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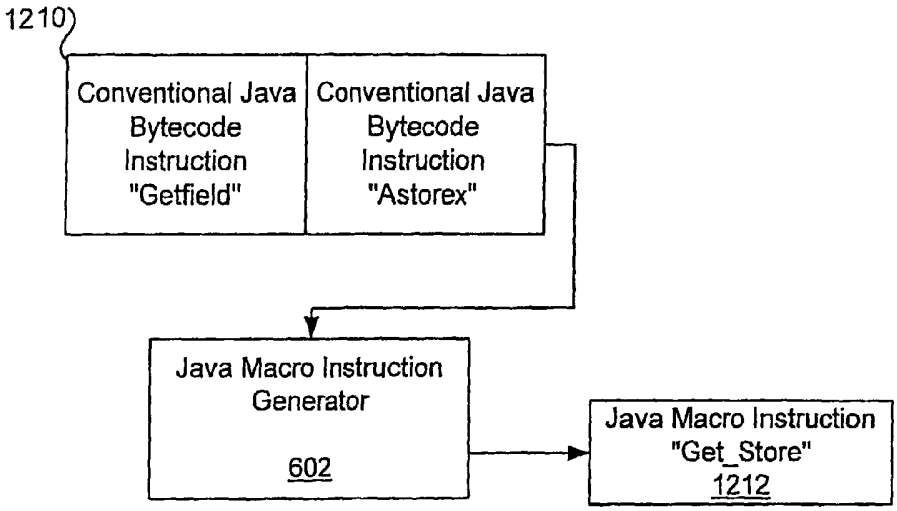


(57) Abstract: Techniques for generation of Java macro instructions suitable for use in Java computing environments are disclosed. As such, the techniques can be implemented in a Java virtual machine to efficiently execute Java instructions. As will be appreciated, a Java macro instruction can be substituted for two or more Java Bytecode instructions. This, in turn, reduces the number of Java instructions that are executed by the interpreter. As a result, the performance of virtual machines, especially those operating with limited resources, is improved. A Java macro instruction can be generated for conventional Java instruction sequences or sequences of Java instruction that are provided in a reduced set of instruction. In any case, sequences that are frequently encountered can be replaced by a Java macro instruction. These sequences are typically encountered when Java objects are instantiated, during programming loops, and when a local variables are assigned a value.

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# FRAMEWORKS FOR GENERATION OF JAVA MACRO INSTRUCTIONS FOR STORING VALUES INTO LOCAL VARIABLES

## CROSS-REFERENCE TO RELATED APPLICATION

## BACKGROUND OF THE INVENTION

[0001] The present invention relates generally to Java programming environments, and more particularly, to frameworks for generation of Java macro instructions in Java computing environments.

[0002] One of the goals of high level languages is to provide a portable programming environment such that the computer programs may easily be ported to another computer platform. High level languages such as "C" provide a level of abstraction from the underlying computer architecture and their success is well evidenced from the fact that most computer applications are now written in a high level language.

[0003] Portability has been taken to new heights with the advent of the World Wide Web ("the Web") which is an interface protocol for the Internet that allows communication between diverse computer platforms through a graphical interface. Computers communicating over the Web are able to download and execute small applications called applets. Given that applets may be executed on a diverse assortment of computer platforms, the applets are typically executed by a Java virtual machine.

[0004] Recently, the Java programming environment has become quite popular. The Java programming language is a language that is designed to be portable enough to be executed on a wide range of computers ranging from small devices (e.g., pagers, cell phones and smart cards) up to supercomputers. Computer programs written in the Java programming language (and other languages) may be compiled into Java Bytecode instructions that are suitable for execution by a Java virtual machine implementation. The Java virtual machine is commonly implemented in software by means of an interpreter for the Java virtual machine instruction

set but, in general, may be software, hardware, or both. A particular Java virtual machine implementation and corresponding support libraries together constitute a Java runtime environment.

[0005] Computer programs in the Java programming language are arranged in one or more classes or interfaces (referred to herein jointly as classes or class files). Such programs are generally platform, i.e., hardware and operating system, independent. As such, these computer programs may be executed, without modification, on any computer that is able to run an implementation of the Java runtime environment.

[0006] Object-oriented classes written in the Java programming language are compiled to a particular binary format called the "class file format." The class file includes various components associated with a single class. These components can be, for example, methods and/or interfaces associated with the class. In addition, the class file format can include a significant amount of ancillary information that is associated with the class. The class file format (as well as the general operation of the Java virtual machine) is described in some detail in The Java Virtual Machine Specification, Second Edition, by Tim Lindholm and Frank Yellin, which is hereby incorporated herein by reference.

[0007] Fig. 1A shows a progression of a simple piece of a Java source code 101 through execution by an interpreter, the Java virtual machine. The Java source code 101 includes the classic Hello World program written in Java. The source code is then input into a Bytecode compiler 103 that compiles the source code into Bytecodes. The Bytecodes are virtual machine instructions as they will be executed by a software emulated computer. Typically, virtual machine instructions are generic (*i.e.*, not designed for any specific microprocessor or computer architecture) but this is not required. The Bytecode compiler outputs a Java class file 105 that includes the Bytecodes for the Java program. The Java class file is input into a Java virtual machine 107. The Java virtual machine is an interpreter that decodes and executes the Bytecodes in the Java class file. The Java

virtual machine is an interpreter, but is commonly referred to as a virtual machine as it emulates a microprocessor or computer architecture in software (e.g., the microprocessor or computer architecture may not exist in hardware).

[0008] Fig. 1B illustrates a simplified class file 100. As shown in Fig. 1B, the class file 100 includes a constant pool 102 portion, interfaces portion 104, fields portion 106, methods portion 108, and attributes portion 110. The methods portion 108 can include, or have references to, several Java methods associated with the Java class which is represented in the class file 100. One of these methods is an initialization method used to initialize the Java class after the class file has been loaded by the virtual machine but before other methods can be invoked. In other words, typically, an initialization method is used to initialize a Java class before the classes can be used.

[0009] A conventional virtual machine's interpreter decodes and executes the Java Bytecode instructions, one instruction at a time, during execution, e.g., "at runtime." Typically, several operations have to be performed to obtain the information that is necessary to execute a Java instruction. Furthermore, there is a significant overhead associated with dispatching Bytecode instructions. In other words, the Java interpreter has to perform a significant amount of processing in order to switch from one instruction to the next. Accordingly, it is highly desirable to reduce the number of times the interpreter has to dispatch instructions. This, in turn, can improve the performance of virtual machines, especially those operating with limited resources.

[0010] In view of the foregoing, improved frameworks for execution of Java Bytecode instructions are needed.

## SUMMARY OF THE INVENTION

[0011] Broadly speaking, the invention relates to Java programming environments, and more particularly, to frameworks for generation of Java macro instructions in Java computing environments. Accordingly, techniques for generation of Java macro instructions suitable for use in Java computing environments are disclosed. As such, the techniques can be implemented in a Java virtual machine to efficiently execute Java instructions. As will be appreciated, a Java macro instruction can be substituted for two or more Java Bytecode instructions. This, in turn, reduces the number of Java instructions that are executed by the interpreter. As a result, the performance of virtual machines, especially those operating with limited resources, is improved.

[0012] The invention can be implemented in numerous ways, including as a method, an apparatus, a computer readable medium, and a database system. Several embodiments of the invention are discussed below.

[0013] One embodiment of the invention includes a Java macro instruction representing a sequence of Java Bytecode instructions consisting of a Java Getfield Bytecode instruction immediately followed by a Java Astore Bytecode instruction. The Java macro instruction can be executed by a Java virtual machine operating in a Java computing environment. When the Java macro instruction is executed, the operations that are performed by the conventional sequence of Java Bytecode instructions are performed.

[0014] Another embodiment of the invention discloses a Java macro instruction representing a sequence of Java Bytecode instructions consisting of an inventive Java Getfield Bytecode instruction immediately followed by an inventive Java Astore Bytecode instruction. The Java macro instruction can be executed by a Java virtual machine operating in a Java computing environment. The Java macro instruction is executed, the operations that are performed by the sequence of Java Bytecode instructions are performed.

[0015] As a computer readable media including computer program code for a Java macro instruction, one embodiment of the invention includes a Java

macro instruction representing a sequence of Java Bytecode instructions consisting of a Java Getfield Bytecode instruction immediately followed by a Java Astore Bytecode instruction. The Java macro instruction can be executed by a Java virtual machine operating in a Java computing environment. When the Java macro instruction is executed, the operations that are performed by the conventional sequence of Java Bytecode instructions are performed.

**[0016]** These and other aspects and advantages of the present invention will become more apparent when the detailed description below is read in conjunction with the accompanying drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

[0017] The present invention will be readily understood by the following detailed description in conjunction with the accompanying drawings, wherein like reference numerals designate like structural elements, and in which:

Fig. 1A shows a progression of a simple piece of a Java source code through execution by an interpreter, the Java virtual machine.

Fig. 1B illustrates a simplified class file.

Figs. 2A-2B illustrate Java computing environments including Java macro instruction generators.

Fig. 3 illustrates a method for generating Java macro instructions in accordance with one embodiment of the invention.

Fig. 4 illustrates a method for generating Java macro instructions in accordance with another embodiment of the invention.

Fig. 5 illustrates a Java Bytecode verifier in accordance with one embodiment of the invention.

Figs. 6A-6B illustrate Java computing environments including Java macro instruction generators and Java Bytecode translators in accordance with one embodiment of the invention.

Fig. 7A illustrates a computing environment including an internal representation of an inventive "DUP" instruction suitable for duplicating values on the stack in accordance with one embodiment of the invention.

Figs. 7B-7C illustrate some of the Java Bytecode instructions described in Fig. 7A.

Fig. 8 illustrates a mapping of Java Bytecode instantiation instructions to the virtual machine instructions provided in accordance with one embodiment of the invention.

Fig. 9A illustrates another sequence of conventional Java Bytecodes that can be executed frequently by a Java interpreter.

Fig. 9B illustrates a Java computing environment including a Java macro instruction generator and a Java Bytecode translator in accordance with another embodiment of the invention.

Fig. 10A illustrates an internal representation of a set of Java "Load" instructions suitable for loading values from a local variable in accordance with another embodiment of the invention.

Fig. 10B illustrates a set of Java Bytecode instructions for loading 4 byte local variables that can be represented by an inventive "Load" command in accordance with one embodiment of the invention.

Fig. 10C illustrates a set of Java Bytecode instructions for loading 8 byte local variables in accordance with one embodiment of the invention.

Figs. 11A and 11B illustrate some Java conventional Bytecode instructions for performing conditional flow operations which can be represented by two inventive virtual machine instructions in accordance with one embodiment of the invention.

Fig. 12A illustrates yet another sequence of conventional Java Bytecodes that can be executed frequently by a Java interpreter.

Fig. 12B illustrates the Java Bytecode translator operating to translate conventional Java instructions into inventive Java instructions.

Fig. 13A illustrates a computing environment in accordance with one embodiment of the invention.

Figs. 13B and 13C illustrate a set of conventional Java Bytecode instructions for storing arrays that can be represented by an inventive virtual machine instruction (e.g., Astore) in accordance with one embodiment of the invention.

## DETAILED DESCRIPTION OF THE INVENTION

[0018] As described in the background section, the Java programming environment has enjoyed widespread success. Therefore, there are continuing efforts to extend the breadth of Java compatible devices and to improve the performance of such devices. One of the most significant factors influencing the performance of Java based programs on a particular platform is the performance of the underlying virtual machine. Accordingly, there have been extensive efforts by a number of entities to improve performance in Java compliant virtual machines.

[0019] To achieve this and other objects of the invention, techniques for generation of Java macro instructions suitable for use in Java computing environments are disclosed. As such, the techniques can be implemented in a Java virtual machine to efficiently execute Java instructions. As will be appreciated, a Java macro instruction can be substituted for two or more Java Bytecode instructions. This, in turn, reduces the number of Java instructions that are executed by the interpreter. As a result, the performance of virtual machines, especially those operating with limited resources, is improved.

[0020] Embodiments of the invention are discussed below with reference to Figs. 2A-13C. However, those skilled in the art will readily appreciate that the detailed description given herein with respect to these figures is for explanatory purposes only as the invention extends beyond these limited embodiments.

[0021] Fig. 2A illustrates a Java computing environment 200 in accordance with one embodiment of the invention. The Java computing environment 200 includes a Java macro instruction generator 202 suitable for generation of macro instructions which are suitable for execution by an interpreter. As shown in Fig. 2A, the Java macro instruction generator 202 can read a stream of Java Bytecode instructions 204 (Java Bytecode instructions 1-N). Moreover, the Java macro instruction generator 202 can produce a Java

macro instruction 206 which represents two or more Java Bytecode instructions in the stream 204.

[0022] The Java Bytecode instructions in the stream 204 can be conventional Java Bytecode instructions, for example, conventional instructions "new" and "dup" which typically appear in sequence in order to instantiate a Java object. As will be appreciated by those skilled in the art, certain sequences appear frequently during the execution of Java programs. Thus, replacing such sequences with a single macro instruction can reduce the overhead associated with dispatching Java Bytecode instructions. As a result, the performance of virtual machines, especially those operating with limited resources, is enhanced.

[0023] It should be noted that the Java macro instruction generator 202 can also be used in conjunction with a Java Bytecode translator in accordance with one preferred embodiment of the invention. Referring now to Fig. 2B, a Java Bytecode translator 230 operates to translate conventional Java instructions 1-M into inventive Java instructions 234 (1-N), wherein N is an integer less than the integer M. More details about the Java Bytecode translator 230 and inventive Java instructions 1-N are described in U.S. Patent Application No. 09/819,120 (Att.Dkt.No. SUN1P811/P5512), entitled "REDUCED INSTRUCTION SET FOR JAVA VIRTUAL MACHINES," and U.S. Patent Application No. 09/820,097 (Att.Dkt.No. SUN1P827/P6095), entitled "ENHANCED VIRTUAL MACHINE INSTRUCTIONS." As will be appreciated, the use of the inventive Java instructions in conjunction with the Java macro instruction generator can further enhance the performance of virtual machines.

[0024] It should also be noted that the Java macro instruction can be internally represented in the virtual machine as a pair of Java streams in accordance with one embodiment of the invention. The pair of Java streams can be a code stream and a data stream. The code stream is suitable for containing the code portion of Java macro instructions, and the data stream is suitable for containing a data portion of said Java macro

instruction. More details about representing instructions as a pair of streams can be found in the U.S. Patent Application No. 09/703,449 (Att.Dkt.No. SUN1P814/P5417), entitled "IMPROVED FRAMEWORKS FOR LOADING AND EXECUTION OF OBJECT-BASED PROGRAMS."

[0025] Fig. 3 illustrates a method 300 for generating Java macro instructions in accordance with one embodiment of the invention. The method 300 can be used, for example, by the Java macro instruction generator 202 of Figs. 2A-B. Initially, at operation 302, a stream of Java Bytecode instructions is read. As will be appreciated, the stream of Java Bytecode instructions can be read during the Bytecode verification phase. Java Bytecode verification is typically performed in order to ensure the accuracy of Java instructions. As such, operation 302 can be efficiently performed during Bytecode verification since typically there is a need to verify Bytecode instructions.

[0026] Next, at operation 304, a determination is made as to whether a predetermined sequence of two or more Java Bytecode instructions has been found. If it is determined at operation 304 that a predetermined sequence of two or more Java Bytecode instructions has not been found, the method 300 ends. However, if it is determined at operation 304 that a predetermined sequence of two or more Java Bytecode instructions has been found, the method 300 proceeds to operation 306 where a Java macro instruction that represents the sequence of two or more Java Bytecode instructions is generated. The method 300 ends following operation 306. It should be noted that operations 304 and 306 can also be performed during the Java Bytecode verification phase.

[0027] Fig. 4 illustrates a method 400 for generating Java macro instructions in accordance with another embodiment of the invention. The method 400 can be used, for example, by the Java macro instruction generator 202 of Figs. 2A-B. Initially, at operation 402, a stream of Java Bytecode instructions is read. Again, operation 402 can efficiently be

performed during Bytecode verification since Bytecode verification is typically performed anyway.

[0028] Next, at operation 404, the number of times a sequence of Java Bytecode instructions appear in the stream of Java Bytecode instructions is counted. Thereafter, at operation 406, a determination is made as to whether the sequence has been counted for at least a predetermined number of times. If it is determined at operation 406 that the sequence has not been counted for at least a predetermined number of times, the method 400 ends. However, if it is determined at operation 406 that the sequence has been counted for at least a predetermined number of times, the method 400 proceeds to operation 408 where a Java macro instruction that represents the sequence of Java Bytecode instructions is generated. The method 400 ends following operation 408.

[0029] Fig. 5 illustrates a Java Bytecode verifier 500 in accordance with one embodiment of the invention. The Java Bytecode verifier 500 includes a sequence analyzer 502 suitable for analyzing a stream of Java Bytecodes 504. As shown in Fig. 5, the stream of Java Bytecodes 504 consists of a sequence of Java Bytecode instructions 1–N. The Java Bytecode verifier 500 operates to determine whether a sequence of two or more Java Bytecode instructions can be represented as a Java macro instruction. If the Bytecode verifier 500 determines that a sequence of two or more Java Bytecode instructions can be represented as a Java macro instruction, the Bytecode verifier 500 produces a Java macro instruction. The Java macro instruction corresponds to the sequence of two or more Java Bytecode instructions. Accordingly, the Java macro instruction can replace the sequence of two or more Java Bytecode instructions in the Java stream.

[0030] Referring to Fig. 5, a sequence of two or more Java Bytecode instructions 506 in the stream 504 can be identified by the Java Bytecode verifier 500. The sequence of two or more Java Bytecode instructions 506 (instructions I1-IM) can be located in positions K through (K+M-1) in the stream 504. After identifying the sequence of two or more Java Bytecode

instructions 506, the Java Bytecode verifier 500 can operate to replace the sequence with a Java macro instruction 508 (I1-IM). As a result, the stream 504 is reduced to a stream 510 consisting of (N-M) Java Bytecode instructions. As will be appreciated, the Java Bytecode verifier 500 can identify a number of predetermined sequences of Java Bytecode instructions and replace them with the appropriate Java macro instruction. The Java Bytecode verifier 500 can also be implemented to analyze the sequences that appear in the stream 504 and replace only those that meet a criteria (e.g., a sequence that has appeared more than a predetermined number of times). In any case, the number of Java Bytecode instructions in an input stream 504 (e.g., stream 504) can be reduced significantly. Thus, the performance of virtual machines, especially those operating with limited resources, can be enhanced.

**[0031]** As noted above, the Java Bytecode instructions which are replaced in the stream can be conventional Java Bytecode instructions which often appear in a sequence. One such example is the various combinations of the conventional instructions representing "$New_x$" and "$Dup_x$" which typically appear in sequence in order to instantiate a Java object (e.g., New-Dup, Newarray-Dup_x1, Anewarray-Dup_x2 , etc.).

**[0032]** Fig. 6A illustrates a Java computing environment 600 including a Java macro instruction generator 602 in accordance with one embodiment of the invention. Referring now to Fig. 6A, conventional Java Bytecode instructions "$New_x$" and "$Dup_x$" are depicted in a sequence 610. The sequence 610 can be replaced by a single Java macro instruction "New-Dup" 612 by the Java macro instruction generator 602. As will be appreciated by those skilled in the art, the sequence 610 can appear frequently during the execution of Java programs. Thus, replacing this sequence with a single macro instruction can reduce the overhead associated with dispatching Java Bytecode instructions.

**[0033]** Again, it should be noted that the Java macro instruction 602 can also be used in conjunction with a Java Bytecode translator in accordance

with one preferred embodiment of the invention. More details about the Java Bytecode translator and inventive Java Bytecode instructions are described in U.S. Patent Application No. 09/819,120 (Att.Dkt.No. SUN1P811/P5512), entitled "REDUCED INSTRUCTION SET FOR JAVA VIRTUAL MACHINES," and U.S. Patent Application No. 09/820,097 (Att.Dkt.No. SUN1P827/P6095), entitled "ENHANCED VIRTUAL MACHINE INSTRUCTIONS."

[0034] Fig. 6B illustrates a Java computing environment 620, including a Java macro instruction generator 602 and a Java Bytecode translator 622, in accordance with one embodiment of the invention. Referring now to Fig. 6B, the Java Bytecode translator 622 operates to translate conventional Java instructions 610 into inventive Java instructions 630. The Java macro instruction generator 602 can receive the inventive Java instructions 630 and generate a corresponding Java macro instruction "New-Dup" 624.

[0035] It should be noted that the inventive Java instructions 630 represent a reduced set of Java instructions suitable for execution by a Java virtual machine. This means that the number of instructions in the inventive reduced set is significantly less than the number of instructions in the conventional Java Bytecode instruction set. Furthermore, the inventive Java instructions provide for inventive operations that cannot be performed by conventional Java Bytecode instructions. By way of example, an inventive virtual machine operation "DUP" (shown in sequence 630) can be provided in accordance with one embodiment of the invention. The inventive virtual machine instruction DUP allows values in various positions on the execution stack to be duplicated on the top of the execution stack.

[0036] Fig. 7A illustrates a computing environment 700 including an internal representation 701 of an inventive "DUP" instruction 702 suitable for duplicating values on the stack in accordance with one embodiment of the invention. The internal representation 701 includes a pair of streams, namely, a code stream 706 and a data stream 708. In the described embodiment, each entry in the code stream 706 and data stream 708

represents one byte. The inventive virtual machine instruction DUP 702 is associated with a data parameter A in the code stream 706. It should be noted that data parameter A may also be implemented in the data stream 708. In any case, the data parameter A indicates which 4 byte value (word value) on an execution stack 704 should be duplicated on the top of the execution stack 704. The data parameter A can indicate, for example, an offset from the top of the execution stack 704. As shown in Fig. 7A, the data parameter A can be a reference to "Wi," a word (4 byte) value on the execution stack. Accordingly, at execution time, the virtual machine can execute the "DUP" command 702. As a result, the Wi word will be duplicated on the top of the stack. Thus, the inventive "DUP" instruction can effectively replace various Java Bytecode instructions that operate to duplicate 4 byte values on top of the execution stack. Fig. 7B illustrates some of these Java Bytecode instructions. Similarly, as illustrated in Fig. 7C, an inventive "DUPL" instruction can be provided to effectively replace various Java Bytecode instructions that operate to duplicate 8 byte values (2 words) on top of the execution stack.

[0037] It should be noted that conventional Java Bytecode "$Dup_x$" instructions only allow for duplication of values in certain positions on the execution stack (i.e., conventional instructions Dup, Dup_x1 and Dup_x2 respectively allow duplication of the first, second and third words on the execution stack). However, the inventive instructions "DUP" and "DUPL" can be used to duplicate a much wider range of values on the execution stack (e.g., W4, Wi, WN, etc.).

[0038] Referring back to Fig. 6B, another inventive instruction, Java Bytecode instruction "New" is shown in the sequence 630. The Java Bytecode instruction "New" can effectively replace various conventional Java Bytecodes used for instantiation.

[0039] Fig. 8 illustrates a mapping of Java Bytecode instantiation instructions to the virtual machine instructions provided in accordance with one embodiment of the invention. As will be appreciated, the four

conventional Java Bytecode instructions can effectively be mapped into a single virtual machine instruction (e.g., NEW). The virtual machine instruction NEW operates to instantiate objects and arrays of various types. In one embodiment, the inventive virtual machine instruction NEW operates to determine the types of the objects or arrays based on the parameter value of the Java Bytecode instantiation instruction. As will be appreciated, the Java Bytecode instructions for instantiation are typically followed by a parameter value that indicates the type. Thus, the parameter value is readily available and can be used to allow the NEW virtual machine instruction to instantiate the appropriate type at execution time.

**[0040]** Fig. 9A illustrates another sequence 902 of conventional Java Bytecodes that can be executed frequently by a Java interpreter. The sequence 902 represents an exemplary sequence of instructions that are used in programming loops. As such, sequences, such as the sequence 902, can be repeated over and over again during the execution of Java Bytecode instructions. As shown in Fig. 9A, the Java macro instruction generator 202 can replace the conventional sequence of Java instructions "iinc," "iload," and "if_cmplt" with a Java macro instruction "Loop1."

**[0041]** Fig. 9B illustrates a Java computing environment 900, including a Java macro instruction generator 902 and a Java Bytecode translator 904, in accordance with one embodiment of the invention. Referring now to Fig. 9B, the Java Bytecode translator 904 operates to translate conventional Java instructions 910 into inventive Java instructions 920. The Java macro instruction generator 902 can receive the inventive Java instructions 920 and generate a corresponding Java macro instruction "Loop1" 940.

**[0042]** One of the inventive instructions in the sequence 920 is the inventive instruction "Load." Fig. 10A illustrates an internal representation 1000 of a set of Java "Load" instructions suitable for loading values from a local variable in accordance with another embodiment of the invention. In the described embodiment, a code stream 1002 of the internal representation 1000 includes a Load command 1006 representing an inventive virtual

machine instruction suitable for representation of one or more Java "Load from a local variable" Bytecode instructions. It should be noted that the Load command 1006 has a one byte parameter associated with it, namely, an index i 1008 in the data stream 1004. As will be appreciated, at run time, the Load command 1006 can be executed by a virtual machine to load (or push) a local variable on top of the execution stack 1020. By way of example, an offset 0 1022 can indicate the starting offset for the local variables stored on the execution stack 1020. Accordingly, an offset i 1024 identifies the position in the execution stack 1020 which corresponds to the index i 1008.

**[0043]** It should be noted that in the described embodiment, the Load command 1006 is used to load local variables as 4 bytes (one word). As a result, the value indicated by the 4 bytes A, B, C and D (starting at offset i 1024) is loaded on the top of the execution stack 1020 when the Load command 1006 is executed. In this manner, the Load command 1006 and index i 1008 can be used to load (or push) 4 byte local variables on top of the execution stack at run time. As will be appreciated, the Load command 1006 can effectively represent various conventional Java Bytecode instructions. Fig. 10B illustrates a set of Java Bytecode instructions for loading 4 byte local variables that can be represented by an inventive "Load" command in accordance with one embodiment of the invention.

**[0044]** It should be noted that the invention also provides for loading local variables that do not have values represented by 4 bytes. For example, Fig. 10C illustrates a set of Java Bytecode instructions for loading 8 byte local variables in accordance with one embodiment of the invention. As will be appreciated, all of the Java Bytecode instructions listed in Fig. 10C can be represented by a single inventive virtual machine instruction (e.g., a "LoadL" command). The "LoadL" command can operate, for example, in a similar manner as discussed above.

**[0045]** Referring back to Fig. 9B, the Java Bytecode translator 904 operates to replace the conventional Bytecode instruction "if_cmplt" in the sequence

910 with the two Bytecode instructions "OP_ISUB" and "OP_JMPLT" in the reduced set of Java Bytecode instructions. As will be appreciated, two or more of the inventive virtual machine instructions can be combined to perform relatively more complicated operations in accordance with one embodiment of the invention. By way of example, the conditional flow control operation performed by the Java Bytecode instruction "lcmp" (compare two long values on the stack and, based on the comparison, push 0 or 1 on the stack) can effectively be performed by performing an inventive virtual machine instruction LSUB (Long subdivision) followed by another inventive virtual machine instruction JMPEQ (Jump if equal). Figs. 11A and 11B illustrate some conventional Java Bytecode instructions for performing conditional flow operations which can be represented by two inventive virtual machine instructions in accordance with one embodiment of the invention.

[0046] Fig. 12A illustrates yet another sequence 1210 of conventional Java Bytecodes that can be executed frequently by a Java interpreter. The sequence 1210 represents an exemplary sequence of instructions that perform to obtain a field value and put it on the execution stack. As shown in Fig. 12A, the Java macro instruction generator 602 can replace the conventional sequence 1210 of Java instructions "Getfield" and "Astore$_x$" with a Java macro instruction "Get_Store" 1212. The conventional instruction "Astore$_x$" represents various conventional Java instructions used to store values on the execution stack.

[0047] Fig. 12B illustrates a Java computing environment 1200, including a Java macro instruction generator 602 and a Java Bytecode translator 622, in accordance with one embodiment of the invention. Referring now to Fig. 12B, the Java Bytecode translator 622 operates to translate conventional Java instructions 1210 into inventive Java instructions 1220. The Java macro instruction generator 602 can receive the inventive Java instructions 1220 and generate a corresponding Java macro instruction "Resolve_Astore" 1222.

[0048] The inventive instruction "Astore" represents a virtual machine instruction suitable for storing values into arrays. By way of example, Fig. 13A illustrates a computing environment 1320 in accordance with one embodiment of the invention. An inventive AStore 1322 (store into array) virtual machine instruction can be used to store various values from the execution stack 1304 into different types of arrays in accordance with one embodiment of the invention. Again, the header 1310 of the array 1302 can be read to determine the array's type. Based on the array's type, the appropriate value (i.e., the appropriate number of bytes N on the execution stack 1304) can be determined. This value can then be stored in the array 1302 by using the array-index 1326. Thus, the inventive virtual machine instruction AStore can effectively represent various Java Bytecode instructions that are used to store values into an array. Figs. 13B and 13C illustrate a set of conventional Java Bytecode instructions for storing arrays that can be represented by an inventive virtual machine instruction (e.g., Astore) in accordance with one embodiment of the invention.

[0049] Appendix A illustrates mapping of a set of conventional Java Bytecode instructions to one or more of the inventive virtual machine instructions listed in the right column.

[0050] The many features and advantages of the present invention are apparent from the written description, and thus, it is intended by the appended claims to cover all such features and advantages of the invention. Further, since numerous modifications and changes will readily occur to those skilled in the art, it is not desired to limit the invention to the exact construction and operation as illustrated and described. Hence, all suitable modifications and equivalents may be resorted to as falling within the scope of the invention.

# Appendix A

| | |
|---|---|
| nop | IGNORE_OPCODE |
| aconst_null | OP_PUSHB |
| iconst_ml | OP_PUSHB |
| iconst_0 | OP_PUSHB |
| iconst_1 | OP_PUSHB |
| iconst_2 | OP_PUSHB |
| iconst_3 | OP_PUSHB |
| iconst_4 | OP_PUSHB |
| iconst_5 | OP_PUSHB |
| lconst_0 | OP_PUSHL |
| lconst_1 | OP_PUSHL |
| fconst_0 | OP_PUSH |
| fconst_1 | OP_PUSH |
| fconst_2 | OP_PUSH |
| dconst_0 | OP_PUSHL |
| dconst_1 | OP_PUSHL |
| bipush | OP_PUSHB |
| sipush | OP_PUSH |
| ldc | OP_PUSH |
| ldc_w | OP_PUSH |
| ldc2_w | OP_PUSHL |
| iload | OP_LOAD |
| lload | OP_LOADL |
| fload | OP_LOAD |
| d1oad | OP_LOADL |
| aload | OP_LOAD |
| iload_0 | OP_LOAD |
| iload_1 | OP_LOAD |
| iload_2 | OP_LOAD |
| iload_3 | OP_LOAD |
| lload_0 | OP_LOADL |
| 11oad_1 | OP_LOADL |
| 11oad_2 | OP_LOADL |

| | |
|---|---|
| lload_3 | OP_LOADL |
| fload_0 | OP_LOADL |
| fload_1 | OP_LOAD |
| fload_2 | OP_LOAD |
| fload_3 | OP_LOAD |
| dload_0 | OP_LOADL |
| d1oad_1 | OP_LOADL |
| dload_2 | OP_LOADL |
| dload_3 | OP_LOADL |
| aload_0 | OP_LOAD |
| aload_l | OP_LOAD |
| aload_2 | OP_LOAD |
| aload_3 | OP_LOAD |
| iaload | OP_ALOAD |
| laload | OP_ALOAD |
| faload | OP_ALOAD |
| daload | OP_ALOAD |
| aaload | OP_ALOAD |
| baload | OP_ALOAD |
| caload | OP_ALOAD |
| saload | OP_ALOAD |
| istore | OP_STOR |
| lstore | OP_STORL |
| fstore | OP_STOR |
| dstore | OP_STORL |
| astore | OP_STOR |
| istore_0 | OP_STOR |
| istore_1 | OP_STOR |
| istore_2 | OP_STOR |
| istore_3 | OP_STOR |
| 1store_0 | OP_STORL |
| 1store_1 | OP_STORL |
| lstore_2 | OP_STORL |
| 1store_3 | OP_STORL |
| fstore_0 | OP_STOR |
| fstore_1 | OP_STOR |

| | |
|---|---|
| fstore_2 | OP_STOR |
| fstore_3 | OP_STOR |
| dstore_0 | OP_STORL |
| dstore_1 | OP_STORL |
| dstore_2 | OP_STORL |
| dstore_3 | OP_STORL |
| astore_0 | OP_STOR |
| astore_1 | OP_STOR |
| astore_2 | OP_STOR |
| astore_3 | OP_STOR |
| iastore | OP_ASTORE |
| lastore | OP_ASTOREL |
| fastore | OP_ASTORE |
| dastore | OP_ASTOREL |
| aastore | OP_ASTORE |
| bastore | OP_ASTORE |
| castore | OP_ASTORE |
| sastore | OP_ASTORE |
| pop | OP_POP |
| pop2 | OP_POP |
| dup | OP_DUP |
| dup_x1 | OP_DUP |
| dup_x2 | OP_DUP |
| dup2 | OP_DUPL |
| dup2_x1 | OP_DUPL |
| dup2_x2 | OP_DUPL |
| swap | OP_SWAP |
| iadd | OP_IADD |
| ladd | OP_LADD |
| fadd | OP_FADD |
| dadd | OP_DADD |
| isub | OP_ISUB |
| lsub | OP_LSUB |
| fsub | OP_FSUB |
| dsub | OP_DSUB |
| imul | OP_IMUL |

| | |
|---|---|
| lmul | OP_LMUL |
| fmul | OP_FMUL |
| dmul | OP_DMUL |
| idiv | OP_IDIV |
| ldiv | OP_LDIV |
| fdiv | OP_FDIV |
| ddiv | OP_DDIV |
| irem | OP_IREM |
| lrem | OP_LREM |
| frem | OP_FREM |
| drem | OP_DREM |
| ineg | OP_INEG |
| lneg | OP_LNEG |
| fneg | OP_FNEG |
| dneg | OP_DNEG |
| ishl | OP_ISHL |
| lshl | OP_LSHL |
| ishr | OP_ISHR |
| lshr | OP_LSHR |
| iushr | OP_IUSHR |
| lushr | OP_LUSHR |
| iand | OP_IAND |
| land | OP_LAND |
| ior | OP_IOR |
| lor | OP_LOR |
| ixor | OP_IXOR |
| lxor | OP_LXOR |
| iinc | OP_IINC |
| i2l | OP_I2L |
| i2f | IGNORE_OPCODE |
| i2d | OP_I2D |
| 12i | OP_L2I |
| 12f | OP_L2F |
| 12d | OP_L2D |
| f2i | IGNORE_OPCODE |
| f2l | OP_F2L |

| | |
|---|---|
| f2d | OP_F2D |
| d2i | OP_D2I |
| d2l | OP_D2L |
| d2f | OP_D2F |
| i2b | IGNORE_OPCODE |
| i2c | IGNORE_OPCODE |
| i2s | IGNORE_OPCODE |
| lcmp | OP_LSUB, OP_JMPEQ |
| fcmpl | OP_FSUB, OP_JMPLE |
| fcmpg | OP_FSUB, OP_JMPGE |
| dcmpl | OP_DCMP, OP_JMPLE |
| dcmpg | OP_DCMP, OP_JMPGE |
| ifeq | OP_JMPEQ |
| ifne | OP_JMPNE |
| iflt | OP_JMPLT |
| ifge | OP_JMPGE |
| ifgt | OP_JMPGT |
| ifle | OP_JMPLE |
| if icmpeq | OP_ISUB, OP_JMPEQ |
| if icmpne | OP_ISUB, OP_JMPNE |
| if icmplt | OP_ISUB, OP_JMPLT |
| if icmpge | OP_ISUB, OP_JMPGE |
| if icmpgt | OP_ISUB, OP_JMPGT |
| if icmple | OP_ISUB, OP_JMPLE |
| if acmpeq | OP_ISUB, OP_JMPEQ |
| if acmpne | OP_ISUB, OP_JMPNE |
| goto | OP_JMP |
| jsr | OP_JSR |
| ret | OP_RET |
| tableswitch | OP_SWITCH |
| lookupswitch | OP_SWITCH |
| ireturn | OP_RETURN |
| lreturn | OP_LRETURN |
| freturn | OP_RETURN |
| dreturn | OP_LRETURN |
| areturn | OP_RETURN |

| | |
|---|---|
| return | OP_RETURNV |
| getstatic | OP_RESOLVE |
| putstatic | OP_RESOLVEP |
| getfield | OP_RESOLVE |
| putfield | OP_RESOLVEP |
| invokevirtual | OP_RESOLVE |
| invokespecial | OP_RESOLVE |
| invokestatic | OP_RESOLVE |
| invokeinterface | OP_RESOLVE |
| xxxunusedxxx | IGNORE_OPCODE |
| new | OP_NEW |
| newarray | OP_NEW |
| anewarray | OP_NEW |
| arraylength | OP_ARRAYLENGTH |
| athrow | OP_THROW |
| checkcast | IGNORE_OPCODE |
| instanceof | OP_INSTANCEOF |
| monitorenter | OP_MUTEXINC |
| monitorexit | OP_MUTEXDEC |
| wide | OP_WIDE |
| multianewarray | OP_NEW |
| ifnull | OP_JMPEQ |
| ifnonnull | OP_JMPNE |
| goto_w | OP_JMP |
| jsr_w | OP_JSR |

*What is claimed is:*

## CLAIMS

1. In a Java computing environment, a Java macro instruction representing:

a sequence of Java Bytecode instructions consisting of a Java Getfield Bytecode instruction immediately followed by a Java Astore Bytecode instruction,

wherein said Java macro instruction can be executed by a Java virtual machine operating in said Java computing environment, and

wherein when said Java macro instruction is executed, the operations that are performed by said conventional sequence of Java Bytecode instructions are performed.

2. A Java macro instruction as recited in claim 1, wherein said Java macro instruction consists of a conventional Java Getfield Bytecode instruction immediately followed by a conventional Java Astore Bytecode instruction.

3. A Java macro instruction as recited in claim 1, wherein said Java macro instruction is generated during the Java Bytecode verification phase.

4. A Java macro instruction as recited in claim 1, wherein said Java virtual machine internally represents Java instructions as a pair of streams.

5. A Java macro instruction as recited in claim 4,

wherein said pair of streams includes a code stream and a data stream,

wherein said code stream is suitable for containing a code portion of said Java macro instruction, and

wherein said data stream is suitable for containing a data portion of said Java macro instruction.

6. A Java macro instruction as recited in claim 5,

wherein said Java macro instruction is generated only when said virtual machine determines that said Java macro instruction should replace said conventional sequence.

7. A Java macro instruction as recited in claim 6, wherein said determination is made based on a predetermined criteria.

8. A Java macro instruction as recited in claim 7, wherein said predetermined criteria is whether said conventional sequence has been repeated more than a predetermined number of times.

9. In a Java computing environment, a Java macro instruction representing:

a sequence of Java Bytecode instructions consisting of an inventive Java Getfield Bytecode instruction immediately followed by an inventive Java Astore Bytecode instruction,

wherein said Java macro instruction can be executed by a Java virtual machine operating in said Java computing environment, and

wherein when said Java macro instruction is executed, the operations that are performed by said sequence of Java Bytecode instructions are performed.

10. A Java macro instruction as recited in claim 9,

wherein said inventive Astore instruction operates to store values located on an execution stack into arrays, the virtual machine instruction representing two or more Java Bytecode executable instructions that are also suitable for storing values located on an execution stack into an array.

11. A Java macro instruction as recited in claim 10, wherein the arrays can be an array of 1 byte values, 2 byte values, 4 byte values, or 8 byte values.

12. A Java macro instruction as recited in claim 11, wherein a header of an array is read to determine the type of the array.

13. A computer readable media including computer program code for a Java macro instruction, said Java macro instruction representing:

a sequence of Java Bytecode instructions consisting of a Java Getfield Bytecode instruction immediately followed by a Java Astore Bytecode instruction,

wherein said Java macro instruction can be executed by a Java virtual machine operating in said Java computing environment, and

wherein, when said Java macro instruction is executed, the operations that are performed by said conventional sequence of Java Bytecode instructions are performed.

14. A computer readable media as recited in claim 13, wherein said Java macro instruction consists of a conventional Java Getfield Bytecode instruction immediately followed by a conventional Java Astore Bytecode instruction.

15. A computer readable media as recited in claim 14, wherein said Java macro instruction is generated during the Java Bytecode verification phase.

16. A computer readable media as recited in claim 15, wherein said Java virtual machine internally represents Java instructions as a pair of streams.

17. A computer readable media as recited in claim 16,

wherein said pair of streams includes a code stream and a data stream,

wherein said code stream is suitable for containing a code portion of said Java macro instruction, and

wherein said data stream is suitable for containing a data portion of said Java macro instruction.

18. A computer readable media as recited in claim 17,

wherein said Java macro instruction is generated only when said virtual machine determines that said Java macro instruction should replace said conventional sequence.

19. A computer readable media as recited in claim 18, wherein said determination is made based on a predetermined criteria.

20. A computer readable media as recited in claim 19, wherein said predetermined criteria is whether said conventional sequence has been repeated more than a predetermined number of times.

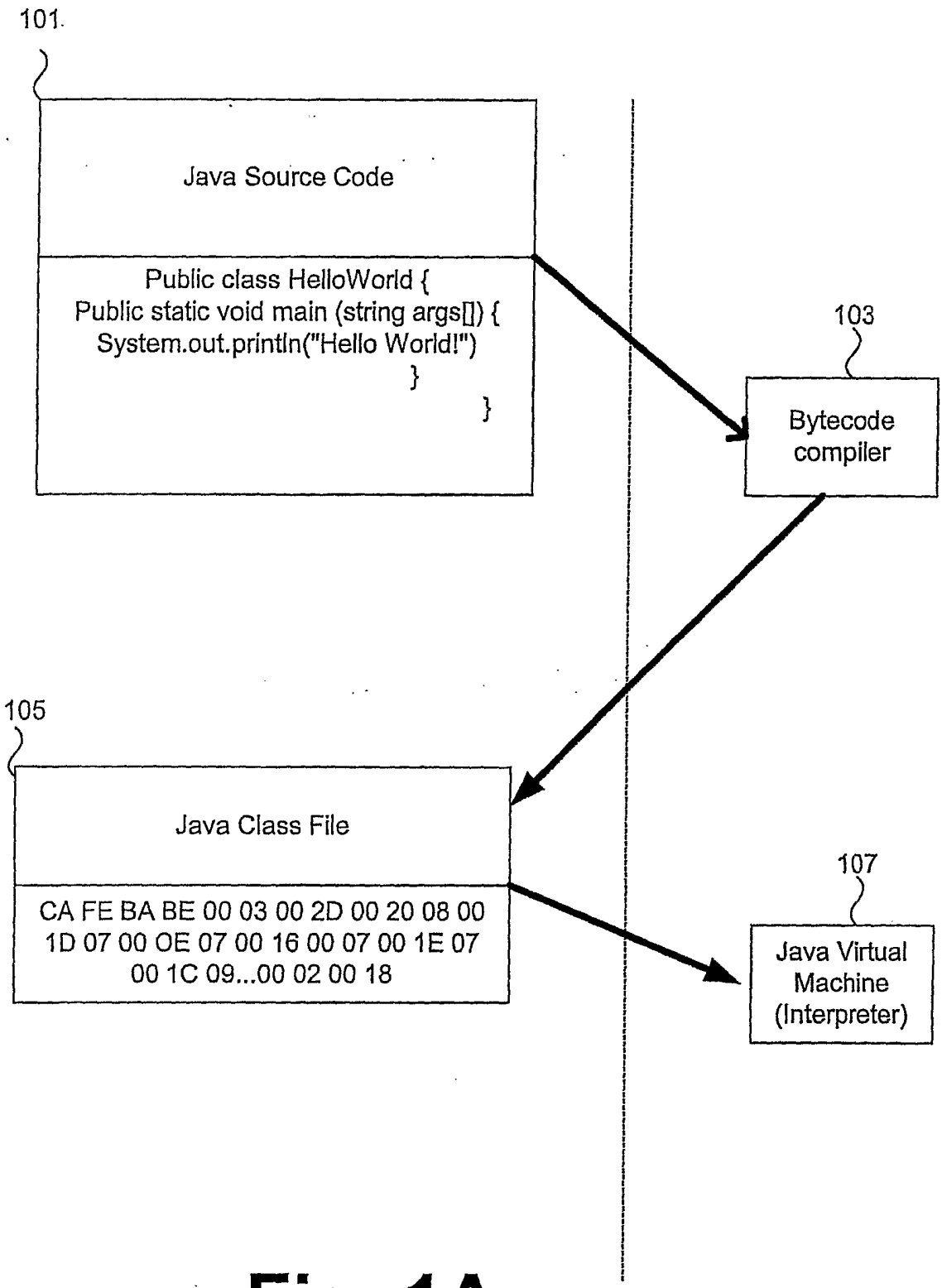

101
Java Source Code
Public class HelloWorld {
Public static void main (string args[]) {
System.out.println("Hello World!")
}
}
103
Bytecode compiler
105
Java Class File
CA FE BA BE 00 03 00 2D 00 20 08 00
1D 07 00 OE 07 00 16 00 07 00 1E 07
00 1C 09...00 02 00 18
107
Java Virtual Machine (Interpreter)

Fig. 1A

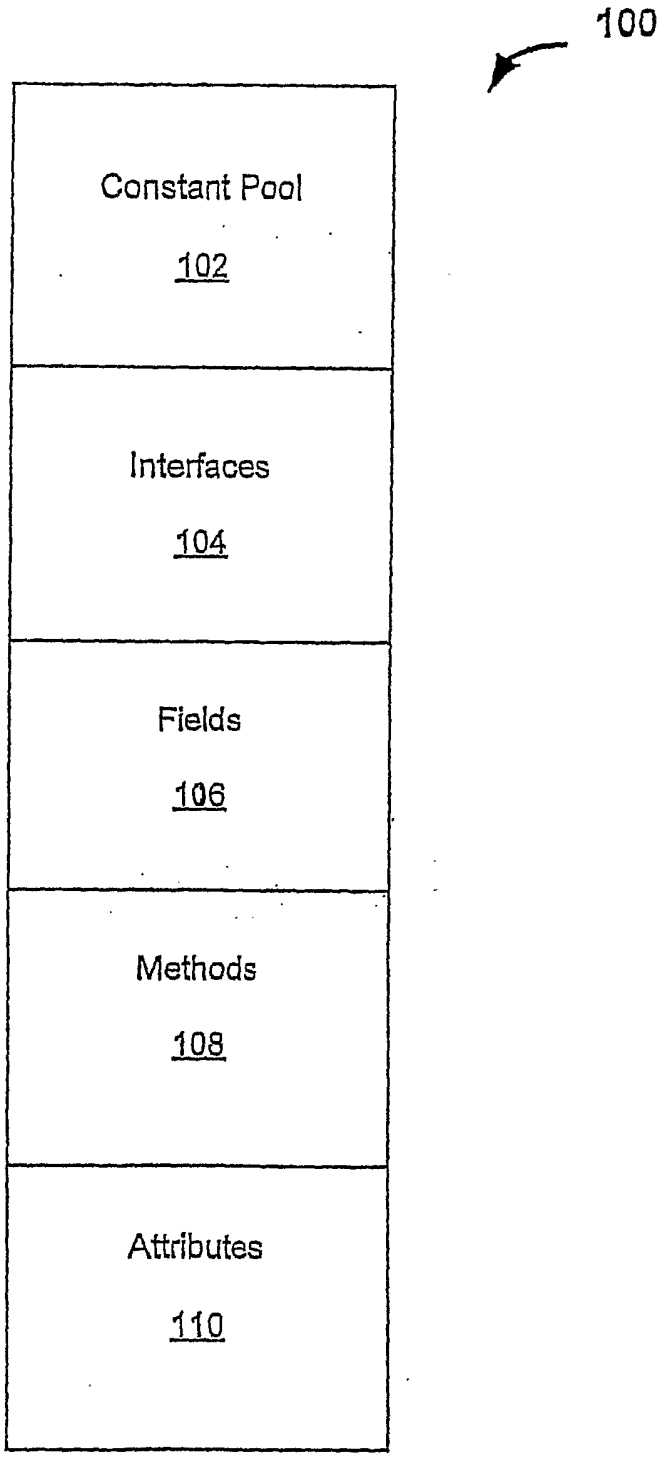

100
Constant Pool
102
Interfaces
104
Fields
106
Methods
108
Attributes
110

Fig. 1B

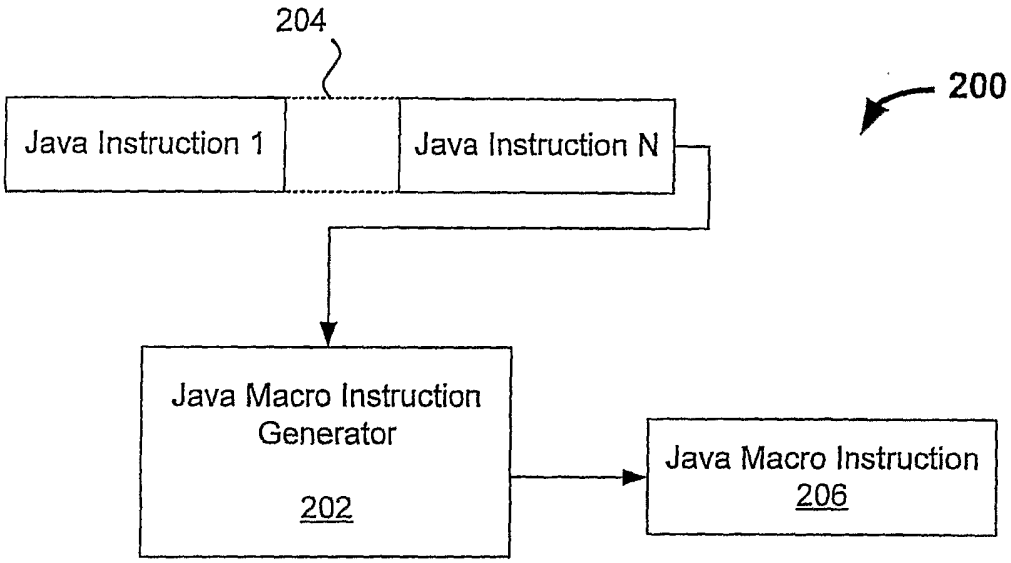

204
200
Java Instruction 1
Java Instruction N
Java Macro Instruction Generator
202
Java Macro Instruction
206

Fig. 2A

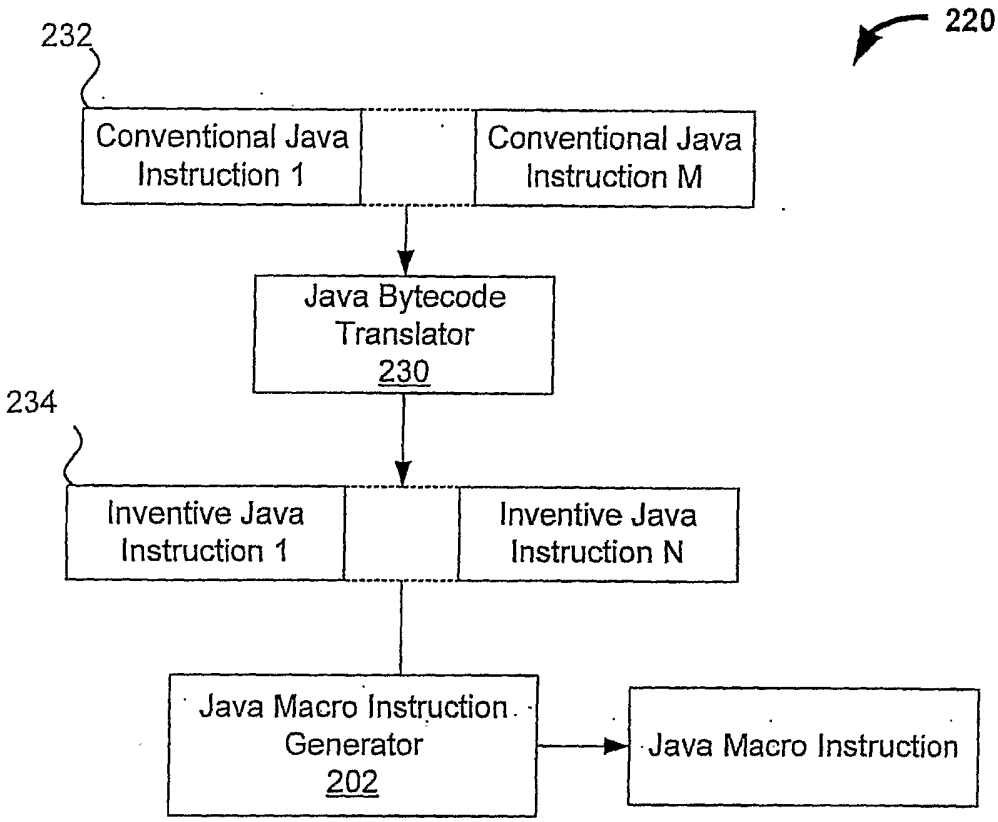

220
232
Conventional Java Instruction 1
Conventional Java Instruction M
Java Bytecode Translator 230
234
Inventive Java Instruction 1
Inventive Java Instruction N
Java Macro Instruction Generator 202
Java Macro Instruction

Fig. 2B

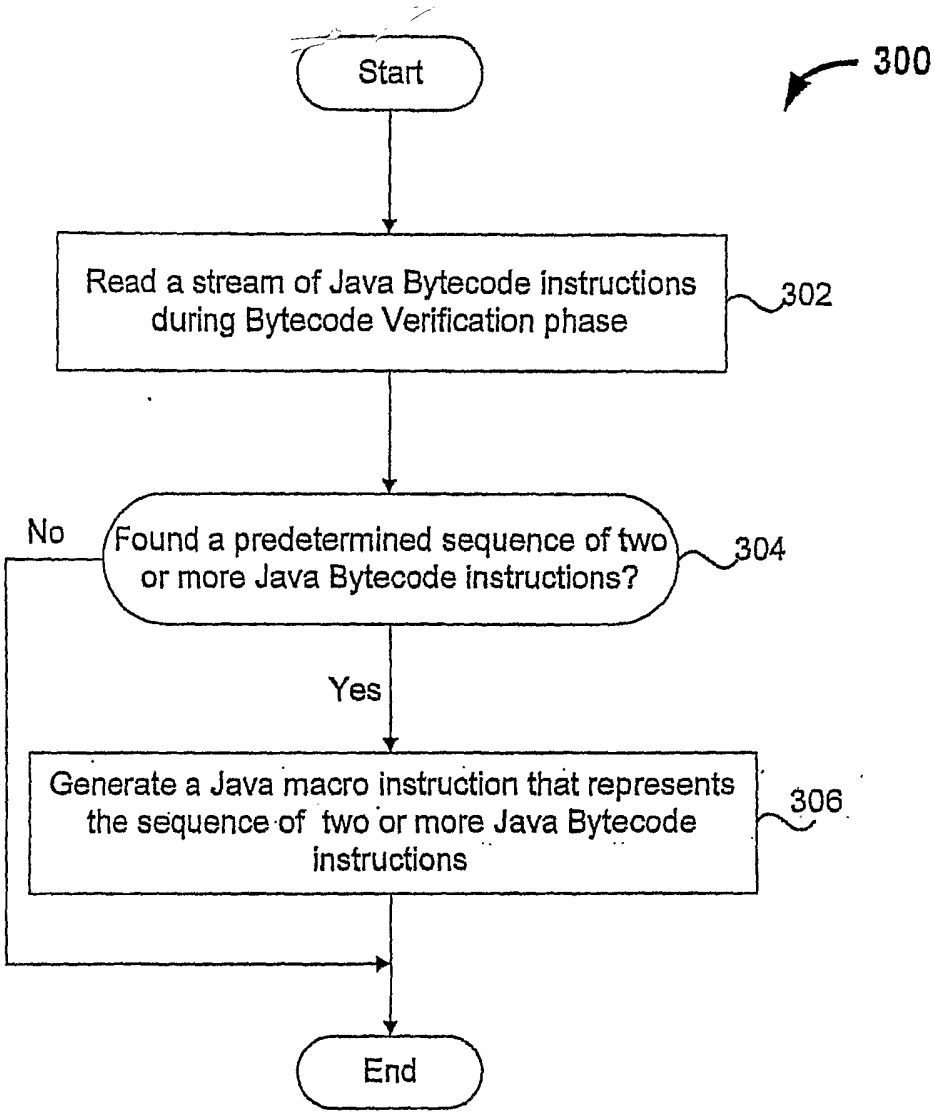

Start
300
Read a stream of Java Bytecode instructions during Bytecode Verification phase
302
No
Found a predetermined sequence of two or more Java Bytecode instructions?
304
Yes
Generate a Java macro instruction that represents the sequence of two or more Java Bytecode instructions
306
End

Fig. 3

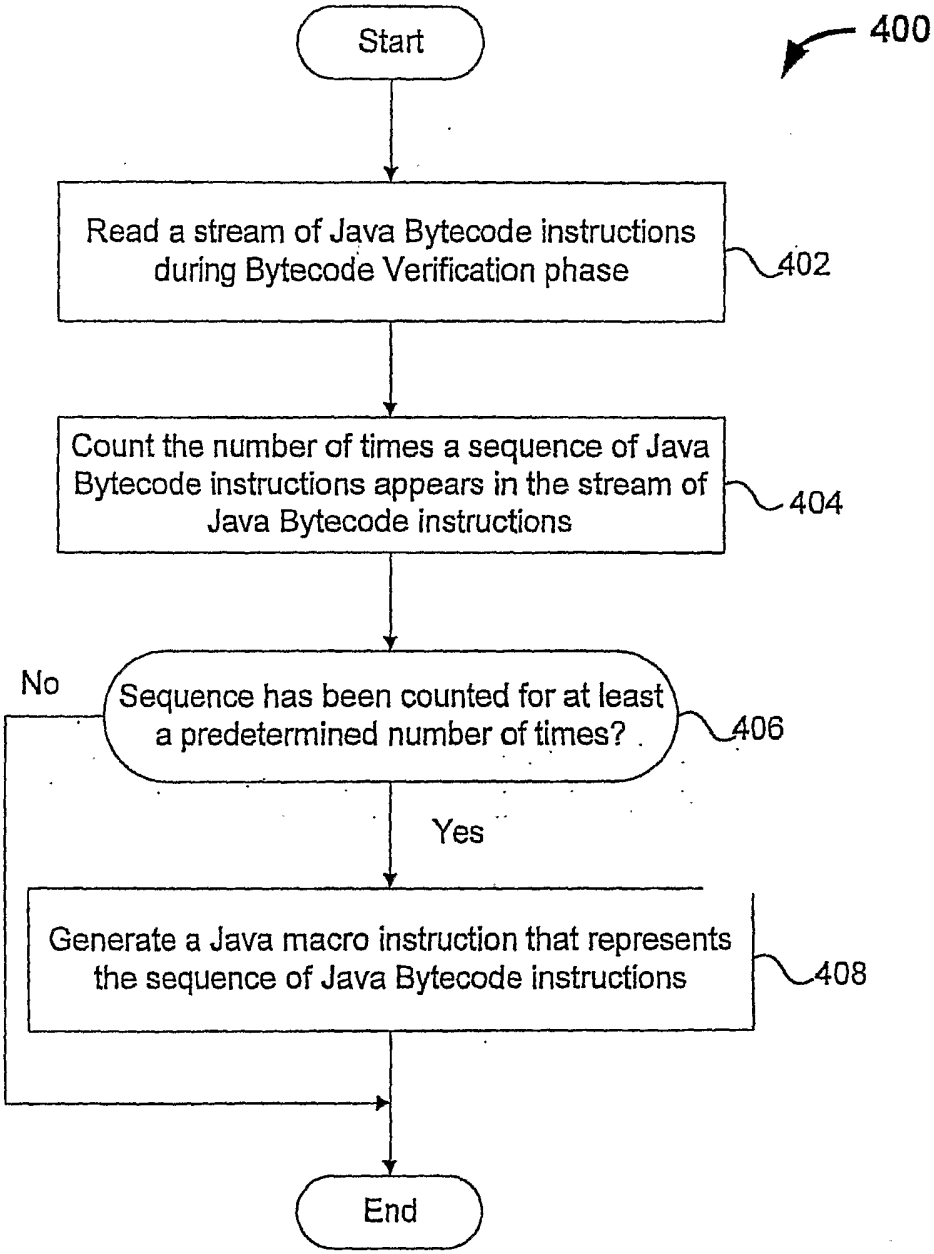

Start
400
Read a stream of Java Bytecode instructions during Bytecode Verification phase
402
Count the number of times a sequence of Java Bytecode instructions appears in the stream of Java Bytecode instructions
404
No
Sequence has been counted for at least a predetermined number of times?
406
Yes
Generate a Java macro instruction that represents the sequence of Java Bytecode instructions
408
End

Fig. 4

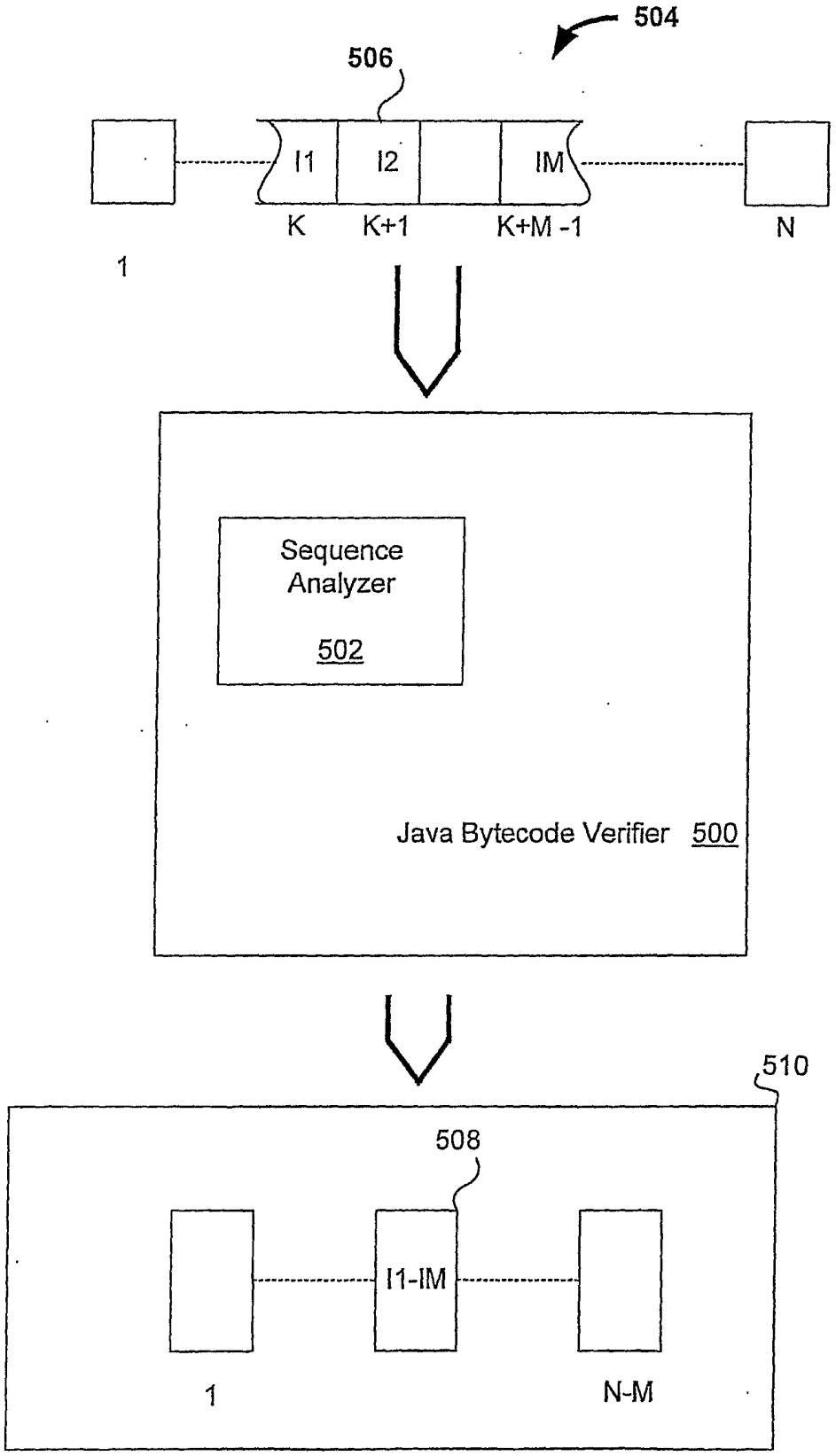

504
506
I1
I2
IM
K
K+1
K+M -1
N
1
Sequence Analyzer
502
Java Bytecode Verifier 500
510
508
I1-IM
1
N-M

Fig. 5

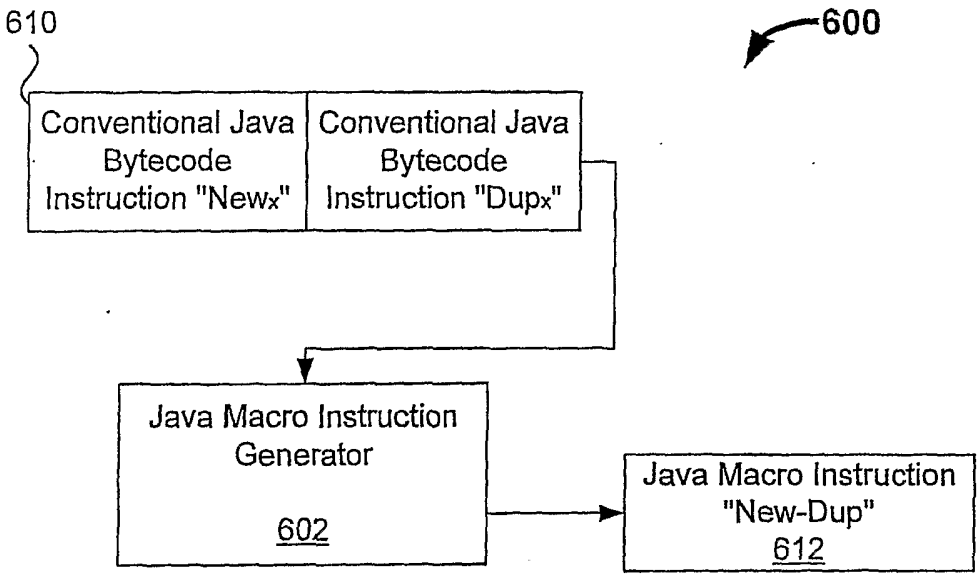

610
600
Conventional Java Bytecode Instruction "Newx"
Conventional Java Bytecode Instruction "Dupx"
Java Macro Instruction Generator
602
Java Macro Instruction "New-Dup"
612

Fig. 6A

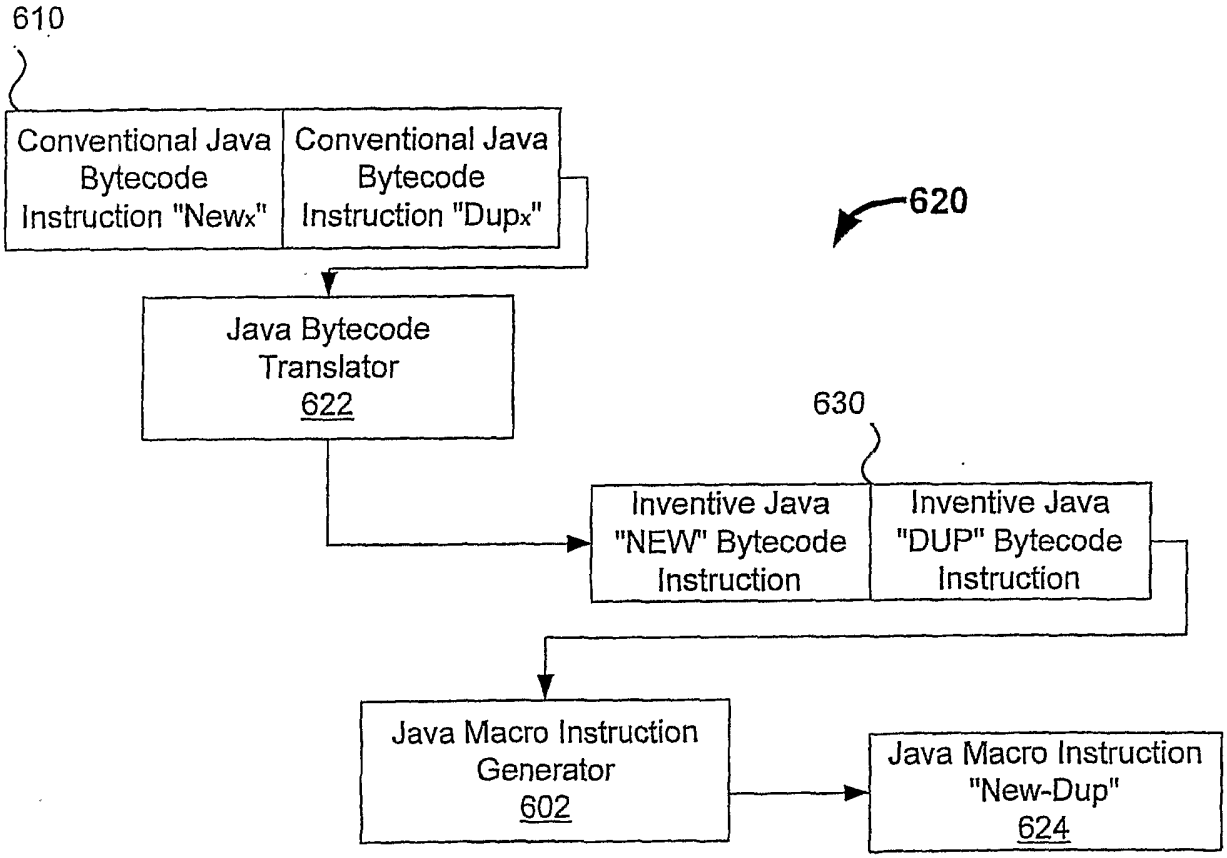

610
Conventional Java Bytecode Instruction "Newx"
Conventional Java Bytecode Instruction "Dupx"
620
Java Bytecode Translator
622
630
Inventive Java "NEW" Bytecode Instruction
Inventive Java "DUP" Bytecode Instruction
Java Macro Instruction Generator
602
Java Macro Instruction "New-Dup"
624

Fig. 6B

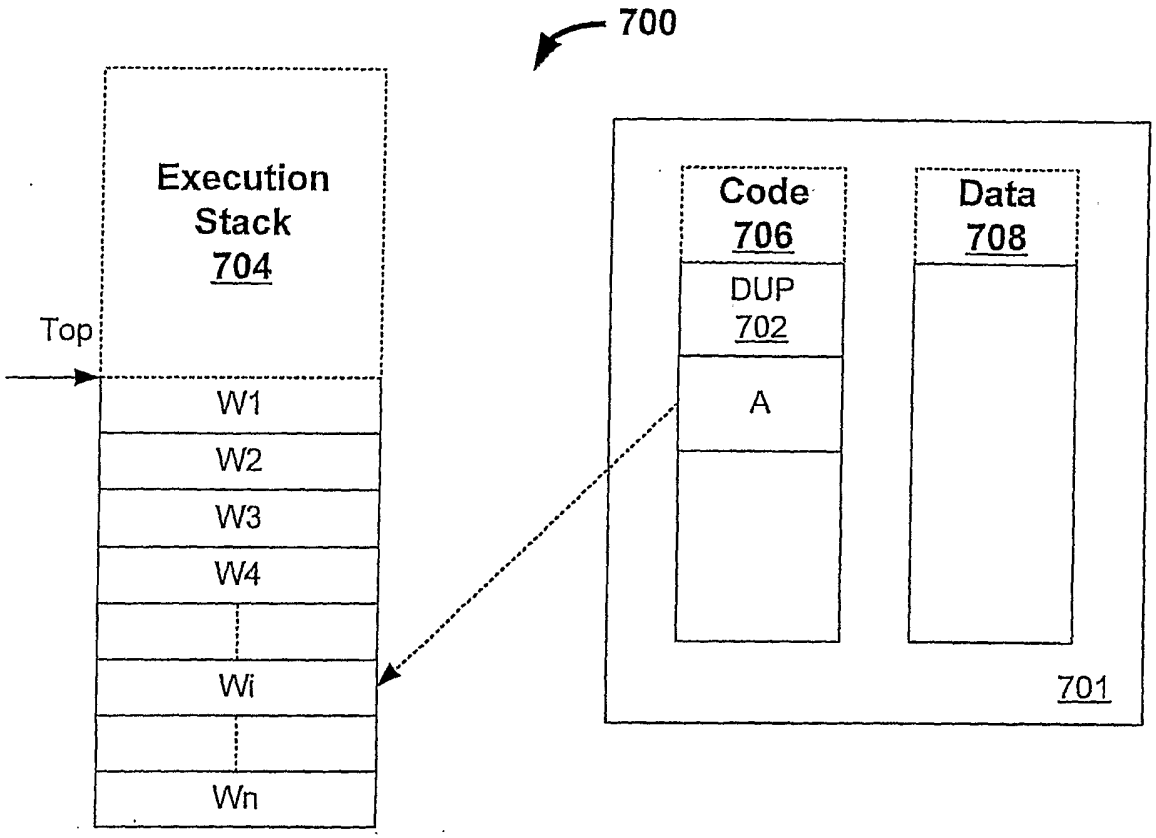
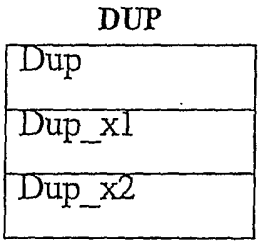
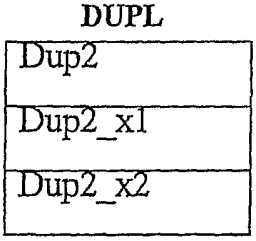



Fig. 7A



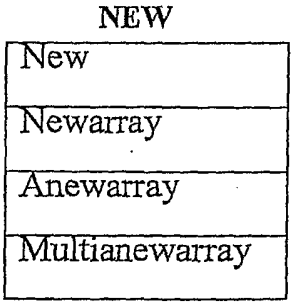




Fig. 7B Fig. 7C Fig. 8

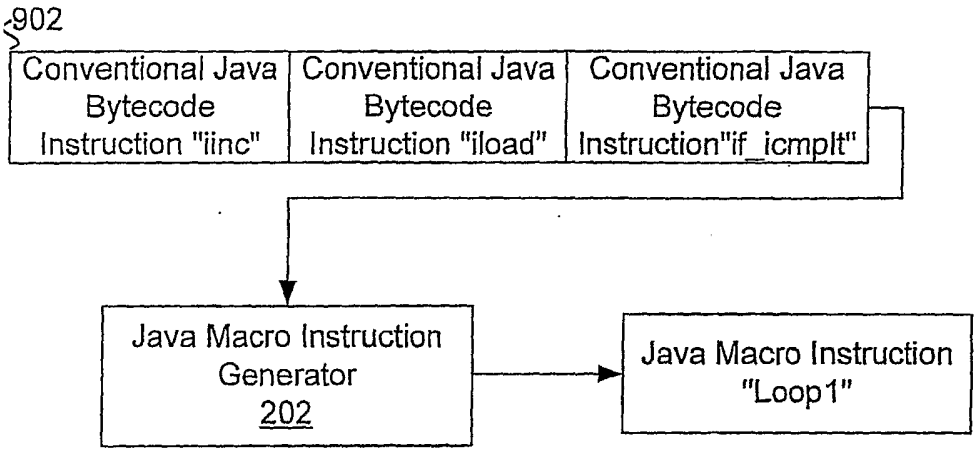

902
Conventional Java Bytecode Instruction "iinc"
Conventional Java Bytecode Instruction "iload"
Conventional Java Bytecode Instruction"if_icmplt"
Java Macro Instruction Generator 202
Java Macro Instruction "Loop1"

Fig. 9A

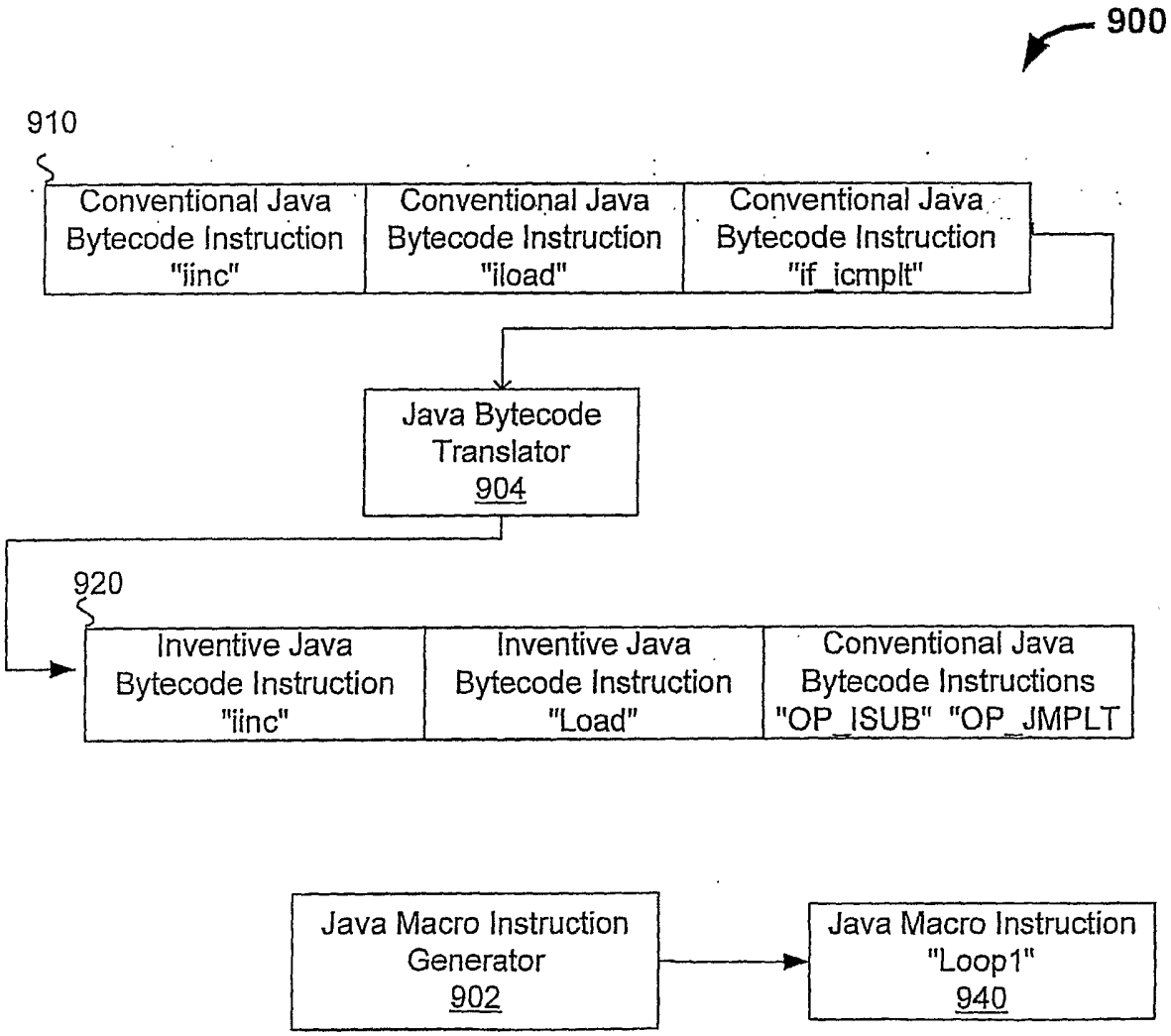

900
910
Conventional Java Bytecode Instruction "iinc"
Conventional Java Bytecode Instruction "iload"
Conventional Java Bytecode Instruction "if_icmplt"
Java Bytecode Translator 904
920
Inventive Java Bytecode Instruction "iinc"
Inventive Java Bytecode Instruction "Load"
Conventional Java Bytecode Instructions "OP_ISUB" "OP_JMPLT
Java Macro Instruction Generator 902
Java Macro Instruction "Loop1" 940

Fig. 9B

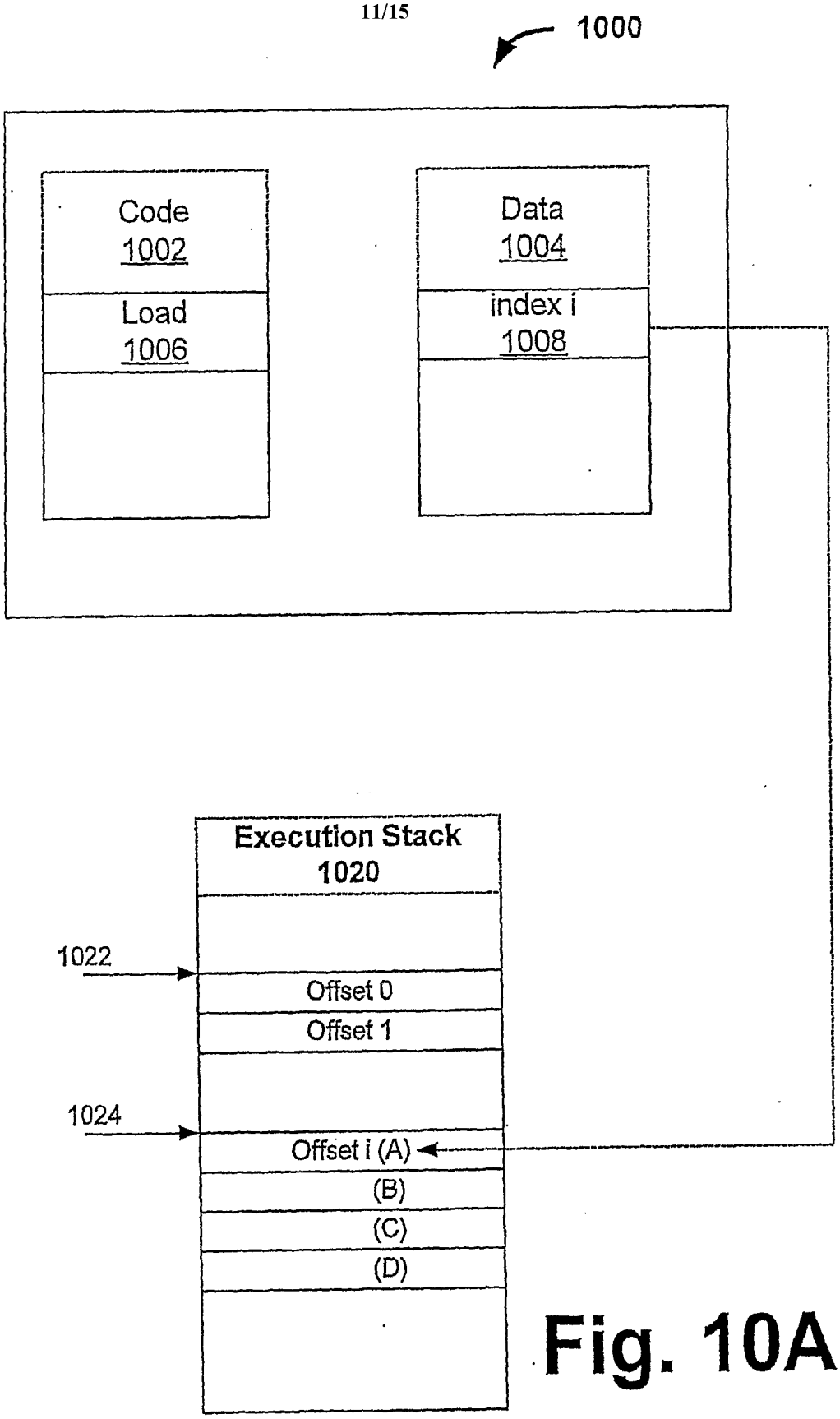

1000
Code
1002
Load
1006
Data
1004
index i
1008
Execution Stack
1020
1022
Offset 0
Offset 1
1024
Offset i (A)
(B)
(C)
(D)

Fig. 10A

| LOAD |
| --- |
| iload |
| fload |
| aload |
| iload_0 |
| iload_1 |
| iload_2 |
| iload_3 |
| fload_1 |
| fload_2 |
| fload_3 |
| aload_0 |
| aload_1 |
| aload_2 |
| aload_3 |

Fig. 10B

| LOADL |
| --- |
| lload |
| dload |
| lload_0 |
| lload_1 |
| lload_2 |
| lload_3 |
| fload_0 |
| dload_0 |
| dload_1 |
| dload_2 |
| dload_3 |

Fig. 10C

| | |
|---|---|
| lcmp | OP_LSUB, OP_JMPEQ |
| fcmpl | OP_FSUB, OP_JMPLE |
| fcmpg | OP_FSUB, OP_JMPGE |
| dcmpl | OP_DCMP, OP_JMPLE |
| dcmpg | OP_DCMP, OP_JMPGE |

Fig. 11A

| | |
|---|---|
| if_icmpeq | OP_ISUB, OP_JMPEQ |
| if_icmpne | OP_ISUB, OP_JMPNE |
| if_icmplt | OP_ISUB, OP_JMPLT |
| if_icmpge | OP_ISUB, OP_JMPGE |
| if_icmpgt | OP_ISUB, OP_JMPGT |
| if_icmple | OP_ISUB, OP_JMPLE |
| if_acmpeq | OP_ISUB, OP_JMPEQ |
| if_acmpne | OP_ISUB, OP_JMPNE |

Fig. 11B

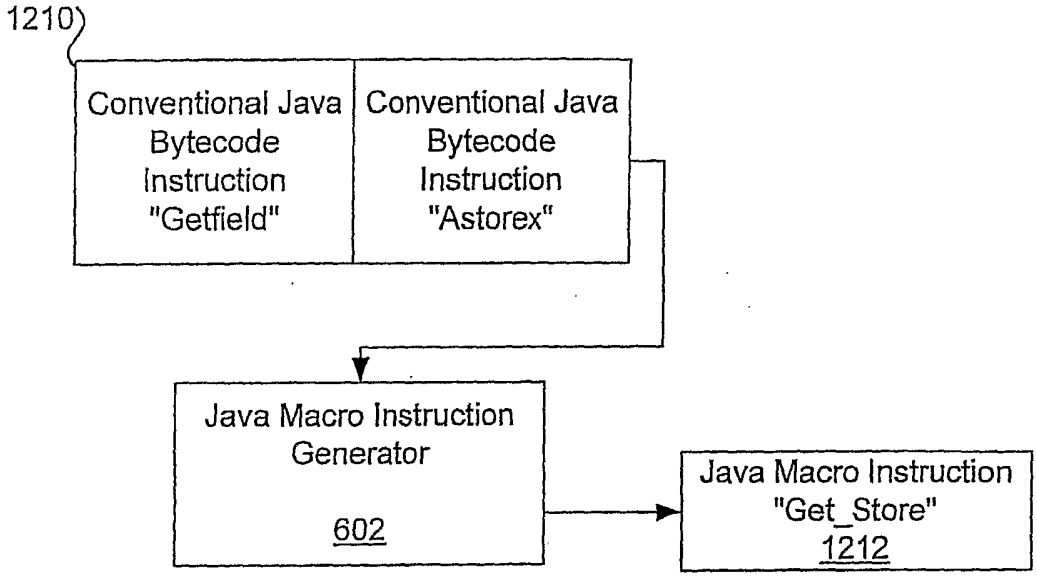



Fig. 12A

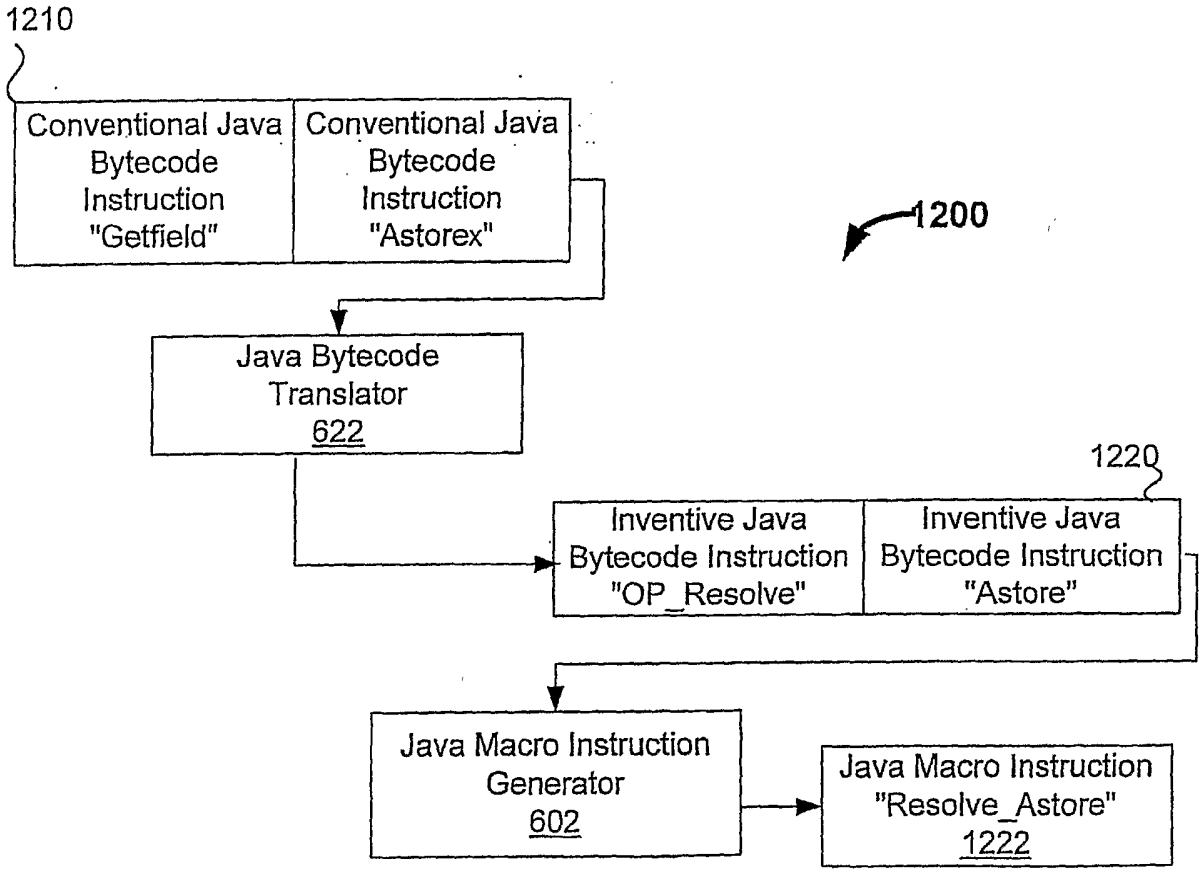



Fig. 12B

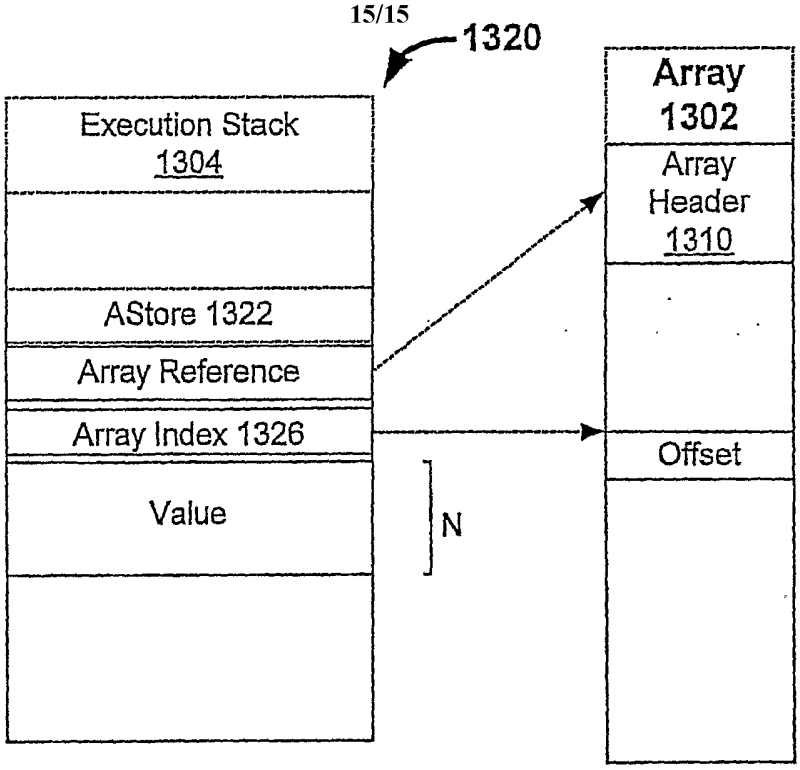



Fig. 13A

| ASTORE |
| --- |
| iastore |
| fastore |
| aastore |
| bastore |
| castore |
| sastore |

Fig. 13B

| ASTOREL |
| --- |
| lastore |
| dastore |

Fig. 13C