

The VEX System

This manual describes the VEX (“*VLIW Example*”) system. VEX includes three basic components:

1. **The VEX Instruction Set Architecture.** VEX defines a 32-bit clustered VLIW ISA that is scalable and customizable to individual application domains. The VEX ISA is loosely modeled upon the ISA of the HP/STMicroelectronics Lx/ST200 family of VLIW embedded cores. Scalability includes the ability to change the number of clusters, execution units, registers and latencies; customizability enables users to define *special-purpose* instructions in a structured way.
2. **The VEX C Compiler.** The VEX C compiler is a derivation of the Lx/ST200 C compiler, itself a descendant of the *Multiflow* C compiler. It is a robust, ISO/C89 compiler that uses *Trace Scheduling* as its global scheduling engine. A very flexible table-like machine model determines the target architecture. For VEX, we selectively expose some of the parameters to allow architecture exploration by changing the number of clusters, execution units, issue width and operation latencies, without having to recompile the compiler.
3. **The VEX Simulation System.** The VEX simulator is an architecture-level (functional) simulator that uses *compiled simulator* technology to achieve a speed of many equivalent ‘MIPS’. The simulation system also comes with a fairly complete set of POSIX-like *libc* and *libm* libraries (based on the GNU *newlib* libraries), a simple built-in cache simulator (level-1 cache only), and an API that enables other plug-ins used for modeling the memory system.

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1 The VEX Instruction Set Architecture

VEX defines an ISA in terms of the *Visible Architecture*, that is the syntax, semantics and constraints of operations. Since VEX is a flexible architecture, we can distinguish two types of constraints: the set of rules that all the implementations have to obey (such as the base ISA, register connectivity, memory coherency, architecture state, etc.); and the set of rules of a specific VEX instance (such as the issue width, the number of clusters, the mix of functional units, latencies and custom instructions).

VEX models a scalable technology platform for embedded VLIW processors that allows variation in issue width, the number and capabilities of structures such as functional units and register files, and the processor instruction set. In the spirit of statically scheduled VLIW architectures, the compiler is responsible for schedule correctness. In addition to basic data and operation semantics, VEX includes features to give the compiler greater flexibility in scheduling multiple concurrent operations. These include a complete exposure of all architecture latencies and resource constraints:

- Parallel execution units, including multiple integer ALUs and multipliers
- Parallel memory pipelines, including access to multiple data ports
- Architectural support for data prefetch and other locality hints
- A large architecturally visible register set
- Partial predication through *select* operations
- An efficient branch architecture with multiple condition registers
- Encoding of long immediate (32b) operands within the same instruction

This section specifies the structure and behavior of the VEX Architecture, and it excludes most implementation and microarchitecture details except those embodied in VEX.

VEX defines a parametric space of architectures that share a common set of application and system resources, such as registers and operations. A VEX instance (that is, an individual processor) implements a variation of the base architecture, that we obtain by specializing the set of customizable parameters, such as the issue width, the number and mix of functional units, etc. The most basic unit of execution in VEX is an **operation**, similar to a typical RISC-style instruction. An encoded operation is called a **syllable**, and a collection of syllables issued in a single cycle and executed in VLIW mode as an atomic unit is called an **instruction**.

VEX Assembler Notation

To understand the assembler notation for a VEX operation, consider the following example:

```
c0 cmpne $b0.3 = $r0.4, $r0.5
;;
```

The cluster identifier *c0* denotes the cluster upon which the operation is to be executed—0 in this case. The destination operand(s) are given by a list to the left of the “=”, while the source operands are listed to the right of the “=”. In this case, the only destination operand is *branch register #3 of cluster 0*, and the source operands are *general-purpose registers #4 and #5 of cluster 0*. In general, the cluster identifier is optional where registers are used as operands, since they uniquely identify the cluster upon which the operation is to be executed. The instruction separator “;;” indicates the end of a group of operations that are issued in the same cycle. Figure 1 shows a more detailed breakdown of the notation for a VEX instruction.

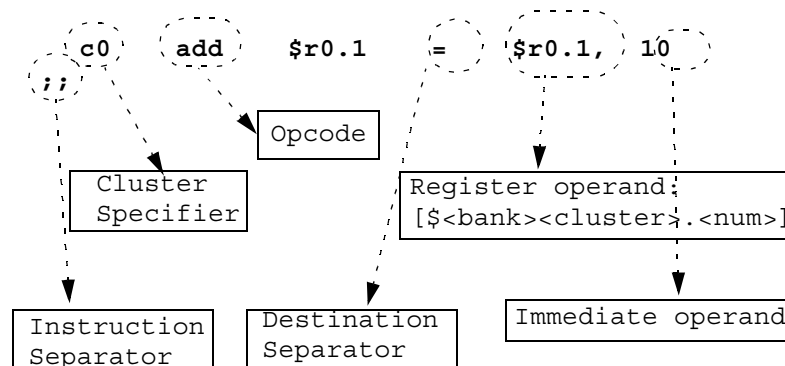


Figure 1 Anatomy of the assembler notation for a VEX instruction

Instructions that include multiple operations simply list each operation on a separate line, with a double semicolon as a separator of instructions. For example, the following assembler listing shows two instructions, the first one with two operations, and the second one with three.

```

c0 add $r0.13 = $r0.3, $r0.0    # instr 0, op 0
c0 sub $r0.16 = $r0.6, 3        # instr 0, op 1
;; ## end of first instruction

c0 shl $r0.13 = $r0.13, 3       # instr 1, op 0
c0 shr $r0.15 = $r0.15, 9       # instr 1, op 1
c0 ldw.d $r0.14 = 0[$r0.4]      # instr 1, op 2
;; ## end of second instruction

```

1.1 Clusters

VEX is a **clustered** architecture (Figure 2): it provides scalability of issue width and functionality using modular execution clusters. A cluster is a collection of register files and a tightly coupled set of functional units. Functional units within a cluster directly access only the cluster register files, with only a few exceptions. VEX clusters are architecturally visible and the code contains explicit cluster assignments (to choose the execution cluster for an operation), and explicit inter-cluster copy operations (to move data across clusters). Inter-cluster copy operations may require more than one cycle (pipelined or not) and may consume resources in both the source and the destination cluster. Since we can associate data cache ports and/or private memories with each cluster, VEX allows multiple memory accesses to execute simultaneously. Clusters obey the following set of

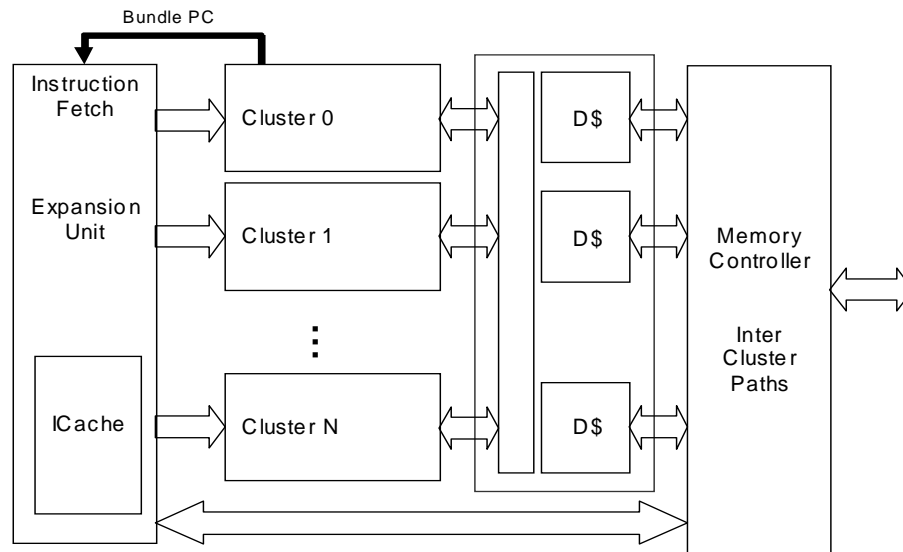


Figure 2 Structure of a VEX multi-cluster implementation. At the multi-cluster level, VEX defines the infrastructure to fetch and decode instructions, to sequence programs, to access memory and to move data across clusters.

rules:

- A single cluster can issue multiple operations in the same instruction
- Clusters can have different widths and different operation mixes
- Not all clusters have to support the entire VEX ISA
- Units within a single cluster are indistinguishable. In other words, a cluster can only execute a finite set of simultaneous operations, but these operations do not have to be assigned to particular units within the cluster. The hardware assigns operations to units within a cluster

By convention, VEX clusters are numbered from zero. Control operations execute on Cluster 0, which is—in this sense—a “special” cluster which must always be present in any VEX implementation.

At the architecture level, functional units are only connected to register files and not to other functional units. Microarchitecture bypassing (forwarding) is not exposed at the architecture level, but translates into shorter producer-consumer latencies. Functional units and register files within a single cluster are fully interconnected. In other words, it is always possible to write

the result of a functional unit to a register in the same cluster without passing through intermediate storage. Functional units and register files in different clusters may have limited connectivity: VEX only guarantees the minimal functionality to move data between general-purpose register files in different clusters. Note that some functional units (such as the branch unit) may read registers from other clusters.

1.2 Execution Model

A VEX architecture issues multiple operations in an instruction in a single cycle, and these operations are executed as **a single atomic action** (this is sometimes called *VLIW mode*). Instructions are executed strictly in program order, but within an instruction, **all operands are read before any results are written**. For example, it is possible to swap the value of a pair of registers in a single instruction. Instructions cannot contain sequential constraints among their operations.

The execution model treats instructions as atomic units. An exception caused by an instruction may not affect the execution of any instruction that was issued earlier and must prevent the instruction generating the exception from modifying the programmer visible state. The execution behavior is that of an *in-order* machine: each instruction executes to completion before the start of the next one. In other words, all syllables of an instruction **start together and commit their results together**. Committing results includes modifying register state, updating memory, and generating exceptions.

Operations may have architecturally visible non-unit latency (*Non-Uniform Assigned Latencies—NUAL*—model). Not all operations are required to have the same latency, and the compiler has to schedule the code while obeying latency constraints. Operations may have a different latency, depending on the functional unit or the source/destination register pair. If the hardware can complete an operation in the same number of cycles (or fewer) than assumed by the compiler, no stalls or interlocks are required. If an operation requires longer than the assumed latency, the hardware stalls execution until the architectural assumptions hold again (cache misses and branches fall into this category). In this sense VEX is a *less-than-or-equal—LEQ*—machine. When the hardware does not provide support to check for latency violations, the behavior of a code sequence that violates latency constraints is undefined.

Each VEX instance imposes limits on the number and type of operations that fit in a single instruction. When it is not possible to fill every available operation “slot”, the VEX encoding scheme ensures that no space is wasted. VEX encodes operations in 32-bit *syllables*, that include two reserved bits for sequencing and cluster encoding:

- The **instruction-stop bit** (set in the last syllable of an instruction) indicates the end of an instruction and is used by the sequencing logic to identify the execution boundaries within a cycle
- The **cluster-start bit** (set in the first syllable of a cluster within an instruction) indicates the beginning of the section of the instruction corresponding to a new cluster. Syllables of an instruction are required to be sorted in cluster order – from low to high addresses. The cluster-start bit is used by the dispersal logic to route the proper section of the instruction to the corresponding cluster

1.3 Architecture State

The architecturally visible state is composed of the collection of the state of all the architecturally visible **containers**. VEX containers include general-purpose registers, branch registers, control registers and in general any non-volatile and addressable storage element. VEX containers obey the following constraints.

- All architecturally visible containers must be individually addressable. In other words, no architecturally visible element can be implicitly part of a larger container without an operation that allows it to be individually addressed
- Architecturally visible containers are never overwritten by operations that do not explicitly specify the container among their destinations. Containers may not be implicitly overwritten (this would be an example of a “*hot spot*”).
- The architecture implementation must provide a “copy” mechanism to move data to and from any architecturally visible container

All VEX operations operate on 32-bit containers, and do not include specific support for non-32-bit values. For example, the memory architecture widens smaller accesses (8- and 16-bit) to 32-bit containers. Larger data types (e.g., 64-bit) are accessed with multiple 32-bit memory operations. Operations on smaller data types require the compiler to execute the proper sign/zero extensions. Note that, although they may appear as an exception of the previous rule, single-bit branch registers are actually a concise representation of the integer values ‘1’ and ‘0’. Operations that manipulate branch registers must perform the proper conversions when moving values between general-purpose registers and branch registers.

1.4 Arithmetic and Logic Operations

VEX supports a “traditional” set of RISC-style integer operations. Less traditional operations include *shift-and-add* (for effi-

cient address computations), *select* (for partial predication), logical *and/or* operations (for control-flow simplification), *min/max* operations and a rich set of *integer multiplication* operations. This version of VEX focuses on *integer* operations, and does not include any specific hardware support for floating-point, which is emulated through a library of intrinsics derived from the public-domain *SoftFloat*¹ package.

Table 1, Table 2 and Table 3 list the VEX arithmetic and logical operation with a brief description of each. In Table 2 we show the rich set of multiplication operations that VEX supports, as often required in DSP-like algorithms. In the tables, we use the notations *s1*, *s2* to indicate a source general-purpose register, *t* for a target general-purpose register, *b* for a branch register (source or destination), and *im* to indicate a source immediate (constant). VEX operations are semantics-based and format-independent, and the same opcode is used regardless of the type of operands and results. For example, VEX uses *add* for additions between registers, or between register and immediates.

Table 1: Integer Arithmetic Operations in VEX

Operation	Description
ADD $t=s1,\{s2 im\}$	Add
ADD ^{CG} $t,b=b,s1,s2$	Add with Carry and Generate Carry
AND $t=s1,\{s2 im\}$	Bitwise AND
ANDC $t=s1,\{s2 im\}$	Bitwise Complement and AND
DIVS $t,b=b,s1,s2$	Division step with Carry and Generate Carry
MAX $t=s1,\{s2 im\}$	Maximum signed
MAXU $t=s1,\{s2 im\}$	Maximum unsigned
MIN $t=s1,\{s2 im\}$	Minimum signed
MINU $t=s1,\{s2 im\}$	Minimum unsigned
OR $t=s1,\{s2 im\}$	Bitwise OR
ORC $t=s1,\{s2 im\}$	Bitwise complement and OR
SH1ADD $t=s1,\{s2 im\}$	Shift left 1 and add
SH2ADD $t=s1,\{s2 im\}$	Shift left 2 and add
SH3ADD $t=s1,\{s2 im\}$	Shift left 3 and add
SH4ADD $t=s1,\{s2 im\}$	Shift left 4 and add
SHL $t=s1,\{s2 im\}$	Shift left
SHR $t=s1,\{s2 im\}$	Shift right signed
SHRU $t=s1,\{s2 im\}$	Shift right unsigned
SUB $t=\{s2 im\},s1$	Subtract
SXTB $t=s1$	Sign extend byte
SXTH $t=s1$	Sign extend half
ZXTB $t=s1$	Zero extend byte
ZXTH $t=s1$	Zero extend half
XOR $t=s1,\{s2 im\}$	Bitwise Exclusive OR

Table 2: Multiplication Operations in VEX

Operation	Description
MPYLL $t=s1,\{s2 im\}$	Multiply Signed Low 16 x Low 16 bits
MPYLLU $t=s1,\{s2 im\}$	Multiply Unsigned Low 16 x Low 16 bits
MPYLH $t=s1,\{s2 im\}$	Multiply Signed Low 16 x High 16 bits
MPYLHU $t=s1,\{s2 im\}$	Multiply Unsigned Low 16 x High 16 bits
MPYHH $t=s1,\{s2 im\}$	Multiply Signed High 16 x High 16 bits
MPYHHU $t=s1,\{s2 im\}$	Multiply Unsigned High 16 x High 16 bits
MPYL $t=s1,\{s2 im\}$	Multiply Signed Low 16 x 32 bits
MPYLU $t=s1,\{s2 im\}$	Multiply Unsigned Low 16 x 32 bits
MPYH $t=s1,\{s2 im\}$	Multiply Signed High 16 x 32 bits

1. *SoftFloat* was written by John R. Hauser at the International Computer Science Institute (ICSI), in collaboration with the University of California at Berkeley. See <http://www.cs.berkeley.edu/~jhauser/arithmetic/softfloat.html> for more information.

Table 2: Multiplication Operations in VEX

MPYHU $t=s1,\{s2\}im$	Multiply Unsigned High 16 x 32 bits
MPYHS $t=s1,\{s2\}im$	Multiply Signed High 16 x 32, shift left 16

Table 3: Logical and Select Operations in VEX

Operation	Description
CMPEQ $\{t\}b=s1,\{s2\}im$	Compare (equal)
CMPEGE $\{t\}b=s1,\{s2\}im$	Compare (greater equal - signed)
CMPEGEU $\{t\}b=s1,\{s2\}im$	Compare (greater equal - unsigned)
CMPGT $\{t\}b=s1,\{s2\}im$	Compare (greater - signed)
CMPGTU $\{t\}b=s1,\{s2\}im$	Compare (greater - unsigned)
CMPLT $\{t\}b=s1,\{s2\}im$	Compare (less than equal - signed)
CMPLTEU $\{t\}b=s1,\{s2\}im$	Compare (less than equal - unsigned)
CMPLT $\{t\}b=s1,\{s2\}im$	Compare (less than - signed)
CMPLTU $\{t\}b=s1,\{s2\}im$	Compare (less than - unsigned)
CMPNE $\{t\}b=s1,\{s2\}im$	Compare (not equal)
NANDL $\{t\}b=s1,s2$	Logical NAND
NORL $\{t\}b=s1,s2$	Logical NOR
ORL $\{t\}b=s1,s2$	Logical OR
SLCT $t=b,s1,\{s2\}im$	Select $s1$ on True Condition
SLCTF $t=b,s1,\{s2\}im$	Select $s1$ on False Condition

Examples

The following example shows how to use *select* operations in a simple if-conversion (note that the VEX compiler would recognize this as *min* and *max*).

```
## Implements:
##         if (x > 10) t = 10;
##         if (x < 0) t = 0;
## where x is in $r0.1 and t is in $r0.2
##
c0 cmpgt $b0.0 = $r0.1, 10
c0 cmplt $b0.1 = $r0.1, 0
;;
c0 slctf $r0.2 = $b0.0, $r0.2, 10
;;
c0 slctf $r0.2 = $b0.1, $r0.2, 0
;;
```

The following example shows how to efficiently use the extensive multiplication repertoire in VEX (assumes a 2-cycle multiplication)

```
## Implements:
## int t = ((short)a)*((short)b) + (a>>16)*(b>>16)
## where a is in $r0.1, b in $r0.2 and t in $r0.3
##
c0 mpyll $r0.4 = $r0.1, $r0.2
c0 mpyhh $r0.5 = $r0.1, $r0.2
  xnop 1
;;
c0 add $r0.3 = $r0.4, $r0.5
;;
```

The following example shows how to efficiently use the logical operation repertoire in VEX to implement complex conditional expressions (assumes a 2-cycle compare-to-branch delay and a 2-cycle memory load). Note the use of speculation (*ldw.d*) to enable the manipulation of memory operations in conditionals.

```
## Implements:
## if ((a > 0 || d < 0) && *pb > c)
##     goto LABEL;
## a in $r0.3, pb in $r0.4, c in $r0.5, d in $r0.6
##
c0 cmpgt $r0.13 = $r0.3, $r0.0
c0 cmplt $r0.16 = $r0.6, $r0.0
c0 ldw.d $r0.14 = 0[$r0.4]
;;
```

```

c0 orl $r0.13 = $r0.13, $r0.16
;;
c0 cmpgt $r0.14 = $r0.14, $r0.5
;;
c0 andl $b0.0 = $r0.13, $r0.14
xnop 1
;;
c0 br $b0.0, LABEL
;;

```

1.5 Intercluster Communication

VEX uses a pair of *send* and *receive* operations to implement inter-cluster communication. Send/Receive operations specify a source/destination register and an intercluster path identifier. A *send* operation places the source register value on the specified inter-cluster path. The corresponding *receive* operation, which must be issued in the same instruction, retrieves the data from the specified inter-cluster path and stores it in the destination register. The immediate operand enables a large number of microarchitectural paths.

Table 4 shows the basic intercluster operations that VEX supports. For convenience and readability, VEX assembler usually represents pairs of *send/receive* operations with the macro *mov* as the example shows.

Table 4: Intercluster Operations in VEX

Operation	Description
SEND s1, im	Send <s1> to the path identified by <im>
RECV t = im	Assigns the value from the path identified by <im> to <t>

Example

```

## Copy reg.3 of cluster 0 to reg.4 of cluster 1
## Copy reg.1 of cluster 2 to reg.7 of cluster 3
## (in the same instruction)
##
c1=c0 mov $r1.4 = $r0.3
c3=c2 mov $r3.7 = $r2.1
;;

```

1.6 Memory Operations

VEX is a *load/store* architecture, meaning that only *load* and *store* operations can access memory, and that memory operations only target general-purpose registers (e.g., there are no *memory-to-memory* operations). This version uses a *big-endian* byte ordering model. Memory accesses in VEX are restricted to native alignment (i.e., *0 mod 2* for short, *0 mod 4* for int, *0 mod 8* for double). Misaligned accesses cause a non-recoverable trap.

VEX only supports a *base plus offset* addressing mode, where the base may be any general-purpose register, but the offset must be an immediate. For example, the following examples represent a subset of the supported load operations:

```

## int a[]; t = a[10] (a in $r0.2, t in $r0.1)
c0 ldw $r0.1 = 40[$r0.2]
;;

## short a[]; t = a[10] (a in $r0.2, t in $r0.1)
c0 ldh $r0.1 = 20[$r0.2]
;;

## char a[]; t = a[10] (a in $r0.2, t in $r0.1)
c0 ldb $r0.1 = 10[$r0.2]
;;

```

VEX supports speculative execution of memory *load operations*. Control speculation occurs when the compiler moves a load operation before a controlling branch in the original program order. VEX supports this form of speculation through *dismissible load* operations. A *dismissible load* (sometimes called *silent load*) ignores non-recoverable exceptions, so it guarantees that *correct programs run correctly*. On the other hand, programs that rely on the generation of non-recoverable exceptions may not be compatible with the VEX speculation model. VEX also supports the concept of explicit memory prefetching, through a *prefetch* operation.

When multiple memory accesses are allowed, VEX guarantees coherency between the memory structures, including caches and local memories. A VEX implementation may introduce stall cycles in order to provide this guarantee. Users are responsi-

ble for guaranteeing coherency beyond the uniprocessor model.

Table 5 shows the repertoire of VEX memory operations, including possible modifiers (represented as *{.modifier}*). VEX supports two flavors of memory modifiers: *dismissible* (“*d*”) to indicate *speculative operations*; and optional *locality hints* (“*s*” for “streaming” accesses, and “*l*” for “local” accesses).

Table 5: Memory Operations in VEX

Operation	Description
LDW{.d}{.s}{.l} t = im[s]	Load word
LDH{.d}{.s}{.l} t = im[s1]	Load halfword signed
LDHU{.d}{.s}{.l} t = im[s1]	Load halfword unsigned
LDB{.d}{.s}{.l} t = im[s1]	Load byte signed
LDBU{.d}{.s}{.l} t = im[s1]	Load byte unsigned
STW{.s}{.l} im[s1] = s2	Store word
STH{.s}{.l} im[s1] = s2	Store halfword
STB{.s}{.l} im[s1] = s2	Store byte
PFT{.s}{.l} im[s1]	Prefetch

The semantics of dismissible load operations are somewhat subtle. A dismissible load must return exactly the same value as a corresponding conventional load if such a load could be executed. When a conventional load would suffer a non-recoverable exception, the dismissible load must return a 0. Thus, the correct behavior of dismissible loads is tightly coupled with the processor exception model.

Access hints are performance enhancement hints and a VEX implementation may choose to ignore them. The VEX memory system may use different caching methods and/or memory structures depending on the access hint. For example, cache lines loaded by addresses tagged with spatial-only locality may be flagged to be replaced sooner than others.

Prefetch operations are also defined as hints to the underlying memory system. The intended behavior is to cause the requested data to be loaded into the local data cache (or prefetch buffer) if not already present. A legal, but not very interesting, implementation of prefetch is a NOP; semantically, a prefetch operation is indeed equivalent to a NOP—it is not allowed to modify the programmer visible state or to cause an exception. Properly implemented prefetch operations may be used to reduce cache miss rates by loading data into the cache in advance of a load or store operations, without stalling execution.

The following code shows an example of dismissible load:

```
## Implements:
##   if (p != 0) *p += 2
## With p in $r0.1, 2-cycle load, 2-cycle compare
##
c0 cmpne $b0.0 = $r0.1, 0
c0 ldw.d $r0.2 = 0[$r0.1]
   xnop 2
;;
c0 add $r0.2 = $r0.2, 2
c0 br $b0.0, L1
;;
c0 stw 0[$r0.1] = $r0.2
;;
L1:
```

1.7 Control Operations

VEX supports a simple statically-predicted branch architecture; branches are not considered the most critical operations for the typical media-processing embedded applications. The VEX compiler uses profiling and static branch prediction extensively to linearize the predicted paths—which coincide with the *fall-through* paths. To remove microarchitecture dependencies from the ISA level, VEX does not expose branch delay slots; the assumption is that the microarchitecture quashes the necessary instructions in the pipeline following a taken branch. In this way, it is possible to apply *dynamic branch prediction* schemes when they prove to be effective. VEX branches execute in two phases.

1. **Prepare the condition** specifying the branch, in advance of the control flow change point, and store it in a set of single-bit *branch registers*
2. **Execute the branch** based on the condition as the very last action of an instruction.

The presence of multiple branch registers allows the compiler to start preparing multiple conditions before executing the first branch. All compare and logical operations can target either a branch or a general register for flexibility. The delay between the generation of a condition and its use in a branch is exposed to the compiler. Only *cluster 0* supports the execution

of branch operations; however, all clusters can execute compare/logical operations and write the condition result to their own branch registers. In a multicluster organization, branches execute on *cluster 0*, but can read conditions from other clusters.

VEX specifies branch target addresses in two alternative ways: through a relative displacement from the program counter; or through the content of a special register (the *link register*) for indirect jumps. A simplifying assumption in VEX is that branch displacements (typically 24 bits) are wide enough to reach the entire *text* section. VEX support for *call* operations is limited to a simple *branch-and-link* operation, that saves the return pointer to the special *link register*. The software is responsible for all other calling conventions (save and restore registers, manage the stack), as we describe in Section 2 "The VEX Run-Time Architecture". Table 6 lists the VEX control operations; in addition to the standard notations, we also use *off* to indicate a PC-relative code offset, and *lr* for the VEX link register (*\$l0.0*).

Finally, a special operation is the multi-cycle no-operation control (*xnop*). In VEX, *xnop* operations take an argument and define the number of cycles that the machine must stall before issuing the next instruction. This can be implemented in various ways: with a separate operation (very inefficient), with a few bits in each instruction (good to cover small latencies), or it could even be completely ignored for a microarchitecture with a scoreboarded register file. The compiler can optionally be instructed to emit explicit *nop* operations (empty instructions) with the *-fno-xnop* flag.

Table 6: Control Operations in VEX

Operation	Description
GOTO <i>off</i>	Unconditional relative jump
IGOTO <i>lr</i>	Unconditional absolute indirect jump to link register
CALL <i>lr = im</i>	Unconditional relative call
ICALL <i>lr = lr</i>	Unconditional absolute indirect call to link register
BR <i>b, off</i>	Conditional relative branch on true condition
BRF <i>b, off</i>	Conditional relative branch on false condition
RETURN <i>t = t, off, lr</i>	Pop stack frame (<i>t = t + off</i>) and goto link register
RFI	Return from interrupt
XNOP <i>n</i>	Multicycle No-Operation(advance the pipeline for <i>n</i> cycles)

Examples

The following example shows how to use a combination of compare and logical operations to simplify the control flow and to start the preparation of multiple branches with multiple condition registers.

```
## Implements:
##           if (a || b) { [Block 1] };
##           if (a > 0 && b < 0) { [Block 2] } ;
## where a is in $r0.1 and b is in $r0.2
##
c0 orl $b0.0 = $r0.1, $r0.2
c0 cmpgt $r0.3 = $r0.1, 0
c0 cmplt $r0.4 = $r0.2, 0
;;
c0 andl $b1.0, $r0.3, $r0.4
;;
c0 br $b0.0, L1 ## L1 starts [Block 1]
;;
c0 br $b1.0, L2 ## L2 starts [Block 2]
;;
## Continue with the fallthrough path
```

In the multicluster case, two identical branch syllables are encoded in the instruction: the first (in cluster 0) provides the branch target, the second (in the condition cluster) provides the branch condition. For example, the following code sequence branches on a condition on cluster 2.

```
##
## Generate condition on cluster 2
##
c2 cmplt $b2.0 = $r2.1, $r2.0
xnop 1
;;
##
## Branch on cl.0 (also uses a syllable on cl.2)
##
c0 br $b2.0, L2
```

1.8 Structure of the default VEX Cluster

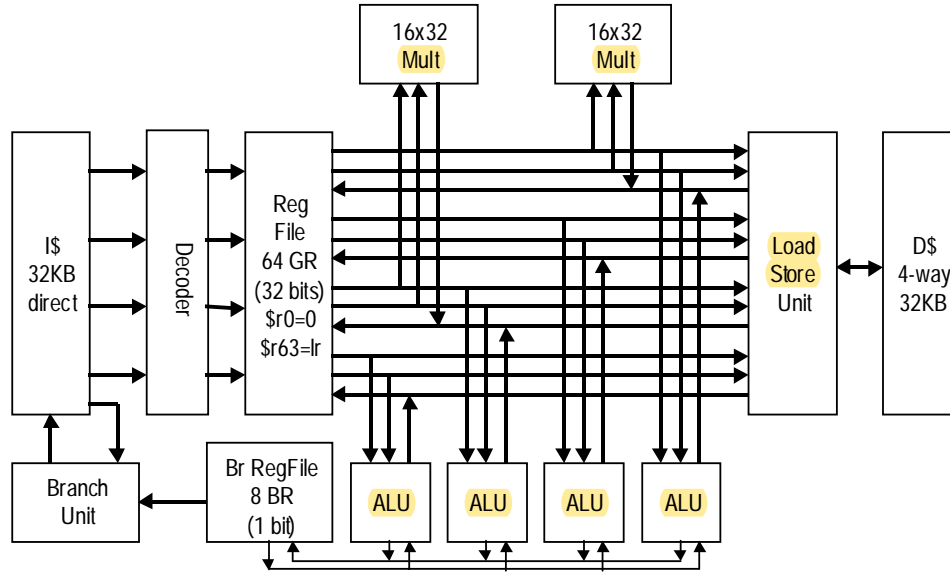


Figure 3 Structure of the default VEX cluster. What the VEX default configuration implements is a 4-issue cluster that loosely resembles the HP/ST ST220 VLIW processor core. The cluster includes 4 integer units, 2 multipliers, a load-store unit and a control unit. VEX allows to extend the cluster by changing issue width, number of clusters as well as other architecture parameters.

The default VEX cluster (supported by the default tool configuration) has two register files, four integer ALUs, two 16x32-bit multiply units, and a data cache port (Figure 3). The cluster can issue up to four operations per instruction. The register set consists of 64 general-purpose 32-bit registers (GRs) and 8 1-bit branch registers (BRs). In addition to the base computational resources, the default VEX cluster also contains a control unit (Branch Unit) for program sequencing.

Note that, without changing the base instruction set, the cluster organization could be significantly altered, with no impact on the software. For example, we could produce a cluster with two integer ALUs and one multiply unit. Similarly, the functionality of the cluster could be expanded with additional special purpose operations. The default VEX clusters contains *Memory*, *Integer*, and *Branch* functional units.

- **Memory Units** perform load, store, and prefetch operations. There are as many units as data cache memory ports connected to the cluster. Each Memory unit is associated with an access to the memory system.
- **Integer Units** execute the common set of integer, compare, shift and select operations, on registers or immediate operands
- **Branch Units** execute control operations based on the conditions stored in the branch registers, such as conditional branches, unconditional jumps, direct and indirect calls and returns.

Given the restriction that only four syllables may be used to encode the operations for the cluster, at most four operations may be issued in a single instruction.

Register Files and Immediates

VEX operand can be *general purpose* (GR) registers, *branch* (BR) registers, *link* registers (LR) or *immediates* (constants).

- **General-purpose Registers** are a set of 64 32-bit general-purpose registers, including one special registers: *register #0* wired to the constant '0'. The software conventions of the VEX RTA (see Section 2 "The VEX Run-Time Architecture") define other usage rules for other VEX registers.
- **Branch Registers** are a set of 8 1-bit registers written by compare/logical operations and read by conditional branches. In addition, branch registers are used as conditions for select operations and also store the carry bit for the operations that manipulate carries.

- **Link Register** for procedure calls, returns and indirect jumps.
- **Immediate Operands** encode compile-time and load-time constants. VEX instructions encode the necessary immediates without requiring extra operations. VEX supports three types of immediates: *branch offsets* (24-bit, for branch operations) fit in a single syllable; *short immediates* (9 bits, for all operations) fit in a single syllable; *long immediates* (32 bit, for all operations) draw bits upon one adjacent extension syllable in the same cluster and instruction. Immediate extensions are decoded in the same instruction of the operation that reads them, and carry no performance penalty.

1.9 VEX Semantics

This section describes the semantics of the VEX operations using the syntax of C preprocessor macros. This set of macros is very similar to what—for example—the VEX compiled simulator emits to implement VEX operations. The description only covers the architectural state changes of each operation without considering the exception behavior. The description of the computational operations is self-explanatory. The description of memory operations uses the set of “`sim_mem_access_safe*`()” utilities to mimic the behavior of *speculative* memory accesses that silently dismiss non-recoverable exceptions. The description of control operations uses the “`goto_instr(x)`” utility to indicate changes in control flow, and the “`next_instr()`” utility to indicate the address of the instruction following the current. Note that the *link register* used for system calls and indirect jumps is always explicitly nominated, since the VEX ISA prohibits “invisible” side-effects of operations on architecturally visible state.

```
/* Memory Macros and Operations */
#define UINT8(s) ((s) & 0xff)
#define INT8(s) (((signed) ((s) << 24)) >> 24)
#define UINT16(s) ((s) & 0xffff)
#define INT16(s) (((signed) ((s) << 16)) >> 16)
#define UINT32(s) ((unsigned) (s))
#define INT32(s) ((signed) (s))
#define MEM8(a) (*(volatile unsigned char*)(a))
#define MEM16(a) (*(volatile unsigned short*)(a))
#define MEM32(a) (*(volatile unsigned*)(a))
#define MEMSPEC8(a) sim_mem_access_safe8(a)
#define MEMSPEC16(a) sim_mem_access_safe16(a)
#define MEMSPEC32(a) sim_mem_access_safe32(a)

#define LDBs(t,s1) t = INT8(MEMSPEC8(s1)) /* speculative */
#define LDB(t,s1) t = INT8(MEM8(s1))
#define LDBUs(t,s1) t = UINT8(MEMSPEC8(s1)) /* speculative */
#define LDBU(t,s1) t = UINT8(MEM8(s1))
#define LDHs(t,s1) t = INT16(MEMSPEC16(s1)) /* speculative */
#define LDH(t,s1) t = INT16(MEM16(s1))
#define LDHUs(t,s1) t = UINT16(MEMSPEC16(s1)) /* speculative */
#define LDHU(t,s1) t = UINT16(MEM16(s1))
#define LDWs(t,s1) t = INT32(MEMSPEC32(s1)) /* speculative */
#define LDW(t,s1) t = INT32(MEM32(s1))
#define STB(t,s1) MEM8(t) = UINT8(s1)
#define STH(t,s1) MEM16(t) = UINT16(s1)
#define STW(t,s1) MEM32(t) = UINT32(s1)

/* Computational and Logical Operations */
#define ADD(t,s1,s2) t = (s1) + (s2)
#define AND(t,s1,s2) t = (s1) & (s2)
#define ANDC(t,s1,s2) t = ~(s1) & (s2)
#define ANDL(t,s1,s2) t = (((s1) == 0) | ((s2) == 0)) ? 0 : 1)
#define CMPEQ(t,s1,s2) t = ((s1) == (s2))
#define CMPNE(t,s1,s2) t = ((s1) != (s2))
#define CMPGT(t,s1,s2) t = (INT32(s1) > INT32(s2))
#define CMPGE(t,s1,s2) t = (INT32(s1) >= INT32(s2))
#define CMPLT(t,s1,s2) t = (INT32(s1) < INT32(s2))
#define CMPLE(t,s1,s2) t = (INT32(s1) <= INT32(s2))
#define CMPGTU(t,s1,s2) t = (UINT32(s1) > UINT32(s2))
#define CMPGEU(t,s1,s2) t = (UINT32(s1) >= UINT32(s2))
#define CMPLTU(t,s1,s2) t = (UINT32(s1) < UINT32(s2))
#define CMPLEU(t,s1,s2) t = (UINT32(s1) <= UINT32(s2))
#define MOV(t,s1) t = s1
#define MPYL(t,s1,s2) t = (s1) * INT16(s2)
```

```

#define MPYH(t,s1,s2) t = (s1) * INT16((s2) >> 16)
#define MPYHS(t,s1,s2) t = ((s1) * INT16((s2) >> 16)) << 16
#define MPYLU(t,s1,s2) t = (s1) * UINT16(s2)
#define MPYHU(t,s1,s2) t = (s1) * UINT16((s2) >> 16)
#define MPYLL(t,s1,s2) t = INT16(s1) * INT16(s2)
#define MPYLH(t,s1,s2) t = INT16(s1) * INT16((s2) >> 16)
#define MPYHH(t,s1,s2) t = INT16((s1) >> 16) * INT16((s2) >> 16)
#define MPYLLU(t,s1,s2) t = UINT16(s1) * UINT16(s2)
#define MPYLHU(t,s1,s2) t = UINT16(s1) * UINT16((s2) >> 16)
#define MPYHHU(t,s1,s2) t = UINT16((s1) >> 16) * UINT16((s2) >> 16)
#define NANDL(t,s1,s2) t = ((s1) == 0) | ((s2) == 0) ? 1 : 0
#define NOP() /* do nothing */
#define NORL(t,s1,s2) t = (((s1) == 0) & ((s2) == 0)) ? 1 : 0
#define ORL(t,s1,s2) t = (((s1) == 0) & ((s2) == 0)) ? 0 : 1
#define OR(t,s1,s2) t = (s1) | (s2)
#define ORC(t,s1,s2) t = ~(s1) | (s2)
#define SH1ADD(t,s1,s2) t = ((s1) << 1) + (s2)
#define SH2ADD(t,s1,s2) t = ((s1) << 2) + (s2)
#define SH3ADD(t,s1,s2) t = ((s1) << 3) + (s2)
#define SH4ADD(t,s1,s2) t = ((s1) << 4) + (s2)
#define SHL(t,s1,s2) t = (INT32(s1)) << (s2)
#define SHR(t,s1,s2) t = (INT32(s1)) >> (s2)
#define SHRU(t,s1,s2) t = (UINT32(s1)) >> (s2)
#define SLCT(t,s1,s2,s3) t = UINT32(((s1) == 1) ? (s2) : (s3))
#define SLCTF(t,s1,s2,s3) t = UINT32(((s1) == 0) ? (s2) : (s3))
#define SUB(t,s1,s2) t = (s1) - (s2)
#define SXTB(t,s1) t = UINT32((INT32((s1) << 24)) >> 24)
#define SXTH(t,s1) t = UINT32((INT32((s1) << 16)) >> 16)
#define XOR(t,s1,s2) t = (s1) ^ (s2)
#define XNOP(n) /* do nothing */
#define ZXTB(t,s1) t = ((s1) & 0xff)
#define ZXTH(t,s1) t = ((s1) & 0xffff)

/* Carry Manipulation */
#define ADDCG(t,cout,s1,s2,cin) { \
    t = (s1) + (s2) + ((cin) & 0x1); \
    cout = ((cin) & 0x1) \
        ? (UINT32(t) <= UINT32(s1)) \
        : (UINT32(t) <  UINT32(s1)); \
}
#define DIVS(t,cout,s1,s2,cin) { \
    unsigned tmp = ((s1) << 1) | (cin); \
    cout = UINT32(s1) >> 31; \
    t = cout ? tmp + (s2) : tmp - (s2); \
}

/* Basic Control Operations */
#define goto_instr(X) /* jumps to the instruction at address "x" */
#define next_instr() /* address of the instr following address "x" */

#define BR(b1,off) if (b1 == 1) goto_instr(off)
#define BRF(b1,off) if (b1 == 0) goto_instr(off)
#define GOTO(off) goto_instr(off)
#define IGOTO(lr) goto_instr(lr) /* "lr" is the link reg (l0)*/
#define CALL(off,lr) { lr = next_instr(); goto_instr(off); }
#define ICALL(off) { lr = next_instr(); goto_instr(s1); }
#define RETURN(sp,off,lr) { sp += off; goto_instr(lr); }

```

2 The VEX Run-Time Architecture

This VEX *Run-Time Architecture* (RTA) defines the common software conventions necessary to compile, link, and execute a VEX program. In other systems, it is sometimes also called *Application Binary Interface* (ABI). VEX applications run in a 32-bit environment and use the "ILP32" data model: where integers, long, and pointers are 32 bits. Within this specification, *half-word* refers to a 16-bit object, *word* refers to a 32-bit object, and *doubleword* refers to a 64-bit object

In the following we focus on a RTA model that is well suited for embedded systems, since it is restricted to a *single, stati-*

cally bound, non-relocatable load module. This model does not support dynamically-linked libraries, allows the use of absolute addresses, and it does not use function descriptors or a global data pointer.

2.1 Data Allocation and Layout

This section describes how to access and layout various types of data objects in the VEX world. All VEX items greater than 8 bytes must all be aligned on a 16-byte boundary. Smaller data items must be aligned on the next larger power-of-two boundary. In other words, 1-byte objects have no alignment restrictions, 2-byte objects have to be aligned $0 \bmod 2$; objects of size 3 and 4: $0 \bmod 4$; objects of size 5 to 8: $0 \bmod 8$; and so on

- **Global variables.** Common blocks, dynamically allocated regions (such as object returned by *malloc()*), and external data access are made with an *absolute address*.
- **Local static data** accesses are made with an *absolute address*
- **Local memory stack variables** accesses are relative to the stack-pointer register. Stack frames must always be aligned on a 32-byte boundary. That is, the stack pointer register must always be aligned on a 32-byte boundary.
- **Constants and literals.** may be placed in the text or data segments

Table 7 lists the fundamental scalar data types supported by the VEX architecture (values expressed in bytes).

Table 7: Scalar data types in VEX

Type	C	Size	Align	Hardware Representation
Integral	char	1	1	signed byte
	signed char			
	unsigned char	1	1	unsigned byte
	short	2	2	signed halfword
	signed short			
	unsigned short	2	2	unsigned halfword
	int, signed int	4	4	signed word
	long, signed long			
	enum			
	unsigned int	4	4	unsigned word
	unsigned long			
Pointer	<i>any-type</i> * <i>any-type</i> (*)()	4	4	unsigned word
Floating point	float	4	4	IEEE single precision
	double	8	8	IEEE double precision

Aggregate data types (structures, unions and arrays) assume the alignment of their most strictly aligned component. The size of any object, including aggregates and unions, is always a multiple of the object's alignment. An array uses the same alignment as its elements. Structure and union objects can require padding to meet size and alignment constraints. An entire structure or union object is aligned on the same boundary as its most strictly aligned member; an array object is aligned on the same boundary as its element type. Each structure member is assigned to the lowest available offset with the appropriate alignment. This may require internal padding, depending on the previous member. A structure's size is increased, if necessary, to make it a multiple of the alignment. This may require tail padding, depending on the last member. Figure 4 shows the layout of typical structures and bitfields.

2.2 Register Usage

VEX registers are partitioned into the following classes:

- **Scratch registers** may be destroyed by a procedure call; the caller must save these registers before a call if needed (also called *caller-saves*)
- **Preserved registers** must not be destroyed by a procedure call; the callee must save and restore these registers if used (also called *callee-saves*)
- **Constant registers** contain a fixed value that cannot be changed

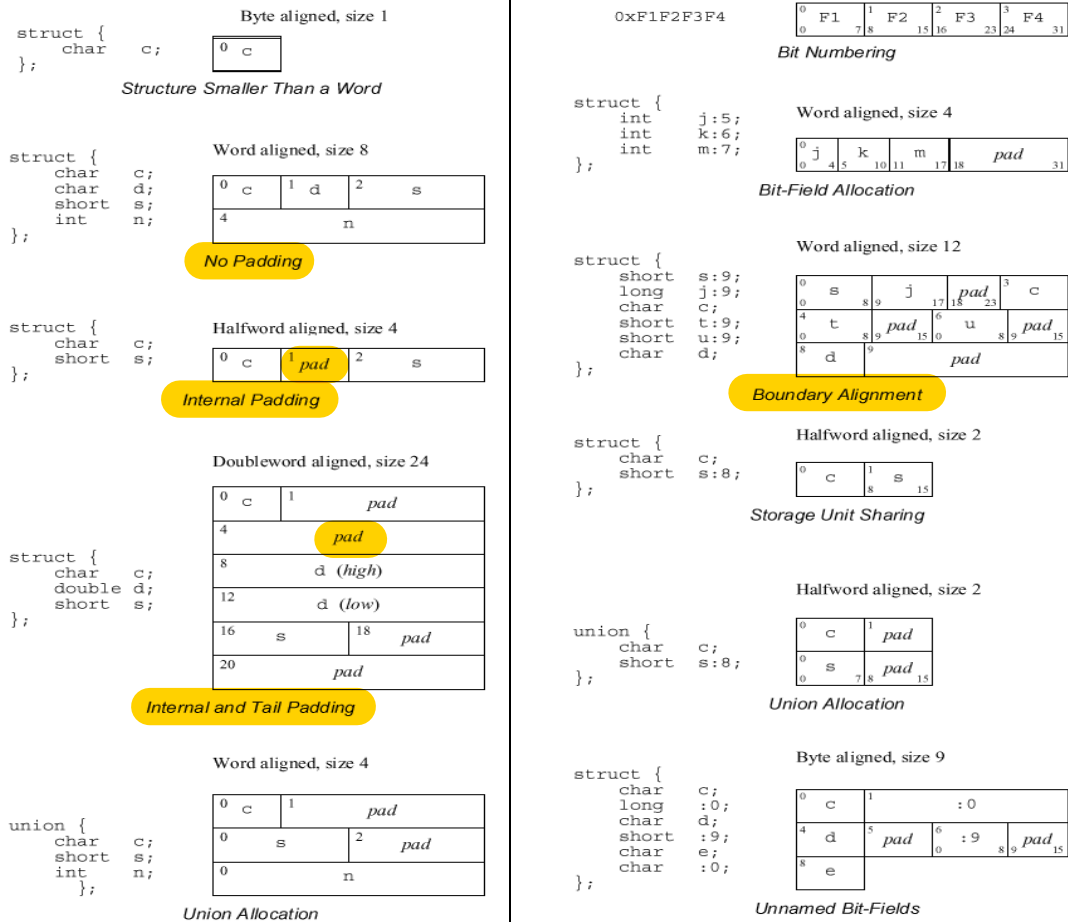


Figure 4 Layout of typical structures and unions (left) and bitfields (right) in VEX. The picture refers to a big-endian byte ordering model. Bit numbering is left-to-right for LSB-to-MSB bits.

- **Special registers**, used in the call/return mechanism

The following tables (Table 8 and Table 9) show a description of the register usage in VEX. Note that VEX defines a *user mode* where all the registers are available, and a *kernel mode* where only a subset of registers are available. The kernel mode is useful to reduce the overhead of context switches that do not require the whole set of registers offered by the processor.

Table 8: Register Usage in VEX

Register	Class	Usage (user-mode)	Usage (kernel-mode)
General Registers (cluster 0)			
\$r0.0	Constant	always zero	always zero
\$r0.1	Special	stack pointer	stack pointer
\$r0.2	Scratch	struct return pointer	struct return pointer
\$r0.3-\$r0.10	Scratch	argument/return value	argument/return value
\$r0.11-\$r0.15	Scratch	temporaries	temporaries
\$r0.16-\$r0.56	Scratch	temporaries	(unavailable)
\$r0.57-\$r0.63	Preserved	temporaries(callee-save)	
\$I0.0	Special	link register	link register
General Registers (other clusters)			
\$ri.0	Constant	always zero	always zero
\$ri.1-\$ri.56	Scratch	temporaries	(unavailable)
\$ri.57-\$ri.63	Preserved	temporaries(callee-save)	
Branch Registers (cluster 0)			

Table 8: Register Usage in VEX

Register	Class	Usage (user-mode)	Usage (kernel-mode)
\$b0.0–\$b0.3	scratch	temporaries	temporaries
\$b0.4–\$b0.7	scratch	temporaries	(unavailable)
<i>Branch Registers (other clusters)</i>			
\$bi.0–\$bi.7	scratch	temporaries	(unavailable)

2.3 Stack Layout and Procedure Linkage

Table 9: Detailed register usage in VEX

<i>Cluster 0</i>	
\$r0.0	Constant register 0; if written to, it represents a <i>bit-bucket</i> (written values are discarded)
\$r0.1	The stack pointer holds the limit of the current stack frame, which is the address of the stack's bottommost, valid word. At all times, the stack pointer must point to a 0 mod 32 aligned area. The stack pointer is also used to access any memory arguments upon entry to a function and is preserved across any functions called by the current function
\$r0.2	Struct return pointer register. If the function called returns a struct or union value larger than 32 bytes, the register contains, on entry, the appropriately aligned address of the caller-allocated area to contain the value being returned. Scratch otherwise.
\$r0.3–\$r0.10	Argument and return values up to 32 bytes are passed in these registers. Arguments beyond these registers appear in memory (see Section 2.3 "Stack Layout and Procedure Linkage"). Within the called function, these registers are scratch registers.
\$r0.11–\$r0.56	Scratch registers (caller-saves) with no specific role in the calling sequence
\$r0.57–\$r0.63	Preserved registers (callee-saves) with no specific role in the calling sequence.
\$i0.0	Link register to store the return address on entry to a procedure. Branch operations read it for indirect local jumps, returns, and indirect function calls.
\$b0.0–\$b0.7	Scratch registers (caller-saves) with no specified role in the calling sequence.
<i>Other Clusters</i>	
\$ri.0	Constant register 0; if written to, it represents a <i>bit-bucket</i> (written values are discarded)
\$ri.1–\$ri.56	Scratch registers (caller-saves) with no specific role in the function calling sequence
\$ri.57–\$ri.63	Preserved registers (callee-saves) with no specific role in the calling sequence
\$bi.0–\$bi.7	Scratch registers (caller-saves) with no specified role in the calling sequence

The memory stack in VEX is used for spilled registers and parameter passing. It is organized as a stack of procedure frames, beginning with the main program's frame at the base of the stack, and continuing towards the top of the stack with nested procedure calls. The frame for the currently active procedure is at the top of the stack. The memory stack begins at an address determined by the operating system, and grows towards lower memory addresses. The stack pointer register always points to the lowest address in the current frame on the stack.

Each procedure creates its frame on entry by subtracting its frame size from the stack pointer, and removes its frame from the stack on exit by restoring the previous value of the stack pointer, usually by adding its frame size. Not every procedure needs a memory stack frame; however, every non-leaf procedure needs to save at least its return link.

A procedure frame (Figure 5) consists of two regions:

1. **Local storage.** A procedure may store local variables, temporaries, and spilled registers in this region
2. **Outgoing parameters.** Parameters in excess to those passed in registers are stored in this region. A procedure accesses its incoming parameters in the outgoing parameter region of its caller's stack frame
3. **Scratch area.** A 16-byte region provided as scratch storage for procedures called by the current procedure, so that each procedure may use the 16 bytes at the top of its own frame as scratch memory

The stack pointer must always be aligned at a 32-byte boundary (i.e., stack frames sizes are a multiple of 32 bytes), and programs may not write below the stack pointer. Most procedures have a fixed size frame. The VEX compiler determines the size required for each region, pads the local storage area to a multiple of 32 bytes, creates the frame by subtracting a constant from the previous stack pointer, and removes the frame by adding the same constant to the stack pointer before returning.

Procedure Linkage

VEX defines the following types of calls:

- **Direct calls**, made directly to the entry point of the target procedure

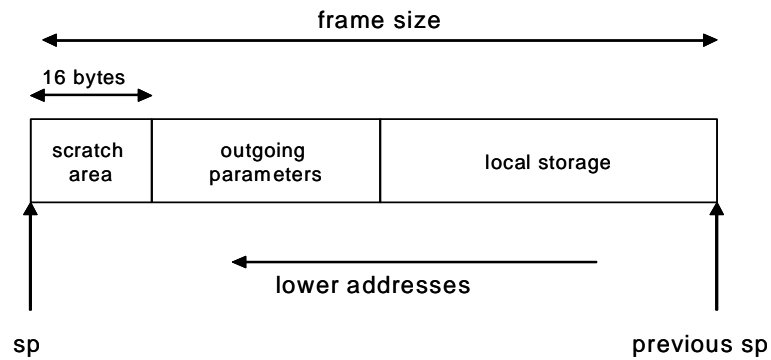


Figure 5 The VEX Procedure Frame

- **Indirect calls** made through a function pointer that points to the address of the function entry point for the target function.
- **Special calls** made through a special calling convention negotiated between the compiler and the run-time system (e.g., *intrinsics* calls).

For all calls, the compiler has to keep the values that live across the call alive in scratch registers, by saving them into preserved registers or on the memory stack; it must set up parameters in registers and memory; then issue the call operation, assuming that the call displacement field is sufficiently wide to reach any target. The call operation saves the return link in the link register.

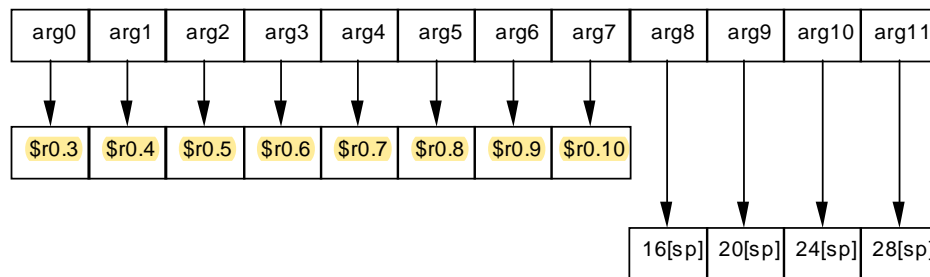


Figure 6 Parameter Passing in VEX

At **procedure entry**, the compiler allocates a frame on the memory stack, if necessary. Then, if it is a non-leaf procedure, it must save the return link in the memory stack frame, together with any preserved registers that will be used in this procedure.

At **procedure exit**, the compiler is responsible for restoring the return link and any preserved registers that were saved, as well as for deallocating the memory stack frame (if created). Finally, the procedure exits by branching through the link register with the *return* instruction. After the call, any saved values must be restored.

Parameters are passed in a combination of general registers and memory (Figure 6). The first 32 bytes of the parameter list are passed in registers, and the rest of the parameters are passed on the memory stack, beginning at the caller's stack pointer plus 16 bytes. The caller uses up to 8 general registers for parameters. To accommodate variable argument lists, there is a fixed correspondence between an argument's position in the parameter list and the register used for general register arguments. This allows a procedure to spill its register arguments easily to memory before stepping through the argument list with a pointer.

Parameters are first allocated on a conceptual argument list, which is then mapped to a combination of registers and the memory stack. The argument list begins at relative address 0, and is allocated towards increasing addresses. Each parameter begins on a 4-byte boundary. Each 4-byte unit in the argument list is called an *argument slot* (named *arg0*, *arg1*, *arg2*,...). Parameters may use more than one argument slot, and are aligned and padded within the argument list according to the following rules:

- Small integral scalar parameters (smaller than 4 bytes) are padded on the left to a total width of 4 bytes and placed in the next available argument slot
- 32-bit integral scalar, pointers and single-precision floating-point parameters are placed in the next available argument slot
- Double-precision floating-point scalar parameters are aligned to an 8-byte boundary (possibly leaving an argument slot empty), and placed in the next two consecutive argument slots
- Aggregates up to 4 bytes in size are padded to 4 bytes and placed in the next available argument slot

- Aggregates larger than 4 bytes are padded to a multiple of 4 bytes, aligned to an 8-byte boundary (possibly leaving an argument slot empty), and placed in as many argument slots as needed

The first eight argument slots (32 bytes) in the argument list are passed in registers, according to the previous rules, and are associated, one-to-one, with the procedure arguments. If an aggregate parameter straddles the boundary between *arg7* and *arg8*, the part that lies within the first eight slots is passed in registers, and the remainder is passed in memory. The remainder of the parameter list, beginning with *arg8*, is passed in the outgoing parameter area of the memory stack frame. Parameters are mapped directly to memory, with *arg8* placed at location *sp+16*, *arg9* at *sp+20*, and so on.

A function with variable arguments may assume that the first eight variable arguments can all be found in the argument registers. It may then store these registers to memory, using the 16-byte scratch area for *\$r0.7–\$r0.10*, and using up to 16 bytes at the base of its own stack frame for *\$r0.3–\$r0.6*. This arrangement places all the variable parameters in one contiguous block of memory.

Return values follow rules similar to arguments:

- Integral and floating-point values up to 4 bytes are returned in *\$r0.3*. For smaller integers, the contents of the upper bits must be zero-filled (if unsigned) or sign-extended (if signed) to 4 bytes
- 64-bit floating-point values are returned in *\$r0.3* and *\$r0.4*
- Aggregates smaller than 32 bytes are padded to a multiple of 4 bytes, and returned in successive general registers beginning with *\$r0.3*
- Return values larger than 32 bytes are returned in a buffer allocated by the caller. A pointer to the buffer is passed to the called procedure in *\$r0.2*

3 The VEX C Compiler

The VEX development system (sometimes referred to as the *VEX toolchain*) includes the set of tools that allow C programs compiled for a VEX target to be simulated on a host workstation. The center of the VEX toolchain is the Multiflow/VEX C compiler. The VEX toolchain is mainly intended for architecture exploration, application development, and benchmarking. It includes a very fast architectural simulator that uses a form of binary translation to convert VEX assembler files to native binaries running on the host workstation. The translator annotates the binaries to collect execution statistics and includes an (optional) cache simulator to collect D-cache and I-cache data. Figure 7 shows the overall structure of the VEX toolchain.

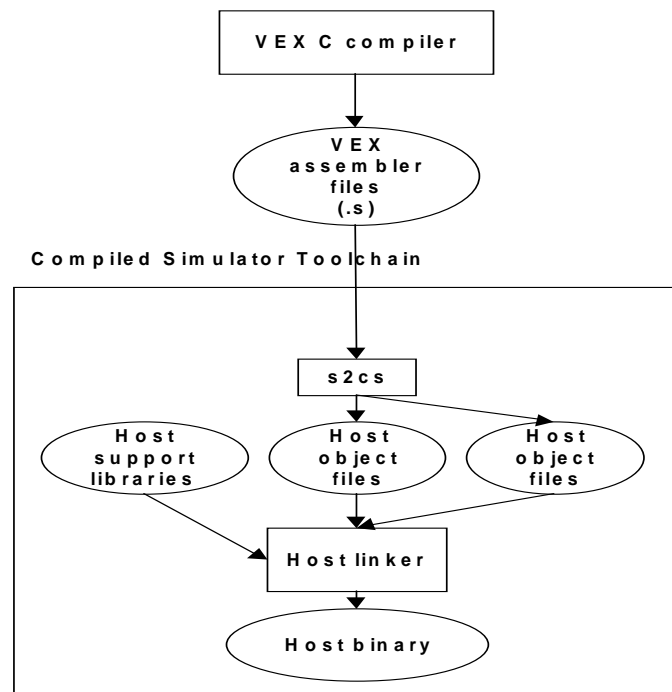


Figure 7 Structure of the VEX toolchain

A command-line interface controls the toolchain). The first level C compiler driver (“cc”) hides all the steps involved in

getting from a C program to an VEX “executable”. The toolchain directory tree looks like a standard compiler development tree, with a */bin* directory containing tools, a */lib* directory for libraries, a */usr/include* directory for headers, and so on.

The VEX *compiled simulator* uses a binary translator to generate an executable binary for the host platform that contains the operations to simulate a program compiler for VEX. For example, assuming that we want to compile two files *file1.c* and *file2.c* into a Linux binary *a.out*, the set of command to issue is:

```
$[1] <vex>/bin/cc -c file1.c
$[2] <vex>/bin/cc -c file2.c
$[3] <vex>/bin/cc -o a.out file1.o file2.o
```

Command 1 causes the following steps to be executed:

```
<vex>/bin/cc# cc shell
<vex>/lib/rcc# "real" cc driver
<vex>/lib/cpp <cpp_flags> file1.c file1.i # C preprocessor
<vex>/lib/ccom <ccom_flags> file1.i file1.s # C compiler
<vex>/lib/as <as_flags> # Assembler driver
<vex>/lib/s2cs <s2cs_flags> file1.s file1.cs.c # Compiled Simulator
<host>/cc -c file1.cs.c# Host C compiler
<host>/mv file1.cs.o file1.o # Move host object file
```

Command 2 causes the equivalent sequence on “file2.c”.

Command [3] causes the following steps to be executed:

```
<vex>/bin/cc# cc shell
<vex>/lib/rcc# "real" cc driver
<vex>/bin/ld <ld_flags> file1.o file1.o -o a.exe # Linker driver
<host>/cc -o a.exe# Linux C linker/loader
<vex>/lib/crt0.o # VEX C runtime initialization
file1.o file2.o # Application object files
<vex>/lib/libc.a # VEX C library
libcache.sl # Cache simulation library
ldcs.a # Simulation support library
<host>/libc.so.6 # Linux C library
```

Once steps 1 to 3 complete, we obtain a host executable binary *a.out* that can be executed simply by invoking it. The file *a.out* contains the compiled simulator image of the user application compiled for VEX and converted back into host object format. The image also contains various simulation helper functions, and the D-cache/I-cache simulators.

According to compile-time flags, the user can select different level of accuracy for the simulation:

- The **default mode** produces an executable that reproduces the correct behavior, and collects standard additional timing information for a set of default architecture parameters. The executable includes instrumentation code that counts execution statistics and optionally invokes the I-cache and the D-cache simulators. This mode can be used to benchmark applications and to evaluate the benefit of code transformations and compiler optimizations. Execution statistics are emitted in text form in files called “*ta.log.###*” that are emitted at program exit.
- When compiled with **profiling flags** (*-mas_g*) the executable includes instrumentation code that collects execution statistics and emits a file that can be interpreted by *gprof* to visualize profile data. This mode uses the native profiling support in the host C compiler to emit calls to the profiling routines at every routine entry point. At program exit the profile data is emitted so that *gprof* correctly interprets *simulated time*.

In default compilation mode, the intermediate steps are hidden to the user, and intermediate files (stored temporarily in the */tmp* directory) are removed after compilation, or on errors. To keep intermediate files, it is necessary to add the *-mas_g* and *-ms* flags to the compilation. Table 10 lists the relevant file suffixes generated by the VEX toolchain.

Table 10: File types in the VEX Toolchain

File type	Description
file.c	C source file
file.i	C preprocessed file, normally removed. Temporarily stored by the <i>rcc</i> driver as <i>/tmp/cpp####</i>
file.s	VEX assembly file, normally removed. Temporarily stored by the <i>rcc</i> driver as <i>/tmp/com####</i>
file.cs.c	VEX compiled simulator translated file, normally removed. Temporarily stored by the <i>as</i> driver as <i>/tmp/csim####.c</i>

Table 10: File types in the VEX Toolchain

file.o	Host object file containing the compilation of the CS translated file. Permanently saved for the link step for compilations with the <code>-c</code> flag
a.out	Host executable image containing the binary representing the user application and the simulation routines
ta.log.###	Output of the simulation, containing simulation and cache statistics
gmon.out gmon-nocache.out gmon-icache.out gmon-dcache.out	Output of the simulation when compiled with profiling flag on (<code>-mas_G</code>). Each of the “gmon-” file contains the gprof database, for cumulative data, execution data (<i>nocache</i>), instruction and data cache only (<i>icache</i> , <i>dcache</i>)
database.ifprob	Output of the VEX compiler when compiling for profile data collection for Profile-Based Optimization (<code>-prob_gen</code>)
ifprob.out ifprob.###	Output of the simulation when collecting profile data for Profile-Based Optimization (<code>-prob_gen</code>)

3.1 Command-line Options

The `cc` program is the driver for the VEX C Compiler. It supports the C language, as Defined by Kernighan and Ritchie in “*The C Programming Language*”, and the ISO C89 standard. A compilation command looks like this:

```
cc -o outputfile source1 source2 . . . sourceN
```

where *outputfile* is the name of the object file (or executable file) that you wish to create, and *source1* through *sourceN* are C source files and compiled object modules. The C compiler determines how to process these files on the basis of their filename, as follows.

- Files whose names end with ‘.c’ are taken to be C source programs; they are preprocessed, compiled, and assembled, and each object program is left on the file whose name is that of the source with ‘.o’ substituted for ‘.c’. The ‘.o’ file is normally deleted. By default, ‘.c’ files are compiled as ISO/ANSI C.
- Files whose names end with ‘.s’ are taken to be assembly source programs and are preprocessed and assembled, producing a ‘.o’ file.
- Files whose names end with ‘.i’ are taken to be compiler source programs and are not preprocessed.

Optimization is in effect by default. For more information about optimization, see the `-O` options (below). The following options (grouped by category) are interpreted by `cc`.

Output Files

This set of options determines which stages the compiler will execute, and which files it will leave after finishing.

-o output	Give the name output to the executable file produced by the loader, rather than the default name a.out. If this option is used, and the file ‘a.out’ already exists, it will be left undisturbed.
-c	Suppress the loading phase of the compilation; do not delete the ‘.o’ files produced by the assembler. These files may be loaded by <code>cc</code> or <code>ld</code> at a later time.
-S	Compile the named C programs, and leave the assembler-language output on corresponding files suffixed ‘.s’. No ‘.o’ file is produced.
-E	Run only the standard preprocessor on the named C programs, and send the result to the standard output. (See “Preprocessing.”)
-M	Run only the standard preprocessor on the named C programs, requesting it to generate Makefile dependencies and send the result to the standard output. (See “Preprocessing.”)

Preprocessing

Before compiling the program, the compiler invokes the standard GNU C preprocessor (`cpp`), which provides features like macro expansion and conditional compilation. The options in this set control `cpp`. Note that when using the K&R mode (`-KR` switch) the preprocessor is invoked with the “*-traditional*” switch, while the default mode of the preprocessor is invoked when

using the ANSI mode of the compiler (default, or *-mansi* switch).

-Dname=def	Define the name to the preprocessor, as if by '#define'. If no definition is given, the name is defined as "1".
-Dname	
-Uname	Remove any initial definition of name.
-Idir	'#include files whose names do not begin with '/' are always sought first in the directory of the file argument, then in directories named in -I options, then in directories on a standard list.
-C	Prevent the preprocessor from eliding comments. Normally, the preprocessor replaces all comments (i.e., all characters falling between /* and the next */) with a single space.
-E	Run only the standard preprocessor on the named C programs, and send the result to the standard output.
-M	Run only the standard preprocessor on the named C programs, requesting it to generate Makefile dependencies and send the result to the standard output. Dependencies are generated by analyzing the program's #include statements.

Optimization

This set of options determines how the compiler will optimize your program. Optimization is in effect by default (i.e., -O2 compilation). We only give rough definitions of the different optimization types. Each successive option provides additional optimizations in addition to those performed at the previous levels. By default, the option -O2 is in effect: this will provide good performance for most C programs. The -O4 -H* options should be used with care and on the basis of experimentation. In any large program, a few routines may benefit from these optimization levels. They should not be used for programs as a whole. For most compilations, you will not need to specify this option. The more aggressive loop unrolling options (-H2 through -H4) should be only be used for routines where experimentation has shown that they are effective. These will typically be routines whose execution time is dominated by a relatively simple loops. Note that the VEX system does not currently support source-level debugging. Although the compiler would correctly generate STABS directive when invoked with a "-g" flag, the VEX simulator would ignore them.

-O	Equivalent to -O2. This option is in effect by default.
-On	This series of options controls which optimizations the compiler performs, as follows: <ul style="list-style-type: none">-O1 All scalar optimizations-O2 Minimal loop unrolling and trace scheduling compilation-O3 Basic loop unrolling, trace scheduling compilation-O4 Heavy loop unrolling (see -H4)
-Hn	This series of options controls loop unrolling. They override the loop unrolling that is implicitly requested by the -On optimization options <ul style="list-style-type: none">-H0 No unrolling-H1 Basic unrolling-H2 Aggressive loop unrolling-H3 Heavy loop unrolling-H4 Very heavy unrolling
-lb_limit n	Set the «loop branch limit» to n. The compiler ceases to unroll any loop when the unrolled loops body has n internal branches. Branches to code outside of the loop body are not counted, and therefore do not inhibit unrolling. That is, -lb_limit puts an implicit limit on loop unrolling, supplementing the explicit limit provided by any source code directives or command line options. By default, the loop branch limit is 0; branches internal to a loop inhibits loop unrolling.
-fexpand-div	Instruct the compiler to replace call to library intrinsics with in-line assembly for integer divide and remainder functions. A single 32-bit division gets expanded to about 60 assembler operations and yields to significant code expansion and compile slow-down. To be used with caution - only when division performance is important.
-fno-xnop	Do not emit <i>xnop</i> instructions, but emit explicit <i>nop</i> instructions instead.

-fmm=<mmf>	Read machine description parameters (latency, resources, etc.) from file <mmf>
-autoinline	Enables automatic function inlining. Automatic inlining attempts to inline functions in the same module until an inlining “budget” is reached. The compiler also emits the code for the function being inlined, assuming that the assembler and the linker will remove unused functions.
-mincode	Turns on a set of flags aiming at minimizing code size of the generated object file. This set of flags usually adversely affects performance and should be used with caution.
-prefetch	Turns on automatic prefetch insertion
-cache_hints	Interprets cache locality hints and emits the corresponding memory instructions

Profiling

The compiler supports profile-based optimization with a three-step compilation process. The options controlling profiling are:

-prob_gen	The compiler annotates conditional branches with code that counts execution statistics (taken/not-taken branches). During this process, it saves the profile information in a file stored in the “ <i>database.ifprob</i> ” directory, corresponding to the name of the module. The module name and the profile directory can be changed through internal compiler options. When the executable is generated, the loader links in a module that contains the routine to dump the profile information. When the executable is run, the exit routine dumps the profile information in a file called “ <i>ifprob.out</i> ”, in the directory where the executable is run. If <i>ifprob.out</i> already exists, the compiler attempts to generate a file called “ <i>ifprob.nnn</i> ”, where <i>nnn</i> is an increasing number, until no file with such a name exists.
-prob_use	The compiler looks for a file called “ <i>ifprob.out</i> ” in the “ <i>database.ifprob</i> ” directory. If such a file exists, the compiler assigns branches the probability that has been computed in the previous profile run(s), and uses it to guide the selection of traces during trace scheduling. It is wise to use the same compiler options (except <i>-prob_gen/-prob_use</i>) in both steps of the compilation, to avoid mismatches between branches and profile information. Also note that the compiler uses line numbers to maintain branch information, hence it is possible for the profile information to be imprecise, in particular when multiple branches map to the same source line number. This may happen – for example – in the presence of large preprocessor macros. In the cases where the compiler detects inconsistencies in the profile information, it emits a warning.
-pg	Generate extra code to write profile information suitable for the analysis program <i>gprof</i> .

A typical profile-based compilation involves the following steps (Figure 8)

1. Compile with *-prob_gen* flag, so that the compiler can instrument the code to count branch probability. This information is saved in the *database.ifprob* directory
2. Run with significant data set, collect the branch statistics and emit them in file at the end of the first run (usually *ifprob.out*)
3. Re-compile with *-prob_use* flag, after having copied the *ifprob.out* file to the *database.ifprob* directory

With the *-prob_use* flag the VEX compiler uses collected data to pick traces. Trace scheduling favors more probable traces. code compaction happens on linear paths, and off-trace paths may be penalized by compensation code. Profiling can have significant impact on performance.

Language Definition

These options control certain extensions to the language. By default, the C compiler obeys the ISO/ANSI C definition.

-K+R	Use the language definition given by Kernighan and Ritchie (“traditional” C)
-mfansi	Use the ANSI/ISO language definition. This is the default.
-mfinline	Allow the Multiflow language extension to manually control inline expansion
-c99inline	Allow c99-style <i>inline</i> keywords to manually control inline expansion

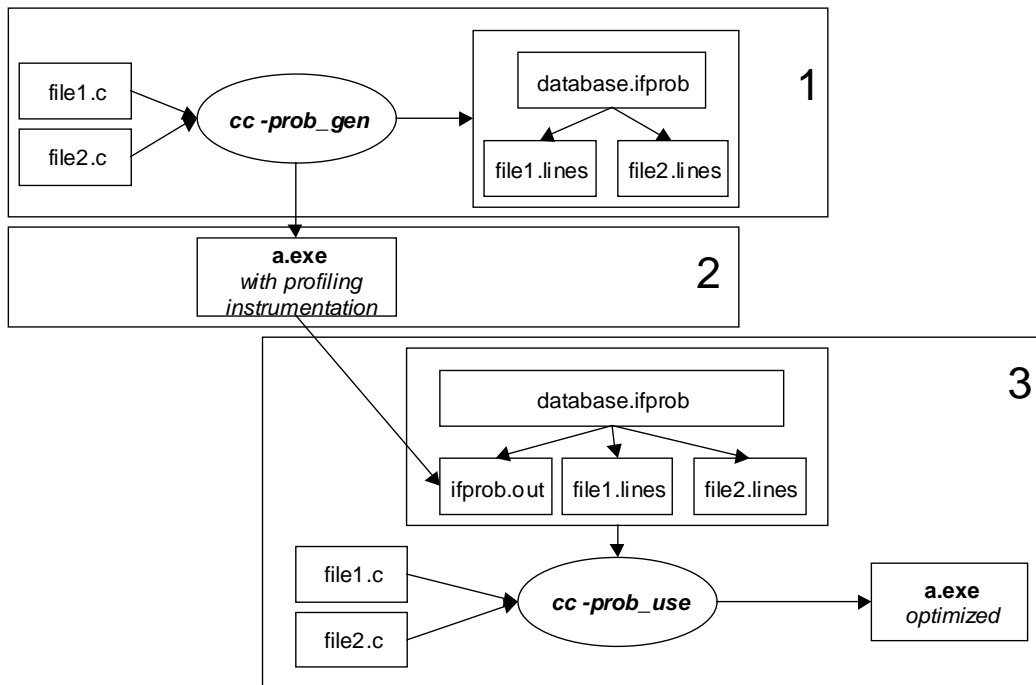


Figure 8 The three steps of profile-based compilation.

-funsigned-char Treat 'char' as unsigned (default is signed)

-align n This option indicates that all data items larger than n bytes obey their optimal alignment, where n is 1, 4, or 8. For example, the option *-align 1* means that any data object may start at any address (i.e., the program does not obey any alignment restrictions). By default, alignment is eight, stating that the program always observes optimal alignment. When accessing data items whose native alignment is larger than the "forced" alignment, the VEX compiler generates a sequence of extract/merge operations to ensure that the accesses are properly aligned, resulting in a performance loss.

Libraries

These options let you link C programs with different subprogram libraries, in addition to the standard libraries. Libraries that are distributed as a part of the VEX compiler are located in the directory *<vex_tree>/lib*.

- lnnn** Links with the library file named 'libnnn.a'. The loader will search for this file in any directories specified with the -L option, in the directories '*<vex_tree>/lib*' and '*<vex_tree>/usr/lib*'. Libraries are searched in the order in which they appear on the command line; therefore, they should normally appear at the end of any cc command. This flag is passed directly to the loader.
- Ldir** Library archives are sought first in directories named in -L options, then in directories on a standard list. This flag is passed directly to the loader.

Passing Options to Compile Phases

This group of options lets you pass options from the cc command to the preprocessor (cpp), the loader (ld) or the assembler (as). Note that any filename or option that cc does not recognize is automatically passed to the loader. Any manual entry for the GNU C preprocessor lists the available *cpp* options.

- mpnnn** Pass the option *-nnn* to the c preprocessor (cpp)
- mannn** Pass the option *-nnn* to the assembler (as).
- mlnnn** Pass the option *-nnn* to the loader (ld).

-Wa,<options>	Pass comma-separated <options> to the assembler
-Wl,<options>	Pass comma-separated <options> to the linker
-Wp,<options>	Pass comma-separated <options> to the C preprocessor

Terminal Output and Process Control

This group of options controls the terminal output of the compiler.

-w	Suppress warning diagnostics from compiler.
-mv	Display a banner line, including the version number
-mve	Display a banner line, including the version number of the compiler, and terminate; do not proceed with compilation.
-d	Show all invocations of the compiler phases and run the compiler
-dn	Show all invocations of the compiler phases and do nothing
-ms	Compile the named programs, leave the assembler-language output on corresponding files suffixed '.s', and continue to generate '.o' files normally. By default cc deletes any '.s' files that it creates.
-temp=directory	Create temporary files used during compilation in <i>directory</i> , rather than in /tmp (the default). An error occurs if directory is missing; if the given path is not the name of the directory; or if the given path is not writable
-S	Only compile to the assembler-level, leave the assembler-language output on corresponding files suffixed '.s', and stop.
-help --help	Show help message for basic options
--license	Show VEX license

Other Options

The following set of option controls the Compiled-Simulator invocation

-mas_g	Compile the named programs, and leave the intermediate files used in the 'Compiled Simulator' step in '.cs.c', then continue to generate '.o' files normally. By default cc deletes any '.cs.c' file
-mas_t	-mas_t enables the collection of 'Compiled Simulator' runtime statistics, I-cache simulation and D-cache simulation when a program is executed. Statistics appear in the <i>ta.log.nnn</i> file at the end of the program execution. It is also possible to individually turn on part of the simulation statistics: -mas_ti collects I-cache simulation data -mas_td collects D-cache simulation data
-mas_ti	
-mas_td	
-mas_G	Turn on gprof-style collection of profiling data. The gprof tool produces an execution profile of programs where the effect of called routines is incorporated into the profile of each caller. Profile data is taken from the call graph profile file (gmon.out default)
-mas_d	Show internal assembler steps
-mld_d	Show internal linker steps

The following options control miscellaneous configuration and diagnostics for the VEX compiler.

-fmm=<mm_file>	Reads the Machine Model configuration file from <mm_file>
-fmmdump	Dumps (to the <i>info_file</i>) the current machine model configuration, which could be used to produce a Machine Model file to pass to the <i>-fmm=<file></i> option.
-fdraw-dag=<n>	Emits to the <i>DAG file</i> (default "DAG.vcg") the VCG representation of the DAG for trace number <n> of the first procedure in the compilation unit.

- fdag-file=<fname>** Sets the *DAG file* to *<fname>*
- fdraw-cfg** Emits the control-flow graph (basic-blocks) for every procedure of the compilation unit. The graphs are emitted to files called "*GRAPH<procname>.vcg*"

3.2 Compiler Pragmas

This section discusses the set of compiler *pragmas* available in the VEX system. Pragmas are hints, directives and assertions that the programmer can pass to the compiler to improve performance.

Unrolling and Profiling

Unrolling pragmas control the loop optimization heuristics applied by the compiler. The loop optimization phase of the compiler consists of two successive phases: *first unrolling*, where the loop induction variables are transformed so that all iterations can be executed in parallel; and *second unrolling*, where the loop induction variables are not transformed. In most cases, the first unrolling phase is sufficient to achieve the desired behavior and the second unrolling phase should be used with caution.

Profiling pragmas control the way the compiler picks traces, when no profiling information is available.

Pragma	Description
#pragma unroll_amount(n1,n2)	Specifies the amount of unrolling that the compiler must perform in the first (<i>n1</i>) and second (<i>n2</i>) unrolling phases for the loop. This pragma applies to the following loop. The statement immediately following the pragma must be a loop statement (<i>for</i> , <i>while</i> or <i>do</i>). The compiler flags a syntax error if the pragma precedes any other statement. This pragma takes precedence over command-line flags.
#pragma precondition_amount(n)	Specifies the amount of preconditioning that the compiler must perform for the loop. This pragma applies to the following loop. The value <i>n</i> must be compatible with the unrolling amount specified for the loop: it is only legal to specify a preconditioning value that is an integer multiple of the unrolling amount. The statement immediately following the pragma must be a loop statement (<i>for</i> , <i>while</i> or <i>do</i>). The compiler flags a syntax error if the pragma precedes any other statement. This pragma takes precedence over command-line flags
#pragma trip_count(n)	Specifies the estimated number of iterations of the loop, and is used to guide compiler heuristics. This pragma applies to the following loop. The statement immediately following the pragma must be a loop statement (<i>for</i> , <i>while</i> or <i>do</i>). The compiler flags a syntax error if the pragma precedes any other statement. This pragma takes precedence over command-line flags
#pragma if_prob(n1,n2)	Specifies the probability of the following branch. The two parameters specify the number of times the following branch is executed (<i>n2</i>) and the number of times the following branch is taken (<i>n1</i>) The compiler computes the taken-branch probability as $n1/n2$. The statement immediately following the pragma must be an <i>if</i> statement. The compiler flags a syntax error if the pragma precedes any other statement.

The following example shows how to tell the compiler to unroll a loop 4 times (using the first unrolling phase), to precondition the loop to 4 iterations and to use a typical trip count of a 1000 iterations for the compiler heuristics.

```
void loop_pragmas(int N, int a[], int b[], int c[])
{
    int i;
    #pragma unroll_amount(4,1)
    #pragma precondition_amount(4)
    #pragma trip_count(1000)
    for(i=0;i<N;++i)
    {
        a[i] = b[i] * c[i];
    }
}
```

The following example shows how to tell the compiler that a branch is biased to be taken 20 times over 100 executions (i.e., a

20% taken probability)

```
int if_pragms(int a, int b)
{
    #pragma if_prob(20,100)
    if (a>b)
        return foo(a + b);
    else
        return bar(a - b);
}
```

Assertions

Assertions give the compiler more information about the program being compiled. Note that assertions are not hints and the compiler trusts the programmer about their validity. If the asserted condition can be false, it is possible for the compiler to generate code that would produce unexpected results. Assertions are valid in the current scope are not propagated to other scopes, and should be used with extreme caution.

Pragma	Description
#pragma assert_eq(exp1,exp2,n) #pragma assert_ne(exp1,exp2,n)	Assert equality (<i>assert_eq</i>) and inequality (<i>assert_ne</i>) of the two C expressions <i>exp1</i> and <i>exp2</i> , modulo <i>n</i> , in the current scope.
#pragma assert_lt(exp1,exp2) #pragma assert_le(exp1,exp2) #pragma assert_gt(exp1,exp2) #pragma assert_ge(exp1,exp2)	Assert less-than (<i>assert_lt</i>), less-equal-than (<i>assert_le</i>), greater-than (<i>assert_g</i>) or greater-equal-than (<i>assert_ge</i>) of the two C expressions <i>exp1</i> and <i>exp2</i> , modulo <i>n</i> , in the current scope

The following example asserts that the pointers *p* and *q* are aligned *0mod4* in the function *foo()*.

```
foo(char *p, char *q, int N)
{
    int i;
    #pragma assert_eq(p,0,4)
    #pragma assert_eq(q,0,4)
    for(i=0; i<N; i++)
        *p++ = *q++
}
```

Memory Disambiguation

Given two memory references to arbitrarily complex address expressions A and B, the compiler applies a set of techniques that try to answer the question “*Can the addresses A and B ever be the same?*”. This set of techniques falls into the category of *Memory Disambiguation*. There are three possible answers to the previous question: *yes*, when the compiler can definitely establish that A and B alias; *no* when the compiler can definitely establish that A and B never alias; *maybe*, when the compiler cannot establish the alias relationship between A and B. In its default operation mode, the compiler has to treat *maybe* memory dependencies as potential aliases, and the scheduler uses this information to limit the code motion.

The compiler supports a set of pragmas to force the scheduler to alter this default behavior and to ignore some of the memory dependencies. Note that—like assertions—the *#pragma ivdep* directive is *not a hint* and the compiler trusts the user on the truth of the assertion. If indeed some memory dependence may exist in the loop, it is possible for the compiler to generate code that would produce unexpected results. The *ivdep* pragma is only valid for the following loop, and should be used with extreme caution.

Pragma	Description
#pragma ivdep	Forces the compiler to treat all “MAYBE” memory aliases as “NO” memory aliases in the following loop. This pragma applies to the following loop. The statement immediately following the pragma must be a loop statement (<i>for</i> , <i>while</i> or <i>do</i>). The compiler flags a syntax error if the pragma precedes any other statement.
#pragma restrict	Implements a variation of the C99 “ <i>restrict</i> ” keyword in the form of a pragma. It is a type-annotation pragma and applies to the following declaration (or <i>typedef</i>). It instructs the compiler that pointers with a “ <i>restrict</i> ” type point to memory areas that cannot overlap.

The following example shows the usage of the *ivdep* pragma. The use of *ivdep* indicates the compiler that no alias exists in the following loop. In the particular example, this means that the user wants to inform the compiler that **the vector `a[]`, `b[]` and `c[]` point to distinct memory areas that do not overlap** (at least for the first *N* elements). The compiler will use the information to reorder the memory accesses, so that – for example – it is legal to load a new value of `b[]` before writing the new value of `a[]`. Obviously, if the two arrays `a[]` and `b[]` ever overlap (i.e., the *ivdep* was asserted incorrectly), the code generated by the compiler will produce unexpected results.

```
void loop_with_ivdep_pragma(
    int N, int a[], int b[], int c[]
) {
    int i;
    #pragma ivdep
    for(i = 0; i < N; ++i) {
        a[i] = b[i] * c[i];
    }
}
```

The following example **shows the usage of the *restrict* pragma**¹. The use of *restrict* indicates the compiler that no alias exists for pointers declared with a "restrict" type. In the particular example, this means that the user wants to inform the compiler that the vector `a[]`, `b[]` and `c[]` point to distinct memory areas that do not overlap for the (at least for the first *N* elements). The compiler will use the information to reorder the memory accesses, so that – for example – it is legal to load a new value of `b[]` before writing the new value of `a[]`. Obviously, if the two arrays `a[]` and `b[]` ever overlap (i.e., the *ivdep* was asserted incorrectly), the code generated by the compiler will produce incorrect results.

```
#pragma restrict
typedef r_int int;

void loop_with_restrict_pragma(
    int N,
    r_int a[],
    r_int b[],
    r_int c[] )
{
    int i;
    for(i=0; i<N; ++i) {
        a[i] = b[i] * c[i];
    }
}
```

The VEX compiler also support a limited form of the ISO-C99 “*restrict*” keyword for pointers. The *restrict* keyword has similar effects (with different syntax) of the *restrict* pragma described above. For example, the following loop generates equivalent annotations, through the use of the C99 syntax.

```
void loop_with_c99_restrict(
    int N,
    int * restrict a,
    int * restrict b,
    int * restrict c
) {
    int i;
    for(i=0; i<N; ++i) {
        a[i] = b[i] * c[i];
    }
}
```

Cache Control

The VEX compiler supports a set of pragmas that allow programmers to attach certain attributes to C data types. The compiler attaches the attributes to the data type and maintains them during the compilation process through the final code-generation back-end. The machine specific back-end is responsible for interpreting the type attributes and for generating the proper actions. The basic concept behind VEX type attributes is that they represent *hints to the compiler* and *never impact the correctness of the program*. In this way, the back-end is free to ignore them if it chooses to do so, or if the particular compilation target lacks hardware support to implement the behavior suggested by the hint.

These type attributes influence data cache accesses and enable the user to manually force a compiler-directed data prefetch-

1. Note that the VEX compiler predates the C99 *restrict* keyword. The *restrict* pragma substantially implemented the same concept, with a different technique. The VEX compiler supports both ways.

ing. VEX memory operations include two qualifiers that specify *streaming* accesses (i.e., accesses to objects that only exhibit *spatial locality*); and *local* accesses (i.e. accesses to objects that exhibit a strong temporal locality). The following pragmas control the prefetching algorithm and the replacement policy of the cache.

Pragma	Description
#pragma imb	Attaches a “ <i>spatial locality</i> ” attribute the following type definition or variable declaration. The statement immediately following the pragma must be a type declaration (typedef) or variable declaration. The compiler flags a syntax error if the pragma precedes any other statement. In case of a type declaration, the attribute applies to all variables of the same type. In case of a variable declaration, the attribute applies to the declared variable only.
#pragma stream	Attaches a “ <i>temporal locality</i> ” attribute the following type definition or variable declaration. The statement immediately following the pragma must be a type declaration (typedef) or variable declaration. The compiler flags a syntax error if the pragma precedes any other statement. In case of a type declaration, the attribute applies to all variables of the same type. In case of a variable declaration, the attribute applies to the declared variable only.
#pragma prefetch(num)	Attaches a “ <i>prefetch</i> ” attribute to the following type definition, or variable declaration. The statement immediately following the pragma must be a type declaration (typedef) or variable declaration. The compiler flags a syntax error if the pragma precedes any other statement. In case of a type declaration, the attribute applies to all variables of the same type. In case of a variable declaration, the attribute applies to the declared variable only. The value <i>num</i> indicates the prefetch distance (expressed in multiples of D-cache lines).

Note that type annotation pragmas always refer to the physical memory storage implied by the definition/declaration. The following construct:

```
#pragma stream
typedef int stream_int;

stream_int *p;
```

defines a *stream_int* type derived from the basic type *int*, tagged with a *streaming* attribute, and declares a pointer *p* pointing to data of type *stream_int*. In other words, the pragma will affect all accesses through *p* (such as **p*), but not the accesses to set or read the value of *p* itself. If the desired behavior is to have the pointer *p* itself be tagged with the *spatial locality* attribute, then we need the following statements:

```
#pragma stream
typedef int *stream_int_ptr;

stream_int_ptr *p;
```

Finally, if we want both *p* and **p* to be tagged with the *spatial locality* attribute, we can use the following combination:

```
#pragma stream
typedef int stream_int;

#pragma stream
typedef stream_int *stream_int_stream_ptr;

stream_int_stream_ptr *p;
```

Similarly, it is possible to annotate types with a “prefetch” attribute, as in the following example.

```
#pragma prefetch(1)
typedef int pft1_int;
```

One way of using the “prefetch” attribute to operate fine-grain prefetch control is in a *cast* operator, as the following example (multiplication of a vector by a constant) shows:

```
for(i=0; i<100; i++) {
    ((pft1_int *)c)[i] = ((pft1_int *)a)[i] * k;
```

```
}
```

This example suggests to the compiler that it add a prefetch operation to the accesses of the arrays *c[]* and *a[]* in the loop. The parameter “1” to the prefetch pragma indicates that the amount to prefetch is 1 D-cache line. If the size of a D-cache line is (for example) 32 Bytes, the compiler will emit one prefetch operation for the line containing *c+i+32* and one prefetch operation for the line containing *a+i+32* at each loop iteration. In this case if *i* >> 32, adding the prefetch will cause the values of *c[]* and *a[]* to be loaded in the cache long before their use, in this way avoiding a potential cache miss.

3.3 Inline Expansion

Inline expansion is an optimization that replaces calls to functions by the function itself. It is beneficial, since it eliminates the overhead required to make a function call, and it allows optimizations to take place which otherwise would be inhibited by function calls (such as *loop unrolling*). For example, the two pieces of code below show a simple example of manual inline expansion:

```
int f1(int x,int y,int q)  int f1(int x, int y, int q)
{
    int z = mac(x,y,q);    {
    return z * 2 + 4;      z = x * y + q;
                          return z * 2 + 4;
}                          }

int mac(int a,int b,int c)
{
    return a*b + c;
}
```

The code on the left calls the function *mac*. This involves some overhead for saving and restoring registers. Inline substitution, performed “by hand” on the right, eliminates the overhead for calling *mac* by rewriting the calling program so that the definition of *mac* is substituted “inline.”

The mechanics of actual inline expansion are significantly more complex. When the compiler performs inline expansion, it guarantees that the expansion will not affect the program’s behavior at all. In particular, this means that static and external variables will behave correctly, and that local variable names within the expanded function will not conflict with variables in the calling function.

A function that is expanded inline disappears completely into the function that calls it, and this has consequences on both debugging and profiling. Calls to inlined functions do not appear in profiles produced by *gprof*. Most debugging tools cannot set breakpoints within inlined functions.

The VEX-compiler supports two methods of user-controlled inlining.

Multiflow-style inlining. This inline facility in the VEX compiler (triggered by the *-mfinline* flag) extends the syntax of C¹, and it is based on the concept of an *inline module*. An inline module is a group of functions which can be substituted inline. Functions to be inlined need to be enclosed in an *inline declaration*. The compiler does not generate code or storage for an inline declaration; therefore inline expansion can only take place after the function being expanded has appeared within an inline declaration. The compiler inlines all functions in an inline module that are declared with the *inline* attribute. For example, the following code expands all calls to the function “*mac()*” within the function “*f()*”.

```
inline_declare {
  inline_module maclib {
    inline int mac(int,int,int) {
      return a*b + c;
    }
  }
}

inline_module maclib {
  inline int mac(int a, int b, int c) {
    return a*b + c;
  }
}
inline_use maclib;

int f(int x, int y, int q)
{
  int z = mac(x,y,q); /* this call is inlined */
  return z * 2 + 4;
}
```

1. Note that the VEX compiler predates the C99 *inline* keyword, which is more user-friendly, but also more limited than the *inline module* concept.

```
}
```

C99-style inlining. This inline facility resembles the *inline* hint in C99¹. All functions in scope marked with *inline* are considered candidates for inlining. This mode is triggered by the **-c99inline** flag. The following example implements the same inlining functionality of the *mac()* function within *f()*.

```
inline int mac(int a, int b, int c) {
    return a*b + c;
}

int f(int x, int y, int q)
{
    int z = mac(x,y,q); /* this call is inlined */
    return z * 2 + 4;
}
```

Finally, note that the **-autoinline** flag of the VEX compiler uses the same mechanisms in a transparent way, and is equivalent to doing the following (with all functions of “*hello.c*” marked as *inline*):

```
inline module hello_1234 {
    inline_declare {
        inline_module hello_1234 {
            #include "hello.c"
        }
    }
    #include "hello.c"
}
```

3.4 Machine Model Parameters

The version of the VEX compiler supports a limited form of dynamic reconfigurability. The VEX compiler optionally parses a configuration file passed through **-fmm=<mm_file>** option. For example, the command

```
<vex>/bin/cc hello.c -fmm=config.mm
```

reads in the configuration from the *config.mm* file. The configuration file syntax is a free-format list of *<directive, property, value>* tuples. The *<property>* fields are machine-model specific strings and have to match the ones used in the default machine description (Section 6 “Customizing the VEX Toolchain” specifies the VEX-specific configuration properties). The *<value>* field is an integer value. The currently supported *<directive>* commands are:

- **CFG:** To set a configuration option. Currently, only “*Debug*” and “*Dump*” are supported, “*Debug*” sets the “verbosity” level of compiler messages when parsing the configuration file. “*Dump*” instructs the compiler to dump the variables that can be reconfigured with their value, in a format that can be re-read by the compiler itself
- **RES:** To set the size of a machine resource. This can be used to set the quantity of resources available in a single instruction. For example: 4 multipliers, 8 issue slots, 3 memory ports, etc.
- **DEL:** To set the delay of a computation machine element. This can be used to modify the issue-use delay of an operation (number of instructions between the issue of an operation and the instruction where a consumer of any output can be scheduled).
- **REG:** To set the number of registers of a register bank machine element. Note that registers in a bank can only be reduced from the statically compiled value, and that lower bounds mandated by the RTA must be obeyed (see Section 2 “The VEX Run-Time Architecture”) for the banks that participate in the calling convention.

For example, here is a legal configuration file:

```
CFG: Debug      1## Verbose compilation
RES: Alu.0      2## 2 ALUs on cluster 0
RES: Memory.0   1## 1 Mem port on cluster 0
DEL: AluR.0     3## 3-cycle integer ops on cluster 0
DEL: CmpGr.0    3## 3-cycle compare ops on cluster 0
REG: $r0        32## Use 32 general purpose registers
REG: $b0        2## Use 2 branch registers
```

1. For readers that are more familiar with the GNU C (*gcc*) compiler, C99 inline hints are very similar to what *gcc* supports.

3.5 Custom Instructions

The VEX compiler includes a limited form of support for user-defined operations at the C language level through `_asm*()` **intrinsics**. Since these intrinsics map directly into VEX intermediate-level operations (and ultimately assembler operations), they are limited to operations that have no side effects, do not access memory and do not modify any hidden state. When the user inserts a call to `_asm()` in a C program with the proper parameters, the compiler schedules the operation and allocates the registers. In this way, the user can refer to C variables for operands and destinations. The compiler interprets calls to `_asm*()` in a special way. The implicit function prototypes for the intrinsics (included in the “*vexasm.h*” header) are:

```
/* From "<vex>/usr/include/vexasm.h" */

typedef unsigned int          __vexasm1;
typedef struct {unsigned int n0,n1;} __vexasm2;
typedef struct {unsigned int n0,n1,n2;} __vexasm3;
typedef struct {unsigned int n0,n1,n2,n3;} __vexasm4;

void      _asm0(int opcode, ...);
__vexasm1 _asm1(int opcode, ...);
__vexasm2 _asm2(int opcode, ...);
__vexasm3 _asm3(int opcode, ...);
__vexasm4 _asm4(int opcode, ...);
```

The first argument (*opcode*) is a numeric identifier for the operation; the other (optional) arguments after *opcode* represent the values read by the operation (with a limit of 8). Currently, `_asm*()` calls can only represent operations with zero to four return values. Taking the address of an `_asm*()` function is illegal. The following is an example of `_asm*()` usage.

```
#include <vexasm.h>
void foo(int *c, int *a, int *b, int size)
{
    int p;
    for (p = 0; p < size; p++) {
        *c++ = (int)_asm1(0x12, *a++, *b++);
    }
}
```

In the above example, we are calling the **intrinsic number 0x12** with 2 arguments for all the elements of an array and storing its result in a third array. If, for example, **the intrinsic 0x12 implements the “average” function**, we can think of writing the **code in a more readable form**, such as:

```
#include <vexasm.h>

#define AVG(a,b) ((int)_asm1(0x12, (a), (b)))

void average (int *c, int *a, int *b, int size)
{
    int p;
    for (p = 0; p < size; p++) {
        c++ = AVG(*a++, *b++);
    }
}
```

This produces the following code for the loop body (for a 1-cluster VEX, unrolled twice). The highlighted instructions are the ones that the compiler produces to map the `_asm1()` intrinsic calls. As we can see, the compiler schedules the code around the intrinsic calls and operates the usual optimizations and register allocation tasks.

```
L0?3:
    c0      cmplt $b0.0 = $r0.5, 1
    c0      ldw.d $r0.3 = 0[$r0.2]
    c0      cmplt $b0.1 = $r0.5, $r0.0
    c0      add $r0.5 = $r0.5, 2
;;
    c0      ldw.d $r0.7 = 0[$r0.4]
;;
    c0      ldw.d $r0.8 = 4[$r0.2]
    c0      add $r0.2 = $r0.2, 8
    c0      brf $b0.0, L1?3
;;
    c0      ldw.d $r0.9 = 4[$r0.4]
    c0      add $r0.4 = $r0.4, 8
```

```

;;
c0    asm,18 $r0.3 = $r0.3, $r0.7
;;
c0    stw 0[$r0.6] = $r0.3
c0    brf $b0.1, L2?3
;;
c0    asm,18 $r0.8 = $r0.8, $r0.9
;;
c0    stw 4[$r0.6] = $r0.8
c0    add $r0.6 = $r0.6, 8
c0    goto L0?3
;;
L1$3:

```

In terms of resource usage, the compiler built-in assumption is that an `_asm*()` operation occupies a number of issue slots that is the maximum of the number of output registers it produces (with a minimum of one) and half the number of input registers it consumes (with a minimum of one). This default can be overridden with a compiler configuration file, as described in Section 3.4 "Machine Model Parameters". The VEX compiler implicitly assumes two groups of `_asm` intrinsics: *group A* (with `asm` opcodes from 0 to 63) has a default latency of 1 cycle, and *group B* (with `asm` opcodes from 64 to 127) has a default latency of 2 cycles. Default latencies can be changed by providing a machine model configuration file to the compiler, as we describe in Section 3.4 "Machine Model Parameters".

4 Visualization Tools

Many of the VEX tools are capable of emitting graph information that is compatible with the VCG (*Visualization of Compiler Graph*¹) tools. The compiler can emit the following information in VCG form:

- Control flow graphs (Figure 9) for each of the procedures of a compilation unit, through the “`-fdraw-cfg`” command-line option.
- DAGs (Figure 10) for each of the individual traces of the first procedure of a compilation unit, through the “`-fdraw-dag=<trace_num>`” and “`-fdag-file=<name>`” command-line options.
- Compacted schedules (Figure 11) in VCG form can be produced from any VEX assembler file by using the *schplot* utility (in `<vex>/bin/schplot`).

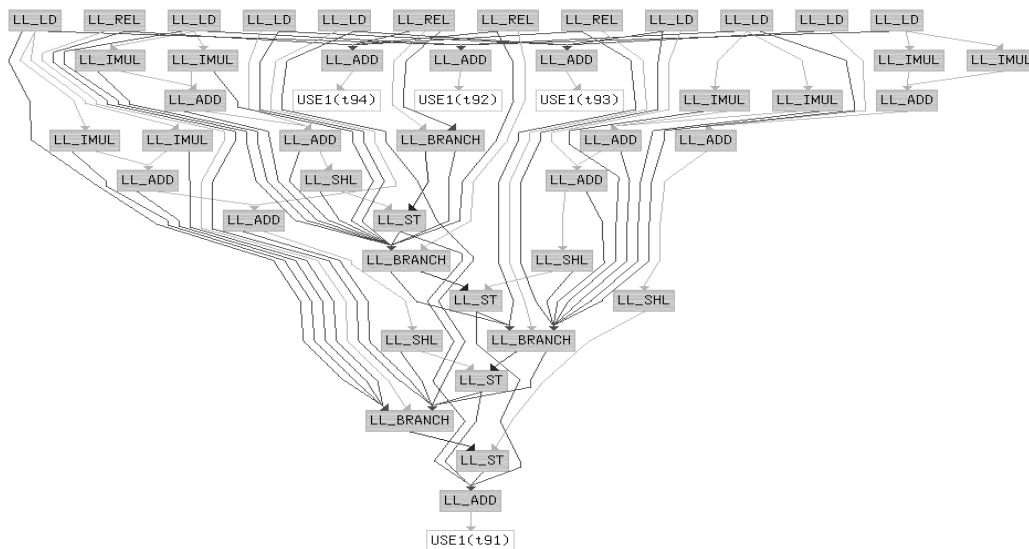


Figure 10 Example of DAG visualization. As one could expect, nodes are VEX operations, and edges are dependence graphs. The description allows turning on and off edge types (flow, anti, constraints, etc.) for easier visualization of complex DAGs.

1. VCG stands for “Visualization of Compiler Graphs”, and is a tool (designed primarily by George Sanders and used in the ESPRIT project #5399 COMPARE) that generates and displays a layout of the graphs as they occur typically in compiler construction.

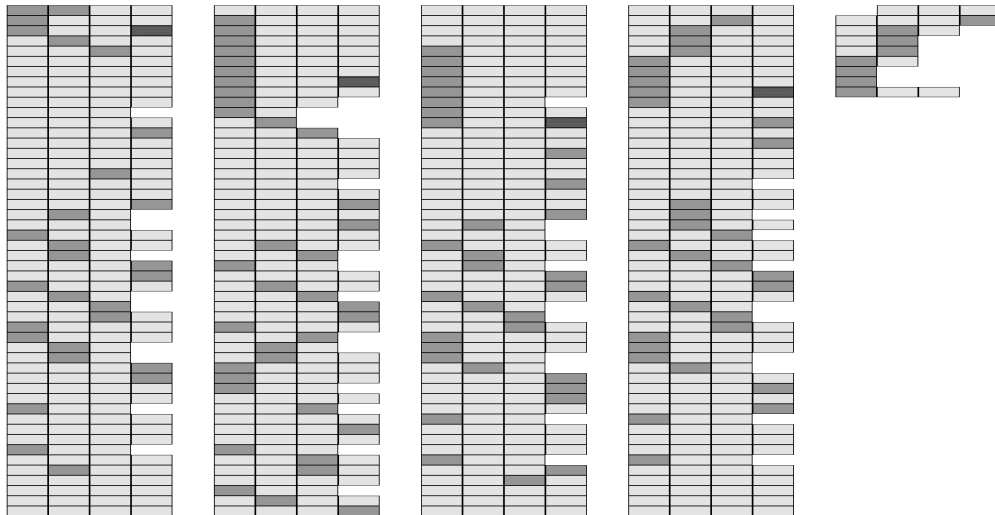
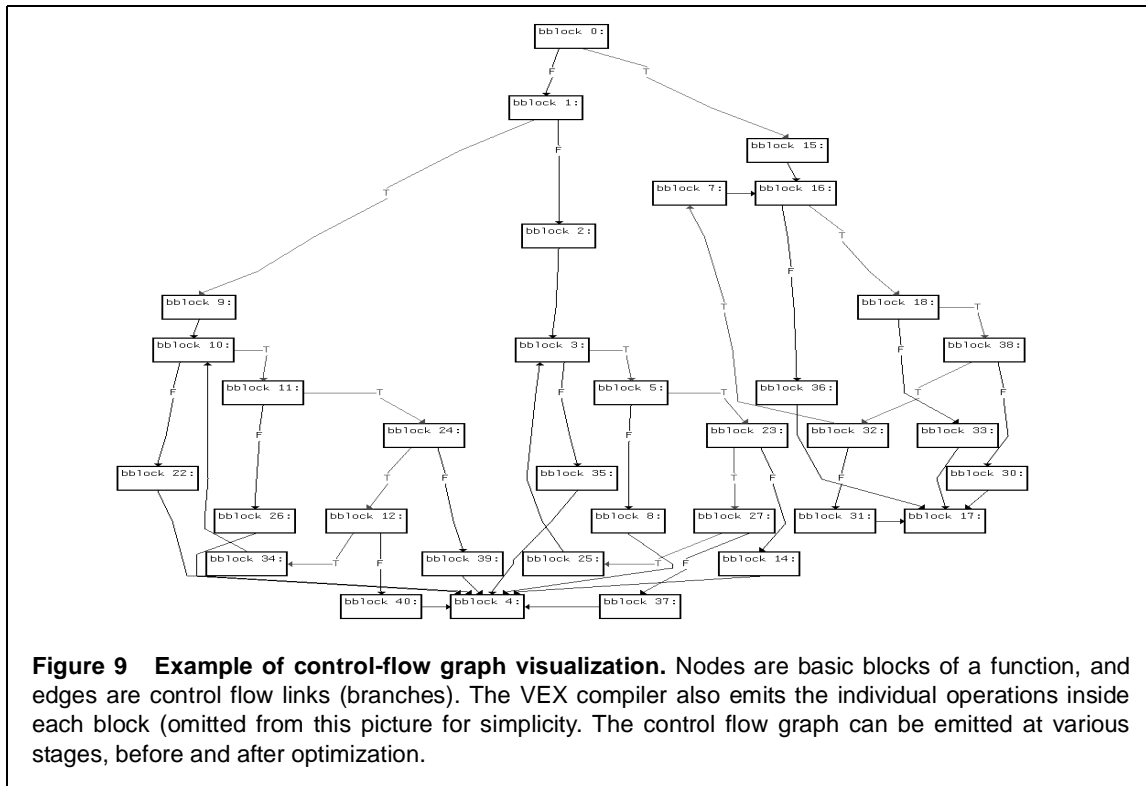


Figure 11 Example of schedule visualization. This is a pictorial representation of the scheduled VEX assembler output. While its primary use is mostly decorative (or educational), it also provides a quick visual impression of the utilization of the machine in a given trace.

- Profiling information. To visualize profiling information, the VEX distribution includes the *rgg* utility (in `<vex>/bin/rgg`) that converts the standard *gprof* output into a VCG call graph (Figure 13).

Visualization tools are often a very useful instrument in the development of tuned applications. In particular, profiling visualization is an invaluable tool to help determine where to spend time in the source-level optimization of a complex application. Profiling is usually necessary regardless of the target architecture style. For machines with ILP like VEX, once the most important routines are isolated, DAG visualization helps the fine-tuning of the implementation. For example, it easily shows if we are successful in removing dependences: by turning a “deep” DAG into a “shallow” DAG, we can immediately see that we have exposed a larger amount of ILP ().

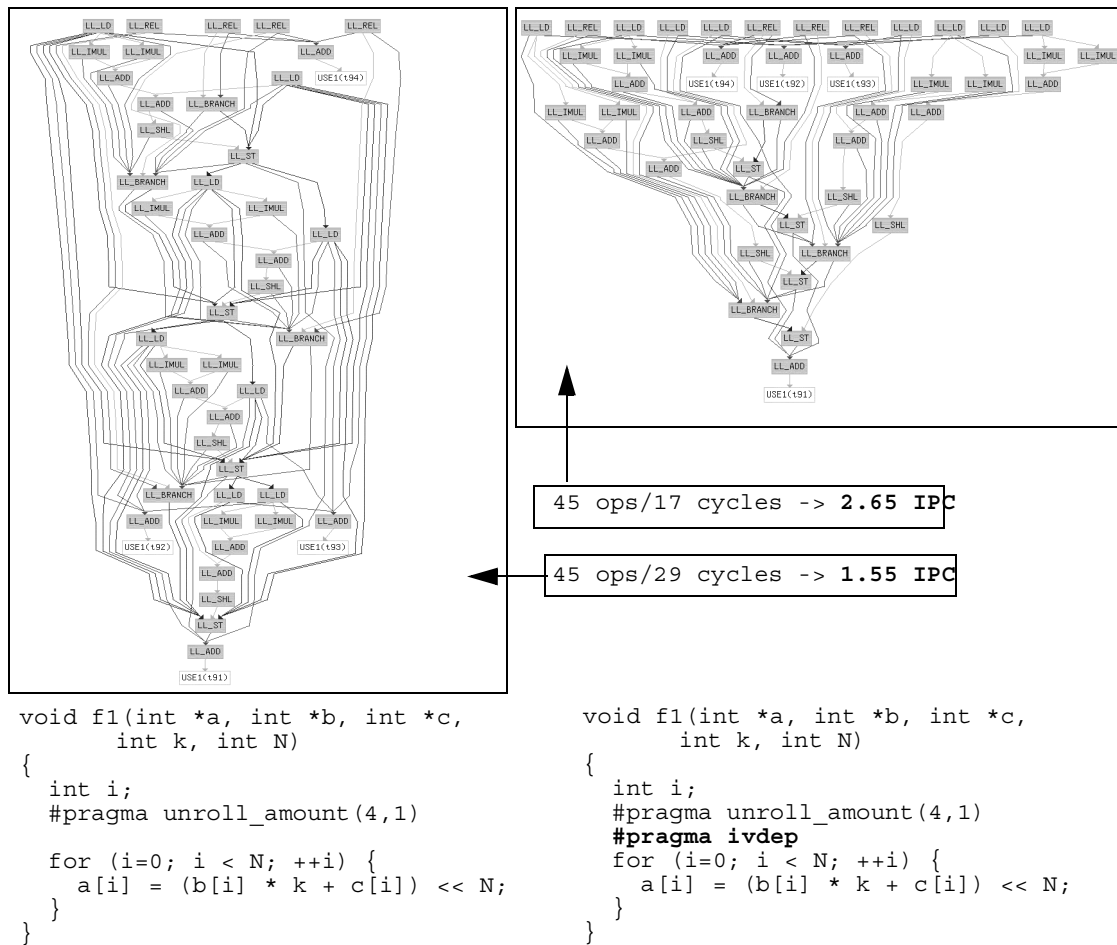


Figure 12 DAG visualization and ILP. Both DAGs represent the same simple loop code with or without the `#pragma ivdep` (no IV-carried dependencies). Just looking at the DAGs, it is pretty obvious that the version on the right exposes a much higher degree of ILP (the DAG is “shallow”). In fact, this corresponds to a 70% increase in performance (from IPC of 1.55 to 2.65) for a default VEX machine.

5 The VEX Simulation System

The VEX simulator used a so-called *compiled simulation* technique. The compiled simulator (CS) translates the VEX binary to the binary of the host computer, by first converting VEX to C, and then invoking the host C compiler to produce a host executable.

In addition to the standard semantics of the instructions, CS also emits instrumentation code to count cycles (and other interesting statistics), as well as code to dump the results to a log file at the end of the simulation (the log file is called ‘*ta.log.###*’). Timing instrumentation is turned on with the “**-mas_t**” flag passed to the compiler driver (or “**-mas_ti**” and “**-mas_td**” for finer grain control - see the section on compiler flags). By default, CS also performs a simple one-level cache simulation.

CS operates on each of the individual VEX assembler (.s) files corresponding to the compilation units of a program and translates them back to C by implementing the VEX operation semantics, the calling convention (ABI), and introducing the appropriate instrumentation code. The CS-generated C files are then compiled with the host platform C compiler (e.g., *gcc* for Linux) and linked with the support libraries that deal with the instrumentation. During linking, the CS *ld* wrapper ensures that the right libraries are linked in the right order, and performs the necessary “magic” (such as wrapping system functions so that they don’t cause problems) for the binary to execute correctly.

By default, VEX links in a simple cache simulation library, which models an L1 instruction and data cache. The cache simulator is really a trace simulator, which is embedded in the same binary for performance reasons, but only communicates with the VEX execution engines through simple events that identify memory locations, access types and simulation time. If desired, the default cache simulation can be replaced by a user-defined library which overrides the event-handling routines.

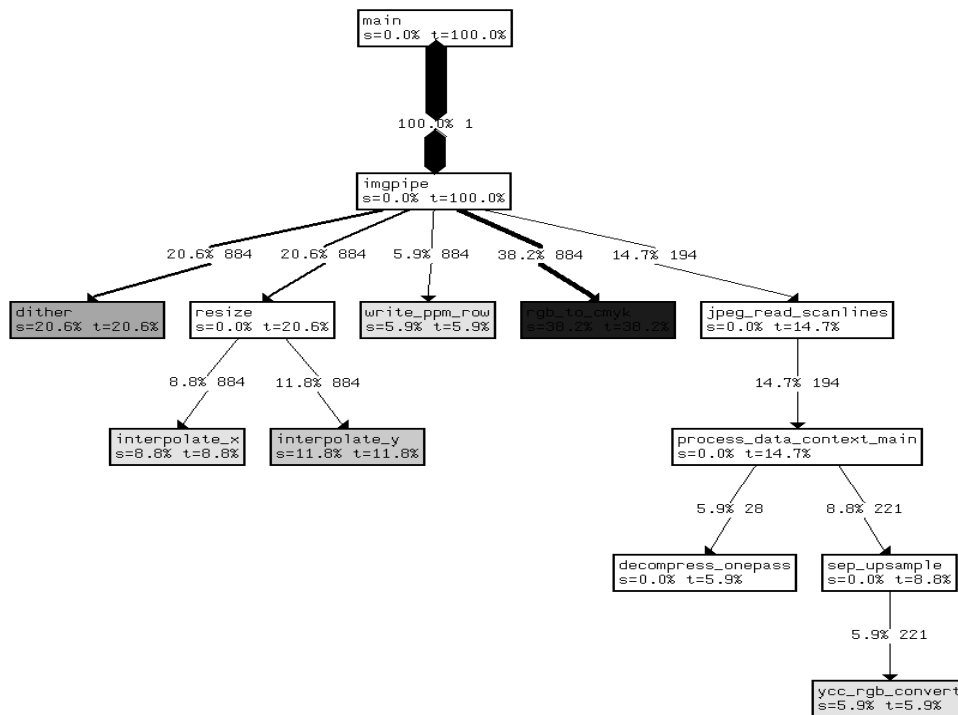


Figure 13 Example of visualization of a profiled call graph. The *rgg* utility emits a graph representation of the function-level call graph. Each node in the graph corresponds to a procedure and each edge to a procedure call. Nodes are labeled with relative execution times for themselves (*s*=%), for the descendent subgraph (*t*=%), and are color-coded for importance. Edges are labeled with execution counts, with relative execution time, and have a thickness based on their importance. For example, the *rgb_to_cmyk* function is called 882 times by *imgpipe* and amounts to 38.2% of execution time (all in the function itself) of the execution under test.

Gprof support

The VEX simulator includes “simulated” support for *gprof*, when invoked with the “*-mas_G*” option. Unlike *gprof* running in the host environment, the VEX *gprof* instrumentation only adds time to the simulation: it is *non-invasive* as far as the simulation itself is concerned, and it is *not based on statistical PC-sampling*. At the end of simulation, four files are emitted: *gmon.out* containing profile data that include cache simulation, *gmon-nocache.out* containing profile data that does not include cache simulation, and *gmon-icache.out/gmon-dcache.out* containing data for respectively only Instruction cache and only Data cache statistics (this requires using the built-in cache simulator). Programmers can compare the two files to identify the parts of an application that put particular pressure on the D-cache or on the I-cache subsystems. To visualize profile data, users can run the `<vex>/bin/rgg` utility that converts *gprof* data into a call graph compatible with the format of the graphical interface *vcg* (also distributed as `<vex>/bin/xvcg`).

Note that the compiler also supports the *-pg* option to emit *gprof* instrumentation part of the VEX code itself. Unlike the instrumentation emitted with *-mas_G*, this instrumentation is invasive, and models what would be necessary to do for a non-simulated target.

Profiling flags are most commonly used in conjunction with timing flags (*-mas_t*). If the profiling flag is turned off without the timing flag, the *call tree* is emitted at exit, but no timing information is available in the *gmon.out* files.

Note that *gprof* profiling and *Profile-Based Optimization* are two completely separate and distinct features not to be confused. Profile-Based Optimization (triggered by *-prob_gen* and *-prob_use* flags) is a two-step compilation process that allows the compiler to collect branch profile data to drive optimizations in a second phase. Profiling with *gprof* (triggered by the *-mas_G* flag), on the other hand, collects routine-level profile data for analysis and there is currently no feedback path to the compiler.

Simulating custom instructions

The VEX compiled simulator parses and converts the code produced by the compiler from *_asm*()* calls (see Section 3.5 “Custom Instructions”), but does not know about the semantics of the operations themselves. To be able to simulate a user-

defined library, the simulator defines a standard interface for `_asm*()` type operations as follows:

- For each *asm* operation, it produces a call to the function *sim_asm_op*()* with the proper arguments. The symbols *sim_asm_op0*—*sim_asm_op4* are reserved and cannot be used in the user program.
- The prototypes for the *sim_asm_op** symbols are:

```
typedef unsigned int          __vexasm1;
typedef struct {unsigned int n0,n1;} __vexasm2;
typedef struct {unsigned int n0,n1,n2;} __vexasm3;
typedef struct {unsigned int n0,n1,n2,n3;} __vexasm4;

void      sim_asm_op0(int, ...);
__vexasm1 sim_asm_op1(int, ...);
__vexasm2 sim_asm_op2(int, ...);
__vexasm3 sim_asm_op3(int, ...);
__vexasm4 sim_asm_op4(int, ...);
```

The users must provide an implementation of *sim_asm_op*()* for the opcodes used in the program, compile it with the host compiler and link the object file to the executable. Otherwise a link error would be generated. A sample implementation of the *sim_asm_op1()* function for the previous example may look like this:

```
#include <stdarg.h>
#include <stdio.h>

extern unsigned int sim_asm_op1(
    unsigned int opcode,
    ...)
{
    va_list ap;
    unsigned int t, s1, s2;
    va_start(ap, opcode);

    switch(opcode) {

    case 0x12: /* AVG(s1,s2) */
        s1 = va_arg(ap, unsigned int);
        s2 = va_arg(ap, unsigned int);
        t = (s1 + s2) / 2;
        break;

    default:
        _linux_fprintf(stderr,
            "Error: opcode %d not supported\n",
            opcode);
        _linux_exit(1);
    }
    return t;
}
```

If we write the *sim_asm_op1()* implementation in *asmlib.c*, a sample compilation and simulation sequence to be able to test the file *average.c* is:

1. Compile the VEX with the `_asm()` calls:
`<vex>/bin/cc -c average.c`
2. Compile (natively) the asm library
`gcc -c asmlib.c`
3. Link (with the VEX compiler) the 2 parts together
`<vex>/bin/cc -o average average.o asmlib.o`
4. Run the *average* binary

Simulating Memory Hierarchy

As we mentioned above, VEX links a simple cache simulation library by default, which only models a (configurable) L1 instruction and data cache. In addition, VEX also contains a basic software development kit (SDK) to replace the built-in cache library with a set of user-defined functions. The SDK is in the form of a set of headers for the API that the VEX simulator expects when running VEX code. Because of the way in which dynamically linked library work, the default functions can be overridden by linking a natively compiled library that redefines them. Users must redefine *initialization* and *finalization*

routines (called at the begin and end of the simulation), as well as *data tracing* functions for each of the memory access types. The *tracing* functions are called at every data memory access (or simulated instruction cache line fetch), but do not affect the execution of the program semantics. In this way, the redefined routines can implement arbitrary behaviors, while preserving the correct program execution. Time is accounted for separately in the execution engine and in the cache simulation model.

Simulating instruction caches is a particularly challenging task in a compiled simulator, if we want to be able to link with modules compiled for the simulation host. In this case, we cannot build a simulated VEX memory model, but we have to keep the one that the host mandates. VEX models instruction caches by simulating a dynamic loader that assigns addresses to every compilation unit as soon as one of its functions is loaded. This deviates from a statically linked model, but still provides significant instruction cache behavior.

6 Customizing the VEX Toolchain

The idea behind VEX is to provide a flexible environment for architecture exploration of VLIW architectures. As such, it allows users to selectively change the compiler target and many of the simulation parameters. The VEX compiler, in addition to the standard compile-time options (flags), optionally reads a compile-time configuration file where it is possible to define machine resources such as number and latency of functional units, and number of registers for each architected register files. The compiled simulator also optionally reads a configuration file where users can specify execution-time parameters, such as clock and bus cycles, cache parameters (size, associativity, refill latency, etc.) and various advanced options. Finally, VEX includes an extension mechanism by means of which it is possible to introduce user-defined custom instructions (also known as *assembler intrinsics*). VEX *intrinsics* are modeled as black boxes, so they need to be explicitly instantiated (through a special naming convention) in the C sources; once the compiler recognizes them, it optimizes around them, schedules and registers allocates them like any other operation.

The following sections describe in some detail the three configuration options in VEX. Note that all VEX tools come with a default configuration described in Table 11.

Table 11: VEX default parameters

Parameter	Description	Default	How to change
Clusters	VLIW clusters (fully inter-connected groups of units and register files)	1	Compile time flag: <code>-width <n></code> option (only 1, 2 and 4 clusters allowed)
Issue width	Total number of operations in a VLIW instruction (cycle)	4 per cluster	Compile time machine model
Integer ALUs	Units for integer operations, comparisons, shifts	4 per cluster, 1-cycle latency	Compile time machine model
Integer MULs	Units for integer multiplications	2 per cluster, 2-cycle latency	Compile time machine model
Integer registers (GRs)	General purpose registers	64 per cluster, 32 bits	Compile time machine model (GRs can only be decreased)
Branch registers (BRs)	Branch condition and predicate registers	8 per cluster, 1 bit	Compile time machine model (BRs can only be decreased)
Link register	Address for indirect branches	1 in cluster 0, 32 bits	Cannot be changed
Memory load	Units to load from mem	1 per cluster, 3-cycle latency	Compile time machine model
Memory store	Units to store to mem	1 per cluster, 1-cycle latency	Compile time machine model
Memory pft	Units to prefetch mem	1 per cluster	Compile time machine model
Copy units	Src/dst for intercluster copy operations	1 src + 1 dst per cluster, 1-cycle	Compile time machine model

Clusters

By default, the VEX compiler generates code for a one-cluster VEX architecture. The option **-width *n*** changes the number of clusters to *n*, which must be either 1, 2, or 4.

Machine Model Resources

Here we describe the properties that are relevant for the VEX-specific machine description. Most of these should be supported with the compiler producing correct code. They are classified in:

- **Computational Machine Elements:** properties for *DEL* directives
- **Register Bank Machine Elements:** properties for *REG* directives
- **Machine Resources:** properties for *RES* directives

Note that some of these properties are cluster-specific. The example below shows properties for cluster 0 (suffix '.0'). To get the same properties for the other identical clusters, replace prefix/suffix accordingly (for example: *DEL:CmpGr.1* is for cluster 1, *RES:Alu.2* is for cluster 2, etc.).

Computational MEs can be used in a “DEL” directive:

AluR.0	Integer Op, Immediate on Src1
Alu.0	Integer Op, Immediate on Src2
CmpGr.0	Compare to general register / select
CmpBr.0	Compare to branch
Select.0	Select
Multiply.0	Multiply
Load.0	Load Word to GR
LoadLr.0	Load Word to LR
Pft.0	Prefetch
Asm1L.0	User-defined asm, Group A, 1 Slot
Asm2L.0	User-defined asm, Group A, 2 Slots
Asm3L.0	User-defined asm, Group A, 3 Slots
Asm4L.0	User-defined asm, Group A, 4 Slots
Asm1H.0	User-defined asm, Group B, 1 Slot
Asm2H.0	User-defined asm, Group B, 2 Slots
Asm3H.0	User-defined asm, Group B, 3 Slots
Asm4H.0	User-defined asm, Group B, 4 Slots
CpGrBr.0	Copy GR to BR
CpBrGr.0	Copy BR to GR
CpGrLr.0	Copy GR to LR
CpLrGr.0	Copy LR to GR
Spill.0	Spill (Store)
Restore.0	Restore GR (Load)
RestoreLr.0	Restore LR (Load)

Register Bank MEs can be used in a “REG” directive:

\$r0	General Purpose Register Bank
\$b0	Branch Register Bank

Machine Resources can be used in a “RES” directive.

Global Resources

IssueWidth	Total issued operations (> 0)
MemStore	Total Store Ops (> 0)
MemLoad	Total Load Ops (> 0)

Cluster Resources

Alu.0	Integer ALU slots (>= 2)
AluR.0	Integer ALU slots - imm. on src1 (>= 2)
Mpy.0	Multiply slots (> 0)
CopySrc.0	Copy-Source slots (> 0)
CopyDst.0	Copy-Dest slots (> 0)
Memory.0	Memory load slots (> 0)

Memory Hierarchy Parameters

The built-in cache simulator in the Compiled Simulator currently supports a method to set most of the relevant parameters for the simulated memory and bus.. The method to instruct the compiled simulator about the configuration parameters is through a

configuration file made of `<property> <value>` pairs. An example follows.

```
CoreCkFreq      500
BusCkFreq       200
lg2CacheSize    15 # (CacheSize = 32768)
lg2Sets         2 # (Sets = 4)
lg2LineSize     5 # (LineSize = 32)
MissPenalty     25
WBPenalty       22
lg2StrSize      9 # (StrSize = 512)
lg2StrSets      4 # (StrSets = 16)
lg2StrLineSize  5 # (StrLineSize = 32)
StrMissPenalty  25
StrWBPenalty    22
lg2ICacheSize   15 # (ICacheSize = 32768)
lg2ICacheSets   0 # (ICacheSets = 1)
lg2ICacheLineSize 6 # (ICacheLineSize = 64)
ICachePenalty   30
NumCaches       1
StreamEnable    FALSE
PrefetchEnable  TRUE
LockEnable      FALSE
ProfGranularity 1.000000
```

In the following table we describe the individual parameters in detail.

Table 12: Parameters for the built-in VEX cache simulator

<i>CoreCkFreq</i>	The frequency of the core clock, in MHz
<i>BusCkFreq</i>	The frequency of the bus clock, in MHz
<i>lg2CacheSize</i>	The log2 of the data cache size in bytes (e.g., 10 => 1KB)
<i>lg2Sets</i>	The log2 of the data cache associativity (e.g, 2 => 4-way set-associative)
<i>lg2LineSize</i>	The log2 of the data cache line size in bytes (e.g. 8 => 64B)
<i>MissPenalty</i>	The stall penalty of a data cache miss in core cycles
<i>WBPenalty</i>	The stall penalty of a data cache writeback in core cycles
<i>PrefetchEnable</i>	Enable prefetching (TRUE or FALSE)
<i>NumCaches</i>	Number of caches in the architecture.
<i>StreamEnable</i>	Enable the stream buffer (TRUE or FALSE)
<i>lg2StrSize</i>	The log2 of the stream buffer size in bytes (e.g., 10 => 1KB)
<i>lg2StrSets</i>	The log2 of the stream buffer associativity (e.g, 2 => 4-way set-associative)
<i>lg2StrLineSize</i>	The log2 of the stream buffer line size in bytes (e.g. 8 => 64B)
<i>StrMissPenalty</i>	The stall penalty of a stream buffer miss in core cycles
<i>StrWBPenalty</i>	The stall penalty of a stream buffer writeback in core cycles
<i>lg2ICacheSize</i>	The log2 of the instruction cache size in bytes (e.g., 10 => 1KB)
<i>lg2ICacheSets</i>	The log2 of the I-cache associativity (e.g, 2 => 4-way set-associative)
<i>lg2ICacheLineSize</i>	The log2 of the I-cache line size in bytes (e.g. 8 => 64B)
<i>ICachePenalty</i>	The stall penalty of an instruction cache miss in core cycles

The compiled simulator looks for a file called *vex.cfg* in the invocation directory and parses it according to the syntax above, if the file is present. Alternatively, it is possible to use the environment variable *VEXCFG* to pass the name of the simulation configuration file.

7 Examples of tool usage

This last section lists some sample use of the VEX tools to cover the most likely scenarios for software development, experimentation and architecture exploration through the VEX toolset. The example assume familiarity with the Linux operating system and command-line shells. All examples assume that the VEX toolchain is installed in */home/vex*.

7.1 Compile and run

The first example is a simple “compile-and-run” sequence of a program composed of two compilation units *file1.o* and *file2.o*

and the math library (*-lm*), instructing the compiler to maximize optimization (*-O4*) and keep the assembler file around (*-ms*).

```
## Compile individual modules
/home/vex/bin/cc -ms -O4 -c file1.c
/home/vex/bin/cc -ms -O4 -c file2.c

## Link (with math library)
/home/bin/cc -o test file1.o file2.o -lm

## Run the program
./test
```

This command sequence, in addition to any side effect (like terminal output) that the execution of *test* produces, generates two VEX assembler files (*file1.s* and *file2.s*), two host (Linux) object files containing the compiled version of the CS-instrumented VEX assembler files (*file1.o* and *file2.o*), a host executable file containing the instrumented version of the executable compiled simulator for the code (*test*) and a simulation logfile (*ta.log.000*) containing the statistics corresponding to the simulation of the execution of *test* on the default VEX platform.

The assembler files are useful to check the static behavior of the compiler, and can be analyzed with the *pcntl* utility which collects static compile information from a VEX assembler file. For example, if we invoke

```
## Analyze file1.s
/home/vex/bin/pcntl file1.s
```

we obtain a breakdown of every function in the assembler file, and every compilation *trace* per function, with the vital statistics (instructions per cycle, number of scheduled cycles, number of scheduled operations and NOPs, number of copies for a multicycle configuration, and so on). The listing also includes cumulative statistics that can be used as a first approximation to evaluate the effectiveness of code reorganizations or different combinations of compiler flags.

```
Procedure: rgb_to_cmyk_and_dither::
Trace      IPC Cycles  Oper   Copy    Nop
-----
      3      1.58      12      19       0       1
      1      3.33     232     773       0       0
      7      1.00       1       1       0       0
      6      1.00       1       1       0       0
      5      1.00       1       1       0       0
      4      0.50       2       1       0       0
Operations = 796
Instructions = 249
Reg. moves = 0
Nops       = 1
Avg ILP = 3.19679
```

The simulation output file, as described, contains a set of self-explanatory statistics, such as cycles (total, execution, stalls, operations, equivalent time), branch statistics (executed, taken, conditional, unconditional), instruction memory statistics (estimated code size, hits/misses) data memory statistics (hits/misses, bus conflicts, copybacks), bus statistics (bandwidth usage fraction), as well as cumulative figures (overall IPC with and without accounting for stalls) and simulation statistics (simulation time, equivalent “MIPS” speed). The output of a simulation run is the primary tool to guide experimentation.

7.2 Profiling

A common use of the VEX tools is with the *gprof* profiling tool. By using the same example of Section 7.1 “Compile and run” we can insert profiling instrumentation (at the simulation level) through the *-mas_G* flag:

```
# Compile individual modules with CS profiling
/home/vex/bin/cc -ms -mas_G -O4 -c file1.c
/home/vex/bin/cc -ms -mas_G -O4 -c file2.c

## Link (with math library)
/home/bin/cc -mas_G -o test file1.o file2.o -lm

## Run the program
./test
```

The run of the profiled CS binary, in addition to the standard simulation output, also produces a set of data files for *gprof*, including *gmon.out* (containing the data for the overall execution), *gmon-nocache.out*, *gmon-icache.out* and *gmon-dcache.out* (containing respectively the data for the execution assuming infinite caches, the instruction cache only, and the data

cache only). The latter three are particularly useful to identify pathological situations that affect the instruction or data caches for a specific benchmark. By running the standard *gprof* utility on the instrumented binary, we can get individual statistics from the *gmon*.out* files.

```
# Get overall execution statistics
gprof test gmon.out

# Get execution statistics assuming infinite caches
gprof test gmon-nocache.out

# Get execution statistics on instruction cache
gprof test gmon-icache.out

# Get overall execution on data cache
gprof test gmon-dcache.out
```

In addition to the *gprof* data files, an instrumented profiled run also produces a flattened version of the function profile, with broken down statistics for the number of cycles spent in the instruction and data cache for each executed functions.

```
Flat profile (cycles)
  Total      D-cache      I-cache  Function
142934306    20005200    983340  rgb_to_cmyk
 89338101    23394096    622665  dither
41688760     3077172    400635  interpolate_x
34709205    12166200    238410  interpolate_y
24579498     1818396     57375  write_ppm_row
10075928     1472580     22005  ycc_rgb_convert
 5548602      510300     21600  jpeg_idct_islow
3494605      963936     52740  h2v2_fancy_upsample
2743026      192132     53595  decode_mcu
1350417       43092      3915  jpeg_fill_bit_buffer
 671699       17028    248625  decompress_onepass
167867        81000    44325  imgpipe
131632        38232    69615  process_data_context_main
109835        47520    14850  sep_upsample
 69817         9828     2340  jpeg_huff_decode
 69082        36540    15165  jpeg_read_scanlines
  ...          ...          ...  ...
```

Finally, it is possible to produce a graphical representation of the call graph (as described in Section 4 "Visualization Tools") with the *rgg* tool

```
# Generate visual call graph, excluding cache effects
# and filtering out functions taking less than 1%

/home/vex/bin/rgg test -m gmon-nocache.out -m 0.01
```

7.3 Custom architectures

The support for customization in VEX is present at three different levels

1. **Custom instructions**, inserted through *_asm()* intrinsics and simulated through a custom host-level library
2. **Custom clusters, resources and latencies**, controlled through a compile-time configuration file (*-fmm=<machine-model>*)
3. **Custom memory architecture**, where simple deviations from the default model are captured through the CS configuration file (*vex.cfg*), and complex memory architectures require writing a user-level instrumentation routine.

As we described in Section 3.5 "Custom Instructions", we can instantiate custom instructions simply by including the *vex-asm.h* header file and by using the *_asm(...)* syntax. This instantiates a "black-box" assembler instructions that the compiler schedules based on the resource pattern and delay information that we define. Additionally, the compiler also requires a separate simulation library that contains the helper code to implement the semantics of the custom instruction. If our simulation library is called *asmlib.c*, the following command sequence compiles our canonical example.

```
# Compile (VEX compiler) individual modules
/home/vex/bin/cc -ms -O3 -c file1.c
/home/vex/bin/cc -ms -O3 -c file2.c

# Compile (host compiler) simulation library
gcc -c asmlib.c
```



```
## Link (with math library and assembler library)
/home/bin/cc -o test file1.o file2.o -lm asmlib.o
```

If we want to instruct the compiler to target a custom machine model, we can pass the `-fmm=<machine-model>` flag during the compilation phase, or we can use the `-width <clusters>` to model a clustered architecture. A common experiment (for example, to create a reference baseline) is to model a single-issue RISC-like target, which we can simply do by creating a `risc.mm` file containing the following directives (limit issue slots to one operation, reduce registers to 32):

```
RES: IssueWidth 1
REG: $r0 32
```

and passing the right flags to the compiler:

```
# Compile modules with "risc" machine model
/home/vex/bin/cc -ms -O3 -fmm=risc.mm -c file1.c
/home/vex/bin/cc -ms -O3 -fmm=risc.mm -c file2.c
```

At the other end of the extreme, we can try to model a very wide architecture (4 clusters, 32 issue slots, 32 memory operations, 32 multipliers, 32 send/receive paths) which will most likely provide an upper bound to performance. To this aim, we can generate a `verywide.mm` configuration file, containing:

```
RES: IssueWidth 32
RES: MemLoad 32
RES: MemStore 32
RES: MemPft 32
RES: Alu.0 32
RES: Mpy.0 32
RES: CopySrc.0 32
RES: CopyDst.0 32
RES: Memory.0 32
RES: Alu.1 32
RES: Mpy.1 32
RES: CopySrc.1 32
RES: CopyDst.1 32
RES: Memory.1 32
RES: Alu.2 32
RES: Mpy.2 32
RES: CopySrc.2 32
RES: CopyDst.2 32
RES: Memory.2 32
RES: Alu.3 32
RES: Mpy.3 32
RES: CopySrc.3 32
RES: CopyDst.3 32
RES: Memory.3 32
```

and invoking the compiler with the proper flag:

```
# Compile modules with "risc" machine model
/home/vex/bin/cc -ms -O3 -fmm=verywide.mm -c file1.c
/home/vex/bin/cc -ms -O3 -fmm=verywide.mm -c file2.c
```

Finally, when we invoke the CS-generated binary, we can also change the runtime simulation statistics by writing a `vex.cfg` file for CS. At simulation time, we can change cache configuration, core and bus frequency, and — in general — any parameter that does not require recompilation. For example, if we want to model a machine with 64KB data cache (4-way), 16KB instruction cache (2-way), 1GHz core clock, 200MHz memory bus clock, we can write a `vex.cfg` file containing:

```
CoreCkFreq          500
BusCkFreq           200
lg2CacheSize        16 # 64KB dcache
lg2Sets             4  # 4-way dcache
lg2ICacheSize       14 # 16KB icache
lg2ICacheSets       1  # 2-way icache
```

Then, we can simply invoke the simulation of our benchmark

```
## Run the program
./test
```

and look at the `ta.log.<nnn>` output file to analyze the statistics corresponding to the new configuration defined in `vex.cfg`.