>

Forms *instanceof*= 193 (0xc1)

Operand ..., *objectref* \Rightarrow

Stack ..., *result*

Description The *objectref*, which must be of type `reference`, is popped from the operand stack. The unsigned *indexbyte1* and *indexbyte2* are used to construct an index into the runtime constant pool of the current class (§2.6), where the value of the index is $(\text{indexbyte1} \ll 8) | \text{indexbyte2}$. The runtime constant pool item at the index must be a symbolic reference to a class, array, or interface type.

If *objectref* is `null`, the *instanceof* instruction pushes an `int result` of 0 as an int on the operand stack.

Otherwise, the named class, array, or interface type is resolved (§5.4.3.1). If *objectref* is an instance of the resolved class or array or implements the resolved interface, the *instanceof* instruction pushes an `int result` of 1 as an int on the operand stack; otherwise, it pushes an `int result` of 0.

The following rules are used to determine whether an *objectref* that is not `null` is an instance of the resolved type: If S is the class of the object referred to by *objectref* and T is the resolved class, array, or interface type, *instanceof* determines whether *objectref* is an instance of T as follows:

- If S is an ordinary (nonarray) class, then:
 - If T is a class type, then S must be the same class as T or a subclass of T.
 - If T is an interface type, then S must implement interface T.

instanceof (cont.)*instanceof* (cont.)

- If S is an interface type, then:
 - If T is a class type, then T must be `Object`.
 - If T is an interface type, then T must be the same interface as S, or a superinterface of S.
- If S is a class representing the array type SC[], that is, an array of components of type SC, then:
 - If T is a class type, then T must be `Object`.
 - If T is an array type TC[], that is, an array of components of type TC, then one of the following must be true:
 - TC and SC are the same primitive type.
 - TC and SC are reference types, and type SC can be cast to TC by these runtime rules.
 - If T is an interface type, T must be one of the interfaces implemented by arrays (JLS3 §4.10.3).

Linking Exceptions During resolution of symbolic reference to the class, array, or interface type, any of the exceptions documented in §5.4.3.1 can be thrown.

Notes The *instanceof* instruction is very similar to the *checkcast* instruction. It differs in its treatment of `null`, its behavior when its test fails (*checkcast* throws an exception, *instanceof* pushes a result code), and its effect on the operand stack.

*invokeinterface**invokeinterface*

Operation Invoke interface method

Format

<i>invokeinterface</i>
<i>indexbyte1</i>
<i>indexbyte2</i>
<i>count</i>
0

Forms *invokeinterface* = 185 (0xb9)

Operand ..., *objectref*, [*arg1*, [*arg2* ...]] \Rightarrow
Stack ...

Description The unsigned *indexbyte1* and *indexbyte2* are used to construct an index into the runtime constant pool of the current class (§2.6), where the value of the index is (*indexbyte1* \ll 8) | *indexbyte2*. The runtime constant pool item at that index must be a symbolic reference to an interface method (§5.1), which gives the name and descriptor (§4.3.3) of the interface method as well as a symbolic reference to the interface in which the interface method is to be found. The named interface method is resolved (§5.4.3.4). The interface method must not be an instance initialization method (§2.9) or the class or interface initialization method (§2.9).

The *count* operand is an unsigned byte that must not be zero. The *objectref* must be of type **reference** and must be followed on the operand stack by *nargs* argument values, where the number, type, and order of the values must be consistent with the descriptor of the resolved interface method. The value of the fourth operand byte must always be zero.

Let *C* be the class of *objectref*. The actual method to be invoked is selected by the following lookup procedure:

invokeinterface* (cont.)**invokeinterface* (cont.)**

- If C contains a declaration for an instance method with the same name and descriptor as the resolved method, then this is the method to be invoked, and the lookup procedure terminates.
- Otherwise, if C has a superclass, this same lookup procedure is performed recursively using the direct superclass of C; the method to be invoked is the result of the recursive invocation of this lookup procedure.
- Otherwise, an `AbstractMethodError` is raised.

If the method is `synchronized`, the monitor associated with *objectref* is entered or reentered as if by execution of a `monitorenter` instruction in the current thread.

If the method is not `native`, the *nargs* argument values and *objectref* are popped from the operand stack. A new frame is created on the Java virtual machine stack for the method being invoked. The *objectref* and the argument values are consecutively made the values of local variables of the new frame, with *objectref* in local variable 0, *arg1* in local variable 1 (or, if *arg1* is of type `long` or `double`, in local variables 1 and 2), and so on. Any argument value that is of a floating-point type undergoes value set conversion (§2.8.3) prior to being stored in a local variable. The new frame is then made current, and the Java virtual machine `pc` is set to the opcode of the first instruction of the method to be invoked. Execution continues with the first instruction of the method.

If the method is `native` and the platform-dependent code that implements it has not yet been bound (§5.6) into the Java virtual machine, that is done. The *nargs* argument values and *objectref* are popped from the operand stack and are passed as parameters to the code that implements the method. Any argument value that is of a floating-point type undergoes value set conversion (§2.8.3) prior to being passed as a parameter. The parameters are passed and the code is invoked in an implementation-dependent manner. When the platform-dependent code returns:

invokeinterface* (cont.)**invokeinterface* (cont.)**

- If the **native** method is **synchronized**, the monitor associated with *objectref* is updated and possibly exited as if by execution of a *monitor-exit* instruction in the current thread.
- If the **native** method returns a value, the return value of the platform-dependent code is converted in an implementation-dependent way to the return type of the **native** method and pushed onto the operand stack.

Linking Exceptions During resolution of the symbolic reference to the interface method, any of the exceptions documented in §5.4.3.4 can be thrown.

Runtime Exceptions Otherwise, if *objectref* is **null**, the *invokeinterface* instruction throws a **NullPointerException**.

Otherwise, if the class of *objectref* does not implement the resolved interface, *invokeinterface* throws an **IncompatibleClassChangeError**.

Otherwise, if no method matching the resolved name and descriptor is selected, *invokeinterface* throws an **AbstractMethodError**.

Otherwise, if the selected method is not **public**, *invokeinterface* throws an **IllegalAccessException**.

Otherwise, if the selected method is **abstract**, *invokeinterface* throws an **AbstractMethodError**.

Otherwise, if the selected method is **native** and the code that implements the method cannot be bound, *invokeinterface* throws an **UnsatisfiedLinkError**.

invokeinterface (cont.)***invokeinterface (cont.)*****Notes**

The *count* operand of the *invokeinterface* instruction records a measure of the number of argument values, where an argument value of type `long` or type `double` contributes two units to the *count* value and an argument of any other type contributes one unit. This information can also be derived from the descriptor of the selected method. The redundancy is historical.

| The fourth operand byte exists to reserve space for an additional operand used in certain of Oracle's implementations, which replace the *invokeinterface* instruction by a specialized pseudo-instruction at runtime. It must be retained for backwards compatibility.

The *nargs* argument values and *objectref* are not one-to-one with the first $nargs + 1$ local variables. Argument values of types `long` and `double` must be stored in two consecutive local variables, thus more than *nargs* local variables may be required to pass *nargs* argument values to the invoked method.

*invokespecial**invokespecial*

Operation Invoke instance method; special handling for superclass, private, and instance initialization method invocations

Format

<i>invokespecial</i>
<i>indexbyte1</i>
<i>indexbyte2</i>

Forms *invokespecial* = 183 (0xb7)

Operand ..., *objectref*, [*arg1*, [*arg2* ...]] \Rightarrow

Stack ...

Description The unsigned *indexbyte1* and *indexbyte2* are used to construct an index into the runtime constant pool of the current class (§2.6), where the value of the index is (*indexbyte1* << 8) | *indexbyte2*. The runtime constant pool item at that index must be a symbolic reference to a method (§5.1), which gives the name and descriptor (§4.3.3) of the method as well as a symbolic reference to the class in which the method is to be found. The named method is resolved (§5.4.3.3). Finally, if the resolved method is protected (§4.6), and it is a member of a superclass of the current class, and the method is not declared in the same runtime package (§5.3) as the current class, then the class of *objectref* must be either the current class or a subclass of the current class.

Next, the resolved method is selected for invocation unless all of the following conditions are true:

- The ACC_SUPER flag (see Table 4.1, “Class access and property modifiers”) is set for the current class.
- The class of the resolved method is a superclass of the current class.
- The resolved method is not an instance initialization method (§2.9).

invokespecial* (cont.)**invokespecial* (cont.)**

If the above conditions are true, the actual method to be invoked is selected by the following lookup procedure. Let C be the direct superclass of the current class:

- If C contains a declaration for an instance method with the same name and descriptor as the resolved method, then this method will be invoked. The lookup procedure terminates.
- Otherwise, if C has a superclass, this same lookup procedure is performed recursively using the direct superclass of C. The method to be invoked is the result of the recursive invocation of this lookup procedure.
- Otherwise, an `AbstractMethodError` is raised.

The *objectref* must be of type `reference` and must be followed on the operand stack by *nargs* argument values, where the number, type, and order of the values must be consistent with the descriptor of the selected instance method.

If the method is `synchronized`, the monitor associated with *objectref* is entered or reentered as if by execution of a `monitorenter` instruction in the current thread.

If the method is not `native`, the *nargs* argument values and *objectref* are popped from the operand stack. A new frame is created on the Java virtual machine stack for the method being invoked. The *objectref* and the argument values are consecutively made the values of local variables of the new frame, with *objectref* in local variable 0, *arg1* in local variable 1 (or, if *arg1* is of type `long` or `double`, in local variables 1 and 2), and so on. Any argument value that is of a floating-point type undergoes value set conversion (§2.8.3) prior to being stored in a local variable. The new frame is then made current, and the Java virtual machine `pc` is set to the opcode of the first instruction of the method to be invoked. Execution continues with the first instruction of the method.

invokespecial* (cont.)**invokespecial* (cont.)**

If the method is `native` and the platform-dependent code that implements it has not yet been bound (§5.6) into the Java virtual machine, that is done. The *nargs* argument values and *objectref* are popped from the operand stack and are passed as parameters to the code that implements the method. Any argument value that is of a floating-point type undergoes value set conversion (§2.8.3) prior to being passed as a parameter. The parameters are passed and the code is invoked in an implementation-dependent manner. When the platform-dependent code returns, the following take place:

- If the `native` method is `synchronized`, the monitor associated with *objectref* is updated and possibly exited as if by execution of a `monitor-exit` instruction in the current thread.
- If the `native` method returns a value, the return value of the platform-dependent code is converted in an implementation-dependent way to the return type of the `native` method and pushed onto the operand stack.

Linking Exceptions

During resolution of the symbolic reference to the method, any of the exceptions pertaining to method resolution documented in §5.4.3.3 can be thrown.

Otherwise, if the resolved method is an instance initialization method, and the class in which it is declared is not the class symbolically referenced by the instruction, a `NoSuchMethodError` is thrown.

Otherwise, if the resolved method is a class (`static`) method, the *invokespecial* instruction throws an `IncompatibleClassChangeError`.

invokespecial* (cont.)**invokespecial* (cont.)**

Runtime Exceptions Otherwise, if *objectref* is `null`, the *invokespecial* instruction throws a `NullPointerException`.

Otherwise, if no method matching the resolved name and descriptor is selected, *invokespecial* throws an `AbstractMethodError`.

Otherwise, if the selected method is `abstract`, *invokespecial* throws an `AbstractMethodError`.

Otherwise, if the selected method is `native` and the code that implements the method cannot be bound, *invokespecial* throws an `UnsatisfiedLinkError`.

Notes The difference between the *invokespecial* and the *invokevirtual* instructions is that *invokevirtual* invokes a method based on the class of the object. The *invokespecial* instruction is used to invoke instance initialization methods (§2.9) as well as `private` methods and methods of a super-class of the current class.

The *invokespecial* instruction was named *invokenonvirtual* prior to JDK release 1.0.2.

The *nargs* argument values and *objectref* are not one-to-one with the first *nargs* + 1 local variables. Argument values of types `long` and `double` must be stored in two consecutive local variables, thus more than *nargs* local variables may be required to pass *nargs* argument values to the invoked method.

invokestatic***invokestatic***

Operation Invoke a class (`static`) method

Format

<i>invokestatic</i>
<i>indexbyte1</i>
<i>indexbyte2</i>

Forms *invokestatic* = 184 (0xb8)

Operand ..., [*arg1*, [*arg2* ...]] \Rightarrow
Stack ...

Description The unsigned *indexbyte1* and *indexbyte2* are used to construct an index into the runtime constant pool of the current class (§2.6), where the value of the index is $(\text{indexbyte1} \ll 8) | \text{indexbyte2}$. The runtime constant pool item at that index must be a symbolic reference to a method (§5.1), which gives the name and descriptor (§4.3.3) of the method as well as a symbolic reference to the class in which the method is to be found. The named method is resolved (§5.4.3.3). The method must not be an instance initialization method (§2.9) or the class or interface initialization method (§2.9). It must be `static`, and therefore cannot be `abstract`.

On successful resolution of the method, the class that declared the resolved method is initialized (§5.5) if that class has not already been initialized.

The operand stack must contain *nargs* argument values, where the number, type, and order of the values must be consistent with the descriptor of the resolved method.

If the method is `synchronized`, the monitor associated with the resolved `Class` object is entered or reentered as if by execution of a `monitorenter` instruction in the current thread.

invokestatic* (cont.)**invokestatic* (cont.)**

If the method is not `native`, the *nargs* argument values are popped from the operand stack. A new frame is created on the Java virtual machine stack for the method being invoked. The *nargs* argument values are consecutively made the values of local variables of the new frame, with *arg1* in local variable *0* (or, if *arg1* is of type `long` or `double`, in local variables *0* and *1*) and so on. Any argument value that is of a floating-point type undergoes value set conversion (§2.8.3) prior to being stored in a local variable. The new frame is then made current, and the Java virtual machine `pc` is set to the opcode of the first instruction of the method to be invoked. Execution continues with the first instruction of the method.

If the method is `native` and the platform-dependent code that implements it has not yet been bound (§5.6) into the Java virtual machine, that is done. The *nargs* argument values are popped from the operand stack and are passed as parameters to the code that implements the method. Any argument value that is of a floating-point type undergoes value set conversion (§2.8.3) prior to being passed as a parameter. The parameters are passed and the code is invoked in an implementation-dependent manner. When the platform-dependent code returns, the following take place:

- If the `native` method is `synchronized`, the monitor associated with the resolved `Class` object is updated and possibly exited as if by execution of a `monitorexit` instruction in the current thread.
- If the `native` method returns a value, the return value of the platform-dependent code is converted in an implementation-dependent way to the return type of the `native` method and pushed onto the operand stack.

Linking Exceptions

During resolution of the symbolic reference to the method, any of the exceptions pertaining to method resolution documented in §5.4.3.3 can be thrown.

Otherwise, if the resolved method is an instance method, the *invokestatic* instruction throws an `IncompatibleClassChangeError`.

invokestatic* (cont.)**invokestatic* (cont.)**

Runtime Exceptions Otherwise, if execution of this *invokestatic* instruction causes initialization of the referenced class, *invokestatic* may throw an `Error` as detailed in §5.5.

Otherwise, if the resolved method is `native` and the code that implements the method cannot be bound, *invokestatic* throws an `UnsatisfiedLinkError`.

Notes The *nargs* argument values are not one-to-one with the first *nargs* local variables. Argument values of types `long` and `double` must be stored in two consecutive local variables, thus more than *nargs* local variables may be required to pass *nargs* argument values to the invoked method.

invokevirtual***invokevirtual***

Operation Invoke instance method; dispatch based on class

Format

<i>invokevirtual</i>
<i>indexbyte1</i>
<i>indexbyte2</i>

Forms *invokevirtual* = 182 (0xb6)

Operand ..., *objectref*, [*arg1*, [*arg2* ...]] \Rightarrow
Stack ...

Description The unsigned *indexbyte1* and *indexbyte2* are used to construct an index into the runtime constant pool of the current class (§2.6), where the value of the index is (*indexbyte1* \ll 8) | *indexbyte2*. The runtime constant pool item at that index must be a symbolic reference to a method (§5.1), which gives the name and descriptor (§4.3.3) of the method as well as a symbolic reference to the class in which the method is to be found. The named method is resolved (§5.4.3.3). The method must not be an instance initialization method (§2.9) or the class or interface initialization method (§2.9). Finally, if the resolved method is **protected** (§4.6), and it is a member of a superclass of the current class, and the method is not declared in the same runtime package (§5.3) as the current class, then the class of *objectref* must be either the current class or a subclass of the current class.

Let C be the class of *objectref*. The actual method to be invoked is selected by the following lookup procedure:

- If C contains a declaration for an instance method M that overrides (§5.4.3.5) the resolved method, then M is the method to be invoked, and the lookup procedure terminates.

invokevirtual (cont.)

- Otherwise, if C has a superclass, this same lookup procedure is performed recursively using the direct superclass of C; the method to be invoked is the result of the recursive invocation of this lookup procedure.
- Otherwise, an `AbstractMethodError` is raised.

The *objectref* must be followed on the operand stack by *nargs* argument values, where the number, type, and order of the values must be consistent with the descriptor of the selected instance method.

If the method is `synchronized`, the monitor associated with *objectref* is entered or reentered as if by execution of a `monitorenter` instruction in the current thread.

If the method is not `native`, the *nargs* argument values and *objectref* are popped from the operand stack. A new frame is created on the Java virtual machine stack for the method being invoked. The *objectref* and the argument values are consecutively made the values of local variables of the new frame, with *objectref* in local variable 0, *arg1* in local variable 1 (or, if *arg1* is of type `long` or `double`, in local variables 1 and 2), and so on. Any argument value that is of a floating-point type undergoes value set conversion (§2.8.3) prior to being stored in a local variable. The new frame is then made current, and the Java virtual machine `pc` is set to the opcode of the first instruction of the method to be invoked. Execution continues with the first instruction of the method.

If the method is `native` and the platform-dependent code that implements it has not yet been bound (§5.6) into the Java virtual machine, that is done. The *nargs* argument values and *objectref* are popped from the operand stack and are passed as parameters to the code that implements the method. Any argument value that is of a floating-point type undergoes value set conversion (§2.8.3) prior to being passed as a parameter. The parameters are passed and the code is invoked in an implementation-dependent manner. When the platform-dependent code returns, the following take place:

invokevirtual (cont.)

invokevirtual* (cont.)**invokevirtual* (cont.)**

- If the **native** method is **synchronized**, the monitor associated with *objectref* is updated and possibly exited as if by execution of a *monitor-exit* instruction in the current thread.
- If the **native** method returns a value, the return value of the platform-dependent code is converted in an implementation-dependent way to the return type of the **native** method and pushed onto the operand stack.

Linking Exceptions

During resolution of the symbolic reference to the method, any of the exceptions pertaining to method resolution documented in §5.4.3.3 can be thrown.

Otherwise, if the resolved method is a class (**static**) method, the *invokevirtual* instruction throws an **IncompatibleClassChangeError**.

Runtime Exceptions

Otherwise, if *objectref* is **null**, the *invokevirtual* instruction throws a **NullPointerException**.

Otherwise, if no method matching the resolved name and descriptor is selected, *invokevirtual* throws an **AbstractMethodError**.

Otherwise, if the selected method is **abstract**, *invokevirtual* throws an **AbstractMethodError**.

Otherwise, if the selected method is **native** and the code that implements the method cannot be bound, *invokevirtual* throws an **UnsatisfiedLinkError**.

Notes

The *nargs* argument values and *objectref* are not one-to-one with the first *nargs* + 1 local variables. Argument values of types **long** and **double** must be stored in two consecutive local variables, thus more than *nargs* local variables may be required to pass *nargs* argument values to the invoked method.

ior***ior*****Operation** Boolean OR `int`**Format**

<i>ior</i>

Forms *ior* = 128 (0x80)**Operand** ..., *value1*, *value2* \Rightarrow **Stack** ..., *result***Description** Both *value1* and *value2* must be of type `int`. They are popped from the operand stack. An `int` *result* is calculated by taking the bitwise inclusive OR of *value1* and *value2*. The *result* is pushed onto the operand stack.

irem***irem***

Operation Remainder `int`

Format

<i>irem</i>

Forms *irem* = 112 (0x70)

Operand $\dots, value1, value2 \Rightarrow$

Stack $\dots, result$

Description Both *value1* and *value2* must be of type `int`. The values are popped from the operand stack. The `int` *result* is *value1* – (*value1* / *value2*) * *value2*. The *result* is pushed onto the operand stack.

The result of the *irem* instruction is such that $(a/b)*b + (a\%b)$ is equal to *a*. This identity holds even in the special case in which the dividend is the negative `int` of largest possible magnitude for its type and the divisor is -1 (the remainder is 0). It follows from this rule that the result of the remainder operation can be negative only if the dividend is negative and can be positive only if the dividend is positive. Moreover, the magnitude of the result is always less than the magnitude of the divisor.

Runtime Exception If the value of the divisor for an `int` remainder operator is 0 , *irem* throws an `ArithmetiException`.

ireturn***ireturn***

Operation Return `int` from method

Format

<i>ireturn</i>

Forms *ireturn* = 172 (0xac)

Operand ..., *value* ⇒
Stack [empty]

Description The current method must have return type `boolean`, `byte`, `short`, `char`, or `int`. The *value* must be of type `int`. If the current method is a `synchronized` method, the monitor entered or reentered on invocation of the method is updated and possibly exited as if by execution of a `monitorexit` instruction in the current thread. If no exception is thrown, *value* is popped from the operand stack of the current frame (§2.6) and pushed onto the operand stack of the frame of the invoker. Any other values on the operand stack of the current method are discarded.

The interpreter then returns control to the invoker of the method, reinstating the frame of the invoker.

Runtime Exceptions If the virtual machine implementation does not enforce the rules on structured locking described in §2.11.10, then if the current method is a `synchronized` method and the current thread is not the owner of the monitor entered or reentered on invocation of the method, *ireturn* throws an `IllegalMonitorStateException`. This can happen, for example, if a `synchronized` method contains a `monitorexit` instruction, but no `monitorenter` instruction, on the object on which the method is synchronized.

Otherwise, if the virtual machine implementation enforces the rules on structured locking described in §2.11.10 and if the first of those rules is violated during invocation of the current method, then *ireturn* throws an `IllegalMonitorStateException`.

ishl***ishl***

Operation Shift left `int`

Format

<i>ishl</i>

Forms *ishl* = 120 (0x78)

Operand $\dots, value1, value2 \Rightarrow$

Stack $\dots, result$

Description Both *value1* and *value2* must be of type `int`. The values are popped from the operand stack. An `int` *result* is calculated by shifting *value1* left by *s* bit positions, where *s* is the value of the low 5 bits of *value2*. The *result* is pushed onto the operand stack.

Notes This is equivalent (even if overflow occurs) to multiplication by 2 to the power *s*. The shift distance actually used is always in the range 0 to 31, inclusive, as if *value2* were subjected to a bitwise logical AND with the mask value 0x1f.

ishr***ishr***

Operation Arithmetic shift right `int`

Format

`ishr`

Forms $ishr = 122 \text{ (0x7a)}$

Operand $\dots, value1, value2 \Rightarrow$

Stack $\dots, result$

Description Both $value1$ and $value2$ must be of type `int`. The values are popped from the operand stack. An `int` $result$ is calculated by shifting $value1$ right by s bit positions, with sign extension, where s is the value of the low 5 bits of $value2$. The $result$ is pushed onto the operand stack.

Notes The resulting value is $\lfloor value1 / 2^s \rfloor$, where s is $value2 \& 0x1f$. For non-negative $value1$, this is equivalent to truncating `int` division by 2 to the power s . The shift distance actually used is always in the range 0 to 31, inclusive, as if $value2$ were subjected to a bitwise logical AND with the mask value `0x1f`.

istore***istore***

Operation Store `int` into local variable

Format

<i>istore</i>
<i>index</i>

Forms $istore = 54 \ (0x36)$

Operand $\dots, value \Rightarrow$

Stack \dots

Description The *index* is an unsigned byte that must be an index into the local variable array of the current frame (§2.6). The *value* on the top of the operand stack must be of type `int`. It is popped from the operand stack, and the value of the local variable at *index* is set to *value*.

Notes The *istore* opcode can be used in conjunction with the *wide* instruction to access a local variable using a two-byte unsigned index.

istore_<n>***istore_<n>***

Operation Store `int` into local variable

Format

istore_<n>

Forms *istore_0 = 59 (0x3b)*

istore_1 = 60 (0x3c)

istore_2 = 61 (0x3d)

istore_3 = 62 (0x3e)

Operand ..., *value* ⇒

Stack ...

Description The *<n>* must be an index into the local variable array of the current frame (§2.6). The *value* on the top of the operand stack must be of type `int`. It is popped from the operand stack, and the value of the local variable at *<n>* is set to *value*.

Notes Each of the *istore_<n>* instructions is the same as *istore* with an *index* of *<n>*, except that the operand *<n>* is implicit.

isub***isub***

Operation Subtract `int`

Format

<i>isub</i>

Forms $isub = 100 \text{ (0x64)}$

Operand $\dots, value1, value2 \Rightarrow$

Stack $\dots, result$

Description Both *value1* and *value2* must be of type `int`. The values are popped from the operand stack. The `int` *result* is *value1* – *value2*. The *result* is pushed onto the operand stack.

For `int` subtraction, $a - b$ produces the same result as $a + (-b)$. For `int` values, subtraction from zero is the same as negation.

The result is the 32 low-order bits of the true mathematical result in a sufficiently wide two's-complement format, represented as a value of type `int`. If overflow occurs, then the sign of the result may not be the same as the sign of the mathematical difference of the two values.

Despite the fact that overflow may occur, execution of an *isub* instruction never throws a runtime exception.

iushr***iushr***

Operation Logical shift right `int`

Format

iushr

Forms *iushr* = 124 (0x7c)

Operand $\dots, value1, value2 \Rightarrow$

Stack $\dots, result$

Description Both *value1* and *value2* must be of type `int`. The values are popped from the operand stack. An `int` *result* is calculated by shifting *value1* right by *s* bit positions, with zero extension, where *s* is the value of the low 5 bits of *value2*. The *result* is pushed onto the operand stack.

Notes

If *value1* is positive and *s* is *value2* & 0x1f, the result is the same as that of *value1* $>>$ *s*; if *value1* is negative, the result is equal to the value of the expression $(value1 >> s) + (2 << \sim s)$. The addition of the $(2 << \sim s)$ term cancels out the propagated sign bit. The shift distance actually used is always in the range 0 to 31, inclusive.

ixor***ixor*****Operation** Boolean XOR `int`**Format**

<i>ixor</i>

Forms *ixor* = 130 (0x82)**Operand** ..., *value1*, *value2* \Rightarrow **Stack** ..., *result***Description** Both *value1* and *value2* must be of type `int`. They are popped from the operand stack. An `int` *result* is calculated by taking the bitwise exclusive OR of *value1* and *value2*. The *result* is pushed onto the operand stack.

jsr***jsr*****Operation** Jump subroutine**Format**

<i>jsr</i>
<i>branchbyte1</i>
<i>branchbyte2</i>

Forms $jsr = 168 \ (0xa8)$ **Operand** ... \Rightarrow **Stack** ..., *address*

Description The *address* of the opcode of the instruction immediately following this *jsr* instruction is pushed onto the operand stack as a value of type `returnAddress`. The unsigned *branchbyte1* and *branchbyte2* are used to construct a signed 16-bit offset, where the offset is $(branchbyte1 \ll 8) | branchbyte2$. Execution proceeds at that offset from the address of this *jsr* instruction. The target address must be that of an opcode of an instruction within the method that contains this *jsr* instruction.

Notes The *jsr* instruction is used with the *ret* instruction in the implementation of the `finally` clauses of the Java programming language (see §3.13, “Compiling finally”). Note that *jsr* pushes the address onto the operand stack and *ret* gets it out of a local variable. This asymmetry is intentional.

jsr_w***jsr_w*****Operation** Jump subroutine (wide index)**Format**

<i>jsr_w</i>
<i>branchbyte1</i>
<i>branchbyte2</i>
<i>branchbyte3</i>
<i>branchbyte4</i>

Forms $jsr_w = 201 \text{ (0xc9)}$ **Operand** ... \Rightarrow **Stack** ..., *address***Description** The *address* of the opcode of the instruction immediately following this *jsr_w* instruction is pushed onto the operand stack as a value of type `returnAddress`. The unsigned *branchbyte1*, *branchbyte2*, *branchbyte3*, and *branchbyte4* are used to construct a signed 32-bit offset, where the offset is $(branchbyte1 \ll 24) | (branchbyte2 \ll 16) | (branchbyte3 \ll 8) | branchbyte4$. Execution proceeds at that offset from the address of this *jsr_w* instruction. The target address must be that of an opcode of an instruction within the method that contains this *jsr_w* instruction.**Notes**

The *jsr_w* instruction is used with the *ret* instruction in the implementation of the `finally` clauses of the Java programming language (see §3.13, “Compiling finally”). Note that *jsr_w* pushes the address onto the operand stack and *ret* gets it out of a local variable. This asymmetry is intentional.

Although the *jsr_w* instruction takes a 4-byte branch offset, other factors limit the size of a method to 65535 bytes (§4.11). This limit may be raised in a future release of the Java virtual machine.

l2d***l2d*****Operation** Convert `long` to `double`**Format**

<i>l2d</i>

Forms *l2d* = 138 (0x8a)**Operand** ..., *value* \Rightarrow **Stack** ..., *result***Description** The *value* on the top of the operand stack must be of type `long`. It is popped from the operand stack and converted to a `double` *result* using IEEE 754 round to nearest mode. The *result* is pushed onto the operand stack.**Notes** The *l2d* instruction performs a widening primitive conversion (JLS3 §5.1.2) that may lose precision because values of type `double` have only 53 significand bits.

l2f***l2f***

Operation Convert `long` to `float`

Format

<i>l2f</i>

Forms *l2f* = 137 (0x89)

Operand ..., *value* \Rightarrow

Stack ..., *result*

Description The *value* on the top of the operand stack must be of type `long`. It is popped from the operand stack and converted to a `float` *result* using IEEE 754 round to nearest mode. The *result* is pushed onto the operand stack.

Notes

The *l2f* instruction performs a widening primitive conversion (JLS3 §5.1.2) that may lose precision because values of type `float` have only 24 significand bits.

l2i***l2i*****Operation** Convert `long` to `int`**Format*****l2i*****Forms** $l2i = 136 \text{ (0x88)}$ **Operand** $\dots, value \Rightarrow$ **Stack** $\dots, result$ **Description** The *value* on the top of the operand stack must be of type `long`. It is popped from the operand stack and converted to an `int` *result* by taking the low-order 32 bits of the `long` value and discarding the high-order 32 bits. The *result* is pushed onto the operand stack.**Notes** The *l2i* instruction performs a narrowing primitive conversion (JLS3 §5.1.3). It may lose information about the overall magnitude of *value*. The *result* may also not have the same sign as *value*.

ladd***ladd*****Operation** Add `long`**Format**

<i>ladd</i>

Forms *ladd* = 97 (0x61)**Operand** ..., *value1*, *value2* \Rightarrow **Stack** ..., *result***Description** Both *value1* and *value2* must be of type `long`. The values are popped from the operand stack. The `long` *result* is *value1* + *value2*. The *result* is pushed onto the operand stack.

The result is the 64 low-order bits of the true mathematical result in a sufficiently wide two's-complement format, represented as a value of type `long`. If overflow occurs, the sign of the result may not be the same as the sign of the mathematical sum of the two values.

Despite the fact that overflow may occur, execution of an *ladd* instruction never throws a runtime exception.

laload***laload***

Operation Load long from array

Format

<i>laload</i>

Forms *laload* = 47 (0x2f)

Operand ..., *arrayref*, *index* \Rightarrow

Stack ..., *value*

Description The *arrayref* must be of type `reference` and must refer to an array whose components are of type `long`. The *index* must be of type `int`. Both *arrayref* and *index* are popped from the operand stack. The `long` *value* in the component of the array at *index* is retrieved and pushed onto the operand stack.

Runtime Exceptions If *arrayref* is `null`, *laload* throws a `NullPointerException`.

Otherwise, if *index* is not within the bounds of the array referenced by *arrayref*, the *laload* instruction throws an `ArrayIndexOutOfBoundsException`.

land***land*****Operation** Boolean AND long**Format**

<i>land</i>

Forms *land* = 127 (0x7f)**Operand** ..., *value1*, *value2* \Rightarrow **Stack** ..., *result***Description** Both *value1* and *value2* must be of type long. They are popped from the operand stack. A long *result* is calculated by taking the bitwise AND of *value1* and *value2*. The *result* is pushed onto the operand stack.

lastore***lastore***

Operation Store into long array

Format

<i>lastore</i>

Forms *lastore* = 80 (0x50)

Operand ..., *arrayref*, *index*, *value* ⇒
Stack ...

Description The *arrayref* must be of type `reference` and must refer to an array whose components are of type `long`. The *index* must be of type `int`, and *value* must be of type `long`. The *arrayref*, *index*, and *value* are popped from the operand stack. The `long` *value* is stored as the component of the array indexed by *index*.

Runtime Exceptions If *arrayref* is `null`, *lastore* throws a `NullPointerException`. Otherwise, if *index* is not within the bounds of the array referenced by *arrayref*, the *lastore* instruction throws an `ArrayIndexOutOfBoundsException`.

lcmp***lcmp***

Operation Compare long

Format

<i>lcmp</i>

Forms *lcmp* = 148 (0x94)

Operand ..., *value1*, *value2* ⇒
Stack ..., *result*

Description Both *value1* and *value2* must be of type long. They are both popped from the operand stack, and a signed integer comparison is performed. If *value1* is greater than *value2*, the int value 1 is pushed onto the operand stack. If *value1* is equal to *value2*, the int value 0 is pushed onto the operand stack. If *value1* is less than *value2*, the int value -1 is pushed onto the operand stack.

lconst_<l>***lconst_<l>***

Operation Push long constant

Format

lconst_<l>

Forms *lconst_0* = 9 (0x9)

lconst_1 = 10 (0xa)

Operand ... \Rightarrow

Stack ..., <*l*>

Description Push the long constant <*l*> (*0* or *1*) onto the operand stack.

ldc***ldc***

Operation Push item from runtime constant pool

Format

<i>ldc</i>
<i>index</i>

Forms *ldc* = 18 (0x12)

Operand ... \Rightarrow

Stack ..., *value*

Description The *index* is an unsigned byte that must be a valid index into the runtime constant pool of the current class (§2.6). The runtime constant pool entry at *index* either must be a runtime constant of type `int` or `float`, or must be a symbolic reference to a class (§5.4.3.1) or a string literal (§5.1).

If the runtime constant pool entry is a runtime constant of type `int` or `float`, the numeric *value* of that runtime constant is pushed onto the operand stack as an `int` or `float`, respectively.

Otherwise, if the runtime constant pool entry is a reference to an instance of class `String` representing a string literal (§5.1), then a reference to that instance, *value*, is pushed onto the operand stack.

Otherwise, the runtime constant pool entry must be a symbolic reference to a class (§4.4.1). The named class is resolved (§5.4.3.1) and a reference to the `Class` object representing that class, *value*, is pushed onto the operand stack.

Linking Exceptions During resolution of the symbolic reference to the class, any of the exceptions pertaining to class resolution documented in §5.4.3.1 can be thrown.

Notes

The *ldc* instruction can only be used to push a value of type `float` taken from the float value set (§2.3.2) because a constant of type `float` in the constant pool (§4.4.4) must be taken from the float value set.

ldc_w***ldc_w***

Operation Push item from runtime constant pool (wide index)

Format

<i>ldc_w</i>
<i>indexbyte1</i>
<i>indexbyte2</i>

Forms $ldc_w = 19 \ (0x13)$

Operand ... \Rightarrow

Stack ..., *value*

Description The unsigned *indexbyte1* and *indexbyte2* are assembled into an unsigned 16-bit index into the runtime constant pool of the current class (§2.6), where the value of the index is calculated as $(indexbyte1 \ll 8) | indexbyte2$. The index must be a valid index into the runtime constant pool of the current class. The runtime constant pool entry at the index either must be a runtime constant of type `int` or `float`, or must be a symbolic reference to a class (§5.4.3.1) or a string literal (§5.1).

If the runtime constant pool entry is a runtime constant of type `int` or `float`, the numeric *value* of that runtime constant is pushed onto the operand stack as an `int` or `float`, respectively.

Otherwise, if the runtime constant pool entry is a reference to an instance of class `String` representing a string literal (§5.1), then a reference to that instance, *value*, is pushed onto the operand stack.

Otherwise, the runtime constant pool entry must be a symbolic reference to a class (§4.4.1). The named class is resolved (§5.4.3.1) and a reference to the `Class` object representing that class, *value*, is pushed onto the operand stack.

Linking Exceptions During resolution of the symbolic reference to the class, any of the exceptions pertaining to class resolution documented in §5.4.3.1 can be thrown.

Notes The *ldc_w* instruction is identical to the *ldc* instruction except for its wider runtime constant pool index.

The *ldc_w* instruction can only be used to push a value of type `float` taken from the float value set (§2.3.2) because a constant of type `float` in the constant pool (§4.4.4) must be taken from the float value set.

ldc2_w***ldc2_w***

Operation Push `long` or `double` from runtime constant pool (wide index)

Format

<i>ldc2_w</i>
<i>indexbyte1</i>
<i>indexbyte2</i>

Forms $ldc2_w = 20 \text{ (0x14)}$

Operand ... \Rightarrow

Stack ..., *value*

Description The unsigned *indexbyte1* and *indexbyte2* are assembled into an unsigned 16-bit index into the runtime constant pool of the current class (§2.6), where the value of the index is calculated as $(indexbyte1 \ll 8) | indexbyte2$. The index must be a valid index into the runtime constant pool of the current class. The runtime constant pool entry at the index must be a runtime constant of type `long` or `double` (§5.1). The numeric *value* of that runtime constant is pushed onto the operand stack as a `long` or `double`, respectively.

Notes Only a wide-index version of the *ldc2_w* instruction exists; there is no *ldc2* instruction that pushes a `long` or `double` with a single-byte index.

The *ldc2_w* instruction can only be used to push a value of type `double` taken from the double value set (§2.3.2) because a constant of type `double` in the constant pool (§4.4.5) must be taken from the double value set.

ldiv***ldiv*****Operation** Divide `long`**Format**

<i>ldiv</i>

Forms $ldiv = 109 \text{ (0x6d)}$ **Operand** $\dots, value1, value2 \Rightarrow$ **Stack** $\dots, result$ **Description** Both *value1* and *value2* must be of type `long`. The values are popped from the operand stack. The `long` *result* is the value of the Java programming language expression *value1* / *value2*. The *result* is pushed onto the operand stack.

A `long` division rounds towards 0; that is, the quotient produced for `long` values in n / d is a `long` value q whose magnitude is as large as possible while satisfying $|d \cdot q| \leq |n|$. Moreover, q is positive when $|n| \geq |d|$ and n and d have the same sign, but q is negative when $|n| \geq |d|$ and n and d have opposite signs.

There is one special case that does not satisfy this rule: if the dividend is the negative integer of largest possible magnitude for the `long` type and the divisor is -1 , then overflow occurs and the result is equal to the dividend; despite the overflow, no exception is thrown in this case.

Runtime Exception If the value of the divisor in a `long` division is 0, *ldiv* throws an `ArithmeticalException`.

lload***lload***

Operation Load `long` from local variable

Format

<i>lload</i>
<i>index</i>

Forms $lload = 22 \text{ (0x16)}$

Operand $\dots \Rightarrow$

Stack $\dots, value$

Description The *index* is an unsigned byte. Both *index* and *index* + 1 must be indices into the local variable array of the current frame (§2.6). The local variable at *index* must contain a `long`. The *value* of the local variable at *index* is pushed onto the operand stack.

Notes The *lload* opcode can be used in conjunction with the *wide* instruction to access a local variable using a two-byte unsigned index.

lload_<n>***lload_<n>***

Operation Load long from local variable

Format

lload_<n>

Forms

lload_0 = 30 (0x1e)
lload_1 = 31 (0x1f)
lload_2 = 32 (0x20)
lload_3 = 33 (0x21)

Operand ... \Rightarrow

Stack ..., *value*

Description Both $<n>$ and $<n> + 1$ must be indices into the local variable array of the current frame (§2.6). The local variable at $<n>$ must contain a long. The *value* of the local variable at $<n>$ is pushed onto the operand stack.

Notes Each of the *lload_<n>* instructions is the same as *lload* with an *index* of $<n>$, except that the operand $<n>$ is implicit.

lmul***lmul***

Operation Multiply `long`

Format

<i>lmul</i>

Forms *lmul* = 105 (0x69)

Operand ..., *value1*, *value2* \Rightarrow
Stack ..., *result*

Description Both *value1* and *value2* must be of type `long`. The values are popped from the operand stack. The `long` *result* is *value1* * *value2*. The *result* is pushed onto the operand stack.

The result is the 64 low-order bits of the true mathematical result in a sufficiently wide two's-complement format, represented as a value of type `long`. If overflow occurs, the sign of the result may not be the same as the sign of the mathematical sum of the two values.

Despite the fact that overflow may occur, execution of an *lmul* instruction never throws a runtime exception.

lneg***lneg***

Operation Negate `long`

Format

<i>lneg</i>

Forms $lneg = 117 (0x75)$

Operand $\dots, value \Rightarrow$

Stack $\dots, result$

Description The *value* must be of type `long`. It is popped from the operand stack. The `long` *result* is the arithmetic negation of *value*, $-value$. The *result* is pushed onto the operand stack.

For `long` values, negation is the same as subtraction from zero. Because the Java virtual machine uses two's-complement representation for integers and the range of two's-complement values is not symmetric, the negation of the maximum negative `long` results in that same maximum negative number. Despite the fact that overflow has occurred, no exception is thrown.

For all `long` values x , $-x$ equals $(\sim x) + 1$.

lookupsswitch***lookupsswitch***

Operation Access jump table by key match and jump

Format

<i>lookupsswitch</i>
<0-3 byte pad>
<i>defaultbyte1</i>
<i>defaultbyte2</i>
<i>defaultbyte3</i>
<i>defaultbyte4</i>
<i>npairs1</i>
<i>npairs2</i>
<i>npairs3</i>
<i>npairs4</i>
<i>match-offset pairs...</i>

Forms *lookupsswitch* = 171 (0xab)

Operand ..., *key* \Rightarrow

Stack ...

Description A *lookupsswitch* is a variable-length instruction. Immediately after the *lookupsswitch* opcode, between zero and three bytes must act as padding, such that *defaultbyte1* begins at an address that is a multiple of four bytes from the start of the current method (the opcode of its first instruction). Immediately after the padding follow a series of signed 32-bit values: *default*, *npairs*, and then *npairs* pairs of signed 32-bit values. The *npairs* must be greater than or equal to 0. Each of the *npairs* pairs consists of an *int match* and a signed 32-bit *offset*. Each of these signed 32-bit values is constructed from four unsigned bytes as $(byte1 \ll 24) | (byte2 \ll 16) | (byte3 \ll 8) | byte4$.

lookupsswitch* (cont.)**lookupsswitch* (cont.)**

The table *match-offset* pairs of the *lookupsswitch* instruction must be sorted in increasing numerical order by *match*.

The *key* must be of type `int` and is popped from the operand stack. The *key* is compared against the *match* values. If it is equal to one of them, then a target address is calculated by adding the corresponding *offset* to the address of the opcode of this *lookupsswitch* instruction. If the *key* does not match any of the *match* values, the target address is calculated by adding *default* to the address of the opcode of this *lookupsswitch* instruction. Execution then continues at the target address.

The target address that can be calculated from the offset of each *match-offset* pair, as well as the one calculated from *default*, must be the address of an opcode of an instruction within the method that contains this *lookupsswitch* instruction.

Notes

The alignment required of the 4-byte operands of the *lookupsswitch* instruction guarantees 4-byte alignment of those operands if and only if the method that contains the *lookupsswitch* is positioned on a 4-byte boundary.

The *match-offset* pairs are sorted to support lookup routines that are quicker than linear search.

lor***lor*****Operation** Boolean OR long**Format**

<i>lor</i>

Forms *lor* = 129 (0x81)**Operand** ..., *value1*, *value2* \Rightarrow **Stack** ..., *result***Description** Both *value1* and *value2* must be of type long. They are popped from the operand stack. A long *result* is calculated by taking the bitwise inclusive OR of *value1* and *value2*. The *result* is pushed onto the operand stack.

lrem***lrem***

Operation Remainder long

Format

<i>lrem</i>

Forms *lrem* = 113 (0x71)

Operand ... , *value1*, *value2* \Rightarrow
Stack ... , *result*

Description Both *value1* and *value2* must be of type long. The values are popped from the operand stack. The long *result* is *value1* – (*value1* / *value2*) * *value2*. The *result* is pushed onto the operand stack.

The result of the *lrem* instruction is such that $(a/b)*b + (a\%b)$ is equal to *a*. This identity holds even in the special case in which the dividend is the negative long of largest possible magnitude for its type and the divisor is -1 (the remainder is 0). It follows from this rule that the result of the remainder operation can be negative only if the dividend is negative and can be positive only if the dividend is positive; moreover, the magnitude of the result is always less than the magnitude of the divisor.

Runtime Exception If the value of the divisor for a long remainder operator is 0 , *lrem* throws an `ArithmetiException`.

lreturn***lreturn***

Operation Return `long` from method

Format

<i>lreturn</i>

Forms *lreturn* = 173 (0xad)

Operand ..., *value* ⇒
Stack [empty]

Description The current method must have return type `long`. The *value* must be of type `long`. If the current method is a `synchronized` method, the monitor entered or reentered on invocation of the method is updated and possibly exited as if by execution of a `monitorexit` instruction in the current thread. If no exception is thrown, *value* is popped from the operand stack of the current frame (§2.6) and pushed onto the operand stack of the frame of the invoker. Any other values on the operand stack of the current method are discarded.

The interpreter then returns control to the invoker of the method, reinstating the frame of the invoker.

Runtime Exceptions If the virtual machine implementation does not enforce the rules on structured locking described in §2.11.10, then if the current method is a `synchronized` method and the current thread is not the owner of the monitor entered or reentered on invocation of the method, *lreturn* throws an `IllegalMonitorStateException`. This can happen, for example, if a `synchronized` method contains a `monitorexit` instruction, but no `monitorenter` instruction, on the object on which the method is synchronized.

Otherwise, if the virtual machine implementation enforces the rules on structured locking described in §2.11.10 and if the first of those rules is violated during invocation of the current method, then *lreturn* throws an `IllegalMonitorStateException`.

lshl***lshl***

Operation Shift left `long`

Format

<i>lshl</i>

Forms $lshl = 121 \ (0x79)$

Operand $\dots, value1, value2 \Rightarrow$

Stack $\dots, result$

Description The *value1* must be of type `long`, and *value2* must be of type `int`. The values are popped from the operand stack. A `long` *result* is calculated by shifting *value1* left by *s* bit positions, where *s* is the low 6 bits of *value2*. The *result* is pushed onto the operand stack.

Notes This is equivalent (even if overflow occurs) to multiplication by 2 to the power *s*. The shift distance actually used is therefore always in the range 0 to 63, inclusive, as if *value2* were subjected to a bitwise logical AND with the mask value 0x3f.

lshr***lshr***

Operation Arithmetic shift right `long`

Format

lshr

Forms *lshr* = 123 (0x7b)

Operand ..., *value1*, *value2* \Rightarrow

Stack ..., *result*

Description The *value1* must be of type `long`, and *value2* must be of type `int`. The values are popped from the operand stack. A `long` *result* is calculated by shifting *value1* right by *s* bit positions, with sign extension, where *s* is the value of the low 6 bits of *value2*. The *result* is pushed onto the operand stack.

Notes The resulting value is $\lfloor \text{value1} / 2^s \rfloor$, where *s* is *value2* & 0x3f. For non-negative *value1*, this is equivalent to truncating `long` division by 2 to the power *s*. The shift distance actually used is therefore always in the range 0 to 63, inclusive, as if *value2* were subjected to a bitwise logical AND with the mask value 0x3f.

lstore***lstore***

Operation Store `long` into local variable

Format

<i>lstore</i>
<i>index</i>

Forms $lstore = 55 \ (0x37)$

Operand $\dots, value \Rightarrow$

Stack \dots

Description The *index* is an unsigned byte. Both *index* and *index + 1* must be indices into the local variable array of the current frame (§2.6). The *value* on the top of the operand stack must be of type `long`. It is popped from the operand stack, and the local variables at *index* and *index + 1* are set to *value*.

Notes The *lstore* opcode can be used in conjunction with the *wide* instruction to access a local variable using a two-byte unsigned index.

lstore_<n>***lstore_<n>***

Operation Store long into local variable

Format

lstore_<n>

Forms *lstore_0 = 63 (0x3f)*

lstore_1 = 64 (0x40)

lstore_2 = 65 (0x41)

lstore_3 = 66 (0x42)

Operand ..., *value* \Rightarrow

Stack ...

Description Both $<n>$ and $<n> + 1$ must be indices into the local variable array of the current frame (§2.6). The *value* on the top of the operand stack must be of type long. It is popped from the operand stack, and the local variables at $<n>$ and $<n> + 1$ are set to *value*.

Notes Each of the *lstore_<n>* instructions is the same as *lstore* with an *index* of $<n>$, except that the operand $<n>$ is implicit.

lsub***lsub***

Operation Subtract `long`

Format

<i>lsub</i>

Forms $lsub = 101 \text{ (0x65)}$

Operand $\dots, value1, value2 \Rightarrow$

Stack $\dots, result$

Description Both *value1* and *value2* must be of type `long`. The values are popped from the operand stack. The `long` *result* is *value1* – *value2*. The *result* is pushed onto the operand stack.

For `long` subtraction, $a - b$ produces the same result as $a + (-b)$. For `long` values, subtraction from zero is the same as negation.

The result is the 64 low-order bits of the true mathematical result in a sufficiently wide two's-complement format, represented as a value of type `long`. If overflow occurs, then the sign of the result may not be the same as the sign of the mathematical sum of the two values.

Despite the fact that overflow may occur, execution of an *lsub* instruction never throws a runtime exception.

lushr***lushr***

Operation Logical shift right `long`

Format

<i>lushr</i>

Forms $lushr = 125 \ (0x7d)$

Operand $\dots, value1, value2 \Rightarrow$

Stack $\dots, result$

Description The *value1* must be of type `long`, and *value2* must be of type `int`. The values are popped from the operand stack. A `long` *result* is calculated by shifting *value1* right logically (with zero extension) by the amount indicated by the low 6 bits of *value2*. The *result* is pushed onto the operand stack.

Notes

If *value1* is positive and *s* is *value2* & 0x3f, the result is the same as that of $value1 \gg s$; if *value1* is negative, the result is equal to the value of the expression $(value1 \gg s) + (2L \ll \sim s)$. The addition of the $(2L \ll \sim s)$ term cancels out the propagated sign bit. The shift distance actually used is always in the range 0 to 63, inclusive.

lxor***lxor*****Operation** Boolean XOR `long`**Format**

<i>lxor</i>

Forms *lxor* = 131 (0x83)**Operand** ..., *value1*, *value2* \Rightarrow **Stack** ..., *result***Description** Both *value1* and *value2* must be of type `long`. They are popped from the operand stack. A `long` *result* is calculated by taking the bitwise exclusive OR of *value1* and *value2*. The *result* is pushed onto the operand stack.

monitorenter***monitorenter***

Operation Enter monitor for object

Format

<i>monitorenter</i>

Forms *monitorenter* = 194 (0xc2)

Operand ..., *objectref* ⇒

Stack ...

Description The *objectref* must be of type reference.

Each object is associated with a monitor. A monitor is locked if and only if it has an owner. The thread that executes *monitorenter* attempts to gain ownership of the monitor associated with *objectref*, as follows.

If the entry count of the monitor associated with *objectref* is zero, the thread enters the monitor and sets its entry count to one. The thread is then the owner of the monitor.

If the thread already owns the monitor associated with *objectref*, it reenters the monitor, incrementing its entry count.

If another thread already owns the monitor associated with *objectref*, the thread blocks until the monitor's entry count is zero, then tries again to gain ownership.

Runtime Exception If *objectref* is null, *monitorenter* throws a NullPointerException.

Notes A *monitorenter* instruction may be used with one or more *monitorexit* instructions to implement a synchronized statement in the Java programming language (§3.14). The *monitorenter* and *monitorexit* instructions are not used in the implementation of synchronized methods, although they can be used to provide equivalent locking semantics. Monitor entry on invocation of a synchronized method, and monitor exit on its return, are handled implicitly by the Java virtual machine's method invocation and return instructions, as if *monitorenter* and *monitorexit* were used.

monitorenter (*cont.*)***monitorenter*** (*cont.*)

The association of a monitor with an object may be managed in various ways that are beyond the scope of this specification. For instance, the monitor may be allocated and deallocated at the same time as the object. Alternatively, it may be dynamically allocated at the time when a thread attempts to gain exclusive access to the object and freed at some later time when no thread remains in the monitor for the object.

The synchronization constructs of the Java programming language require support for operations on monitors besides entry and exit. These include waiting on a monitor (`Object.wait`) and notifying other threads waiting on a monitor (`Object.notifyAll` and `Object.notify`). These operations are supported in the standard package `java.lang` supplied with the Java virtual machine. No explicit support for these operations appears in the instruction set of the Java virtual machine.

monitorexit***monitorexit***

Operation Exit monitor for object

Format

<i>monitorexit</i>

Forms *monitorexit* = 195 (0xc3)

Operand ..., *objectref* ⇒

Stack ...

Description The *objectref* must be of type **reference**.

The thread that executes *monitorexit* must be the owner of the monitor associated with the instance referenced by *objectref*.

The thread decrements the entry count of the monitor associated with *objectref*. If as a result the value of the entry count is zero, the thread exits the monitor and is no longer its owner. Other threads that are blocking to enter the monitor are allowed to attempt to do so.

Runtime Exceptions If *objectref* is **null**, *monitorexit* throws a **NullPointerException**.

Otherwise, if the thread that executes *monitorexit* is not the owner of the monitor associated with the instance referenced by *objectref*, *monitorexit* throws an **IllegalMonitorStateException**.

Otherwise, if the virtual machine implementation enforces the rules on structured locking described in §2.11.10 and if the second of those rules is violated by the execution of this *monitorexit* instruction, then *monitorexit* throws an **IllegalMonitorStateException**.

Notes One or more *monitorexit* instructions may be used with a *monitorenter* instruction to implement a **synchronized** statement in the Java programming language (§3.14). The *monitorenter* and *monitorexit* instructions are not used in the implementation of **synchronized** methods, although they can be used to provide equivalent locking semantics.

monitorexit (*cont.*)***monitorexit*** (*cont.*)

The Java virtual machine supports exceptions thrown within `synchronized` methods and `synchronized` statements differently:

- Monitor exit on normal `synchronized` method completion is handled by the Java virtual machine's return instructions. Monitor exit on abrupt `synchronized` method completion is handled implicitly by the Java virtual machine's `athrow` instruction.
- When an exception is thrown from within a `synchronized` statement, exit from the monitor entered prior to the execution of the `synchronized` statement is achieved using the Java virtual machine's exception handling mechanism (§3.14).

multianewarray***multianewarray***

Operation Create new multidimensional array

Format

<i>multianewarray</i>
<i>indexbyte1</i>
<i>indexbyte2</i>
<i>dimensions</i>

Forms *multianewarray* = 197 (0xc5)

Operand ..., *count1*, [*count2*, ...] \Rightarrow

Stack ..., *arrayref*

Description The *dimensions* operand is an unsigned byte that must be greater than or equal to 1. It represents the number of dimensions of the array to be created. The operand stack must contain *dimensions* values. Each such value represents the number of components in a dimension of the array to be created, must be of type `int`, and must be nonnegative. The *count1* is the desired length in the first dimension, *count2* in the second, etc.

All of the *count* values are popped off the operand stack. The unsigned *indexbyte1* and *indexbyte2* are used to construct an index into the runtime constant pool of the current class (§2.6), where the value of the index is $(\text{indexbyte1} \ll 8) \mid \text{indexbyte2}$. The runtime constant pool item at the index must be a symbolic reference to a class, array, or interface type. The named class, array, or interface type is resolved (§5.4.3.1). The resulting entry must be an array class type of dimensionality greater than or equal to *dimensions*.

multianewarray* (cont.)**multianewarray* (cont.)**

A new multidimensional array of the array type is allocated from the garbage-collected heap. If any *count* value is zero, no subsequent dimensions are allocated. The components of the array in the first dimension are initialized to subarrays of the type of the second dimension, and so on. The components of the last allocated dimension of the array are initialized to the default initial value (§2.3, §2.4) for the ~~type of the components~~ element type of the array type. A reference *arrayref* to the new array is pushed onto the operand stack.

Linking Exceptions

During resolution of the symbolic reference to the class, array, or interface type, any of the exceptions documented in §5.4.3.1 can be thrown.

Otherwise, if the current class does not have permission to access the element type of the resolved array class, *multianewarray* throws an `IllegalAccessException`.

Runtime Exception

Otherwise, if any of the *dimensions* values on the operand stack are less than zero, the *multianewarray* instruction throws a `NegativeArraySizeException`.

Notes

It may be more efficient to use *newarray* or *anewarray* when creating an array of a single dimension.

The array class referenced via the runtime constant pool may have more dimensions than the *dimensions* operand of the *multianewarray* instruction. In that case, only the first *dimensions* of the dimensions of the array are created.

new***new*****Operation** Create new object**Format**

<i>new</i>
<i>indexbyte1</i>
<i>indexbyte2</i>

Forms *new* = 187 (0xbb)**Operand** ... \Rightarrow **Stack** ..., *objectref*

Description The unsigned *indexbyte1* and *indexbyte2* are used to construct an index into the runtime constant pool of the current class (§2.6), where the value of the index is $(\text{indexbyte1} \ll 8) | \text{indexbyte2}$. The runtime constant pool item at the index must be a symbolic reference to a class or interface type. The named class or interface type is resolved (§5.4.3.1) and should result in a class type. Memory for a new instance of that class is allocated from the garbage-collected heap, and the instance variables of the new object are initialized to their default initial values (§2.3, §2.4). The *objectref*, a reference to the instance, is pushed onto the operand stack.

On successful resolution of the class, it is initialized (§5.5) if it has not already been initialized.

Linking Exceptions During resolution of the symbolic reference to the class, array, or interface type, any of the exceptions documented in §5.4.3.1 can be thrown.

Otherwise, if the symbolic reference to the class, array, or interface type resolves to an interface or is an abstract class, *new* throws an `InstantiationException`.

new* (cont.)**new* (cont.)**

- | | |
|--------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Runtime Exception | Otherwise, if execution of this <i>new</i> instruction causes initialization of the referenced class, <i>new</i> may throw an <code>Error</code> as detailed in JLS3 §15.9.4. |
| Note | The <i>new</i> instruction does not completely create a new instance; instance creation is not completed until an instance initialization method has been invoked on the uninitialized instance. |

newarray***newarray***

Operation Create new array

Format

<i>newarray</i>
<i>atype</i>

Forms *newarray* = 188 (0xbc)

Operand ..., *count* ⇒

Stack ..., *arrayref*

Description The *count* must be of type `int`. It is popped off the operand stack. The *count* represents the number of elements in the array to be created.

The *atype* is a code that indicates the type of array to create. It must take one of the following values:

Array Type	<i>atype</i>
T_BOOLEAN	4
T_CHAR	5
T_FLOAT	6
T_DOUBLE	7
T_BYTE	8
T_SHORT	9
T_INT	10
T_LONG	11

A new array whose components are of type *atype* and of length *count* is allocated from the garbage-collected heap. A reference *arrayref* to this new array object is pushed into the operand stack. Each of the elements of the new array is initialized to the default initial value (§2.3, §2.4) for the type of the array for the element type of the array type.

newarray (cont.)***newarray (cont.)***

Runtime Exception If *count* is less than zero, *newarray* throws a `NegativeArraySizeException`.

Notes In Oracle's implementation of the Java virtual machine, arrays of type `boolean` (*atype* is `T_BOOLEAN`) are stored as arrays of 8-bit values and are manipulated using the *baload* and *bastore* instructions, instructions that also access arrays of type `byte`. Other implementations may implement packed `boolean` arrays; the *baload* and *bastore* instructions must still be used to access those arrays.

nop

nop

Operation Do nothing

Format

<i>nop</i>

Forms *nop* = 0 (0x0)

Operand No change

Stack

Description Do nothing.

pop***pop***

Operation Pop the top operand stack value

Format

<i>pop</i>

Forms *pop* = 87 (0x57)

Operand ..., *value* \Rightarrow

Stack ...

Description Pop the top value from the operand stack.

The *pop* instruction must not be used unless *value* is a value of a category 1 computational type (§2.11.1).

pop2***pop2***

Operation Pop the top one or two operand stack values

Format

<i>pop2</i>

Forms $pop2 = 88 \text{ (0x58)}$

Operand Form 1:

Stack $\dots, value2, value1 \Rightarrow$
 \dots

where each of *value1* and *value2* is a value of a category 1 computational type (§2.11.1).

Form 2:

$\dots, value \Rightarrow$
 \dots

where *value* is a value of a category 2 computational type (§2.11.1).

Description Pop the top one or two values from the operand stack.

putfield***putfield***

Operation Set field in object

Format

<i>putfield</i>
<i>indexbyte1</i>
<i>indexbyte2</i>

Forms *putfield* = 181 (0xb5)

Operand ..., *objectref*, *value* ⇒

Stack ...

Description The unsigned *indexbyte1* and *indexbyte2* are used to construct an index into the runtime constant pool of the current class (§2.6), where the value of the index is (*indexbyte1* << 8) | *indexbyte2*. The runtime constant pool item at that index must be a symbolic reference to a field (§5.1), which gives the name and descriptor of the field as well as a symbolic reference to the class in which the field is to be found. The class of *objectref* must not be an array. If the field is *protected* (§4.6), and it is a member of a superclass of the current class, and the field is not declared in the same runtime package (§5.3) as the current class, then the class of *objectref* must be either the current class or a subclass of the current class.

The referenced field is resolved (§5.4.3.2). The type of a *value* stored by a *putfield* instruction must be compatible with the descriptor of the referenced field (§4.3.2). If the field descriptor type is *boolean*, *byte*, *char*, *short*, or *int*, then the *value* must be an *int*. If the field descriptor type is *float*, *long*, or *double*, then the *value* must be a *float*, *long*, or *double*, respectively. If the field descriptor type is a reference type, then the *value* must be of a type that is assignment compatible (JLS3 §5.2) with the field descriptor type. If the field is *final*, it must be declared in the current class, and the instruction must occur in an instance initialization method (<*init*>) of the current class.

putfield* (cont.)**putfield* (cont.)**

The *value* and *objectref* are popped from the operand stack. The *objectref* must be of type `reference`. The *value* undergoes value set conversion (§2.8.3), resulting in *value'*, and the referenced field in *objectref* is set to *value'*.

Linking Exceptions During resolution of the symbolic reference to the field, any of the exceptions pertaining to field resolution documented in §5.4.3.2 can be thrown.

Otherwise, if the resolved field is a `static` field, *putfield* throws an `IncompatibleClassChangeError`.

Otherwise, if the field is `final`, it must be declared in the current class, and the instruction must occur in an instance initialization method (`<init>`) of the current class. Otherwise, an `IllegalAccessException` is thrown.

Runtime Exception Otherwise, if *objectref* is `null`, the *putfield* instruction throws a `NullPointerException`.

putstatic***putstatic***

Operation Set `static` field in class

Format

<i>putstatic</i>
<i>indexbyte1</i>
<i>indexbyte2</i>

Forms $\text{putstatic} = 179 \ (0xb3)$

Operand $\dots, \text{value} \Rightarrow$

Stack \dots

Description The unsigned *indexbyte1* and *indexbyte2* are used to construct an index into the runtime constant pool of the current class (§2.6), where the value of the index is $(\text{indexbyte1} \ll 8) | \text{indexbyte2}$. The runtime constant pool item at that index must be a symbolic reference to a field (§5.1), which gives the name and descriptor of the field as well as a symbolic reference to the class or interface in which the field is to be found. The referenced field is resolved (§5.4.3.2).

On successful resolution of the field the class or interface that declared the resolved field is initialized (§5.5) if that class or interface has not already been initialized.

The type of a *value* stored by a *putstatic* instruction must be compatible with the descriptor of the referenced field (§4.3.2). If the field descriptor type is `boolean`, `byte`, `char`, `short`, or `int`, then the *value* must be an `int`. If the field descriptor type is `float`, `long`, or `double`, then the *value* must be a `float`, `long`, or `double`, respectively. If the field descriptor type is a reference type, then the *value* must be of a type that is assignment compatible (JLS3 §5.2) with the field descriptor type. If the field is `final`, it must be declared in the current class, and the instruction must occur in the `<cinit>` method of the current class.

putstatic* (cont.)**putstatic* (cont.)**

The *value* is popped from the operand stack and undergoes value set conversion (§2.8.3), resulting in *value'*. The class field is set to *value'*.

**Linking
Exceptions**

During resolution of the symbolic reference to the class or interface field, any of the exceptions pertaining to field resolution documented in §5.4.3.2 can be thrown.

Otherwise, if the resolved field is not a `static` (class) field or an interface field, *putstatic* throws an `IncompatibleClassChangeError`.

Otherwise, if the field is `final`, it must be declared in the current class, and the instruction must occur in the `<clinit>` method of the current class. Otherwise, an `IllegalAccessException` is thrown.

**Runtime
Exception**

Otherwise, if execution of this *putstatic* instruction causes initialization of the referenced class or interface, *putstatic* may throw an `Error` as detailed in §5.5.

Notes

A *putstatic* instruction may be used only to set the value of an interface field on the initialization of that field. Interface fields may be assigned to only once, on execution of an interface variable initialization expression when the interface is initialized (JLS3 §9.3.1, §5.5).

ret***ret***

Operation Return from subroutine

Format

<i>ret</i>
<i>index</i>

Forms *ret* = 169 (0xa9)

Operand No change
Stack

Description The *index* is an unsigned byte between 0 and 255, inclusive. The local variable at *index* in the current frame (§2.6) must contain a value of type `returnAddress`. The contents of the local variable are written into the Java virtual machine’s pc register, and execution continues there.

Notes The *ret* instruction is used with *jsr* or *jsr_w* instructions in the implementation of the `finally` clauses of the Java programming language (see §3.13, “Compiling finally”). Note that *jsr* pushes the address onto the operand stack and *ret* gets it out of a local variable. This asymmetry is intentional.

The *ret* instruction should not be confused with the *return* instruction. A *return* instruction returns control from a method to its invoker, without passing any value back to the invoker.

The *ret* opcode can be used in conjunction with the *wide* instruction to access a local variable using a two-byte unsigned index.

return***return***

Operation Return `void` from method

Format

<i>return</i>

Forms $return = 177 \text{ (0xb1)}$

Operand $\dots \Rightarrow$
Stack [empty]

Description The current method must have return type `void`. If the current method is a `synchronized` method, the monitor entered or reentered on invocation of the method is updated and possibly exited as if by execution of a *monitorexit* instruction in the current thread. If no exception is thrown, any values on the operand stack of the current frame (§2.6) are discarded.

The interpreter then returns control to the invoker of the method, reinstating the frame of the invoker.

Runtime Exceptions If the virtual machine implementation does not enforce the rules on structured locking described in §2.11.10, then if the current method is a `synchronized` method and the current thread is not the owner of the monitor entered or reentered on invocation of the method, *return* throws an `IllegalMonitorStateException`. This can happen, for example, if a `synchronized` method contains a *monitorexit* instruction, but no *monitorenter* instruction, on the object on which the method is synchronized.

Otherwise, if the virtual machine implementation enforces the rules on structured locking described in §2.11.10 and if the first of those rules is violated during invocation of the current method, then *return* throws an `IllegalMonitorStateException`.

saload***saload***

Operation Load **short** from array

Format

saload

Forms *saload* = 53 (0x35)

Operand ..., *arrayref*, *index* \Rightarrow

Stack ..., *value*

Description The *arrayref* must be of type **reference** and must refer to an array whose components are of type **short**. The *index* must be of type **int**. Both *arrayref* and *index* are popped from the operand stack. The component of the array at *index* is retrieved and sign-extended to an **int** *value*. That *value* is pushed onto the operand stack.

Runtime Exceptions If *arrayref* is **null**, *saload* throws a **NullPointerException**.

Otherwise, if *index* is not within the bounds of the array referenced by *arrayref*, the *saload* instruction throws an **ArrayIndexOutOfBoundsException**.

sastore***sastore***

Operation Store into **short** array

Format

<i>sastore</i>

Forms *sastore* = 86 (0x56)

Operand ..., *arrayref*, *index*, *value* \Rightarrow

Stack ...

Description The *arrayref* must be of type **reference** and must refer to an array whose components are of type **short**. Both *index* and *value* must be of type **int**. The *arrayref*, *index*, and *value* are popped from the operand stack. The **int** *value* is truncated to a **short** and stored as the component of the array indexed by *index*.

Runtime Exceptions If *arrayref* is **null**, *sastore* throws a **NullPointerException**.

Otherwise, if *index* is not within the bounds of the array referenced by *arrayref*, the *sastore* instruction throws an **ArrayIndexOutOfBoundsException**.

sipush***sipush***

Operation Push short

Format

<i>sipush</i>
<i>byte1</i>
<i>byte2</i>

Forms $sipush = 17 \ (0x11)$

Operand ... \Rightarrow

Stack ..., *value*

Description The immediate unsigned *byte1* and *byte2* values are assembled into an intermediate **short** where the value of the short is $(byte1 \ll 8) | byte2$. The intermediate value is then sign-extended to an **int** *value*. That *value* is pushed onto the operand stack.

swap***swap***

Operation Swap the top two operand stack values

Format

swap

Forms *swap* = 95 (0x5f)

Operand Stack $\dots, value_2, value_1 \Rightarrow$
 $\dots, value_1, value_2$

Description Swap the top two values on the operand stack.

The *swap* instruction must not be used unless *value1* and *value2* are both values of a category 1 computational type (§2.11.1).

Notes The Java virtual machine does not provide an instruction implementing a swap on operands of category 2 computational types.

tableswitch***tableswitch***

Operation Access jump table by index and jump

Format

<i>tableswitch</i>
<0-3 byte pad>
<i>defaultbyte1</i>
<i>defaultbyte2</i>
<i>defaultbyte3</i>
<i>defaultbyte4</i>
<i>lowbyte1</i>
<i>lowbyte2</i>
<i>lowbyte3</i>
<i>lowbyte4</i>
<i>highbyte1</i>
<i>highbyte2</i>
<i>highbyte3</i>
<i>highbyte4</i>
<i>jump offsets...</i>

Forms *tableswitch* = 170 (0xaa)

Operand ..., *index* \Rightarrow

Stack ...

Description A *tableswitch* is a variable-length instruction. Immediately after the *tableswitch* opcode, between zero and three bytes must act as padding, such that *defaultbyte1* begins at an address that is a multiple of four bytes from the start of the current method (the opcode of its first instruction). Immediately after the padding are bytes constituting three signed 32-bit values: *default*, *low*, and *high*. Immediately following are bytes constituting a series of *high* – *low* + 1 signed 32-bit offsets. The value *low* must be less than or equal to *high*. The *high* – *low* + 1 signed 32-bit offsets are treated as a 0-based jump table. Each of these signed 32-bit values is constructed as $(byte1 \ll 24) | (byte2 \ll 16) | (byte3 \ll 8) | byte4$.

tableswitch* (cont.)**tableswitch* (cont.)**

The *index* must be of type `int` and is popped from the operand stack. If *index* is less than *low* or *index* is greater than *high*, then a target address is calculated by adding *default* to the address of the opcode of this *tableswitch* instruction. Otherwise, the offset at position *index* – *low* of the jump table is extracted. The target address is calculated by adding that offset to the address of the opcode of this *tableswitch* instruction. Execution then continues at the target address.

The target address that can be calculated from each jump table offset, as well as the one that can be calculated from *default*, must be the address of an opcode of an instruction within the method that contains this *tableswitch* instruction.

Notes

The alignment required of the 4-byte operands of the *tableswitch* instruction guarantees 4-byte alignment of those operands if and only if the method that contains the *tableswitch* starts on a 4-byte boundary.

wide***wide***

Operation Extend local variable index by additional bytes

Format 1:

<i>wide</i>
<i><opcode></i>
<i>indexbyte1</i>
<i>indexbyte2</i>

where *<opcode>* is one of *iload*, *fload*, *aload*, *lload*, *dload*, *istore*, *fstore*, *astore*, *lstore*, *dstore*, or *ret*

Format 2:

<i>wide</i>
<i>iinc</i>
<i>indexbyte1</i>
<i>indexbyte2</i>
<i>constbyte1</i>
<i>constbyte2</i>

Forms *wide* = 196 (0xc4)

Operand Stack Same as modified instruction

Description The *wide* instruction modifies the behavior of another instruction. It takes one of two formats, depending on the instruction being modified. The first form of the *wide* instruction modifies one of the instructions *iload*, *fload*, *aload*, *lload*, *dload*, *istore*, *fstore*, *astore*, *lstore*, *dstore*, or *ret*. The second form applies only to the *iinc* instruction.

In either case, the *wide* opcode itself is followed in the compiled code by the opcode of the instruction *wide* modifies. In either form, two unsigned bytes *indexbyte1* and *indexbyte2* follow the modified opcode and are assembled into a 16-bit unsigned index to a local variable in the current frame (§2.6), where the value of the index is

wide* (cont.)**wide* (cont.)**

$(indexbyte1 \ll 8) | indexbyte2$. The calculated index must be an index into the local variable array of the current frame. Where the *wide* instruction modifies an *lload*, *dload*, *lstore*, or *dstore* instruction, the index following the calculated index ($index + 1$) must also be an index into the local variable array. In the second form, two immediate unsigned bytes *constbyte1* and *constbyte2* follow *indexbyte1* and *indexbyte2* in the code stream. Those bytes are also assembled into a signed 16-bit constant, where the constant is $(constbyte1 \ll 8) | constbyte2$.

The widened bytecode operates as normal, except for the use of the wider index and, in the case of the second form, the larger increment range.

Notes

Although we say that *wide* “modifies the behavior of another instruction,” the *wide* instruction effectively treats the bytes constituting the modified instruction as operands, denaturing the embedded instruction in the process. In the case of a modified *iinc* instruction, one of the logical operands of the *iinc* is not even at the normal offset from the opcode. The embedded instruction must never be executed directly; its opcode must never be the target of any control transfer instruction.

Opcode Mnemonics by Opcode

THIS chapter gives the mapping from Java virtual machine instruction opcodes, including the reserved opcodes (§6.2), to the mnemonics for the instructions represented by those opcodes.

0 (0x00).....	<i>nop</i>	24 (0x18).....	<i>dload</i>
1 (0x01).....	<i>aconst_null</i>	25 (0x19).....	<i>aload</i>
2 (0x02).....	<i>iconst_m1</i>	26 (0x1a).....	<i>iload_0</i>
3 (0x03).....	<i>iconst_0</i>	27 (0x1b).....	<i>iload_1</i>
4 (0x04).....	<i>iconst_1</i>	28 (0x1c).....	<i>iload_2</i>
5 (0x05).....	<i>iconst_2</i>	29 (0x1d).....	<i>iload_3</i>
6 (0x06).....	<i>iconst_3</i>	30 (0x1e).....	<i>lload_0</i>
7 (0x07).....	<i>iconst_4</i>	31 (0x1f).....	<i>lload_1</i>
8 (0x08).....	<i>iconst_5</i>	32 (0x20).....	<i>lload_2</i>
9 (0x09).....	<i>lconst_0</i>	33 (0x21).....	<i>lload_3</i>
10 (0x0a).....	<i>lconst_1</i>	34 (0x22).....	<i>fload_0</i>
11 (0x0b).....	<i>fconst_0</i>	35 (0x23).....	<i>fload_1</i>
12 (0x0c).....	<i>fconst_1</i>	36 (0x24).....	<i>fload_2</i>
13 (0x0d).....	<i>fconst_2</i>	37 (0x25).....	<i>fload_3</i>
14 (0x0e).....	<i>dconst_0</i>	38 (0x26).....	<i>dload_0</i>
15 (0x0f).....	<i>dconst_1</i>	39 (0x27).....	<i>dload_1</i>
16 (0x10).....	<i>bipush</i>	40 (0x28).....	<i>dload_2</i>
17 (0x11).....	<i>sipush</i>	41 (0x29).....	<i>dload_3</i>
18 (0x12).....	<i>ldc</i>	42 (0x2a).....	<i>aload_0</i>
19 (0x13).....	<i>ldc_w</i>	43 (0x2b).....	<i>aload_1</i>
20 (0x14).....	<i>ldc2_w</i>	44 (0x2c).....	<i>aload_2</i>
21 (0x15).....	<i>iload</i>	45 (0x2d).....	<i>aload_3</i>
22 (0x16).....	<i>lload</i>	46 (0x2e).....	<i>iaload</i>
23 (0x17).....	<i>fload</i>	47 (0x2f).....	<i>laload</i>

48 (0x30).....	<i>faload</i>
49 (0x31).....	<i>daload</i>
50 (0x32).....	<i>aaload</i>
51 (0x33).....	<i>baload</i>
52 (0x34).....	<i>caload</i>
53 (0x35).....	<i>saload</i>
54 (0x36).....	<i>istore</i>
55 (0x37).....	<i>lstore</i>
56 (0x38).....	<i>fstore</i>
57 (0x39).....	<i>dstore</i>
58 (0x3a).....	<i>astore</i>
59 (0x3b).....	<i>istore_0</i>
60 (0x3c).....	<i>istore_1</i>
61 (0x3d).....	<i>istore_2</i>
62 (0x3e).....	<i>istore_3</i>
63 (0x3f)	<i>lstore_0</i>
64 (0x40).....	<i>lstore_1</i>
65 (0x41).....	<i>lstore_2</i>
66 (0x42).....	<i>lstore_3</i>
67 (0x43).....	<i>fstore_0</i>
68 (0x44).....	<i>fstore_1</i>
69 (0x45).....	<i>fstore_2</i>
70 (0x46).....	<i>fstore_3</i>
71 (0x47).....	<i>dstore_0</i>
72 (0x48).....	<i>dstore_1</i>
73 (0x49).....	<i>dstore_2</i>
74 (0x4a).....	<i>dstore_3</i>
75 (0x4b).....	<i>astore_0</i>
76 (0x4c).....	<i>astore_1</i>
77 (0x4d).....	<i>astore_2</i>
78 (0x4e).....	<i>astore_3</i>
79 (0x4f)	<i>iastore</i>
80 (0x50).....	<i>lastore</i>
81 (0x51).....	<i>fastore</i>
82 (0x52).....	<i>dastore</i>
83 (0x53).....	<i>aastore</i>
84 (0x54).....	<i>bastore</i>
85 (0x55).....	<i>castore</i>
86 (0x56).....	<i>sastore</i>
87 (0x57).....	<i>pop</i>
88 (0x58).....	<i>pop2</i>

89 (0x59).....	<i>dup</i>
90 (0x5a).....	<i>dup_x1</i>
91 (0x5b).....	<i>dup_x2</i>
92 (0x5c).....	<i>dup2</i>
93 (0x5d).....	<i>dup2_x1</i>
94 (0x5e).....	<i>dup2_x2</i>
95 (0x5f)	<i>swap</i>
96 (0x60).....	<i>iadd</i>
97 (0x61).....	<i>ladd</i>
98 (0x62).....	<i>fadd</i>
99 (0x63).....	<i>dadd</i>
100 (0x64).....	<i>isub</i>
101 (0x65).....	<i>lsub</i>
102 (0x66).....	<i>fsub</i>
103 (0x67).....	<i>dsub</i>
104 (0x68).....	<i>imul</i>
105 (0x69).....	<i>lmul</i>
106 (0x6a).....	<i>fmul</i>
107 (0x6b).....	<i>dmul</i>
108 (0x6c).....	<i>idiv</i>
109 (0x6d).....	<i>ldiv</i>
110 (0x6e).....	<i>fdiv</i>
111 (0x6f).....	<i>ddiv</i>
112 (0x70).....	<i>irem</i>
113 (0x71).....	<i>lrem</i>
114 (0x72).....	<i>frem</i>
115 (0x73).....	<i>drem</i>
116 (0x74).....	<i>ineg</i>
117 (0x75).....	<i>lneg</i>
118 (0x76).....	<i>fneg</i>
119 (0x77).....	<i>dneg</i>
120 (0x78).....	<i>ishl</i>
121 (0x79).....	<i>lshl</i>
122 (0x7a).....	<i>ishr</i>
123 (0x7b).....	<i>lshr</i>
124 (0x7c).....	<i>iushr</i>
125 (0x7d).....	<i>lushr</i>
126 (0x7e).....	<i>iand</i>
127 (0x7f)	<i>land</i>
128 (0x80).....	<i>ior</i>
129 (0x81).....	<i>lor</i>

130 (0x82).....	<i>ixor</i>	168 (0xa8).....	<i>jsr</i>
131 (0x83).....	<i>lxor</i>	169 (0xa9).....	<i>ret</i>
132 (0x84).....	<i>iinc</i>	170 (0xaa).....	<i>tableswitch</i>
133 (0x85).....	<i>i2l</i>	171 (0xab).....	<i>lookupswitch</i>
134 (0x86).....	<i>i2f</i>	172 (0xac).....	<i>ireturn</i>
135 (0x87).....	<i>i2d</i>	173 (0xad).....	<i>lreturn</i>
136 (0x88).....	<i>l2i</i>	174 (0xae).....	<i>freturn</i>
137 (0x89).....	<i>l2f</i>	175 (0xaf).....	<i>dreturn</i>
138 (0x8a).....	<i>l2d</i>	176 (0xb0).....	<i>areturn</i>
139 (0x8b).....	<i>f2i</i>	177 (0xb1).....	<i>return</i>
140 (0x8c).....	<i>f2l</i>	178 (0xb2).....	<i>getstatic</i>
141 (0x8d).....	<i>f2d</i>	179 (0xb3).....	<i>putstatic</i>
142 (0x8e).....	<i>d2i</i>	180 (0xb4).....	<i>getfield</i>
143 (0x8f).....	<i>d2l</i>	181 (0xb5).....	<i>putfield</i>
144 (0x90).....	<i>d2f</i>	182 (0xb6).....	<i>invokevirtual</i>
145 (0x91).....	<i>i2b</i>	183 (0xb7).....	<i>invokespecial</i>
146 (0x92).....	<i>i2c</i>	184 (0xb8).....	<i>invokestatic</i>
147 (0x93).....	<i>i2s</i>	185 (0xb9).....	<i>invokeinterface</i>
148 (0x94).....	<i>lcmp</i>	186 (0xba).....	<i>xxxunusedxxx</i> ¹
149 (0x95).....	<i>fcmpl</i>	187 (0xbb).....	<i>new</i>
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151 (0x97).....	<i>dcmpl</i>	189 (0xbd).....	<i>anewarray</i>
152 (0x98).....	<i>dcmpg</i>	190 (0xbe).....	<i>arraylength</i>
153 (0x99).....	<i>ifeq</i>	191 (0xbf).....	<i>athrow</i>
154 (0x9a).....	<i>ifne</i>	192 (0xc0).....	<i>checkcast</i>
155 (0x9b).....	<i>iflt</i>	193 (0xc1).....	<i>instanceof</i>
156 (0x9c).....	<i>ifge</i>	194 (0xc2).....	<i>monitorenter</i>
157 (0x9d).....	<i>ifgt</i>	195 (0xc3).....	<i>monitorexit</i>
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¹ For historical reasons, opcode value 186 is not used.

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