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JAVA HARDWARE ACCELERATOR USING MICROCODE ENGINE

5 **Background of the Invention**

Java™ is an object-orientated programming language developed by Sun Microsystems. The Java language is small, simple and portable across platforms and operating systems, both at the source and at the binary level. This makes the Java programming
10 language very popular on the Internet.

Java's platform independence and code compaction are the most significant advantages of Java over conventional programming languages. In conventional programming languages, the source code of a program is sent to a compiler which translates the program into
15 machine code or processor instructions. The processor instructions are native to the system's processor. If the code is compiled on an Intel-based system, the resulting program will only run on other Intel-based systems. If it is desired to run the program on another system, the user must go back to the original source code, obtain a compiler
20 for the new processor, and recompile the program into the machine code specific to that other processor.

Java operates differently. The Java compiler takes a Java program and, instead of generating machine code for a particular processor, generates bytecodes. Bytecodes are instructions that look
25 like machine code, but aren't specific to any processor. To execute a Java program, a bytecode interpreter takes the Java bytecode converts them to equivalent native processor instructions and executes the

Java program. The Java bytecode interpreter is one component of the Java Virtual Machine.

5 Having the Java programs in bytecode form means that instead of being specific to any one system, the programs can run on any platform and any operating system as long a Java Virtual Machine is available. This allows a binary bytecode file to be executable across platforms.

10 The disadvantage of using bytecodes is execution speed. System specific programs that run directly on the hardware from which they are compiled, run significantly faster than Java bytecodes, which must be processed by the Java Virtual Machine. The processor must both convert the Java bytecodes into native instructions in the Java Virtual Machine and execute the native instructions.

15 One way to speed up the Java Virtual Machine is by techniques such as the "Just in Time" (JIT) interpreter, and even faster interpreters known as "Hot Spot JITs" interpreters. The JIT versions all result in a JIT compile overhead to generate native processor instructions. These JIT interpreters also result in additional memory overhead.

20 The slow execution speed of Java and overhead of JIT interpreters have made it difficult for consumer appliances requiring local-cost solutions with minimal memory usage and low energy consumption to run Java programs. The performance requirements for existing processors using the fastest JITs more than double to support running the Java Virtual Machine in software. The processor performance requirements could be met by employing superscalar processor architectures or by increasing the processor clock

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frequency. In both cases, the power requirements are dramatically increased. The memory bloat that results from JIT techniques, also goes against the consumer application requirements of low cost and low power.

5 It is desired to have an improved system for implementing Java programs that provides a low-cost solution for running Java programs for consumer appliances.

Summary of the Invention

10 The present invention generally relates to Java hardware accelerators used to translate Java bytecodes into native instructions for a central processing unit (CPU). One embodiment of the present invention comprises a reissue buffer, the reissue buffer associated with a hardware accelerator and adapted to store converted native
15 instructions issued to the CPU along with associated native program counter values. When the CPU returns from an interrupt the reissue buffer examines the program counter to determine whether to reissue a stored native instruction value from the reissue buffer. In this way, returns from interrupts can be efficiently handled without reloading
20 the hardware accelerator with the instructions to convert.

 Another embodiment of the present invention comprises a hardware accelerator to convert stacked-base instructions into register-based instructions native to a central processing unit. The hardware accelerator includes a native program counter monitor. The
25 native program counter monitor checks whether the native program counter is within a hardware accelerator program counter range. When the hardware accelerator program counter is within the hardware accelerator program counter range, the hardware accelerator

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is enabled and converted native instructions are sent to the CPU from the hardware accelerator, the native program counter is not used to determine instructions to load from memory.

5 In this manner, the hardware accelerator can spoof the native program counter to be within a certain range which corresponds to the program counter range in which the stacked-base instructions are stored. By monitoring the program counter, the hardware accelerator can always tell when it needs to be operating and needs to not operate. Thus if a interrupt occurs, causing the data program counter
10 to move to a range outside of the hardware accelerator program counter range, there need be no explicit instruction to the hardware accelerator from the CPU handling the interrupt to stall the hardware accelerator.

Yet another embodiment of the present invention comprises a
15 hardware accelerator operably connected to a central processing unit, the hardware accelerator adapted to convert stack-based instructions into register-based instructions native to the central processing unit. The hardware accelerator includes a microcode stage. The microcode stage includes microcode memory. The microcode
20 memory output includes a number of fields, the fields including a first set of fields corresponding to native instruction fields and a control bit field which affects the interpretation of the first set of fields by the microcode controlled logic to produce a native instruction. Use of a microcode portion allows the same general
25 hardware accelerator architecture to work with a variety of central processing units. In a preferred embodiment, the microcode portion is separate from a decode portion.

Brief Description of the Drawings

The present invention may be further understood from the following description in conjunction with the drawings.

5 Figure 1 is a diagram of the system of the parent invention including a hardware Java accelerator.

Figure 2 is a diagram illustrating the use of the hardware Java accelerator of the parent invention.

10 Figure 3 is a diagram illustrating some the details of a Java hardware accelerator of one embodiment of the parent invention.

Figure 4 is a diagram illustrating the details of one embodiment of a Java accelerator instruction translation in the system of the parent invention.

15 Figure 5 is a diagram illustration the instruction translation operation of one embodiment of the parent invention.

Figure 6 is a diagram illustrating the instruction translation system of one embodiment of the parent invention using instruction level parallelism.

20 Figure 7 is a table of exception bytecodes for one embodiment of the parent invention.

Figure 8 is a diagram of one embodiment of a hardware

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accelerator used with one embodiment of the present invention.

Figure 9 is a diagram that illustrates the decode stage for use in the hardware accelerator of the present invention.

Figure 10 is a diagram that illustrates one embodiment of an instruction decode unit used with the decode stage of Figure 9.

Figure 11 is a diagram that illustrates one embodiment of a microcode stage for use with the embodiment of Figure 8.

Figure 12 is a diagram of a microcode address logic used with the microcode stage of Figure 11.

Figure 13 is a diagram of a native instruction composer unit used with the embodiment of Figure 11.

Figure 14 is a diagram of a register selection logic used with the native instruction composer unit of Figure 13.

Figure 15 illustrates a stack-and-variable-register manager of one embodiment of the present invention.

Figure 16 illustrates a stack-and-variable-register manager of an alternate embodiment of the present invention.

Figure 17 is a diagram of the native PC monitor used with one embodiment of the present invention.

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Figure 18 is a diagram of a reissue buffer used with one embodiment of the present invention.

Figures 19 and 20 are diagrams that illustrate the operation of one embodiment of the present invention.

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Detailed Description of the Preferred Embodiments

Figures 1-7 illustrate the operation of the parent application.

Figure 1 is a diagram of the system 20 showing the use of a hardware Java accelerator 22 in conjunction with a central processing unit 26. The Java hardware accelerator 22 allows part of the Java Virtual Machine to be implemented in hardware. This hardware implementation speeds up the processing of the Java bytecodes. In particular, in a preferred embodiment, the translation of the Java bytecodes into native processor instructions is at least partially done in the hardware Java accelerator 22. This translation has been part of a bottleneck in the Java Virtual Machine when implemented in software. In Figure 1, instructions from the instruction cache 24 or other memory is supplied to the hardware Java accelerator 22. If these instruction are Java bytecode, the hardware Java accelerator 22 can convert these bytecodes into native processor instruction which are supplied through the multiplexer 28 to the CPU. If a non-Java code is used, the hardware accelerator can be by-passed using the multiplexer 26. The Java stack includes the frame, the operand stack, the variables, etc.

The Java hardware accelerator can do some or all of the following tasks:

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1. Java bytecode decode;
2. identifying and encoding instruction level parallelism (ILP), wherever possible;
3. translating bytecodes to native instructions;
- 5 4. managing the Java stack on a register file associated with the CPU or as a separate stack;
5. generating exceptions on instructions on predetermined Java bytecodes;
6. switching to native CPU operation when native CPU code is provided;
7. performing bounds checking on array instructions; and
- 10 8. managing the variables on the register file associated with the CPU.

In a preferred embodiment, the Java Virtual Machine functions of bytecode interpreter, Java register, and Java stack are implemented in the hardware Java accelerator. The garbage collection heap and constant pool area can be maintained in normal memory and accessed through normal memory referencing. In one embodiment, these functions are accelerated in hardware, e.g. write barrier.

The major advantages of the Java hardware accelerator is to increase the speed in which the Java Virtual Machine operates, and allow existing native language legacy applications, software base, and development tools to be used. A dedicated microprocessor in which the Java bytecodes were the native instructions would not have access to those legacy applications.

Although the Java hardware accelerator is shown in Figure 1 as separate from the central processing unit, the Java hardware accelerator can be incorporated into a central processing unit. In that case, the central processing unit has a Java hardware accelerator subunit to translate Java bytecode into the native instructions operated on by the main portion of the

CPU.

Figure 2 is a state machine diagram that shows the operation of one embodiment of the parent invention. Block 32 is the power-on state. During power-on, the multiplexer 28 is set to bypass the Java hardware accelerator. In block 34, the native instruction boot-up sequence is run. Block 36 shows the system in the native mode executing native instructions and by-passing the Java hardware accelerator.

In block 38, the system switches to the Java hardware accelerator mode. In the Java hardware accelerator mode, Java bytecode is transferred to the Java hardware accelerator 22, converted into native instructions then sent to the CPU for operation.

The Java accelerator mode can produce exceptions at certain Java bytecodes. These bytecodes are not processed by the hardware accelerator 22 but are processed in the CPU 26. As shown in block 40, the system operates in the native mode but the Java Virtual Machine is implemented in the accelerator which does the bytecode translation and handles the exception created in the Java accelerator mode.

The longer and more complicated bytecodes that are difficult to handle in hardware can be selected to produce the exceptions. Figure 7 is a table showing one possible list of bytecodes which can cause exceptions in a preferred embodiment.

Figure 3 is a diagram illustrating details of one embodiment of the Java hardware accelerator of the parent invention. The Java hardware accelerator includes Java accelerator instruction translation hardware 42.

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The instruction translation Unit 42 is used to convert Java bytecodes to native instructions. One embodiment of the Java accelerator instruction translation hardware 42 is described in more detail below with respect to Figure 4. This instruction translation hardware 42 uses data stored in hardware Java registers 44. The hardware Java Registers store the Java Registers defined in the Java Virtual Machine. The Java Registers contain the state of the Java Virtual Machine, affect its operation, and are updated at runtime. The Java registers in the Java virtual machine include the PC, the program counter indicating what bytecode is being executed; Optop, a pointer to the top of the operand stack; Frame, a pointer to the execution environment of the current method; and Java variables (*Vars*), a pointer to the first local variable available of the currently executing method. The virtual machine defines these registers to be a single 32-bit word wide. The Java registers are also stored in the Java stack which can be implemented as the hardware Java stack 50 or the Java stack can be stored into the CPU associated register file.

In a preferred embodiment, the hardware Java registers 44 can include additional registers for the use of the instruction translation hardware 42. These registers can include a register indicating a switch to native instructions configuration and control registers and a register indicating the version number of the system.

The Java PC can be used to obtain bytecode instructions from the instruction cache 24 or memory. In one embodiment the Java PC is multiplexed with the normal program counter 54 of the central processing unit 26 in multiplexer 52. The normal PC 54 is not used during the operation of the Java hardware bytecode translation. In another embodiment, the normal program counter 54 is used as the Java program counter.

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The Java registers are a part of the Java Virtual Machine and should not be confused with the general registers 46 or 48 which are operated upon by the central processing unit 26. In one embodiment, the system uses the traditional CPU register file 46 as well as a Java CPU register file 48. When native code is being operated upon the multiplexer 56 connects the conventional register file 46 to the execution logic 26c of the CPU 26. When the Java hardware accelerator is active, the Java CPU register file 48 substitutes for the conventional CPU register file 46. In another embodiment, the conventional CPU register file 46 is used.

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As described below with respect to Figures 3 and 4, the Java CPU register file 48, or in an alternate embodiment the conventional CPU register file 46, can be used to store portions of the operand stack and some of the variables. In this way, the native register-based instructions from the Java accelerator instruction translator 42 can operate upon the operand stack and variable values stored in the Java CPU register file 48, or the values stored in the conventional CPU register file 46. Data can be written in and out of the Java CPU register file 48 from the data cache or other memory 58 through the overflow/underflow line 60 connected to the memory arbiter 62 as well as issued load/store instructions. The overflow/underflow transfer of data to and from the memory can be done concurrently with the CPU operation. Alternately, the overflow/underflow transfer can be done explicitly while the CPU is not operating. The overflow/underflow bus 60 can be implemented as a tri-state bus or as two separate buses to read data in and write data out of the register file when the Java stack overflows or underflows.

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The register files for the CPU could alternately be implemented as a single register file with native instructions used to manipulate the loading of operand stack and variable values to and from memory. Alternately,

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multiple Java CPU register files could be used: one register file for variable values, another register file for the operand stack values, and another register file for the Java frame stack holding the method environment information.

5 The Java accelerator controller (co-processing unit) 64 can be used to control the hardware Java accelerator, read in and out from the hardware Java registers 44 and Java stack 50, and flush the Java accelerator instruction translation pipeline upon a “branch taken” signal from the CPU execute logic 26c.

10 The CPU 26 is divided into pipeline stages including the instruction fetch 26a, instruction decode 26b, execute logic 26c, memory access logic 26d, and writeback logic 26e. The execute logic 26c executes the native instructions and thus can determine whether a branch instruction is taken and issue the “branch taken” signal. In one embodiment, the execute logic 26c monitors addresses for detecting branches. Figure 4 illustrates an
15 embodiment of a Java accelerator instruction translator which can be used with the parent invention. The instruction buffer 70 stores the bytecode instructions from the instruction cache. The bytecodes are sent to a parallel decode unit 72 which decodes multiple bytecodes at the same time. Multiple
20 bytecodes are processed concurrently in order to allow for instruction level parallelism. That is, multiple bytecodes may be converted into a lesser number of native instructions.

 The decoded bytecodes are sent to a state machine unit 74 and Arithmetic Logic Unit (ALU) 76. The ALU 76 is provided to rearrange the bytecode instructions to make them easier to be operated on by the state
25 machine 74 and perform various arithmetic functions including computing memory references. The state machine 74 converts the bytecodes into

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native instructions using the lookup table 78. Thus, the state machine 74 provides an address which indicates the location of the desired native instruction in the microcode look-up table 78. Counters are maintained to keep a count of how many entries have been placed on the operand stack, as well as to keep track of and update the top of the operand stack in memory and in the register file. In a preferred embodiment, the output of the microcode look-up table 78 is augmented with indications of the registers to be operated on in the native CPU register file at line 80. The register indications are from the counters and interpreted from bytecodes. To accomplish this, it is necessary to have a hardware indication of which operands and variables are in which entries in the register file. Native Instructions are composed on this basis. Alternately, these register indications can be sent directly to the Java CPU register file 48 shown in Figure 3.

The state machine 74 has access to the Java registers in 44 as well as an indication of the arrangement of the stack and variables in the Java CPU register file 48 or in the conventional CPU register file 46. The buffer 82 supplies the translated native instructions to the CPU.

The operation of the Java hardware accelerator of one embodiment of the parent invention is illustrated in Figures 5 and 6. Figure 5, section I shows the instruction translation of the Java bytecode. The Java bytecode corresponding to the mnemonic *iadd* is interpreted by the Java virtual machine as an integer operation taking the top two values of the operand stack, adding them together and pushing the result on top of the operand stack. The Java translating machine translates the Java bytecode into a native instruction such as the instruction ADD R1, R2. This is an instruction native to the CPU indicating the adding of value in register R1

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to the value in register R2 and the storing of this result in register R2 . R1 and R2 are the top two entries in the operand stack.

As shown in Figure 5, section II, the Java register includes a PC value of "Value A" that is incremented to "Value A+1". The Optop value changes from "Value B" to "Value B-1" to indicate that the top of the operand stack is at a new location. The *Vars* base value which points to the start of the variable list is not modified. In Figure 5, section III, the contents of a native CPU register file or a Java CPU register file, 48 in Figure 3, is shown. The Java CPU register file starts off with registers R0-10 R5 containing operand stack values and registers R6-R7 containing variable values. Before the operation of the native instruction, register R1 contains the top value of the operand stack. Register R6 contains the first variable. Hardware is used to detect the availability of the Vars in the register file. If the Var is not available, the hardware in conjunction with microcode issue load instructions to the native CPU. Once the value of a Var has been updated in the RF, that entry is marked as being modified so when doing method calls, only the updated Vars in memory are written back to memory. This results in significantly higher performance methods.

After the execution of the native instruction, register R2 now contains the top value of the operand stack. Register R1 no longer contains a valid operand stack value and is available to be overwritten by a operand stack value.

Figure 5, section IV, shows the memory locations of the operand stack and variables which can be stored in the data cache 58 or in main memory. For convenience, the memory is illustrated without illustrating any virtual memory scheme. Before the native instruction executes, the address of the top of the operand stack, Optop, is "Value B". After the

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native instruction executes, the address of the top of the operand stack is "Value B-1" containing the result of the native instruction. Note that the operand stack value "4427" can be written into register R1 across the overflow/underflow line 60. Upon a switch back to the native mode, the data in the Java CPU register file 48 should be written to the data memory.

Consistency must be maintained between the Hardware Java Registers 44, the Java CPU register file 48 and the data memory. The CPU 26 and Java Accelerator Instruction Translation Unit 42 are pipelined and any changes to the hardware java registers 44 and changes to the control information for the Java CPU register file 48 must be able to be undone upon a "branch taken" signal. The system preferably uses buffers (not shown) to ensure this consistency. Additionally, the Java instruction translation must be done so as to avoid pipeline hazards in the instruction translation unit and CPU.

Figure 6 is a diagram illustrating the operation of instruction level parallelism with the parent invention. In Figure 6 the Java bytecodes *iload_n* and *iadd* are converted by the Java bytecode translator to the single native instruction ADD R6, R1. In the Java Virtual Machine, *iload_n* pushes the top local variable indicated by the Java register *Var* onto the operand stack.

In the parent invention the Java hardware translator can combine the *iload_n* and *iadd* bytecode into a single native instruction. As shown in figure 6, section II, the Java Register, PC, is updated from "Value A" to "Value A+2". The Optop value remains "value B". The value *Var* remains at "value C".

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As shown in Figure 6, section III, after the native instruction ADD R6, R1 executes the value of the first local variable stored in register R6, "1221", is added to the value of the top of the operand stack contained in register R1 and the result stored in register R1. In Figure 6, section IV, the
5 Optop value does not change but the value in the top of the register contains the result of the ADD instruction, 1371. This example shows the present invention operating with a native CPU supporting only two operands. The invention can also support three operands and Very Long Instruction Word (VLIW) CPU's.

10 For some byte codes such as SiPush, BiPush, etc., the present invention makes available sign extended data for the immediate field of the native instruction being composed (120) by the hardware and microcode. This data can alternatively be read as a coprocessor register. The coprocessor register read/write instruction can be issued by hardware
15 accelerator as outlined in the present invention. Additionally, the microcode has several fields that aid in composing the native instruction.

The Java hardware accelerator of the parent invention is particularly well suited to a embedded solution in which the hardware accelerator is positioned on the same chip as the existing CPU design. This allows the
20 prior existing software base and development tools for legacy applications to be used. In addition, the architecture of the present embodiment is scalable to fit a variety of applications ranging from smart cards to desktop solutions. This scalability is implemented in the Java accelerator instruction translation unit of Figure 4. For example, the lookup table 78
25 and state machine 74 can be modified for a variety of different CPU architectures. These CPU architectures include reduced instruction set computer (RISC) architectures as well as complex instruction set computer

(CISC) architectures. The present invention can also be used with superscalar CPUs or very long instruction word (VLIW) computers.

Figures 8-20 illustrate the operation of the present invention. Figure 8 is a diagram that shows a system 100 of one embodiment of the present invention. The system includes a CPU 101 and a hardware accelerator. The hardware accelerator portion includes a decode stage 102 for receiving the Java bytecode from the memory. Decode stage 102 preferably uses instruction level parallelism in which more than one Java bytecode can be converted into a single native instruction. In a preferred embodiment, the system 100 includes a microcode stage 104 which receives signals from the decode stage 102 and is used to construct the native instructions. The microcode stage 104 allows for the production of multiple native instructions from a single bytecode. The reissue buffer 106 stores a copy of the converted instructions in the reissue buffer 106 as they are sent to the CPU 101.

The reissue buffer 106 monitors the native PC value 110. In a preferred embodiment, when the hardware accelerator is active, the hardware accelerator does not use the native PC value to determine the memory location to load the instructions from memory. The native PC value is instead maintained within a spoofed range which indicates that the hardware accelerator is active. In a preferred embodiment, the native PC monitor 110 detects whether the native PC value is within the spoofed range. If so, the multiplexer 112 sends the converted instructions from the hardware accelerator to the CPU 101. If not, the native instructions from memory are loaded to the CPU 101. When in the spoofed range, the addresses sourced to memory are the Java PC from the accelerator. Otherwise the native PC is sourced to memory.

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If an interrupt occurs, the native PC value will go to a value outside the spoofed range. The PC monitor 110 will then stall the hardware accelerator. When a return from interrupt occurs, the CPU 101 will be
5 flushed, and upon return from interrupt, the native PC value 108 returned to the PC value prior to the interrupt. The reissue buffer 106 will then reissue stored native instructions flushed from CPU 101 to the CPU 101 that corresponds to this prior native PC value. With the use of this system, the hardware accelerator does not need to be flushed upon an interrupt, nor
10 do previously converted Java bytecodes need to be reloaded into the hardware accelerator. The use of the reissue buffer 106 can thus speed the operation and recovery from interrupt.

The CPU 101 is associated with a register file 113. This register file is the native CPU's normal register file, operably connected to the CPU's
15 ALU but is shown separately here for illustration. The register file 113 stores Stack and Var values which can be used by the converted instructions. The Stack- and Variable-managers 114 keep track of any information stored in the register file 113 and use it to help the microcode stage operations. As described below, in one embodiment there are a
20 fixed number of registers used for Stack values and Variable value. For example, six registers can be used for the top six Stack values and six registers used for six Variable values.

In another embodiment of the present invention, the Stack and Variable manager assigns Stack and Variable values to different registers in
25 the register file. An advantage of this alternate embodiment is that in some cases the Stack and Var values may switch due to an Invoke Call and such a switch can be more efficiently done in the Stack and Var manager

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114 rather than producing a number of native instructions to implement this.

5 In one embodiment a number of important values can be stored in the hardware accelerator to aid in the operation of the system. These values stored in the hardware accelerator help improve the operation of the system, especially when the register files of the CPU are used to store portions of the Java stack.

10 The hardware accelerator preferably stores an indication of the top of the stack value. This top of the stack value aids in the loading of stack values from the memory. The top of the stack value is updated as instructions are converted from stack-based instructions to register-based instructions. When instruction level parallelism is used, each stack-based instruction which is part of a single register-based instruction needs to be evaluated for its effects on the Java stack.

15 In one embodiment, an operand stack depth value is maintained in the hardware accelerator. This operand stack depth indicates the dynamic depth of the operand stack in the CPU's register files. Thus, if four stack values are stored in the register files, the stack depth indicator will read "4." Knowing the depth of the stack in the register file helps in the loading and storing of stack values in and out of the register files.

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In a preferred embodiment, a minimum stack depth value and a maximum stack depth value are maintained within the hardware accelerator. The stack depth value is compared to the maximum and minimum stack depths. When the stack value goes below the minimum value, the hardware accelerator composes load instructions to load stack values from the memory into the register file of the CPU.

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When the stack depth goes above the maximum value, the hardware accelerator composes store instructions to store stack values back out to the memory.

In one embodiment, at least the top four (4) entries of the operand stack in the CPU register file operated as a ring buffer, the ring buffer maintained in the
5 accelerator and operably connected to a overflow/underflow unit.

The hardware accelerator also preferably stores an indication of the operands and variables stored in the register file of the CPU. These indications allow the hardware accelerator to compose the converted register-based instructions from the incoming stack-based instructions.

10 The hardware accelerator also preferably stores an indication of the variable base and operand base in the memory. This allows for the composing of instructions to load and store variables and operands between the register file of the CPU and the memory. For example, When a Var is not available in the register file, the hardware issues load instructions. The hardware adapted to multiply the Var
15 number by four and adding the Var base to produce the memory location of the Var. The instruction produced is based on knowledge that the Var base is in a temporary native CPU register. The Var number times four can be made available as the immediate field of the native instruction being composed, which may be a memory access instruction with the address being the content of the temporary register
20 holding a pointer to the Vars base plus an immediate offset. Alternatively, the final memory location of the Var may be read by the CPU as an instruction saved by the accelerator and then the Var can be loaded.

In one embodiment, the hardware accelerator marks the variables as modified when updated by the execution of Java byte codes. The hardware
25 accelerator

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can copy variables marked as modified to the system memory for some bytecodes.

In one embodiment, the hardware accelerator composes native instructions wherein the native instructions operands contains at least two native CPU register file references where the register file contents are the data for the operand stack and
5 variables.

Figure 9 illustrates a decode stage of one embodiment of the present invention. This decode stage 102' is divided into the prefetch stage 116 and the instruction decode 118. The prefetch stage 116 includes a bytecode buffer and alignment prefetch stage unit 120 which receives the raw bytecodes from a memory
10 (not shown). The Java bytecode buffer control element 122 provides instructions to determine when to load additional bytecodes from the memory. The address unit 124 uses the Java program counter 126 to determine the location of the next bytecode to load. As described above, while the hardware accelerator is active, the Java program counter is used to get the next word from memory containing Java
15 bytecode. The native PC is maintained within a spoofed region and is not used to get the next instruction while the hardware accelerator is active. The bytecode buffer alignment unit 120 contains a number of bytecodes from the memory. When the instructions are passed on from the instruction decode unit 118, a number of bytes are removed from the bytecode buffer alignment unit 120. A signal on line
20 128 indicates the number of bytecodes which are used by the instruction decode unit 118. In one embodiment, the decoded data on line 130 is sent to the microcode stage. This data can include the microcode Start Address data 130a, Index/Address and Vars data 130b, and Var Control data 130c.

Figure 10 shows an instruction decode unit 118'. In this embodiment, a
25 number of bytes are sent to an Instruction Decode unit. Individual Decode units 132, 134, 136, 138 and 140 receive and decode the bytes. Note that the value of

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adjacent bytes affects how the byte is decoded. For example, if byte A is the start of a two-byte instruction, the value of byte B is interpreted as the second half of the two-byte instruction. The instruction level parallelism logic 142 receives the decoded information and then determines the microcode start address for the primary
5 byte-code. Secondary byte codes can be combined with the primary bytecode by the selection of registers accessed by the converted instruction. One example of this embodiment is described below with respect to Figures 19 and 20.

The accelerator ALU 144 is used to calculate index addresses and the like. The accelerator ALU is connected to the register pool. The use of the accelerator
10 ALU allows certain simple calculations to be moved from the CPU unit to the hardware accelerator unit, and thus allows the Java bytecodes to be converted into fewer native instructions. The Variable Selection + Other Control unit 146 determines which registers are used as Vars. The Var control line from the ILP Logic unit 142 indicates how these Vars are interpreted. A Var and associated Var
15 control line can be made available for each operand field in the native CPU's instruction.

In one embodiment, the hardware accelerator issues native load instructions when a variable is not present in the native CPU register file, the memory address being computed by the ALU in the hardware accelerator.

20 The microcode stage 104' shown in Figure 11 includes a microcode address logic 148 and microcode memory 150. The microcode address logic sends microcode addresses to the microcode memory 150. The microcode memory 150 then sends the contents of that address to the Native Instruction Composer Logic 152 which produces the native instruction. Each microcode memory line includes a
25 main instruction portion on line 154, control bits on line 156 and update stack pointer bits on line 158. Both the microcode address logic 148 and the microcode

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150 can produce a string of native instructions until the update stack Bit is sent to the microcode address logic 148. At that point, the microcode address logic obtains another start address from the decode logic (not shown). The native instruction composer receives the main instruction portion on line 154, the control bits from the
5 decode, the index address, Vars, and the Var controls. These inputs allow the native instruction composer 152 to construct the native instructions which are sent to the reissue buffer and the native CPU.

Figure 12 shows a microcode address logic 148' of one embodiment of the present invention. Start address coming from the decode logic goes to multiplexer
10 154. The multiplexer 154 can either send the start address or an incremental or calculated value to the microcode RAM. In a preferred embodiment, while the update stack bit is not set, the address of the next element in the microcode is calculated by the ALU 156 and provided to the multiplexer 154 for sending to the microcode memory (not shown). Space in the microcode RAM memory can be
15 conserved by including jumps to other areas of the microcode memory. These jumps can be done by calculation in unit 158 or by providing the address on line 160.

Figure 13 illustrates an embodiment of a native instruction composer unit for use with the present invention. In this embodiment a number of register
20 selection logic units 162, 164 and 166 are provided. Each register selection logic unit can be used to select a register used with a native instruction. Special resources logic unit 168 and selection logic 170 allow the selection of special instructions.

Figure 14 shows the register selection logic 161' of one embodiment of the present invention. The register determination logic 172 determines from the variable
25 control bits, the microcode control bits and the Stack and Vars register manager information which register to use. For example, if the instruction is to load the top

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of stack and then use this top of stack value in next bytecode register determination logic 172 can be used to determine that register R10 contains the top of stack value and so Register R10 is used in the converted instruction.

Register remapping unit 174 does register remapping. In conventional CPUs, some registers are reserved. Register remapping unit 174 allows the decoder logic to assume that the Stack and Var registers are virtual, which simplifies the calculations. Multiplexer 176 allows the value on line 171 to be passed without being modified.

Figure 15 illustrates an embodiment of a stack-and-variable-register manager 114'. The stack-and-variable-register manager maintains indications of what is stored in the variable and stack registers of the register file of the CPU. This information is then provided to the decode stage and microcode stage in order to help in the decoding of the Java bytecode and generating appropriate native instructions.

In a preferred embodiment, one of the functions of the Stack-and-Var register manager is to maintain an indication of the top of the stack. Thus, if for example registers R1-R4 store the top 4 stack values from memory or by executing byte codes, the top of the stack will change as data is loaded into and out of the register file. Thus, register R2 can be the top of the stack and register R1 be the bottom of the stack in the register file. When a new data is loaded into the stack within the register file, the data will be loaded into register R3, which then becomes the new top of the stack, the bottom of the stack remains R1. With two more items loaded on the stack in the register file, the new top of stack in the register file will be R1 but first R1 will be written back to memory by the accelerators overflow/underflow unit, and R2 will be the bottom of the partial stack in the CPU register file

Figure 16 illustrates an alternate stack-and-variable-register manager 114". In this alternate embodiment, a register assignment table 172 is maintained. The register assignment table maintains an indication of which *Vars* and stack variables are stored in which registers. When an instruction is decoded it is checked whether a
5 *Var* or stack value is stored in the register file using the register assignment table 172. If there is a match to the incoming stack or *Var* value, the values within the register file of the CPU are used. If there is no match, the value can be loaded into the register file from the memory and the register assignment table updated. In one embodiment, an invoke assignment logic unit 174 is operably connected with the
10 register assignment table. When an invoke occurs, typically the values of some of the stack and the *Vars* are switched. By reassigning the values within the register assignment table 172 using reassignment logic 174, the operation of the invoke can be speeded up.

Figure 17 shows one embodiment of a native PC monitor 110'. The native
15 PC value is compared to a high range register and a low range register. If the native PC value is within this range, the hardware accelerator is enabled using line 178. Otherwise the hardware accelerator is disabled. The element 180 tests whether the native PC value is coming close to the high end of the spoof range. If so, the system induces a jump to a lower value of the native PC unit.

Figure 18 illustrates an embodiment of a reissue buffer 106'. The reissue
20 buffer receives the converted instructions and stores them along with the associated native PC value. As long as there is no interrupt, the native PC value will continue to increment, and the next instruction and current native PC is stored in the reissue buffer and instruction issued to the CPU. When an interrupt occurs, the CPU
25 pipeline is flushed, including non-executed instructions, of which there is a copy in the reissue buffer. When a return from an interrupt occurs, the CPU is flushed and the native PC value before the interrupt is restored. This restored native PC value

-26-

matches a native PC stored in the PC value store 184, causing a buffered instruction in the old instruction store 186 to be provided to the CPU. The old instruction store and the PC value store are synchronized. Once all of the old instructions are provided to the CPU 102, the native PC value will be outside of the range of all of the old PC values in store 184, and new converted instructions will be provided. The depth of the reissue buffer depends upon the number of pipeline stages in the CPU 102 (not shown). Under certain conditions such as branches, the reissue buffer is flushed. As described above, the reissue buffer eases the operation of the hardware accelerator. The hardware accelerator need not know the details of the return from interrupt operation of the CPU. Thus the hardware accelerator can operate with a variety of different CPUs without requiring major modification of the hardware accelerator architecture. Changes to the microcode stage are sufficient to change the hardware accelerator so that it could be used with different CPUs.

Figures 19 and 20 illustrate the operation of one embodiment of the system of the present invention. In Figure 19, multiple instructions are shown being received by the decoder stage. The top two instructions are integer loads and the bottom instruction is an integer add. The ideal combination of these bytecodes by the system would be the main op code being an add and the two loads combined together. The system tests whether each of the Vars is in memory. In this example, the *iload* 31 is not a Var which is stored in memory. Thus the value of the *Var* 31 needs to be loaded from memory into a free register. In this example, the Var base stored in the stack manager is loaded into temp register R10. The word is put into the top of the stack, or in this case in the register file indicating the top of the stack.

Figure 20 illustrates an example when *iload_3* and *iload* 5 are used. In this example, both of these Vars are stored within the register file. Thus, the add can be combined with the two loads. In this example, *Var* H is indicated as being a 3, *Var* L is indicated as being a 5. The op type is indicated as being *iadd*. The *Var* H

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Control and *Var L* Control indicate that the *Vars* are load types and in the register file. The top of the stack modification is + 1. This is because two values are loaded upon the stack for the two loads, and one value is removed from the stack as a result of the main add operation.

5 In actuality, as can be understood with respect to the figures described above, the *Var 3* and *Var 5* are already stored within the two register files. The value of these register files is determined by the system. The instructions *iload 3*, *iload 5* and *iadd* are done by determining which two registers store *Var 3* and *Var 5* and also determining which register is to store the new top of the stack. If *Var 3* is
10 stored in register R9 and *Var 5* is stored in register R11 and the top of the stack is to be stored in register R2, the converted native instruction is an add of the value within register R9 to the value within register R11 and store the value into register R2. This native instruction thus does the operation of three bytecodes at the same time, resulting in the instruction level parallelism as operated on a native CPU.

15 Additionally within the hardware accelerator a ALU is deployed where the decoded byte code instructions for bytecodes such as GOTO and GOTO_W, the immediate branch offset following the bytecode instruction is sign extended and added to the Java PC of the current bytecode instruction and the result is stored in the Java PC register. JSR and JSR_W bytecode instructions also do this in addition
20 to pushing the Java PC of the next byte code instruction on the operand stack.

 The Java PC is incremented by a value calculated by the hardware accelerator. This increment value is based on the number of bytes being disposed of during the current decode which may include more than one byte code due to ILP. Similarly, SiPush and BiPush instructions are also sign extended and made available
25 in the immediate field of the native instruction being composed. In some processors, the immediate field of the native instruction has a smaller bit width than is desired

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for the offsets or sign extended constants so this data may be read as memory mapped or I/O mapped reads.

While the present invention has been described with reference to the above embodiments, this description of the preferred embodiments and methods is not meant to be construed in a limiting sense. For example, the term Java in the specification or claims should be construed to cover successor programming languages or other programming languages using basic Java concepts (the use of generic instructions, such as bytecodes, to indicate the operation of a virtual machine). It should also be understood that all aspects of the present invention are not to be limited to the specific descriptions, or to configurations set forth herein. Some modifications in form and detail the various embodiments of the disclosed invention, as well as other variations in the present invention, will be apparent to a person skilled in the art upon reference to the present disclosure. It is therefore contemplated that the following claims will cover any such modifications or variations of the described embodiment as falling within the true spirit and scope of the present invention.

Claims

1. A system comprising:

a pipelined central processing unit with associated native program

5 counter; and

a hardware accelerator operably connected to the central processing unit, the hardware accelerator adapted to convert stack-based instructions into register-based instructions native to the central processing unit, the hardware accelerator including a reissue buffer, the reissue buffer adapted to store converted native
10 instructions issued to the CPU along with an indication of the order of the instructions, the system is such that when the CPU returns from an interrupt, the reissue buffer examines the indication to determine whether to reissue a stored native instruction value.

15 2. A system comprising:

a central processing unit; and

a hardware accelerator operably connected to the central processing unit, the hardware accelerator adapted to convert stack-based instructions into register-based instructions native to the central processing unit, the hardware accelerator
20 including a microcode stage, the microcode stage including a microcode memory, the microcode memory output including a number of fields, the fields including a first set of fields corresponding native instruction fields and control bits field that affects the interpretation of the first set of fields by microcode controlled logic to produce a native instruction.

25

3. A system comprising:

a central processing unit; and

a hardware accelerator operably connected to the central processing unit, the hardware accelerator adapted to receive stack-based instructions, the hardware

-30-

accelerator including a microcode generating unit adapted to receive stack-based instructions and to produce therefrom microcode instructions, the hardware accelerator also including microcode interpretation logic adapted to receive the microcode and to produce therefrom native instructions which are sent to the central
5 processing unit.

4. A system comprising:
a central processing unit; and
a hardware accelerator operably connected to the central processing unit,
10 the hardware accelerator adapted to convert stack-based instructions into register-based instructions native to the central processing unit, the hardware accelerator storing an indication of the top of operand stack pointer, the top of operand stack being stored and updated in hardware, wherein when more than one stack-based instruction is translated into a single register-based instruction, the top of stack
15 pointer is modified so as to reflect the effects of each register-based instruction, stack based instruction and instruction level parallelism.

5. A system comprising:
a central processing unit with associated register file; and
20 a hardware accelerator operably connected to the central processing unit, the hardware accelerator adapted to convert stack-based instructions into register-based instructions native to the central processing unit, the hardware accelerator storing an indication of the depth count of the portion of the operand stack stored in the central processing units register file, the depth count being updated during the
25 translation process.

6. A system comprising:
a central processing unit; and
a hardware accelerator operably connected to the central processing unit,

-31-

the hardware accelerator adapted to convert stack-based instructions into register-based instructions native to the central processing unit, the hardware accelerator storing an indication of the depth count of the portion of the operand stack stored in the central processing units register file, the depth count being updated during the translation process, the hardware accelerator checking to see if the stack depth is below a minimum or above a maximum depth, wherein if the depth is below the minimum depth the hardware accelerator generates load instructions to load operand stack data from external memory to the register file, and wherein if the depth is above the maximum depth the hardware accelerator generates store instructions to move operand stack data from register file to the external memory .

7. A system comprising:

a central processing unit with associated register file; and

a hardware accelerator operably connected to the central processing unit,

the hardware accelerator adapted to convert stack-based instructions into register-based instructions native to the central processing unit, the hardware accelerator storing an indication of the operands and variables stored in the register file of the central processing unit, the stored indications being used during the conversion process and being updated by the hardware accelerator.

8. A system comprising:

a central processing unit with associated register file; and

a hardware accelerator operably connected to the central processing unit,

the hardware accelerator adapted to convert stack-based instructions into register-based instructions native to the central processing unit, the hardware accelerator storing at least the top four (4) entries of the operand stack in the native CPU register file as a ring buffer, the ring buffer maintained in the accelerator and operably connected to a overflow/underflow unit.

-32-

9. A system comprising:

a central processing unit with associated register file; and

a hardware accelerator operably connected to the central processing unit,
the hardware accelerator adapted to convert stack-based instructions into register-
based instructions native to the central processing unit, the hardware accelerator
storing Java variables in the native CPU register file and an indication of which
variables are in the native CPU register file.

10. A system comprising:

a central processing unit with associated register file; and

a hardware accelerator operably connected to the central processing unit,
the hardware accelerator adapted to convert stack-based instructions into register-
based instructions native to the central processing unit, where the hardware
accelerator composes native instructions based on the availability of variables and
operands in the native CPU register file.

11. A system comprising:

a central processing unit with associated register file; and

a hardware accelerator operably connected to the central processing unit,
the hardware accelerator adapted to convert stack-based instructions into register-
based instructions native to the central processing unit, where the hardware
accelerator marks the variables in the native CPU register file as modified when
updated by the execution of Java byte codes.

12. A system comprising:

a central processing unit with associated register file; and

a hardware accelerator operably connected to the central processing unit,
the hardware accelerator adapted to convert stack-based instructions into register-
based instructions native to the central processing unit, where the hardware

-33-

accelerator issues native load instructions when a variable is not present in the native CPU register file, the memory address being computed by an ALU in the hardware accelerator.

- 5 13. A system comprising:
 a central processing unit with associated register file; and
 a hardware accelerator operably connected to the central processing unit,
the hardware accelerator adapted to convert stack-based instructions into register-
based instructions native to the central processing unit, where the hardware
10 accelerator composes native instructions wherein the native instructions operands
contains at least two native CPU register file references where the register file
contents are the data for the operand stack and variables.
14. A system comprising:
15 a central processing unit with associated register file; and
 a hardware accelerator operably connected to the central processing unit,
the hardware accelerator adapted to convert stack-based instructions into register-
based instructions native to the central processing unit, where the hardware
accelerator generates a new Java PC due to a "GOTO" or "GOTO_W" byte code.
20
15. A system comprising:
 a central processing unit with associated register file; and
 a hardware accelerator operably connected to the central processing unit,
the hardware accelerator adapted to convert stack-based instructions into register-
25 based instructions native to the central processing unit, where the hardware
accelerator generates a new Java PC due to a "JSR" or "JSR_W" byte code,
computes the return Java PC and pushes the return Java PC on to the operand stack.

 16. A system comprising:

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a central processing unit with associated register file; and
a hardware accelerator operably connected to the central processing unit,
the hardware accelerator adapted to convert stack-based instructions into register-
based instructions native to the central processing unit; where the hardware
accelerator sign extends the SiPush and Bipush byte codes and appends to the
immediate field of the native instruction being composed.

17. A system comprising:

a central processing unit with associated register file; and
a hardware accelerator operably connected to the central processing unit,
the hardware accelerator adapted to convert stack-based instructions into register-
based instructions native to the central processing unit, where the hardware
accelerator sign extends the SiPush and Bipush byte codes and made available to be
read by the native CPU.

18. A system comprising:

a central processing unit with associated register file; and
a hardware accelerator operably connected to the central processing unit,
the hardware accelerator adapted to convert stack-based instructions into register-
based instructions native to the central processing unit, where the hardware
accelerator increments the Java PC within the hardware accelerator by generating an
increment value based on the number of byte codes being disposed, wherein the Java
PC is incremented in the correct manner if multiple bytecodes are disposed at the
same time .

19. The system of Claims 1-18, wherein the stack-based instructions are
Java bytecodes.

20. The system of Claims 1-18, wherein the hardware accelerator is not

-35-

flushed upon an interrupt.

21. The system of Claims 1-18, wherein the hardware accelerator includes a native PC monitor which monitors the value of the native PC.

22. The system of Claim 21, wherein the native PC monitor enables the hardware accelerator when the native program counter is within a hardware accelerator program counter range.

23. The system of Claim 22, wherein an interrupt causes the native PC to leave the hardware accelerator program counter range, causing the hardware accelerator to stall.

24. The system of Claim 23, wherein the return from interrupt causes the native PC to go back within the hardware accelerator program counter range, enabling the hardware accelerator.

25. The system of Claim 1, wherein the reissue buffer provides stored converted instructions when the system returns from an interrupt.

26. The system of Claims 1-18, wherein at least portions of the hardware accelerator are part of the CPU.

27. The system of Claims 2 and 3, wherein the microcode stage includes a microcode address logic portion and a microcode memory portion.

28. The system of Claim 27, wherein the microcode address logic includes logic to step through addresses so that multiple native instructions can be produced from fewer stack-based instructions.

-36-

29. The system of Claims 2-18, further including a reissue buffer, the reissue buffer adapted to store converted native instructions issued to the CPU along with associated native program counter values, the system being such that when the CPU returns from interrupt, the reissue buffer examines the program counter value to determine whether to reissue a stored native instruction value.

30. The system of Claims 2 and 3, wherein the microcode includes fields for native instruction portion and fields for additional control bits.

31. The system of Claim 30, wherein the control bits control the interpretation of fields for the native instruction.

32. The system of Claims 2 and 3, further comprising a decoding unit, the decoding unit being a part of the microcode generating unit, the decoding unit producing additional control signals which are provided to the native instruction composer unit to produce the native instructions.

33. The system of Claims 1-18, further comprising a stack manager unit used to control which elements in the stack are stored within the register file and to produce data which is used to compose the native instructions.

34. The system of claim 11, wherein the hardware accelerator copies the variables marked as modified to the system memory for some bytecodes.

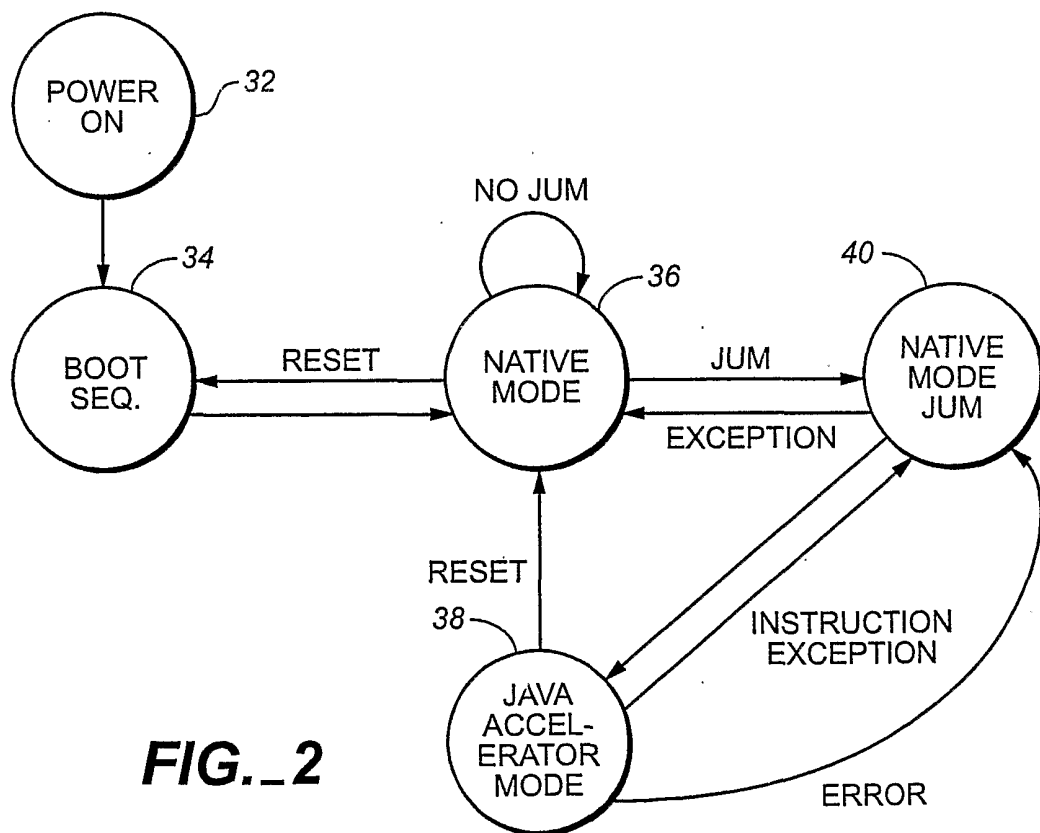
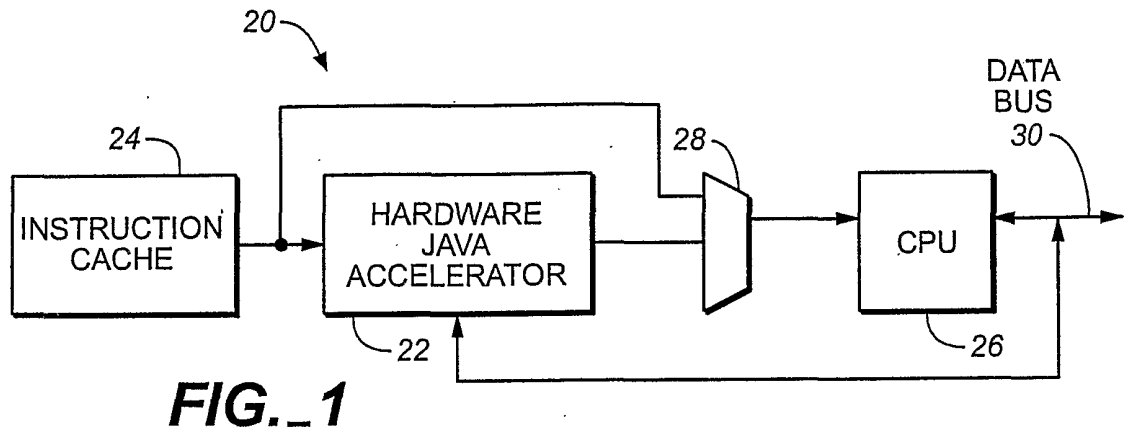
35. The system of Claim 34, wherein at least portions of the hardware accelerator are part of the CPU.

36. The system of claim 1, wherein the indication of the order of the instructions is the native program counter value.

-37-

37. The system of claim 6, wherein if the stack depth is above the maximum depth an overflow flag is generated.

38. The system of claim 6, wherein if the stack depth is below the minimum depth an underflow flag is generated.



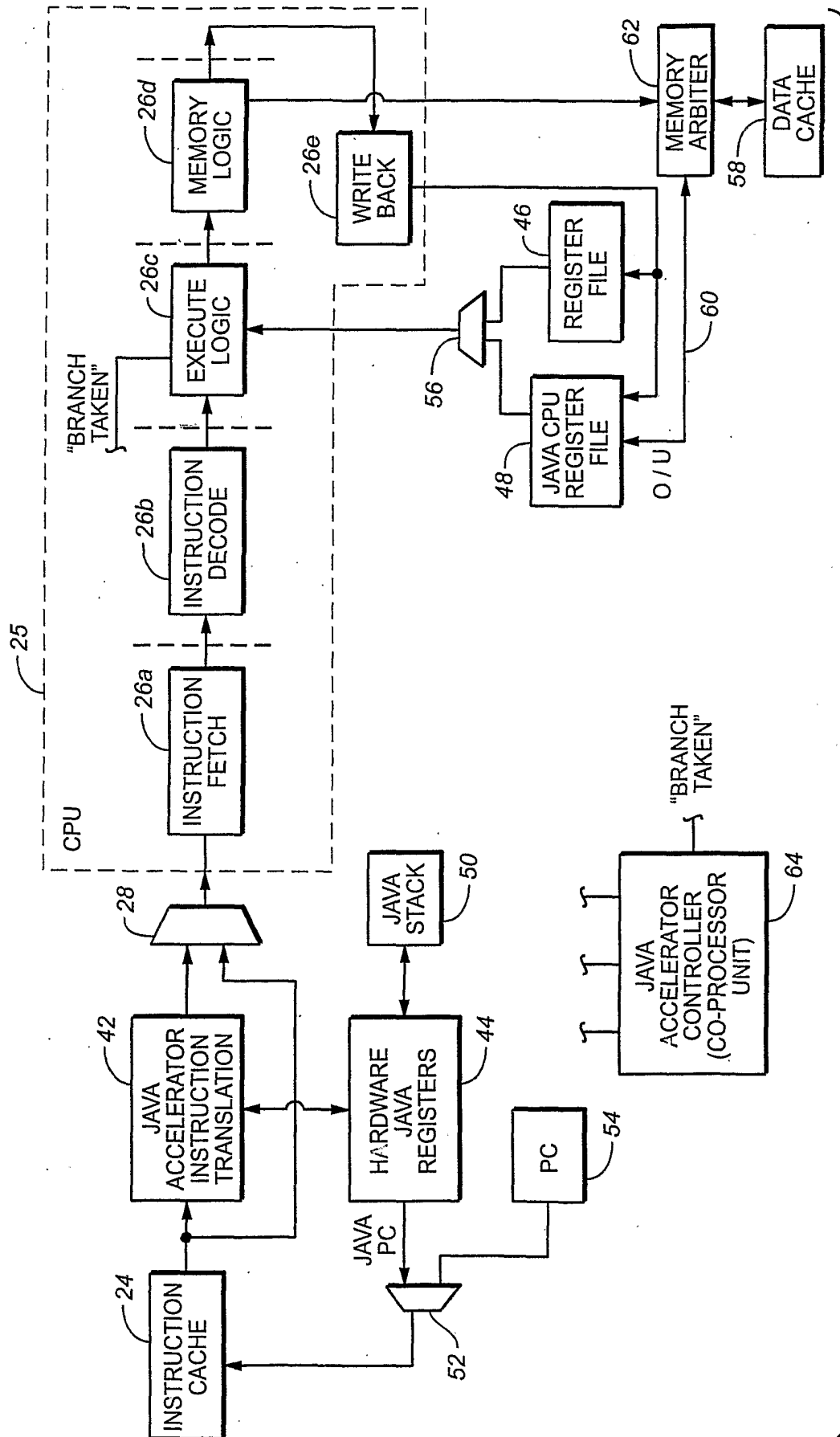


FIG. 3

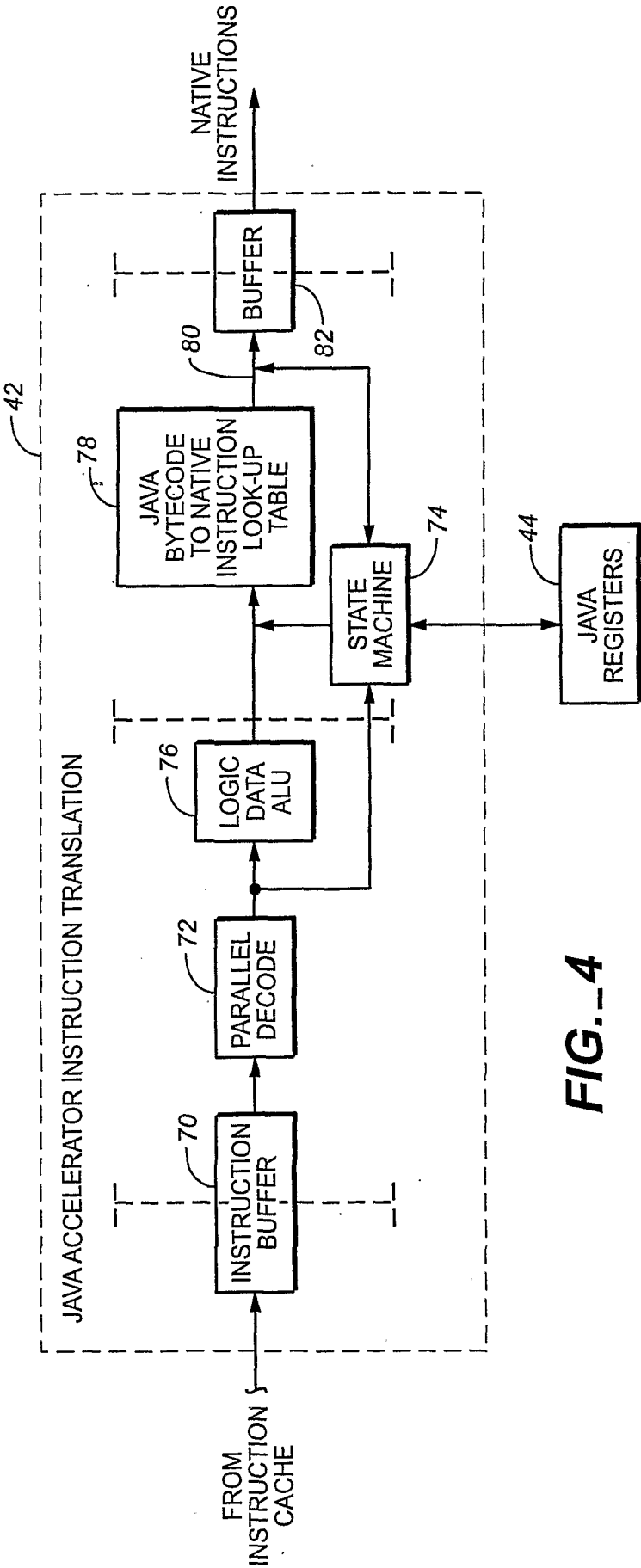


FIG. 4

I. INSTRUCTION TRANSLATION

JAVA
BYTECODE



NATIVE
INSTRUCTION

iadd

ADD R1, R2

II. JAVA REGISTER

PC = VALUE A
OPTOP = VALUE B
(R1)
VAR = VALUE C



PC = VALUE A + 1
OPTOP = VALUE B - 1
(R2)
VAR = VALUE C

III. JAVA CPU REGISTER FILE

CONTAINS VALUE OF TOP OF
OPERAND STACK → R0 0001
R1 0150
R2 1210
R3 0007
R4 0005
R5 0006
CONTAINS FIRST VARIABLE → R6 1221
R7 1361



NOT A VALID STACK VALUE → R0 0001
R1 0150
CONTAINS VALUE OF THE TOP OF
OPERAND STACK → R2 1360
R3 0007
R4 0005
R5 0006
R6 1221
R7 1361

IV. MEMORY

OPTOP = VALUE B → - 0150
(VALUE B - 1) - 1210
- 0007
- 0005
- 0006
- 0001
- 4427



- 0150
OPTOP = VALUE B - 1 - 1360
- 0007
- 0005
- 0006
- 0001
- 4427

VAR = VALUE C - 1221
- 1361
- 1101

VAR = VALUE C - 1221
- 1361
- 1101

FIG._5

I. INSTRUCTION TRANSLATION

JAVA
BYTECODE

iload_n
iadd



NATIVE
INSTRUCTION

ADD R6, R1

II. JAVA REGISTER

PC = VALUE A
OPTOP = VALUE B
 (R1)
VAR = VALUE C



PC = VALUE A + 2
OPTOP = VALUE B
 (R1)
VAR = VALUE C

III. JAVA CPU REGISTER FILE

 R0 0001
CONTAINS → R1 0150
VALUE OF
TOP OF
OPERAND STACK R2 1210
 R3 0007
 R4 0005
 R5 0006
CONTAINS FIRST → R6 1221
VARIABLE R7 1361



 R0 0001
CONTAINS → R1 1371
VALUE OF
TOP OF
STACK R2 1210
 R3 0007
 R4 0005
 R5 0006
CONTAINS → R6 1221
FIRST
VARIABLE R7 1361

IV. MEMORY

OPTOP = VALUE B → - 0150
 - 1210
 - 0007
 - 0005
 - 0006
 - 0001
 - 4427



OPTOP = VALUE B - 1371
 - 1210
 - 0007
 - 0005
 - 0006
 - 0001
 - 4427

VAR = VALUE C - 1221
 - 1361
 - 1101

VAR = VALUE C - 1221
 - 1361
 - 1101

FIG._6

Opcodes Mnemonic	Opcode xHH	Excep Gen
nop	0x00	
aconst_null	x01	
iconst_m1	x02	
iconst_n(0-5)	x03 - x08	
lconst_n(0-1)	x09 - x0a	
fconst_n(0-2)	x0c - x0d	
dconst_n(0-1)	x0e - x0f	
bipush	x10	
sipush	x11	
ldc	x12	y
ldc_w	x13	y
ldc2_w	x14	y
iload	x15	
lload	x16	
fload	x17	
dload	x18	
aload	x19	
iload_n(0-3)	x1a - x1d	
lload_n(0-3)	x1e - x21	
fload_n(0-3)	x22 - x25	
dload_n(0-3)	x26 - x29	
aload_n(0-3)	x2a - x2d	
iaload	x2e	
laload	x2f	
faload	x30	
daload	x31	
aaload	x32	
baload	x33	
caload	x34	
saload	x35	
istore	x36	
lstore	x37	
fstore	x38	
dstore	x39	
astore	x3a	
istore_n(0-3)	x3b - x3e	
lstore_n(0-3)	x3f - x42	
fstore_n(0-3)	x43 - x46	
dstore_n(0-3)	x47 - x4a	
astore_n(0-3)	x4b - x4e	
lstore	x4f	
lstore	x50	
fastroe	x51	
dastore	x52	
bastore	x53	
aastore	x54	
castroe	x55	
sastore	x56	

FIG. 7A

pop	x57	
pop2	x58	
dup	x59	
dup_x1	x5a	
dup_x2	x5b	
dup2	x5c	
dup2_x1	x5d	
dup2_x2	x5e	
swap	x5f	
iadd	x60	
ladd	x61	
fadd	x62	y
dadd	x63	y
isub	x64	
lsub	x65	
fsub	x66	y
dsub	x67	y
imul	x68	
lmul	x69	
fmul	x6a	y
dmul	x6b	y
idiv	x6c	y
ldiv	x6d	y
fdiv	x6e	y
ddiv	x6f	y
irem	x70	y
lrem	x71	y
frem	x72	y
drem	x73	y
ineg	x74	
lneg	x75	
fneg	x76	y
dneg	x77	y
ishl	x78	
lshl	x79	
ishr	x7a	
lshr	x7b	
iushr	x7c	
lushr	x7d	
iand	x7e	
land	x7f	
ior	x80	
lor	x81	
ixor	x82	
lxor	x83	
linc	x84	
i2l	x85	y
i2f	x86	y
i2d	x87	y
l2i	x88	y
l2f	x89	y
l2d	x8a	y

FIG._7B

f2i	x8b	y
f2l	x8c	y
f2d	x8d	y
d2i	x8e	y
d2l	x8f	y
d2f	x90	y
i2b	x91	
i2c	x92	
i2s	x93	
lcmp	x94	y
fcmpl	x95	y
fcmpg	x96	y
dcmpl	x97	y
dcmpg	x98	y
ifeq	x99	
ifne	x9a	
iflt	x9b	
ifge	x9c	
ifgt	x9d	
ifle	x9e	
if_icmpeq	x9f	
if_icmpne	xa0	
if_icmplt	xa1	
if_acmpge	xa2	
if_cmpgt	xa3	
if_icmple	xa4	
if_acmpeq	xa5	
if_acmpne	xa6	
goto	xa7	
jsr	xa8	
ret	xa9	
tableswitch	xaa	y
lookupswitch	xab	y
ireturn	xac	
lreturn	xad	
freturn	xae	
dreturn	xaf	
areturn	xb0	
return	xb1	
getstatic	xb2	y
putstatic	xb3	y
getfield	xb4	y
putfield	xb5	y
invokevirtual	xb6	y
invokespecial	xb7	y
invokestatic	xb8	y
invokeinterface	xb9	y
xxunusedxxx	xba	y
new	xbb	y
newarray	xbc	y
anewarray	xbd	y
arraylength	xbe	y

FIG. 7C

athrow	xbf	y
checkcast	xco	y
instanceof	xc1	y
monitorenter	xc2	y
monitorexit	xc3	y
wide	xc4	y
multianewarray	xc5	y
ifnull	xc6	y
ifnonnull	xc7	y
goto_w	xc8	
jsr_w	xc9	
ldc_quick	xcb	y
ldc_w_quick	xcc	y
ldc2_w_quick	xcd	y
getfield_quick	xce	y
putfield_quick	xcf	y
getfield2_quick	xd0	y
putfield2_quick	xd1	y
getstatic_quick	xd2	y
putstatic_quick	xd3	y
gtestatic2_quick	xd4	y
putstatic2_quick	xd5	y
invokevirtual_quick	xd6	y
invokenonvirtual_quick	xd7	y
invokesuper_quick	xd8	y
invokestatic_quick	xd9	y
invokeinterface_quick	xda	y
invokevirtualobject_quick	xdb	y
new_quick	xdc	y
anewarray_quick	xde	y
multinewarray_quick	xdf	y
checkcast_quick	xe0	y
instanceof_quick	xe1	y
invokevirtual_quick_w	xe2	y
getfield_quick_w	xe3	y
putfield_quick_w	xe4	y
breakpoint	xca	y
impdep1	xfe	y
impdep2	xff	y

FIG._7D

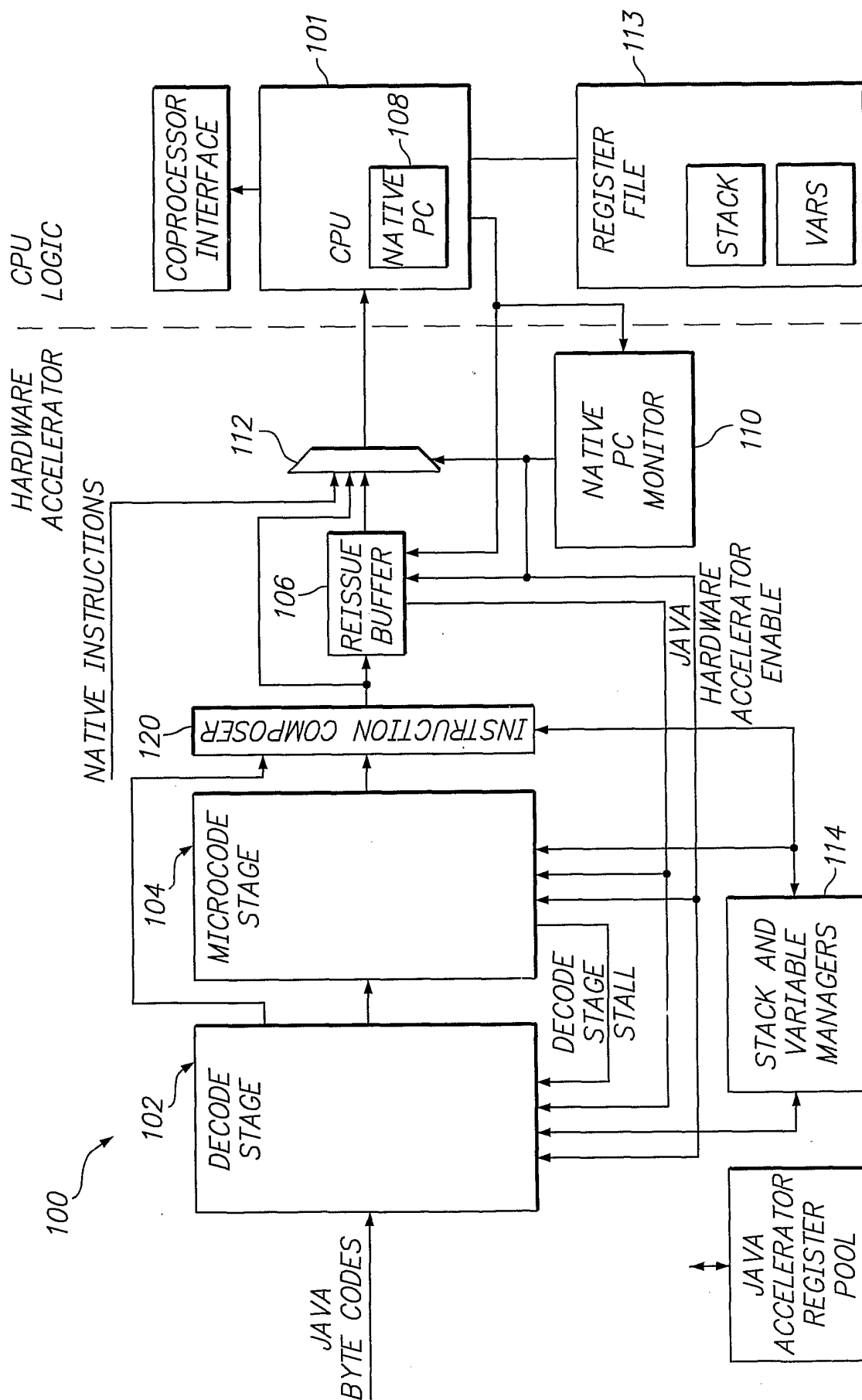


FIG. 8

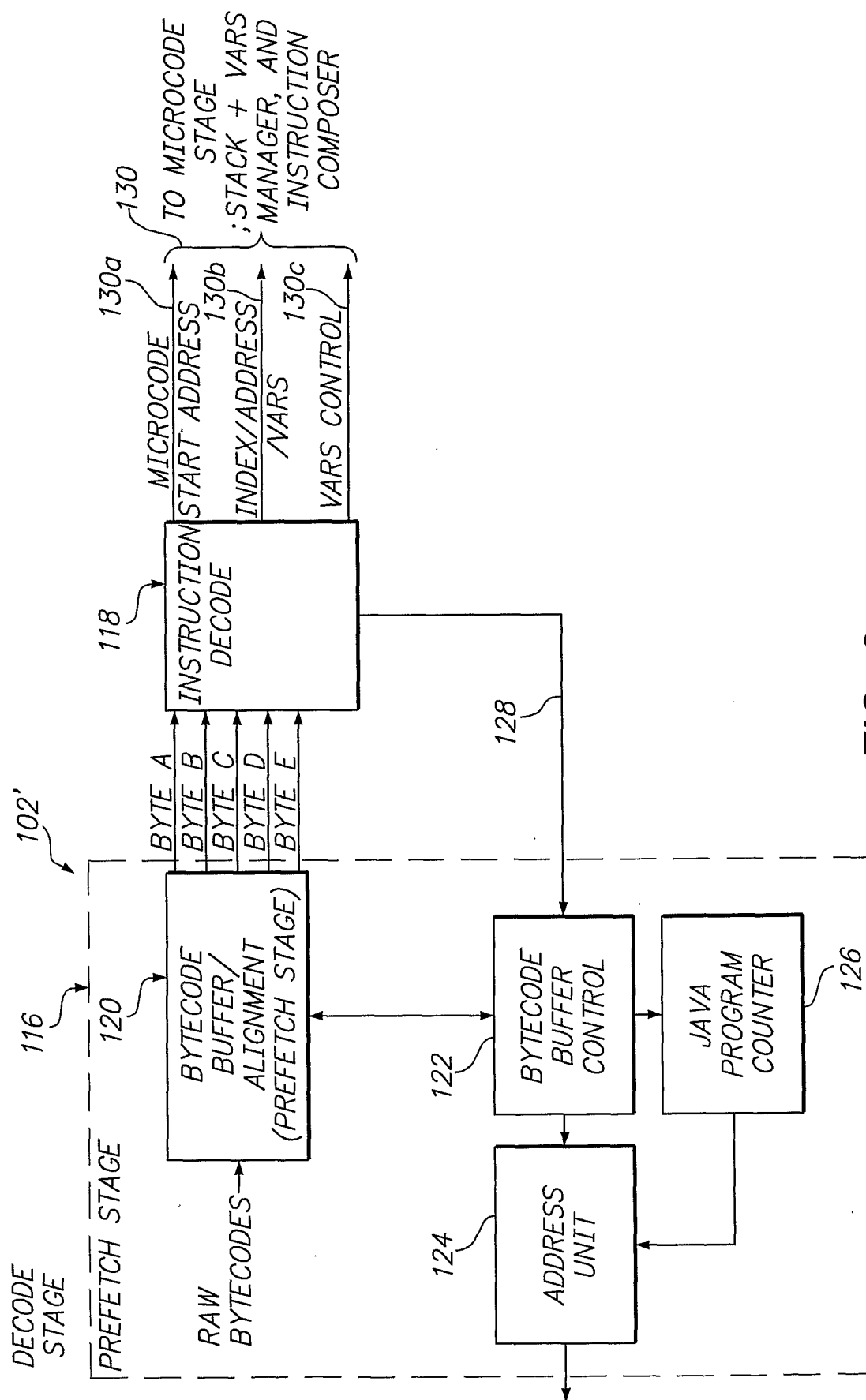


FIG. 9

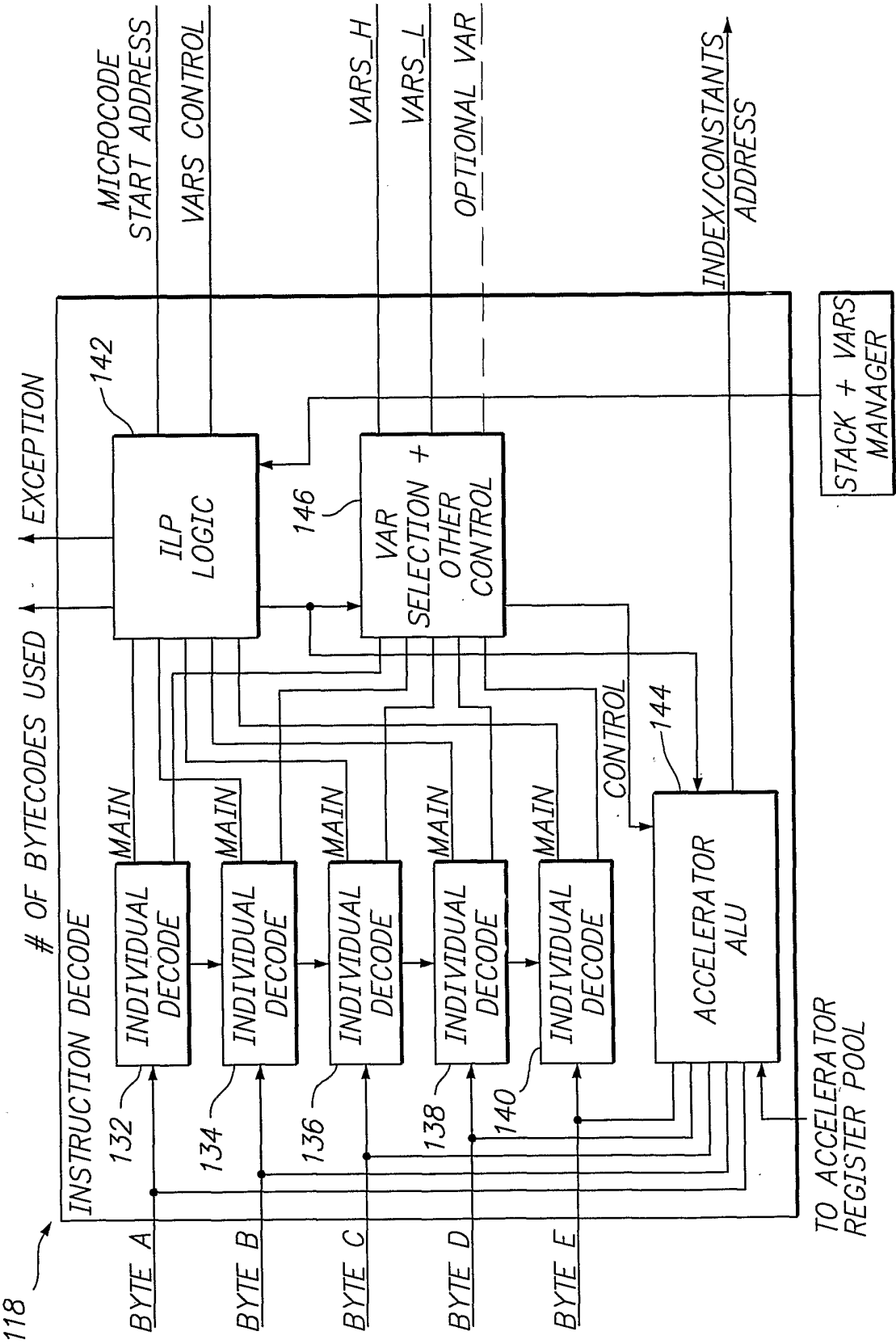


FIG. 10

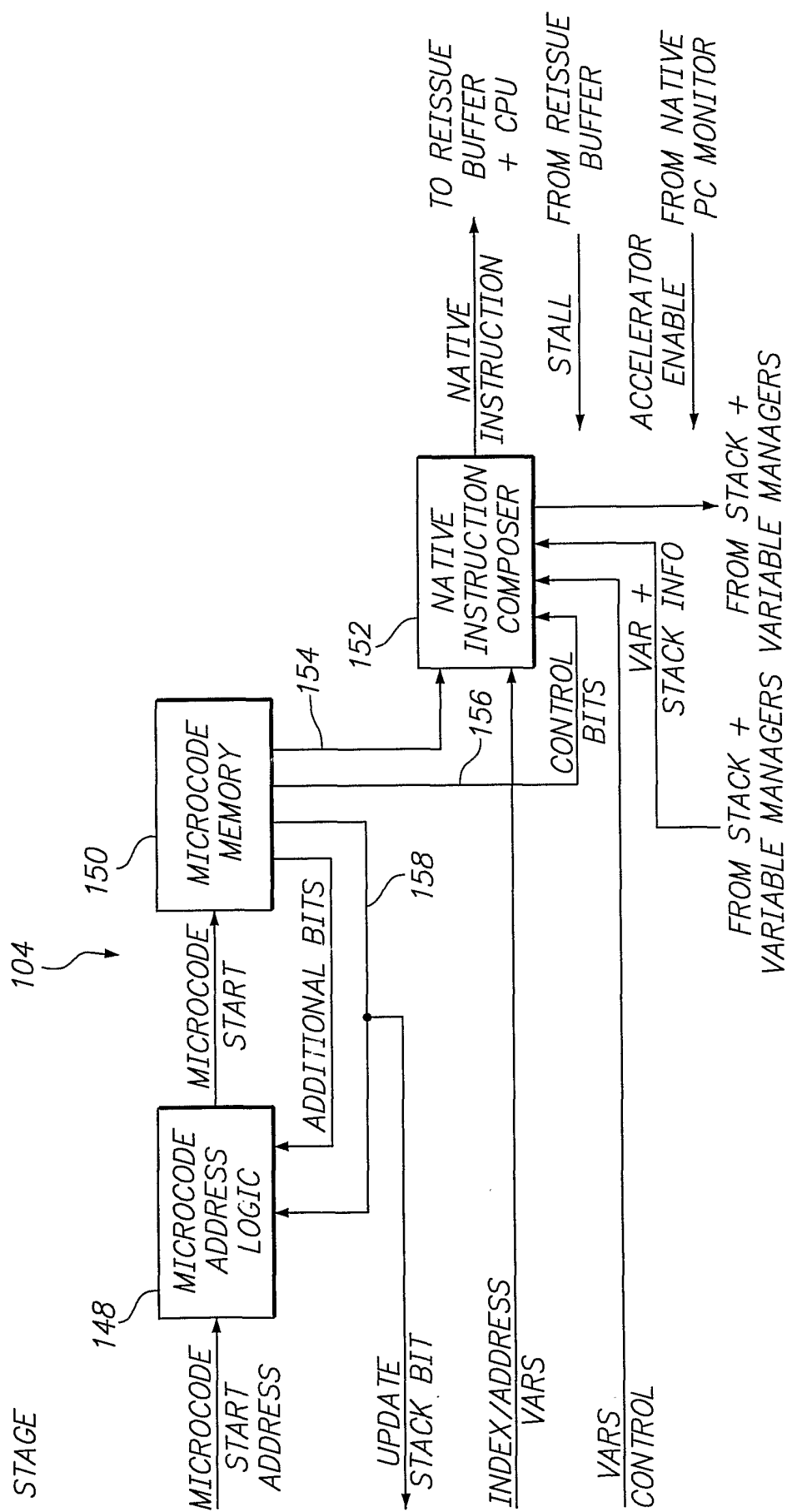
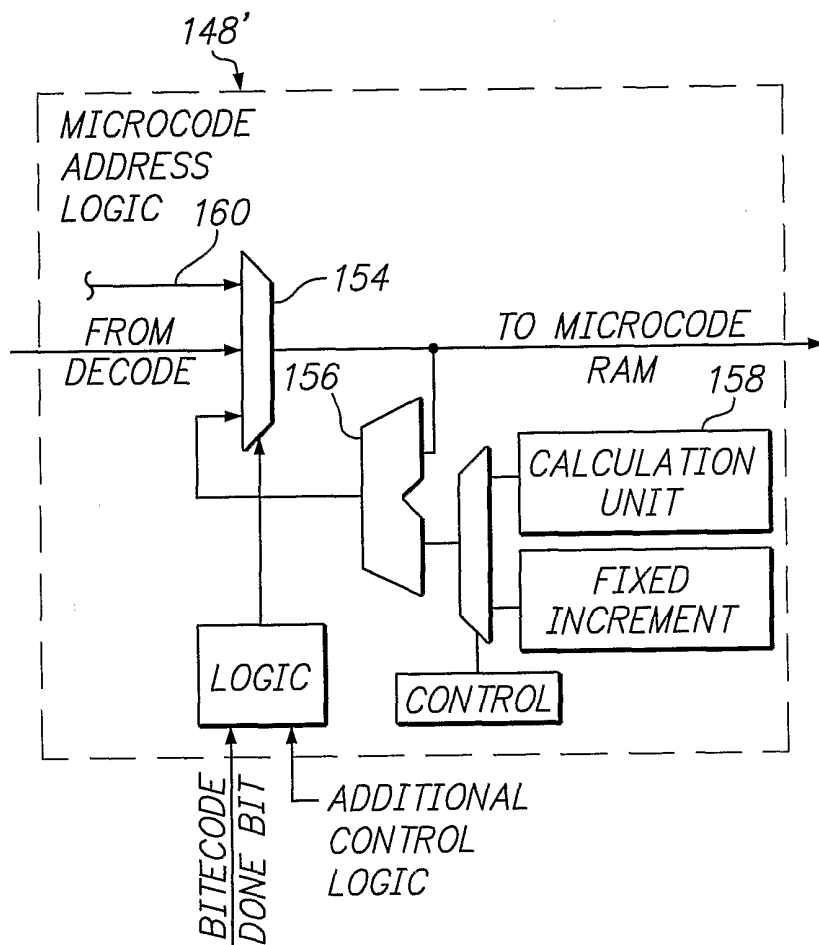


FIG. 11

**FIG. 12**

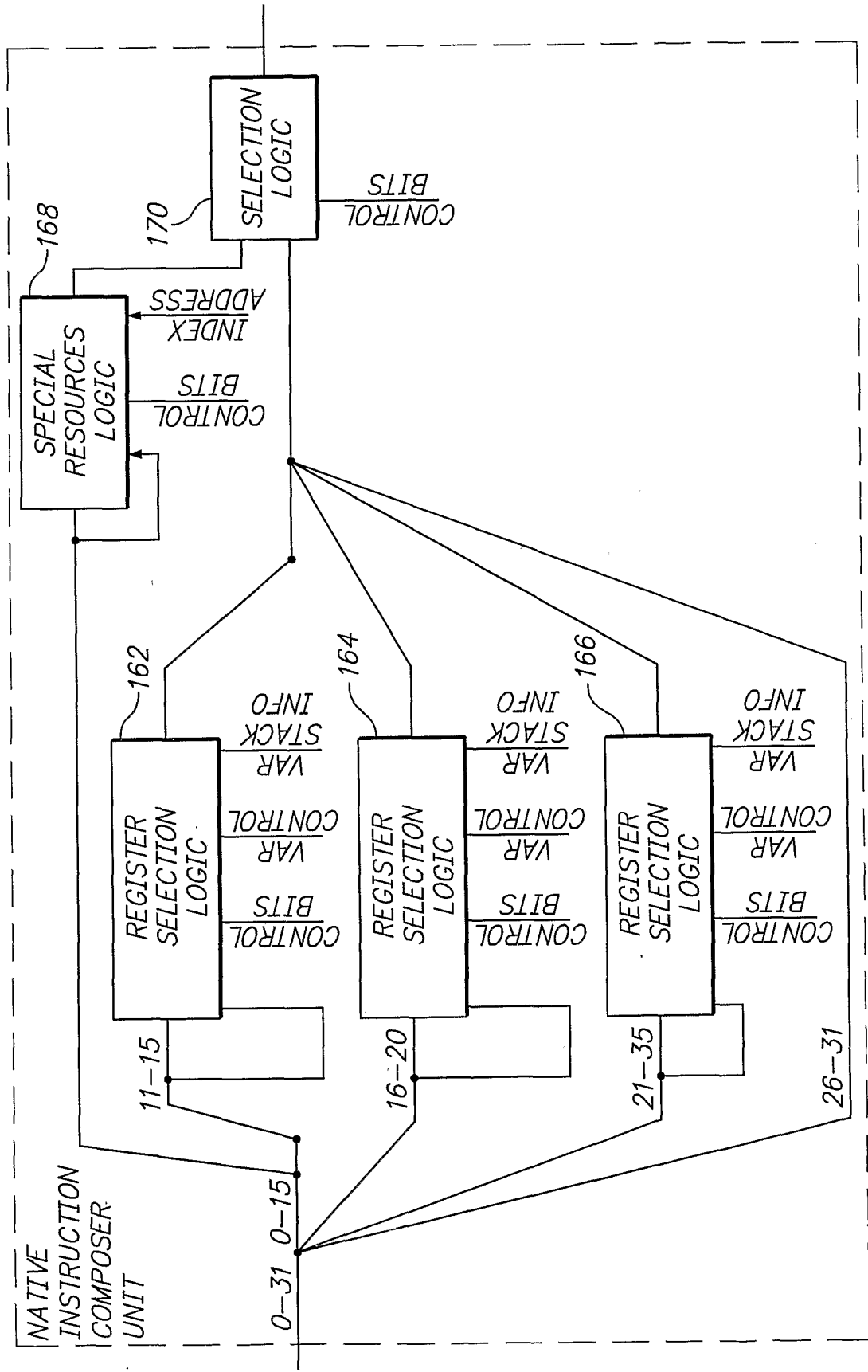
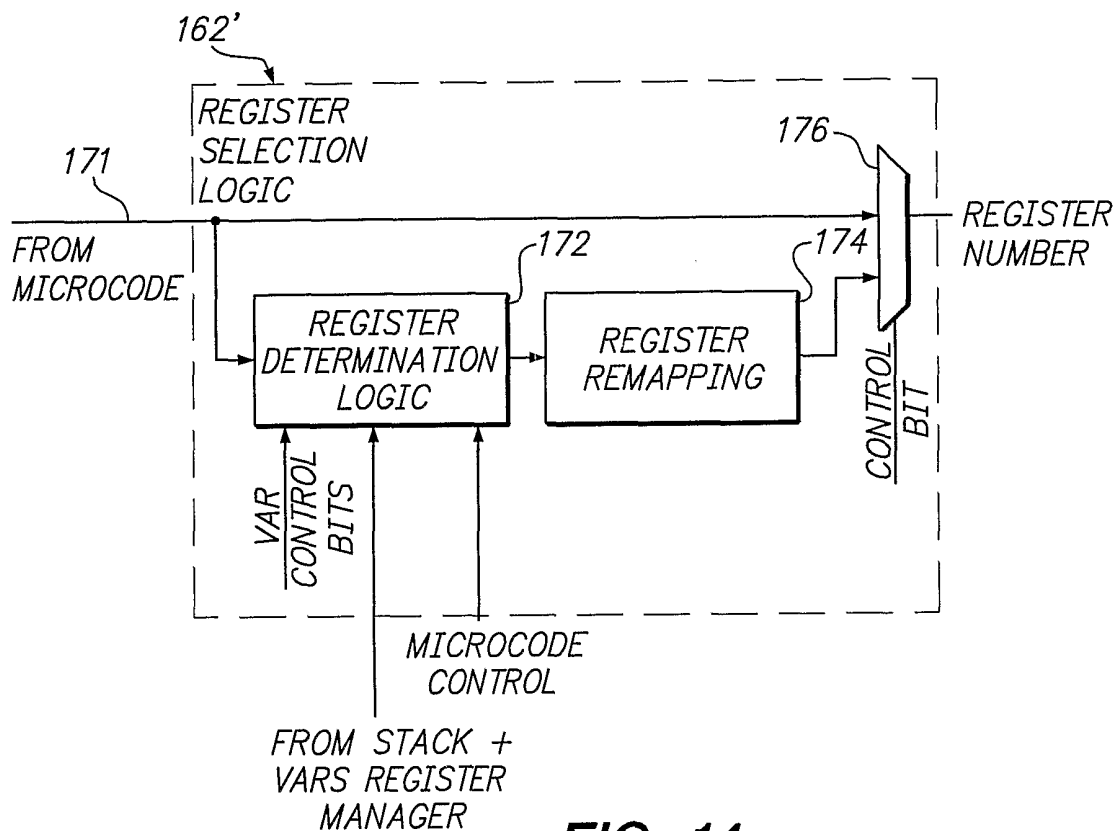
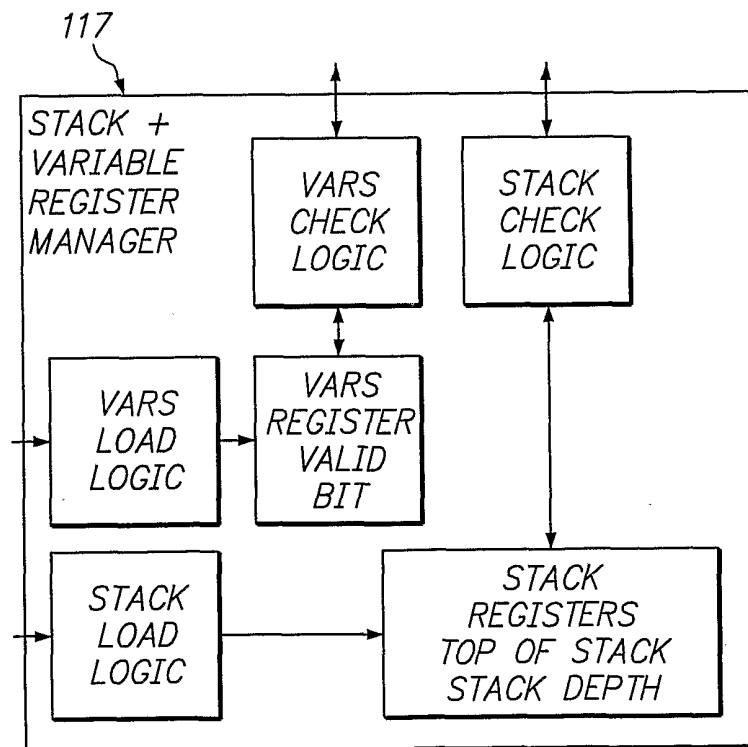


FIG. 13

**FIG. 14****FIG. 15**

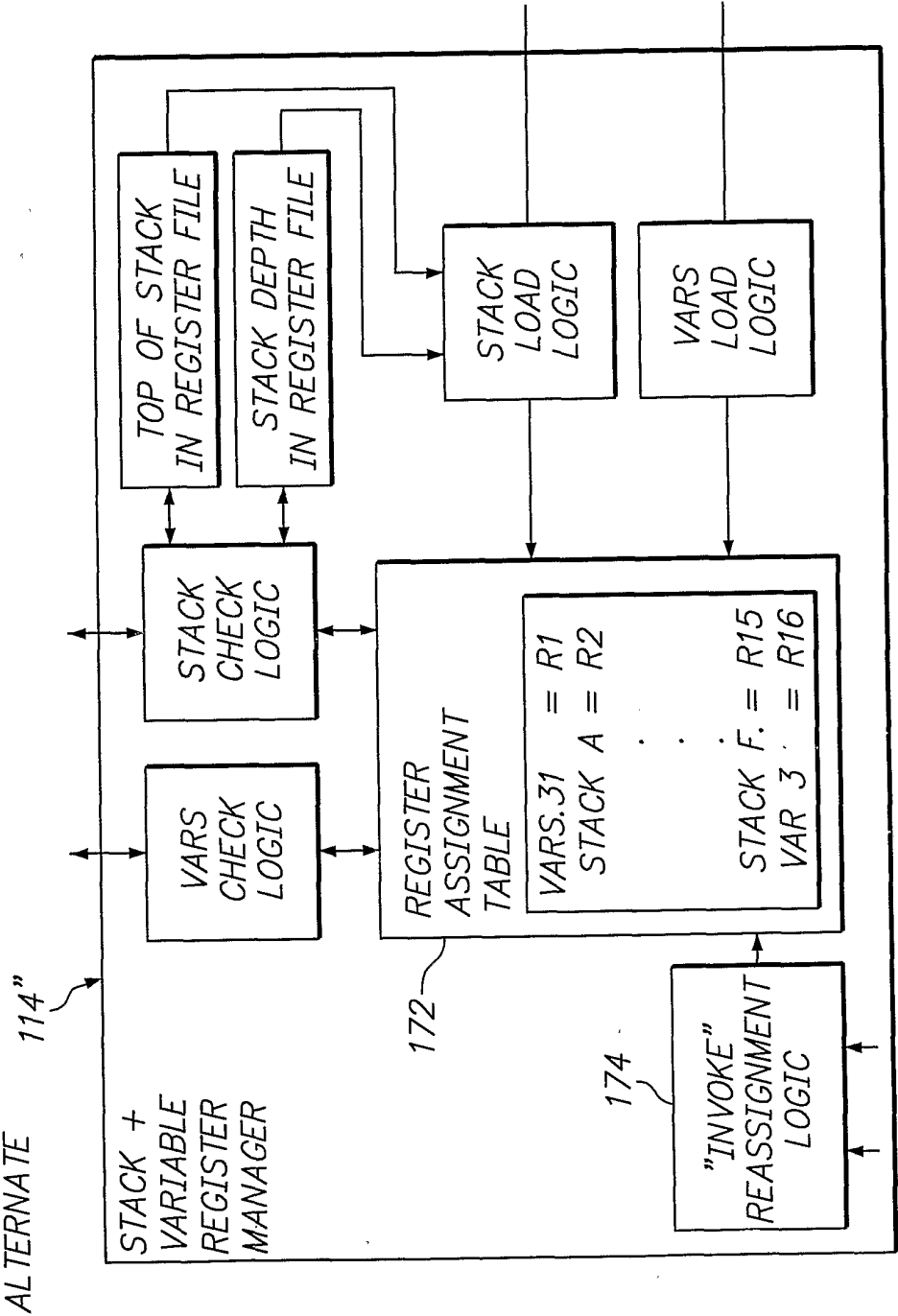
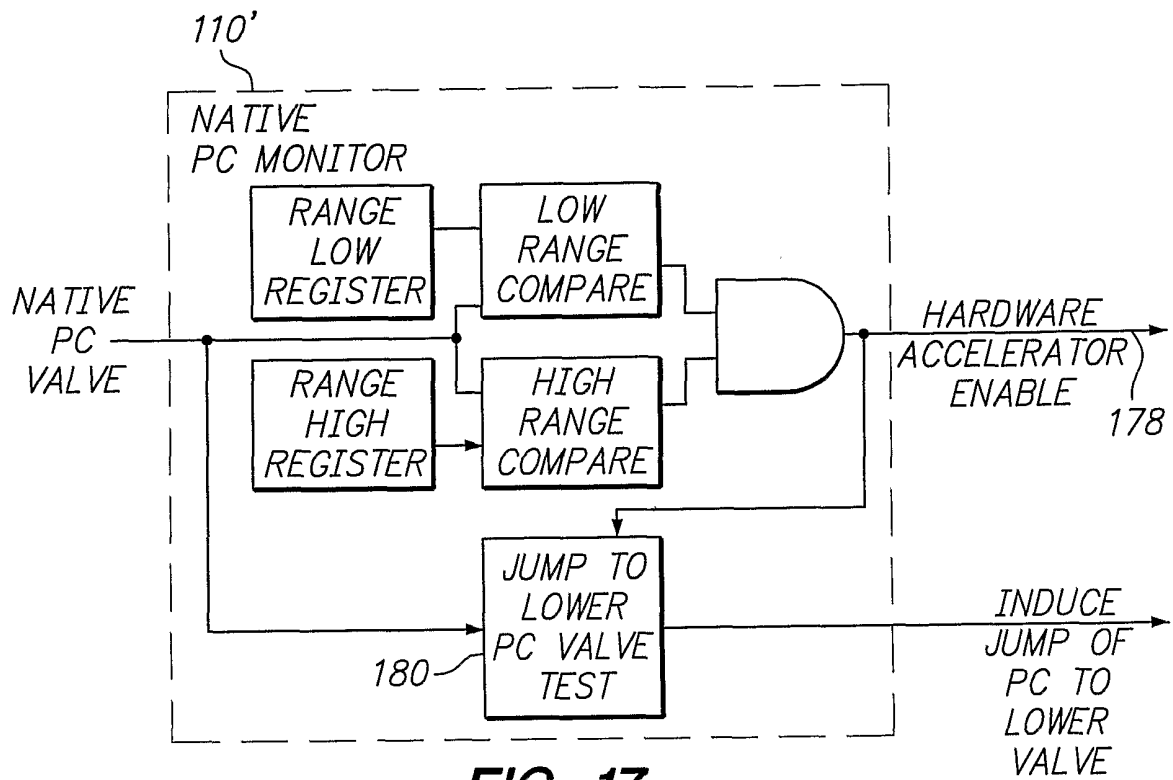
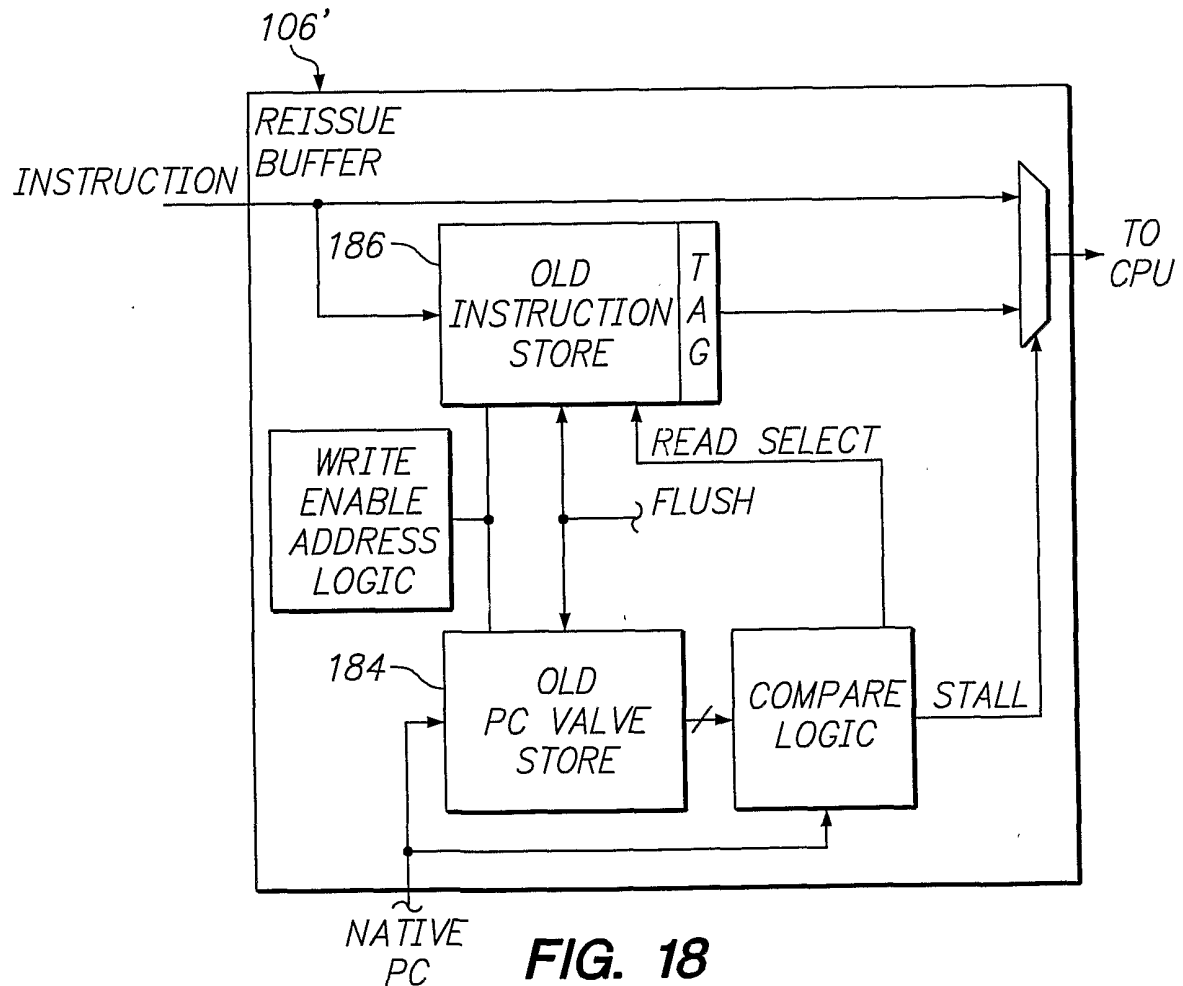


FIG. 16

**FIG. 17****FIG. 18**

TYPE COMBINATION		TEST
iload 31	→ LD →	NO
iload 5	→ LD →	
iadd	→ OP →	
istore 8	→ ST →	

DO LOAD OF
VAR 31 FROM
MEMORY

LOAD VAR BASE STORED IN
STACK MANAGE INTO
TEMP REGISTER R1

LOAD WORD R1 + 31(x4)
PUT RESULT INTO THE TOP
OF THE STACK

FIG. 19

IDEAL			
TYPE COMBINATION		VAR_TEST	
BYTECODE A → iload 3	→ LD →	YES	VAR_S_H=3
BYTECODE B → iload 5	→ LD →	YES	VAR_S_L=5
BYTECODE C → iadd	→ OP →	N/A	OP TYPE=iadd
BYTECODE D → iconst_0	→ CONST		VAR_H CONTROL=01
			VAR_L CONTROL=01
			TOS MODIFICATION=1+1-1-1
			BYTECODES USED=3

FIG. 20

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US01/42610

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :G06F 9/45

US CL :717/5

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 717/5, 717/1, 717/6,

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

STN, WEST, EAST

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,875,336 A (DICKOL et al) 23 February 1999, ABSTRACT, col 1 line 50-55, Fig 5, col 4 line 42-50, col 3 line 20-22, col 4 line 47-51	1-38
A	US 5,761,477 A (WAHBE et al) 02 June 1998, see entire document	1-38
A, P	US 6,167,488 A (KOPPALA) 26 December 2000, see entire document	1-38
A, P	US 6,026,485 A (O'CONNOR et al) 15 February 2000, see entire document	1-38
A, P	US 6,131,144 A (KOPPALA) 10 October 2000, see entire document	1-38

☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be of particular relevance	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E" earlier document published on or after the international filing date	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&" document member of the same patent family
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search Date of mailing of the international search report

02 NOVEMBER 2001

13 DEC 2001

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US01/42610

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	KRALL et al, CACAO - A 64-bit VM just-in-time compiler Concurrency: Practice and Experience, November 1997, vol 9(11), page 1017-1030	1-38