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# $\rho$ -VEX reference manual

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This manual is intended to be used as a reference when working with the  $\rho$ -VEX reconfigurable VLIW processor ecosystem. The initial version was written in parallel with X. Both document essentially the same thing, but there are some key differences in their intended audience and, thus, what they focus on.

- The thesis is intended for the scientific reader, who is expected to be interested primarily in the new concepts introduced in this version of the  $\rho$ -VEX processor, and how they affect the system. As such, the thesis does not describe in detail the parts of the  $\rho$ -VEX core that have little research value. It will instead provide external references for supplemental information.
- This manual is intended for readers who intend to work with the  $\rho$ -VEX processor or want to add onto it. It thus strives to provide detailed documentation of all the parts of the system. In addition, external references are intentionally kept to a minimum in favor of copying information, to prevent the reader from having to constantly cross reference. Finally, the author hopes that this document will be modified over time, to reflect additions and changes made to the system. This is obviously not possible with a thesis.

Jeroen's  
thesis  
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+ refer-  
ence

While certainly possible, it is not intended that one reads this manual linearly. That would be like reading a dictionary from A to Z. Instead, the reader is advised to search for information recursively, first and foremost using the table of contents. Failing that, each section starts with a basic introduction, briefly describing the contents of its subsections. If you are reading this document digitally, references will be clickable to allow you to quickly jump to the parts you are interested in. In addition, almost all syllables, control registers and traps are clickable as well, to jump to their documentation.

## 1.1 Organization

The second chapter doubles as an introduction to the  $\rho$ -VEX processor architecture and a reference manual for those who intend to use the core. The third chapter documents the internal workings of the  $\rho$ -VEX processor core, intended for those who intend to modify or add to the core. The fourth chapter is similar, but instead documents the reconfigurable cache. The fifth chapter documents the bus system used within the  $\rho$ -VEX system to tie components together. The sixth chapter documents the debug support UART peripheral. The seventh chapter documents the  $\rho$ -VEX platforms, the colloquial name for the hardware systems that tie the previously described components together.

The eight chapter describes the host software systems, focussing primarily on the build system, the simulator and the debug communication link with the hardware. Finally, ninth chapter describes the general purpose software that has been written for the  $\rho$ -VEX processor so far.

This chapter is intended as a user guide for using the  $\rho$ -VEX processor core. For documentation about how the core works internally, refer to Chapter 3 instead.

The first section of this chapter gives a general introduction on VLIW processor architecture and the parts that make the  $\rho$ -VEX processor special. The next section describes the instruction set architecture (ISA) in detail, including a list of all instructions and their encodings. The third section lists and documents all the control registers. The fourth section describes the trap and interrupt model of the core, and subsequently lists all currently defined traps. The fifth section briefly documents the reconfiguration system. Finally, the last section documents how the core is configured and instantiated in an HDL design.



## 2.1 Introduction to the $\rho$ -VEX processor

Let us begin by defining some terminology. The  $\rho$ -VEX processor is a Very Large Instruction Word (VLIW) processor, which means that each instruction can specify multiple independent operations. Such operations are called *syllables*; a full instruction is called a *bundle*. *Instruction* may be used for either a bundle or a syllable, depending on context. A VLIW processor capable of executing  $n$  syllables per cycle is called an  $n$ -way VLIW processor.

Because the amount of syllables in a bundle is usually<sup>1</sup> not fixed, the processor needs a way to tell which syllables belong to which bundle. In the VEX architecture, this is done by means of a *stop bit* in each syllable. If the stop bit is set, the next syllable in the program starts a new bundle. Otherwise, the next syllable is part of the same bundle.

When a VLIW processor executes a bundle, each syllable will be routed to its own (*pipe*)*lane*. Note the ‘a’ in lane; this is not a typo for pipeline (although each pipeline, confusingly, does contain its own pipeline). In other words, the pipeline is the thing that contains the computational resources to execute a syllable.

### 2.1.1 Reconfiguration

What makes the  $\rho$ -VEX processor special compared to other VLIW processors, is that while the total number of pipelines is obviously fixed, the pipelines can be distributed between different programs, running in parallel. This distribution can be changed at runtime by means of *reconfiguration*.

Note that ‘reconfiguration’ here is used to describe a process within the system described by a single FPGA bitstream. In other words, the FPGA bitstream does not need to be fully or partially reloaded when the  $\rho$ -VEX processor reconfigures itself. This allows reconfiguration to be done in a single cycle in theory, although it comes at the cost of needing FPGA slice muxes or LUTs to permit reconfiguration, instead of using the FPGA fabric directly.

Not all pipelines are separable by means of reconfiguration. Groups of inseparable pipelines are called *lane groups*. Sometimes they are also referred to as *lanepairs* when a lane group contains two pipelines, which is the most common configuration.

In order to be able to run multiple programs on a single  $\rho$ -VEX processor core at the same time, an  $\rho$ -VEX processor supports multiple *contexts*. Formally, a context contains the complete state of a program, from program counter to register file. However, a more useful way to think of  $\rho$ -VEX contexts is as virtual processor cores. By means of reconfiguration, the amount of lane groups dedicated to each virtual core can be changed. In fact, it is possible to completely pause such a virtual core by simply assigning zero lane groups to it.

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<sup>1</sup>It is uncommon for the compiler to find enough parallelism in a program to fill an entire bundle. Therefore, if the bundle size is fixed, a lot of syllables will be NOP. While a fixed bundle size results in much simpler hardware, the size of the binary will be excessive. While main memory footprint is not so much an issue nowadays, memory throughput and latency is; the efficiency of the instruction coding directly affects execution speed as the memory is usually the bottleneck.

### 2.1.2 Generic binaries

To compile for a VLIW processor, the compiler needs to be aware of what the maximum number of syllables per bundle is. However, reconfiguration changes this value at run-time, which would imply that each program should be compiled multiple times, for each bundle size possible with reconfiguration. This would severely limit the usefulness of reconfiguration, as it would be extremely difficult to reconfigure in the middle of program execution. At best, the program counters would be the only things that would not match between the two binaries.

The solution to this problem is a *generic binary*. Generic binaries are compiled for the largest possible bundle size at which they may execute, referred to as the *generic bundle size*. This allows the compiler to extract as much parallelism as may ever be used. The difference between a normal binary compiled for the generic bundle size and a generic binary lies in additional rules imposed to the program by the assembler. These rules are carefully picked to ensure that, for instance, a bundle with four syllables in it still runs correctly if the two syllable pairs are run sequentially. Unless otherwise specified, an  $\rho$ -VEX generic binary refers to a binary compiled such that it runs correctly on 8-way, 4-way and 2-way  $\rho$ -VEX processor cores.

Reference  
to An-  
thony's  
generic  
binary  
paper  
here

### 2.1.3 Intended applications

On the short term, the current version of the  $\rho$ -VEX processor is still primarily intended for research. The VHDL is written in a highly flexible and configurable way, thus making modifications for experiments relatively easy. At the same time, several complex features have been added to the core, in order to make it possible to, for instance, run Linux on it. Most notably, precise trap support has been added since the previous  $\rho$ -VEX version, necessary for adding a memory-management unit.

This combination of flexibility and complexity comes at a cost: speed. The current version of the  $\rho$ -VEX processor only runs at 37.5 MHz on a high-end Virtex 6 FPGA using the default configuration, while almost completely filling it up. Much more interesting is what the  $\rho$ -VEX architecture is capable of on the long run when better optimized, or even ported to an ASIC.

In general, VLIW processors are well-suited for executing highly parallel programs, such as those found in digital signal processing (DSP). In particular, the reconfiguration capabilities of the  $\rho$ -VEX processor allow it to be used in places where multiple DSP algorithms run in parallel in a real-time system, such that each task has its own deadlines.

To demonstrate, consider a hypothetical audio/video decoder DSP with the following characteristics as an example.

- The audio and video decoders do not depend on each other and can thus be executed in parallel. The decoders themselves are not multithreaded.
- Both tasks run 1.5x as fast when running on a 4-way VLIW compared to a 2-way VLIW.

- The execution times of both tasks are data dependent. For example, if there is a lot of movement in the video, then the video task will take longer to complete.
- It is possible to heuristically predict whether or not either decoder will meet its deadline at its current execution speed before the deadline, in a way that does not cost an excessive amount of additional computation. This can be done, for example, by decoding audio and video a few frames in advance, and assuming that if the current frame is computationally intensive, the next one will probably be too (locality).
- The audio task takes priority over the video task, as choppy audio is perceived as more intrusive than choppy video.
- For simplicity, assume that while the video decoder is decoding a single frame, the audio decoder has to decode a frame's worth of audio samples. In other words, the audio and video decoding tasks start at the same time and have the same deadline. In addition, assume that both tasks need an approximately equal amount of processing time for a single frame.

Let us now analyze the performance of this system if it were implemented on two 2-way VLIW processors. Each processor is simply assigned to one of the tasks. The primary downside to this system in the context of this discussion is that if the audio is overly complex, the audio decoder will miss its deadline, regardless of whether the video processor was fully utilized or not.

To prevent this from happening, one may instead choose to implement the system on a single 4-way VLIW with a real-time operating system (RTOS) kernel. Notice that this system has the same amount of compute resources as the previous system. Now, the RTOS will ensure that the audio decoder runs before the video decoder. Because the audio decoder runs 1.5x as fast, it will likely meet its deadline now. While unlikely, it is possible that the video decoder will also complete in time now, but even if it does not, choppy video was considered favorable over choppy audio. The major downside of this system is that it is effectively much slower than the 2x2-way system, as the decoders do not actually run twice as fast when given twice as many computational resources, as the instruction level parallelism just is not always there.

The power of the  $\rho$ -VEX processor is that it can basically switch between these two implementations at runtime, depending on the actual load each task experiences. When neither task is in danger of failing to meet its deadline, the  $\rho$ -VEX processor could run in 2x2-way mode. However, if one of the tasks starts falling behind the other because it is more computationally intensive, the  $\rho$ -VEX processor could reconfigure to 1x4-way mode for that task. When it catches up, it will switch back to 2x2-way mode, as that is more efficient.

## 2.2 Instruction set architecture

The instruction set architecture (ISA) of the  $\rho$ -VEX processor is based on the HP VEX ISA and the ST200 processor family by STMicroelectronics . More specifically, the ISA is mostly copied from the previous version of the  $\rho$ -VEX processor . Instead of noting the differences between these architectures, this section functions as a reference for the  $\rho$ -VEX processor ISA in its current state, to save the reader from cross-referencing.

Insert reference to HP VEX ISA

### 2.2.1 Assembly syntax

The following listing shows the syntax for a single instruction bundle.

```
start:
  c0 stw  0x10[$r0.1] = $r0.53
  c0 add  $r0.3       = $r0.0, $r0.55
  c0 and  $b0.2       = $r0.0, $r0.10
  c0 call $l0.0       = interrupt
;;
```

Insert reference to information about ST200 family

The first line represents a label, as it ends in a colon. Each non-empty line that does not start with a semicolon and is not a label represents a syllable. The first part of the syllable, `c0`, is optional. It specifies the cluster that the syllable belongs to. Since the  $\rho$ -VEX processor currently does not support clusters, only cluster zero is allowed if specified. The second part represents the opcode of the syllable, defining the operation to be performed. The third part is the parameter list. Anything that is written to is placed before the equals sign, anything that is read is placed after. Finally, a double semicolon is used to mark bundle boundaries.

Insert reference to Roël's thesis if applicable (I never read it...)

The syntax for a general purpose register is `$r0.index`, where *index* is a number from 0 to 63. The first 0 is used to specify the cluster, which, again, is not used in the  $\rho$ -VEX processor. Branch registers and the link register have the same syntax, substituting the 'r' with a 'b' or an 'l' respectively. The *index* for branch registers ranges from 0 to 7. For link registers only 0 is allowed.

Memory references use the following syntax: `literal[$r0.index]`. At runtime, the literal is added to the register value to get the address.

Any literal may be a decimal or hexadecimal number (using `0x` notation), a label reference, or a basic C-like integer expression.

A port of the GNU assembler (gas) is used for assembly. Please refer to its manual for information on target-independent directives or more information on the expressions mentioned above.

In general, the C preprocessor is used to preprocess assembly files. This allows usage of the usual C-style comments, includes, definitions, etc. In particular, the control registers may be easily referenced as long as the appropriate files are included.

### 2.2.2 Registers

The  $\rho$ -VEX processor has five distinguishable register files. Each is described below.

### 2.2.2.1 General purpose registers

The  $\rho$ -VEX core contains 64 32-bit general purpose registers for arithmetic.

Register 0 is special, as it always reads as 0 when used by the processor. Writing to it does however work; the debug bus can read the latest value written to it. This allows the register to be used for debugging on rare occasions.

Register 1 is intended to be used as the stack pointer. The RETURN and RFI instructions can add an immediate value to it for stack adjustment, but otherwise the register is not special.

Register 63 can optionally be mapped to the link register at design time using generics. This allows arithmetic instructions to be performed on the link register without needing to use MOVFL and MOVTL, at the cost of a general purpose register.

There are no explicit move or load immediate operations, as the following syllables are already capable of these operations.

```
c0 or $r0.dest = $r0.0, $r0.src      // Move src to dest
c0 or $r0.dest = $r0.0, immediate    // Load immediate
```

### 2.2.2.2 Branch registers

The  $\rho$ -VEX core contains 8 1-bit registers used for branch conditions, select instructions, divisions, and additions of values wider than 32 bits.

All arithmetic operations that output a boolean value can write to either a general purpose register (in which case they will write 0 for false and 1 for true) or a branch register. These include all integer comparison operations and select boolean operations.

Moving a branch register to another branch register cannot be done in a single cycle, but loading an immediate into a branch register or moving to or from a general purpose register can be done as follows.

```
c0 cmpeq $b0.dest = $r0.0, $r0.0      // Load true
c0 cmpne $b0.dest = $r0.0, $r0.0      // Load false
c0 cmpne $b0.dest = $r0.0, $r0.src     // Move general purpose to branch
c0 slctf $r0.dest = $b0.src, $r0.0, 1 // Move branch to general purpose
```

Branch register can also not be loaded from or stored into memory on their own. However, to improve context switching speed slightly, the LDBR and STBR instructions are available. These load or store a byte containing all eight branch registers in a single syllable.

### 2.2.2.3 Link register

The link register is a 32-bit register used to store the return address when calling. It can also be used as the destination address for an unconditional indirect jump or call, in cases where the branch offset field is too small or when the jump target is determined at runtime.

When general purpose register 63 is not mapped to the link register, the MOVTL and LDW instructions can be used to load the link register from a general purpose register or memory respectively. MOVFL and STW perform the reverse operations.

#### 2.2.2.4 Global and context control registers

These two register files contain special-purpose registers. The global control registers contain status information not related to any context, whereas the context control registers are context specific.

The processor can access these register files through memory operations only. All these accesses are single-cycle. 1 kiB of memory space has to be reserved for this purpose, usually mapped to 0xFFFFFC00..0xFFFFFFFF. The location of the block is design-time configurable. Note that it is impossible for the processor to perform actual memory operations to this region, so the location of the block should be chosen wisely.

The global register file is read-only from the perspective of the program. The context register file is writable, but it should be noted that each program can only access its own hardware context register file. If an application requires that programs can write to the global register file or the other context register files, the debug bus can be made accessible by memory operations outside the core. In most platforms this happens coincidentally, as the processor can access the main bus of the platform, and the main bus is wired to the debug bus.

For more information about the control registers, refer to Section 2.3.

#### 2.2.3 Memory

Each lane group of the  $\rho$ -VEX processor currently has exactly one memory unit. The configurability of this may be extended in the future, as memory operations commonly end up being the critical path when extracting instruction-level parallelism. However, doing so would require significant modifications to the  $\rho$ -VEX core and the reconfigurable cache.

The  $\rho$ -VEX processor is big endian. This means that when accessing a 32-bit or 16-bit word, the most significant byte will reside in the lowest address. This is the opposite of what you may be used to coming from x86.

The  $\rho$ -VEX processor is capable of reading and writing 32-bit, 16-bit and 8-bit words. Separate read instructions exist for reading 16-bit and 8-bit words in signed or unsigned mode. All  $n$ -bit accesses must be  $n$ -bit aligned. If an access is improperly aligned, a MISALIGNED\_ACCESS trap will be caused.

Note that a 1 kiB block of the external memory space must be selected to be remapped to the control register file internally. This prevents the processor from being able to access the block. Refer to Section 2.2.2.4 for more information.

#### 2.2.4 Syllable resource classes and delays

Some syllables take more than one cycle to complete. In this case, they are always pipelined; no multi-cycle syllable will stall the rest of the bundle. While this is good for performance, it does require the attention of the programmer in order to write properly functioning code.

In addition, not all pipelines support execution of all syllables, and as such, requirements are imposed on the position of certain syllables within a bundle in the binary. The assembler will normally ensure that these requirements are met, unlike the delay requirements, which it cannot detect. However, it is still important for the user to know them in order to be able to write assembly.

It is also important that the assembler is configured in the same way as the core. If there are discrepancies, the assembler may still output binaries that the core cannot execute. If this happens, the core will produce an `TRAP_INVALID_OP` trap, with the index of the offending pipeline as the trap argument.

There are five distinguishable classes of syllables. These classes are ALU, multiply, memory, branch and long immediate.

##### 2.2.4.1 ALU class

ALU syllables are the basic  $\rho$ -VEX instructions. They can be processed by every lane. In the default pipeline and forwarding configuration of the  $\rho$ -VEX, their results are available after a single cycle. That is, the bundle immediately following can use their results.

##### 2.2.4.2 Multiply class

Multiply syllables are only allowed in lanes that are configured to have a multiplier. This configuration is done at design time using generics. In the default configuration, every lane has a multiplication unit.

In the default pipeline and forwarding configuration of the  $\rho$ -VEX, multiply instructions are two-cycle pipelined. That is, two bundle boundaries are needed between the syllable producing the value and a syllable that uses it.

##### 2.2.4.3 Memory class

Memory syllables are only allowed in lanes that are configured to have a memory unit. In addition, in most configurations, only one memory unit can be active per context at a time, even if multiple are available. This is due to the fact the data cache can only perform one operation per cycle per context. In theory, it is still permissible in such a system to perform a single memory operation and a single control register operation at the same time, but there is currently no toolchain support for this.

In the default pipeline and forwarding configuration of the  $\rho$ -VEX, memory load instructions are two-cycle pipelined. That is, two bundle boundaries are needed between a load syllable and the first syllable that uses the value. However, there is no store to

load delay; if a bundle with a load of a certain address immediately follows a bundle that stores a value at that address, the newly written value is loaded.

#### 2.2.4.4 Branch class

All syllables that affect the program counter are considered branch syllables. Only one branch syllable is permitted per cycle, and in almost all design-time core configurations, it must be the last syllable in a bundle.

In the previous  $\rho$ -VEX version, a delay was needed between a syllable producing a branch register or link register value and branch operations. This is not the case in the default pipeline and forwarding configuration of this  $\rho$ -VEX version, as the ALU and branch operations are initiated in the same pipeline stage.

#### 2.2.4.5 Long immediate class

Sometimes, one syllable does not contain enough information for one pipeline to execute. The only time when this happens in the  $\rho$ -VEX processor is when an immediate outside the range -256..255 is to be specified. For this purpose, LIMMH syllables exist. These syllables perform no operation in their own pipeline, but instead send 23 additional immediate bits to another lane, which allows a 32-bit immediate to be used in a single cycle.

Any ALU, multiply or memory syllable that supports an immediate can receive a long immediate. However, long immediates can *not* be used to extend the branch offset field.

LIMMH syllables are automatically inferred by the assembler. However, each LIMMH syllable inferred means that one less functional syllable can be scheduled in a single bundle. In addition, a certain pipeline can not ‘send’ a long immediate to any other pipeline.

The  $\rho$ -VEX supports two routes for long immediates to take. They are called ‘long immediate from neighbor’ and ‘long immediate from previous pair’. One or both of these methods may be enabled at design time using generics.

**Long immediate from neighbor** This is the most common route, as it is supported in all  $\rho$ -VEX configurations. This allows all pipelines to forward a long immediate to their immediate neighbor within a pair of pipelines. This is depicted in Figure 2.2 for an 8-way  $\rho$ -VEX processor.

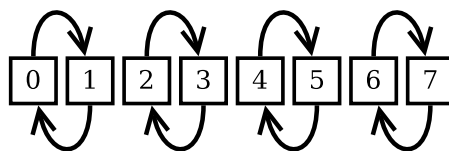


Figure 2.1: Long immediate from neighbor routing.



**Long immediate from previous pair** This provides an alternative place where a long immediate can be placed for lanes 2 and up; when this route is enabled lane  $n$  can send a long immediate to lane  $n + 2$ . This is depicted in Figure 2.2 for an 8-way  $\rho$ -VEX processor. However, due to limitations in the instruction fetch unit, this system is incompatible with the stop bit system. For these reasons, it can only be effectively used in cores with at least four lanes that are not configured to support stop bits.

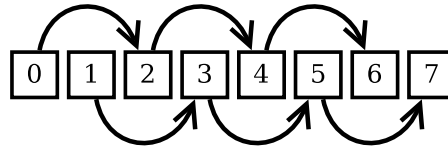


Figure 2.2: Long immediate from previous pair routing.

### 2.2.5 Generic binaries

This section might contain trace amounts of bullshit. Anthony should probably look over this sometime, as he knows more about it than I do. The vexparse stuff might also be wrong because I can't remember properly what I all added to it and what it could already do and I haven't looked into it yet. - Jeroen

Generic binaries are binaries that can be correctly run on different core configurations, even if the core reconfigures during execution. They were introduced in Anthony's generic binary paper. Typically, a generic binary refers to a binary that can be run with two pipelanes (2-way), four pipelanes (4-way) or eight pipelanes (8-way).

Insert reference to Anthony's generic binary paper

A generic binary is typically compiled in the same way as a regular 8-way binary. It is the task of the assembler to ensure that the generic binary requirements are met. For the standard generic binary, these rules are the following.

- *The single branch instruction allowed per bundle must end up in the last execution cycle in 2-way and 4-way execution.* The  $\rho$ -VEX processor imposes the even stricter requirement that branch syllables must always be the last syllable in a bundle.
- *RAW hazards must be avoided in all runtime configurations.* That is, for example, a register that is written in one of the first two syllables may not be read in subsequent slots. This is because the old value of the register would be read in 8-way mode, but the newly written value would be read in 2-way mode.

Extrapolating these rules to the general case should be trivial.

#### 2.2.5.1 Generating generic binaries

In order to generate generic binaries, the `-u` flag needs to be passed to the assembler. By default, the assembler will only try to move syllables around within bundles in order

to meet the requirements imposed above. However, often this is not possible without further processing.

There are two ways to process the assembly files to meet the requirements. The first one can be done by the assembler as well. If the `-autosplit` flag is passed, it will attempt to split bundles that it cannot schedule directly. This solves most problems at the cost of runtime performance. Refer to Anthony's generic binary paper for more information.

The second way involves running a python script called `vexparse` on the assembly compilation output, before passing them to the assembler. Depending on its configuration, `vexparse` will extract a dependency graph of all syllables in a basic block<sup>2</sup> from the assembly code, and then completely reschedule all instructions. As a side effect, it will fix hand-written assembly code that failed to take multiply and load instruction delays into consideration.

Being a python script, `vexparse` is much slower than the `-autosplit` option of the assembler. However, it generates more efficient code, as it is not limited to merely splitting bundles.

Insert  
refer-  
ence  
to An-  
thony's  
generic  
binary  
paper

### 2.2.6 Stop bits

The stop bit system is the colloquial name for the binary compression algorithm that the core may be design-time configured to support. It refers to a bit present in every syllable, which, if set, marks the syllable as the last syllable in the current bundle. In contrast, when the stop bit system is not used, bundle boundaries are based on alignment; each bundle is expected to start on an alignment boundary of the maximum size of a bundle. NOP instructions are then used to fill the unused words. The stop bit should then still be set in the last syllable, as failing to do so will cause a trap if the bundle contains a branch syllable.

The major advantage of stop bits is the decreased size of the binary. This does not only mean that the memory footprint of a program will be smaller; memory is cheap, so this is usually not an issue. More importantly, it means that the processor will need to do less instruction memory accesses for the same amount of computation; memory bandwidth and caches *are* expensive.

There is an additional benefit when combined with generic binaries. When a generic binary without stop bits runs in 8-way mode, the NOP instructions needed for bundle alignment do not cause any delays in execution, aside from the implicit delays due to the strain on the instruction memory system. However, when the binary is run in 2-way mode, these alignment NOPs may actually cost cycles. To illustrate, imagine an 8-way generic binary bundle with only two syllables used. When this bundle is executed in 2-way mode, execution will necessarily still take four cycles, because the processor still needs to work through eight syllables.<sup>3</sup> When stop bits are enabled, such alignment NOPs

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<sup>2</sup>A basic block is a block of instructions with natural scheduling boundaries at the start and end of it. The prime example of such boundaries are branch instructions.

<sup>3</sup>It is certainly possible to avoid this without a complete stop bit system. For example, for the previous version of the  $\rho$ -VEX processor, it was proposed to use the stop bits to mark the end of the useful part of a bundle, instead of the actual boundaries. In the case of our 8-way bundle with only two syllables

do not exist, so they will naturally never waste cycles.

The major disadvantage of using stop bits is its hardware complexity. Without stop bits, the core naturally always fetches a nicely aligned block of instruction memory to process. Each 32-bit word in this block can be wired directly to the syllable input of each lane. In contrast, when stop bits are fully enabled, a bundle may start on any 32-bit word boundary. Thus, a new module is needed between the instruction memory (which expects accesses aligned to its access size) and the pipelines. This module must then be capable of routing any incoming 32-bit word to any pipeline, based on the lower bits of the current program counter and even the syllable type, as branch syllables always need to be routed to the last pipeline. It must also store the previous fetch to handle misaligned bundles, and when a branch to a misaligned address occurs, it must stall execution for an additional cycle, as it will have to fetch both the memory block before and after the crossed alignment boundary.

On the plus side, the large multiplexers involved in this instruction buffer do not increase in size when adding reconfiguration capabilities to an 8-way core with stop bits. Some additional control logic is obviously required, but nothing more.

#### 2.2.6.1 Design-time configuration

The  $\rho$ -VEX processor core allows the designer to make a compromise between the large binary size without stop bits and the additional hardware needed with stop bits. Instead of simply supporting stop bits or not, the stop bit system is configured by specifying the bundle alignment boundaries that the core may expect. When the bundle alignment boundaries equal the size of the maximum bundle size, stop bits are effectively disabled. When the alignment boundary is set to 32-bit words, stop bits are fully enabled. Midway configuration are supported equally well.

Every time the bundle alignment boundary is halved, the multiplexers in the syllable dispatch logic double in size. The complexity of program counter generation increases with each step as well, as does the instruction fetch buffer size. Meanwhile, the number of alignment NOPs required in the binary decreases with each step.

The default 8-way reconfigurable core with stop bits enabled have the bundle alignment boundary set to 64-bit. Going all the way to 32-bit boundaries does not increase 2-way execution performance of an 8-way generic binary further, and most NOPs have already been eliminated, so doubling the hardware complexity once more is generally not justifiable.

#### 2.2.7 Instruction set

The  $\rho$ -VEX instruction set consists of 169 instructions. These instructions are defined by two bitfields in the syllable, called `opcode` and `imm_sw`. The `opcode` field is 8 bits in size,

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used, assuming the two syllables can be placed in the first two slots, the stop bit would be set in the second syllable instead of the eighth. When this code is executed in 2-way mode, the  $\rho$ -VEX processor would recognize that it can jump to the next 8-way bundle alignment boundary, thus skipping the six NOP syllables.

ranging from bit 31 to 24 inclusive, allowing for 256 different operations to be performed. `imm_sw` is a single bit (bit 23) that specifies if the second operand is a register or an immediate. This thus allows a total of 512 different instructions in theory.

However, not all operations support both register and immediate mode. In addition, some instructions have operand fields that extend into the opcode, requiring a single instruction to use multiple opcodes. Taking these things into consideration, the  $\rho$ -VEX instruction set has 113 opcodes that are not yet mapped.

There are two additional fields with a fixed function within the instruction set. The first is the stop bit, bit 1. This bit determines where the bundle boundaries are. Refer to Section 2.2.6 for more information. The second field, bit 0, is reserved for cluster end bits. The toolchain currently always outputs a 0 bit, and the processor ignores it completely.

The following table lists all the instructions in the  $\rho$ -VEX instruction set ordered by opcode. The subsequent sections document each instruction, ordered by function. If you are reading this document digitally, you can click any instruction in the table to jump to its documentation.

31 30 29 28 27 26 25 24	23 22 21 20 19 18 17 16	15 14 13 12 11 10 9 8	7 6 5 4 3 2 1 0			
0 0 0 0 0 0 0 0	0	d	x	y	S	mpyll \$r0.d = \$r0.x, \$r0.y
0 0 0 0 0 0 0 0	1	d	x	imm	S	mpyll \$r0.d = \$r0.x, imm
0 0 0 0 0 0 0 1	0	d	x	y	S	mpyllu \$r0.d = \$r0.x, \$r0.y
0 0 0 0 0 0 0 1	1	d	x	imm	S	mpyllu \$r0.d = \$r0.x, imm
0 0 0 0 0 0 1 0	0	d	x	y	S	mpylh \$r0.d = \$r0.x, \$r0.y
0 0 0 0 0 0 1 0	1	d	x	imm	S	mpylh \$r0.d = \$r0.x, imm
0 0 0 0 0 0 1 1	0	d	x	y	S	mpylhu \$r0.d = \$r0.x, \$r0.y
0 0 0 0 0 0 1 1	1	d	x	imm	S	mpylhu \$r0.d = \$r0.x, imm
0 0 0 0 0 1 0 0	0	d	x	y	S	mpyhh \$r0.d = \$r0.x, \$r0.y
0 0 0 0 0 1 0 0	1	d	x	imm	S	mpyhh \$r0.d = \$r0.x, imm
0 0 0 0 0 1 0 1	0	d	x	y	S	mpyuhu \$r0.d = \$r0.x, \$r0.y
0 0 0 0 0 1 0 1	1	d	x	imm	S	mpyuhu \$r0.d = \$r0.x, imm
0 0 0 0 0 1 1 0	0	d	x	y	S	mpyl \$r0.d = \$r0.x, \$r0.y
0 0 0 0 0 1 1 0	1	d	x	imm	S	mpyl \$r0.d = \$r0.x, imm
0 0 0 0 0 1 1 1	0	d	x	y	S	mpylu \$r0.d = \$r0.x, \$r0.y
0 0 0 0 0 1 1 1	1	d	x	imm	S	mpylu \$r0.d = \$r0.x, imm
0 0 0 0 1 0 0 0	0	d	x	y	S	mpyh \$r0.d = \$r0.x, \$r0.y
0 0 0 0 1 0 0 0	1	d	x	imm	S	mpyh \$r0.d = \$r0.x, imm
0 0 0 0 1 0 0 1	0	d	x	y	S	mpyhu \$r0.d = \$r0.x, \$r0.y
0 0 0 0 1 0 0 1	1	d	x	imm	S	mpyhu \$r0.d = \$r0.x, imm
0 0 0 0 1 0 1 0	0	d	x	y	S	mpyhs \$r0.d = \$r0.x, \$r0.y
0 0 0 0 1 0 1 0	1	d	x	imm	S	mpyhs \$r0.d = \$r0.x, imm
0 0 0 0 1 0 1 1	0			y	S	movtl \$l0.0 = \$r0.y
0 0 0 0 1 0 1 1	1			imm	S	movtl \$l0.0 = imm
0 0 0 0 1 1 0 0	0	d			S	movfl \$r0.d = \$l0.0
0 0 0 0 1 1 0 1	1		x	imm	S	ldw \$l0.0 = imm[\$r0.x]
0 0 0 0 1 1 1 0	1		x	imm	S	stw imm[\$r0.x] = \$l0.0
0 0 0 1 0 0 0 0	1	d	x	imm	S	ldw \$r0.d = imm[\$r0.x]
0 0 0 1 0 0 0 1	1	d	x	imm	S	ldh \$r0.d = imm[\$r0.x]
0 0 0 1 0 0 1 0	1	d	x	imm	S	ldhu \$r0.d = imm[\$r0.x]
0 0 0 1 0 0 1 1	1	d	x	imm	S	ldb \$r0.d = imm[\$r0.x]

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0		
0	0	0	1	0	1	0	0	1			d					x															S	ldbu \$r0.d = imm[\$r0.x]	
0	0	0	1	0	1	0	1	0	1		d					x															S	stw imm[\$r0.x] = \$r0.d	
0	0	0	1	0	1	1	0	1		d						x															S	sth imm[\$r0.x] = \$r0.d	
0	0	0	1	0	1	1	1	1		d						x															S	stb imm[\$r0.x] = \$r0.d	
0	0	0	1	1	0	0	0	0		d						x						y									S	shr \$r0.d = \$r0.x, \$r0.y	
0	0	0	1	1	0	0	0	1		d						x															S	shr \$r0.d = \$r0.x, imm	
0	0	0	1	1	0	0	0	1	0		d					x						y									S	shru \$r0.d = \$r0.x, \$r0.y	
0	0	0	1	1	0	0	1	1		d						x															S	shru \$r0.d = \$r0.x, imm	
0	0	0	1	1	0	1	0	0		d						x						y									S	sub \$r0.d = \$r0.y, \$r0.x	
0	0	0	1	1	0	1	0	1		d						x															S	sub \$r0.d = imm, \$r0.x	
0	0	0	1	1	0	1	1	0		d						x															S	sxtb \$r0.d = \$r0.x	
0	0	0	1	1	1	0	0	0		d						x															S	sxth \$r0.d = \$r0.x	
0	0	0	1	1	1	0	1	0		d						x															S	zxtb \$r0.d = \$r0.x	
0	0	0	1	1	1	1	0	0		d						x															S	zxth \$r0.d = \$r0.x	
0	0	0	1	1	1	1	1	0		d						x						y									S	xor \$r0.d = \$r0.x, \$r0.y	
0	0	0	1	1	1	1	1	1	0		d					x															S	xor \$r0.d = \$r0.x, imm	
0	0	1	0	0	0	0	0	0		offs																					S	goto offs	
0	0	1	0	0	0	0	0	1																								S	igoto \$l0.0
0	0	1	0	0	0	1	0		offs																							S	call \$l0.0 = offs
0	0	1	0	0	0	1	1																									S	icall \$l0.0 = \$l0.0
0	0	1	0	0	1	0	0		offs																				bs		S	br \$b0.bs, offs	
0	0	1	0	0	1	0	1		offs																				bs		S	brf \$b0.bs, offs	
0	0	1	0	0	1	1	0		stackadj																						S	return \$r0.1 = \$r0.1, stackadj, \$l0.0	
0	0	1	0	0	1	1	1		stackadj																						S	rfi \$r0.1 = \$r0.1, stackadj	
0	0	1	0	1	0	0	0																								S	stop	
0	0	1	0	1	1	0	0	0		d						x						y									S	sbit \$r0.d = \$r0.x, \$r0.y	
0	0	1	0	1	1	0	0	1		d						x															S	sbit \$r0.d = \$r0.x, imm	
0	0	1	0	1	1	0	1	0		d						x						y									S	sbitf \$r0.d = \$r0.x, \$r0.y	
0	0	1	0	1	1	0	1	1		d						x															S	sbitf \$r0.d = \$r0.x, imm	
0	0	1	0	1	1	1	0	1								x															S	ldbr imm[\$r0.x]	
0	0	1	0	1	1	1	1	1								x															S	stbr imm[\$r0.x]	
0	0	1	1	0			bs	0		d						x						y									S	slctf \$r0.d = \$b0.bs, \$r0.x, \$r0.y	
0	0	1	1	0			bs	1		d						x															S	slctf \$r0.d = \$b0.bs, \$r0.x, imm	
0	0	1	1	1			bs	0		d						x						y									S	slct \$r0.d = \$b0.bs, \$r0.x, \$r0.y	
0	0	1	1	1			bs	1		d						x															S	slct \$r0.d = \$b0.bs, \$r0.x, imm	
0	1	0	0	0	0	0	0	0		d						x						y									S	cmpeq \$r0.d = \$r0.x, \$r0.y	
0	1	0	0	0	0	0	0	1		d						x															S	cmpeq \$r0.d = \$r0.x, imm	
0	1	0	0	0	0	0	1	0			bd					x						y									S	cmpeq \$b0.bd = \$r0.x, \$r0.y	
0	1	0	0	0	0	0	1	1			bd					x															S	cmpeq \$b0.bd = \$r0.x, imm	
0	1	0	0	0	0	1	0	0		d						x						y									S	cmpge \$r0.d = \$r0.x, \$r0.y	
0	1	0	0	0	0	1	0	1		d						x															S	cmpge \$r0.d = \$r0.x, imm	
0	1	0	0	0	0	1	1	0			bd					x						y									S	cmpge \$b0.bd = \$r0.x, \$r0.y	
0	1	0	0	0	0	1	1	1			bd					x															S	cmpge \$b0.bd = \$r0.x, imm	
0	1	0	0	0	1	0	0	0		d						x						y									S	cmpgeu \$r0.d = \$r0.x, \$r0.y	
0	1	0	0	0	1	0	0	1		d						x															S	cmpgeu \$r0.d = \$r0.x, imm	
0	1	0	0	0	1	0	1	0			bd					x						y									S	cmpgeu \$b0.bd = \$r0.x, \$r0.y	
0	1	0	0	0	1	0	1	1			bd					x															S	cmpgeu \$b0.bd = \$r0.x, imm	
0	1	0	0	0	1	1	0	0		d						x						y									S	cmpgt \$r0.d = \$r0.x, \$r0.y	
0	1	0	0	0	1	1	0	1		d						x															S	cmpgt \$r0.d = \$r0.x, imm	
0	1	0	0	0	1	1	1	0			bd					x						y									S	cmpgt \$b0.bd = \$r0.x, \$r0.y	
0	1	0	0	0	1	1	1	1			bd					x															S	cmpgt \$b0.bd = \$r0.x, imm	
0	1	0	0	1	0	0	0	0		d						x						y									S	cmpgtu \$r0.d = \$r0.x, \$r0.y	

31 30 29 28 27 26 25 24	23 22 21 20 19 18 17 16	15 14 13 12 11 10 9 8	7 6 5 4 3 2 1 0	
0 1 0 0 1 0 0 0	1	d	x	imm
0 1 0 0 1 0 0 1	0		bd	x
0 1 0 0 1 0 0 1	1		bd	x
0 1 0 0 1 0 1 0	0	d	x	y
0 1 0 0 1 0 1 0	1	d	x	imm
0 1 0 0 1 0 1 1	0		bd	x
0 1 0 0 1 0 1 1	1		bd	x
0 1 0 0 1 1 0 0	0	d	x	y
0 1 0 0 1 1 0 0	1	d	x	imm
0 1 0 0 1 1 0 1	0		bd	x
0 1 0 0 1 1 0 1	1		bd	x
0 1 0 0 1 1 1 0	0	d	x	y
0 1 0 0 1 1 1 0	1	d	x	imm
0 1 0 0 1 1 1 1	0		bd	x
0 1 0 0 1 1 1 1	1		bd	x
0 1 0 1 0 0 0 0	0	d	x	y
0 1 0 1 0 0 0 0	1	d	x	imm
0 1 0 1 0 0 0 1	0		bd	x
0 1 0 1 0 0 0 1	1		bd	x
0 1 0 1 0 0 1 0	0	d	x	y
0 1 0 1 0 0 1 0	1	d	x	imm
0 1 0 1 0 0 1 1	0		bd	x
0 1 0 1 0 0 1 1	1		bd	x
0 1 0 1 0 1 0 0	0	d	x	y
0 1 0 1 0 1 0 0	1	d	x	imm
0 1 0 1 0 1 0 1	0		bd	x
0 1 0 1 0 1 0 1	1		bd	x
0 1 0 1 0 1 1 0	0	d	x	y
0 1 0 1 0 1 1 0	1	d	x	imm
0 1 0 1 0 1 1 1	0		bd	x
0 1 0 1 0 1 1 1	1		bd	x
0 1 0 1 1 0 0 0	0	d	x	y
0 1 0 1 1 0 0 0	1	d	x	imm
0 1 0 1 1 0 0 1	0		bd	x
0 1 0 1 1 0 0 1	1		bd	x
0 1 0 1 1 0 1 0	0	d	x	y
0 1 0 1 1 0 1 0	1	d	x	imm
0 1 0 1 1 0 1 1	0		bd	x
0 1 0 1 1 0 1 1	1		bd	x
0 1 0 1 1 1 0 0	0	d	x	y
0 1 0 1 1 1 0 0	1	d	x	imm
0 1 0 1 1 1 0 1	0		bd	x
0 1 0 1 1 1 0 1	1		bd	x
0 1 0 1 1 1 1 0	0	d	x	y
0 1 0 1 1 1 1 0	1	d	x	imm
0 1 0 1 1 1 1 1	0		bd	x
0 1 0 1 1 1 1 1	1		bd	x
0 1 1 0 0 0 0 0				S
0 1 1 0 0 0 0 1	0	d	x	y
0 1 1 0 0 0 1 0	1	d	x	imm
0 1 1 0 0 0 1 1	0	d	x	y
0 1 1 0 0 0 1 1	1	d	x	imm
0 1 1 0 0 0 1 1	1	d	x	imm

cmpgtu \$r0.d = \$r0.x, imm  
 cmpgtu \$b0.bd = \$r0.x, \$r0.y  
 cmpgtu \$b0.bd = \$r0.x, imm  
 cmple \$r0.d = \$r0.x, \$r0.y  
 cmple \$r0.d = \$r0.x, imm  
 cmple \$b0.bd = \$r0.x, \$r0.y  
 cmple \$b0.bd = \$r0.x, imm  
 cmpleu \$r0.d = \$r0.x, \$r0.y  
 cmpleu \$r0.d = \$r0.x, imm  
 cmpleu \$b0.bd = \$r0.x, \$r0.y  
 cmpleu \$b0.bd = \$r0.x, imm  
 cmplt \$r0.d = \$r0.x, \$r0.y  
 cmplt \$r0.d = \$r0.x, imm  
 cmplt \$b0.bd = \$r0.x, \$r0.y  
 cmplt \$b0.bd = \$r0.x, imm  
 cmplt \$b0.bd = \$r0.x, imm  
 cmpltu \$r0.d = \$r0.x, \$r0.y  
 cmpltu \$r0.d = \$r0.x, imm  
 cmpltu \$b0.bd = \$r0.x, \$r0.y  
 cmpltu \$b0.bd = \$r0.x, imm  
 cmpltu \$b0.bd = \$r0.x, imm  
 cmpne \$r0.d = \$r0.x, \$r0.y  
 cmpne \$r0.d = \$r0.x, imm  
 cmpne \$b0.bd = \$r0.x, \$r0.y  
 cmpne \$b0.bd = \$r0.x, imm  
 nandl \$r0.d = \$r0.x, \$r0.y  
 nandl \$r0.d = \$r0.x, imm  
 nandl \$b0.bd = \$r0.x, \$r0.y  
 nandl \$b0.bd = \$r0.x, imm  
 norl \$r0.d = \$r0.x, \$r0.y  
 norl \$r0.d = \$r0.x, imm  
 norl \$b0.bd = \$r0.x, \$r0.y  
 norl \$b0.bd = \$r0.x, imm  
 orl \$r0.d = \$r0.x, \$r0.y  
 orl \$r0.d = \$r0.x, imm  
 orl \$b0.bd = \$r0.x, \$r0.y  
 orl \$b0.bd = \$r0.x, imm  
 andl \$r0.d = \$r0.x, \$r0.y  
 andl \$r0.d = \$r0.x, imm  
 andl \$b0.bd = \$r0.x, \$r0.y  
 andl \$b0.bd = \$r0.x, imm  
 tbit \$r0.d = \$r0.x, \$r0.y  
 tbit \$r0.d = \$r0.x, imm  
 tbit \$b0.bd = \$r0.x, \$r0.y  
 tbit \$b0.bd = \$r0.x, imm  
 tbitf \$r0.d = \$r0.x, \$r0.y  
 tbitf \$r0.d = \$r0.x, imm  
 tbitf \$b0.bd = \$r0.x, \$r0.y  
 tbitf \$b0.bd = \$r0.x, imm  
 nop  
 add \$r0.d = \$r0.x, \$r0.y  
 add \$r0.d = \$r0.x, imm  
 and \$r0.d = \$r0.x, \$r0.y  
 and \$r0.d = \$r0.x, imm

31 30 29 28 27 26 25 24	23 22 21 20 19 18 17 16	15 14 13 12 11 10 9 8	7 6 5 4 3 2 1 0	
0 1 1 0 0 1 0 0	0	d	x	y
0 1 1 0 0 1 0 0	1	d	x	imm
0 1 1 0 0 1 0 1	0	d	x	y
0 1 1 0 0 1 0 1	1	d	x	imm
0 1 1 0 0 1 1 0	0	d	x	y
0 1 1 0 0 1 1 0	1	d	x	imm
0 1 1 0 0 1 1 1	0	d	x	y
0 1 1 0 0 1 1 1	1	d	x	imm
0 1 1 0 1 0 0 0	0	d	x	y
0 1 1 0 1 0 0 0	1	d	x	imm
0 1 1 0 1 0 0 1	0	d	x	y
0 1 1 0 1 0 0 1	1	d	x	imm
0 1 1 0 1 0 1 0	0	d	x	y
0 1 1 0 1 0 1 0	1	d	x	imm
0 1 1 0 1 0 1 1	0	d	x	y
0 1 1 0 1 0 1 1	1	d	x	imm
0 1 1 0 1 1 0 0	0	d	x	y
0 1 1 0 1 1 0 0	1	d	x	imm
0 1 1 0 1 1 0 1	0	d	x	y
0 1 1 0 1 1 0 1	1	d	x	imm
0 1 1 0 1 1 1 0	0	d	x	y
0 1 1 0 1 1 1 0	1	d	x	imm
0 1 1 0 1 1 1 1	0	d	x	y
0 1 1 0 1 1 1 1	1	d	x	imm
0 1 1 1 0	bs	0	d	x
0 1 1 1 1	bs	0	d	x
1 0 0 0	tgt	imm		S
1 0 0 1 0 0 0 0	0		x	y
1 0 0 1 0 0 0 0	1		x	imm
1 0 0 1 0 0 0 1	0	d	x	
1 0 0 1 0 0 1 0	0	d	x	y
1 0 0 1 0 0 1 0	1	d	x	imm
1 0 0 1 0 0 1 1	0	d	x	y
1 0 0 1 0 0 1 1	1	d	x	imm

andc \$r0.d = \$r0.x, \$r0.y
andc \$r0.d = \$r0.x, imm
max \$r0.d = \$r0.x, \$r0.y
max \$r0.d = \$r0.x, imm
maxu \$r0.d = \$r0.x, \$r0.y
maxu \$r0.d = \$r0.x, imm
min \$r0.d = \$r0.x, \$r0.y
min \$r0.d = \$r0.x, imm
minu \$r0.d = \$r0.x, \$r0.y
minu \$r0.d = \$r0.x, imm
or \$r0.d = \$r0.x, \$r0.y
or \$r0.d = \$r0.x, imm
orc \$r0.d = \$r0.x, \$r0.y
orc \$r0.d = \$r0.x, imm
shladd \$r0.d = \$r0.x, \$r0.y
shladd \$r0.d = \$r0.x, imm
sh2add \$r0.d = \$r0.x, \$r0.y
sh2add \$r0.d = \$r0.x, imm
sh3add \$r0.d = \$r0.x, \$r0.y
sh3add \$r0.d = \$r0.x, imm
sh4add \$r0.d = \$r0.x, \$r0.y
sh4add \$r0.d = \$r0.x, imm
shl \$r0.d = \$r0.x, \$r0.y
shl \$r0.d = \$r0.x, imm
divs \$r0.d, \$b0.bd = \$b0.bs, \$r0.x, \$r0.y
addcg \$r0.d, \$b0.bd = \$b0.bs, \$r0.x, \$r0.y
limmh tgt, imm
trap \$r0.x, \$r0.y
trap \$r0.x, imm
clz \$r0.d = \$r0.x
mpylhus \$r0.d = \$r0.x, \$r0.y
mpylhus \$r0.d = \$r0.x, imm
mpyhhs \$r0.d = \$r0.x, \$r0.y
mpyhhs \$r0.d = \$r0.x, imm

### 2.2.7.1 ALU arithmetic instructions

The  $\rho$ -VEX ALU has a 32-bit adder for arithmetic. Some exotic instructions are available to make efficient multiplications by small constants and to speed up software divisions.

**add \$r0.d = \$r0.x, \$r0.y**

**add \$r0.d = \$r0.x, imm**

31 30 29 28 27 26 25 24	23 22 21 20 19 18 17 16	15 14 13 12 11 10 9 8	7 6 5 4 3 2 1 0	
0 1 1 0 0 0 1 0	0	d	x	y
0 1 1 0 0 0 1 0	1	d	x	imm

Performs a 32-bit addition. Notice that ADD instructions may be used as move or load immediate operations when x is set to 0. While the OR instruction is often used instead, there is no functional difference between the two when used in this way.

```
$r0.d = $r0.x + [$r0.y|imm];
```

```
shladd $r0.d = $r0.x, $r0.y
```

```
shladd $r0.d = $r0.x, imm
```

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	1	0	1	0	1	1	0	d						x						y									S	
0	1	1	0	1	0	1	1	1	d						x						imm									S	

Performs a 32-bit addition. \$r0.x is first left-shifted by one.

```
$r0.d = ($r0.x << 1) + [$r0.y|imm];
```

```
sh2add $r0.d = $r0.x, $r0.y
```

```
sh2add $r0.d = $r0.x, imm
```

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	1	0	1	1	0	0	0	d						x					y								S			
0	1	1	0	1	1	0	0	1	d						x					imm										S	

Performs a 32-bit addition. \$r0.x is first left-shifted by two.

```
$r0.d = ($r0.x << 2) + [$r0.y|imm];
```

```
sh3add $r0.d = $r0.x, $r0.y
```

```
sh3add $r0.d = $r0.x, imm
```

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	1	0	1	1	0	1	0	d						x					y								S			
0	1	1	0	1	1	0	1	1	d						x					imm								S			

Performs a 32-bit addition. \$r0.x is first left-shifted by three.

```
$r0.d = ($r0.x << 3) + [$r0.y|imm];
```

```
sh4add $r0.d = $r0.x, $r0.y
```

```
sh4add $r0.d = $r0.x, imm
```

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	1	0	1	1	1	0	0	d						x					y									S		
0	1	1	0	1	1	1	0	1	d						x					imm										S	

Performs a 32-bit addition. \$r0.x is first left-shifted by four.

```
$r0.d = ($r0.x << 4) + [$r0.y|imm];
```

```
sub $r0.d = $r0.y, $r0.x
```

```
sub $r0.d = imm, $r0.x
```

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	1	0	1	0	0	d						x					y								S			
0	0	0	1	1	0	1	0	1	d						x					imm										S	



Performs a 32-bit subtraction. Note that, unlike all other instructions, the immediate must be specified first. This allows SUB to be used to subtract a register from an immediate.

Notice that SUB reduces to two's complement negation when x or imm equal zero.

```
$r0.d = [$r0.y|imm] + $r0.x;
```

**addcg \$r0.d, \$b0.bd = \$b0.bs, \$r0.x, \$r0.y**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	1	1	1			bs	0																							

Primitive for additions of integers wider than 32 bits. Addition is performed by first setting a scratch branch register to false using NEQ for the carry input. Then ADDCG can be used to add up words together one by one with increasing significance, using the scratch branch register for the carry chain.

Subtractions can be performed by setting the carry input to 1 using EQ and ones-complementing one of the inputs using XOR.

```
long long tmp = $r0.x + $r0.y + ($b0.bs ? 1 : 0);
$r0.d = (int)tmp;
$b0.bd = (tmp & 0x100000000) != 0;
```

**divs \$r0.d, \$b0.bd = \$b0.bs, \$r0.x, \$r0.y**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	1	1	0			bs	0																							

Primitive for integer divisions, used in conjunction with ADDCG.

Figure out how divisions work so it can be explained here.

Notice that DIVS reduces to rotate left by one through a branch register when y is zero. This may be used for for shift left by one operations on integers wider than 32 bits.

```
int tmp = ($r0.x << 1) | ($b0.bs ? 1 : 0);
bool flag = ($r0.x & 0x80000000) != 0;
$r0.d = flag ? (tmp + $r0.y) : (tmp - $r0.y);
$b0.bd = flag;
```

## 2.2.7.2 ALU barrel shifter instructions

The  $\rho$ -VEX ALU includes a barrel shifter. It should be noted that the shift amount input to the barrel shifter is 8-bit unsigned, not 32-bit as one might expect. That is, the upper 24 bits of the shift amount are discarded, and for instance a left shift by a negative amount will *not* simply result in a right shift.

**shl \$r0.d = \$r0.x, \$r0.y**

**shl \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	1	0	1	1	1	1	0	d						x					y								S			
0	1	1	0	1	1	1	1	1	d						x					imm										S	

Performs a left-shift operation. Zeros are shifted in from the right.

```
$r0.d = $r0.x << [$r0.y|imm];
```

**shr \$r0.d = \$r0.x, \$r0.y**

**shr \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	1	0	0	0	0	d						x					y								S			
0	0	0	1	1	0	0	0	1	d						x					imm								S			

Performs a signed right-shift operation. That is, the sign bit of \$r0.x is shifted in from the left.

```
$r0.d = $r0.x >> [$r0.y|imm];
```

**shru \$r0.d = \$r0.x, \$r0.y**

**shru \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	1	0	0	1	0	d						x					y								S			
0	0	0	1	1	0	0	1	1	d						x					imm										S	

Performs an unsigned right-shift operation. That is, zeros are shifted in from the left.

```
$r0.d = (unsigned int)$r0.x >> [$r0.y|imm];
```

### 2.2.7.3 ALU bitwise instructions

The  $\rho$ -VEX ALU supports a subset of bitwise operations in a single cycle.

**and \$r0.d = \$r0.x, \$r0.y**

**and \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	1	0	0	0	1	1	0	d				x				y								S						
0	1	1	0	0	0	1	1	1	d				x				imm								S						

Performs a bitwise AND operation.

```
$r0.d = $r0.x & [$r0.y|imm];
```

**andc \$r0.d = \$r0.x, \$r0.y**

**andc \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	1	0	0	1	0	0	0	d						x					y								S			
0	1	1	0	0	1	0	0	1	d						x					imm								S			

Performs a bitwise AND operation, with the first operand one's complemented.

```
$r0.d = ~$r0.x & [$r0.y|imm];
```

**or \$r0.d = \$r0.x, \$r0.y**

**or \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	1	0	1	0	0	1	0	d						x					y								S			
0	1	1	0	1	0	0	1	1	d						x					imm								S			

Performs a bitwise OR operation. Notice that OR instructions reduce to move or load immediate operations when x is set to 0.

```
$r0.d = $r0.x | [$r0.y|imm];
```

**orc \$r0.d = \$r0.x, \$r0.y**

**orc \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	1	0	1	0	1	0	0	d						x					y								S			
0	1	1	0	1	0	1	0	1	d						x					imm								S			

Performs a bitwise OR operation, with the first operand one's complemented. Notice that ORC instructions reduce to one's complement when y or imm is set to 0.

```
$r0.d = ~$r0.x | [$r0.y|imm];
```

**xor \$r0.d = \$r0.x, \$r0.y**

**xor \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	1	1	1	1	0	d						x					y								S			
0	0	0	1	1	1	1	1	1	d						x					imm										S	

Performs a bitwise XOR operation.

```
$r0.d = $r0.x ^ [$r0.y|imm];
```

#### 2.2.7.4 ALU single-bit instructions

The  $\rho$ -VEX ALU supports several bitfield operations in a single cycle. Note that the bit selection logic follows the same rules as the shift amount in the barrel shifter. That is,

only the least significant byte of the bit selection operand is used to select the bit, the rest is ignored.

**sbit \$r0.d = \$r0.x, \$r0.y**

**sbit \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	0	1	1	0	0	0	d						x					y								S			
0	0	1	0	1	1	0	0	1	d						x					imm								S			

Sets a given bit in a 32-bit integer.

```
$r0.d = $r0.x | (1 << [$r0.y|imm]);
```

**sbitf \$r0.d = \$r0.x, \$r0.y**

**sbitf \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	0	1	1	0	1	0	d						x					y								S			
0	0	1	0	1	1	0	1	1	d						x					imm								S			

Clears a given bit in a 32-bit integer.

```
$r0.d = $r0.x & ~(1 << [$r0.y|imm]);
```

**tbit \$r0.d = \$r0.x, \$r0.y**

**tbit \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	1	1	1	0	0	0	d						x					y								S			
0	1	0	1	1	1	0	0	1	d						x					imm										S	

Copies a given bit to an integer register.

```
$r0.d = ($r0.x & (1 << [$r0.y|imm])) != 0;
```

**tbit \$b0.bd = \$r0.x, \$r0.y**

**tbit \$b0.bd = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	1	1	1	0	1	0					bd				x							y					S		
0	1	0	1	1	1	0	1	1					bd				x												S		

Copies a given bit to a branch register.

```
$b0.bd = ($r0.x & (1 << [$r0.y|imm])) != 0;
```

**tbitf \$r0.d = \$r0.x, \$r0.y**

**tbitf \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	1	1	1	1	0	0	d						x					y									S		
0	1	0	1	1	1	1	0	1	d						x					imm										S	

Copies the complement of a given bit to an integer register.

```
$r0.d = ($r0.x & (1 << [$r0.y|imm])) == 0;
```

```
tbitf $b0.bd = $r0.x, $r0.y
```

```
tbitf $b0.bd = $r0.x, imm
```

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	1	1	1	1	1	0				bd		x			y									S					
0	1	0	1	1	1	1	1	1				bd		x			imm										S				

Copies the complement of a given bit to a branch register.

```
$b0.bd = ($r0.x & (1 << [$r0.y|imm])) == 0;
```

### 2.2.7.5 ALU boolean instructions

As well as supporting many bitwise operations, the  $\rho$ -VEX ALU also supports some boolean operations in a single cycle. The boolean operations are defined in the same way as C boolean operations are defined. That is, the value 0 represents false, and any other value represents true.

```
andl $r0.d = $r0.x, $r0.y
```

```
andl $r0.d = $r0.x, imm
```

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	1	1	0	1	0	0	d						x					y									S		
0	1	0	1	1	0	1	0	1	d						x					imm								S			

Performs a boolean AND operation and stores the result in an integer register.

```
$r0.d = $r0.x && [$r0.y|imm];
```

```
andl $b0.bd = $r0.x, $r0.y
```

```
andl $b0.bd = $r0.x, imm
```

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	1	1	0	1	1	0					bd		x				y								S				
0	1	0	1	1	0	1	1	1					bd		x				imm								S				

Performs a boolean AND operation and stores the result in a branch register.

```
$b0.bd = $r0.x && [$r0.y|imm];
```

```
orl $r0.d = $r0.x, $r0.y
```

```
orl $r0.d = $r0.x, imm
```

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	1	1	0	0	0	0	d						x					y								S			
0	1	0	1	1	0	0	0	1	d						x					imm								S			

Performs a boolean OR operation and stores the result in an integer register.

```
$r0.d = $r0.x || [$r0.y|imm];
```

```
orl $b0.bd = $r0.x, $r0.y
```

```
orl $b0.bd = $r0.x, imm
```

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	1	1	0	0	1	0				bd					x			y							S				
0	1	0	1	1	0	0	1	1				bd					x			imm							S				

Performs a boolean OR operation and stores the result in a branch register.

```
$b0.bd = $r0.x || [$r0.y|imm];
```

```
nandl $r0.d = $r0.x, $r0.y
```

```
nandl $r0.d = $r0.x, imm
```

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	1	0	1	0	0	0	d						x					y									S		
0	1	0	1	0	1	0	0	1	d						x					imm										S	

Performs a boolean NAND operation and stores the result in an integer register.

```
$r0.d = !($r0.x && [$r0.y|imm]);
```

```
nandl $b0.bd = $r0.x, $r0.y
```

```
nandl $b0.bd = $r0.x, imm
```

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	1	0	1	0	1	0				bd				x					y								S		
0	1	0	1	0	1	0	1	1				bd				x					imm								S		

Performs a boolean NAND operation and stores the result in a branch register.

```
$b0.bd = !($r0.x && [$r0.y|imm]);
```

```
norl $r0.d = $r0.x, $r0.y
```

```
norl $r0.d = $r0.x, imm
```

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	1	0	1	1	0	0	d						x					y								S			
0	1	0	1	0	1	1	0	1	d						x					imm										S	

Performs a boolean NOR operation and stores the result in an integer register.

```
$r0.d = !($r0.x || [$r0.y|imm]);
```

```
norl $b0.bd = $r0.x, $r0.y
```

```
norl $b0.bd = $r0.x, imm
```

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	1	0	1	1	1	0				bd				x						y							S		
0	1	0	1	0	1	1	1	1				bd				x						imm							S		

Performs a boolean NOR operation and stores the result in a branch register.

```
$b0.bd = !($r0.x || [$r0.y|imm]);
```

### 2.2.7.6 ALU compare instructions

The  $\rho$ -VEX ALU supports all 32-bit possible integer comparison operations in a single cycle. The immediate version of CMPNE that writes to a branch register is used to load an immediate branch register.

**cmpeq \$r0.d = \$r0.x, \$r0.y**

**cmpeq \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	0	0	0	0	0	0			d							x												S	
0	1	0	0	0	0	0	0	1			d							x												S	

Determines whether the first operand is equal to the second operand and stores the result in an integer register.

```
$r0.d = $r0.x == [$r0.y|imm];
```

**cmpeq \$b0.bd = \$r0.x, \$r0.y**

**cmpeq \$b0.bd = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	0	0	0	0	1	0				bd		x			y									S					
0	1	0	0	0	0	0	1	1				bd		x			imm									S					

Determines whether the first operand is equal to the second operand and stores the result in a branch register.

```
$b0.bd = $r0.x == [$r0.y|imm];
```

**cmpge \$r0.d = \$r0.x, \$r0.y**

**cmpge \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	0	0	0	1	0	0			d							x												S	
0	1	0	0	0	0	1	0	1			d							x												S	

Determines whether the first operand is greater than or equal to the second operand and stores the result in an integer register.

```
$r0.d = $r0.x >= [$r0.y|imm];
```

**cmpge \$b0.bd = \$r0.x, \$r0.y**

**cmpge \$b0.bd = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	0	0	0	1	1	0				bd					x						y						S		
0	1	0	0	0	0	1	1	1				bd					x						imm						S		

Determines whether the first operand is greater than or equal to the second operand and stores the result in a branch register.

```
$b0.bd = $r0.x >= [$r0.y|imm];
```

**cmpgeu \$r0.d = \$r0.x, \$r0.y**

**cmpgeu \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	0	0	1	0	0	0	d						x					y									S		
0	1	0	0	0	1	0	0	1	d						x					imm										S	

Determines whether the first operand is greater than or equal to the second operand in unsigned arithmetic and stores the result in an integer register.

```
$r0.d = (unsigned int)$r0.x >= (unsigned int)[$r0.y|imm];
```

**cmpgeu \$b0.bd = \$r0.x, \$r0.y**

**cmpgeu \$b0.bd = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	0	0	1	0	1	0				bd					x					y							S		
0	1	0	0	0	1	0	1	1				bd					x												S		

Determines whether the first operand is greater than or equal to the second operand in unsigned arithmetic and stores the result in a branch register.

```
$b0.bd = (unsigned int)$r0.x >= (unsigned int)[$r0.y|imm];
```

**cmpgt \$r0.d = \$r0.x, \$r0.y**

**cmpgt \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	0	0	1	1	0	0	d						x					y									S		
0	1	0	0	0	1	1	0	1	d						x					imm										S	

Determines whether the first operand is greater than the second operand and stores the result in an integer register.

```
$r0.d = $r0.x > [$r0.y|imm];
```



**cmpgt \$b0.bd = \$r0.x, \$r0.y**

**cmpgt \$b0.bd = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	0	0	1	1	1	0				bd		x				y								S					
0	1	0	0	0	1	1	1	1				bd		x				imm								S					

Determines whether the first operand is greater than the second operand and stores the result in a branch register.

```
$b0.bd = $r0.x > [$r0.y|imm];
```

**cmpgtu \$r0.d = \$r0.x, \$r0.y**

**cmpgtu \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	0	1	0	0	0	0	d							x					y								S		
0	1	0	0	1	0	0	0	1	d							x					imm								S		

Determines whether the first operand is greater than the second operand in unsigned arithmetic and stores the result in an integer register.

```
$r0.d = (unsigned int)$r0.x > (unsigned int)[$r0.y|imm];
```

**cmpgtu \$b0.bd = \$r0.x, \$r0.y**

**cmpgtu \$b0.bd = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	0	1	0	0	1	0					bd			x					y								S		
0	1	0	0	1	0	0	1	1					bd			x					imm								S		

Determines whether the first operand is greater than the second operand in unsigned arithmetic and stores the result in a branch register.

```
$b0.bd = (unsigned int)$r0.x > (unsigned int)[$r0.y|imm];
```

**cmple \$r0.d = \$r0.x, \$r0.y**

**cmple \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	0	1	0	1	0	0	d						x					y									S		
0	1	0	0	1	0	1	0	1	d						x					imm									S		

Determines whether the first operand is less than or equal to the second operand and stores the result in an integer register.

```
$r0.d = $r0.x <= [$r0.y|imm];
```

**cmple \$b0.bd = \$r0.x, \$r0.y**

**cmple \$b0.bd = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	0	1	0	1	1	0				bd				x					y								S		
0	1	0	0	1	0	1	1	1				bd				x					imm								S		

Determines whether the first operand is less than or equal to the second operand and stores the result in a branch register.

```
$b0.bd = $r0.x <= [$r0.y|imm];
```

**cmpleu \$r0.d = \$r0.x, \$r0.y**

**cmpleu \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	0	1	1	0	0	0	d						x					y									S		
0	1	0	0	1	1	0	0	1	d						x					imm										S	

Determines whether the first operand is less than or equal to the second operand in unsigned arithmetic and stores the result in an integer register.

```
$r0.d = (unsigned int)$r0.x <= (unsigned int)[$r0.y|imm];
```

**cmpleu \$b0.bd = \$r0.x, \$r0.y**

**cmpleu \$b0.bd = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	0	1	1	0	1	0				bd				x					y								S		
0	1	0	0	1	1	0	1	1				bd				x					imm								S		

Determines whether the first operand is less than or equal to the second operand in unsigned arithmetic and stores the result in a branch register.

```
$b0.bd = (unsigned int)$r0.x <= (unsigned int)[$r0.y|imm];
```

**cmplt \$r0.d = \$r0.x, \$r0.y**

**cmplt \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	0	1	1	1	0	0	d						x					y									S		
0	1	0	0	1	1	1	0	1	d						x					imm										S	

Determines whether the first operand is less than the second operand and stores the result in an integer register.

```
$r0.d = $r0.x <= [$r0.y|imm];
```

**cmplt \$b0.bd = \$r0.x, \$r0.y**

**cmplt \$b0.bd = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	0	1	1	1	1	0					bd		x				y								S				
0	1	0	0	1	1	1	1	1					bd		x				imm								S				

Determines whether the first operand is less than the second operand and stores the result in a branch register.

```
$b0.bd = $r0.x <= [$r0.y|imm];
```

**cmpltu \$r0.d = \$r0.x, \$r0.y**

**cmpltu \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0	1	0	1	0	0	0	0	0	d							x					y								S			
0	1	0	1	0	0	0	0	1	d							x					imm										S	

Determines whether the first operand is less than the second operand in unsigned arithmetic and stores the result in an integer register.

```
$r0.d = (unsigned int)$r0.x <= (unsigned int)[$r0.y|imm];
```

**cmpltu \$b0.bd = \$r0.x, \$r0.y**

**cmpltu \$b0.bd = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0	1	0	1	0	0	0	1	0					bd				x					y							S			
0	1	0	1	0	0	0	1	1					bd				x												imm		S	

Determines whether the first operand is less than the second operand in unsigned arithmetic and stores the result in a branch register.

```
$b0.bd = (unsigned int)$r0.x <= (unsigned int)[$r0.y|imm];
```

**cmpne \$r0.d = \$r0.x, \$r0.y**

**cmpne \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	1	0	0	1	0	0	d				x				y								S						
0	1	0	1	0	0	1	0	1	d				x				imm								S						

Determines whether the first operand is not equal to the second operand and stores the result in an integer register.

```
$r0.d = $r0.x != [$r0.y|imm];
```

**cmpne \$b0.bd = \$r0.x, \$r0.y**

**cmpne \$b0.bd = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	0	1	0	0	1	1	0				bd					x						y						S		
0	1	0	1	0	0	1	1	1				bd					x						imm						S		

Determines whether the first operand is not equal to the second operand and stores the result in a branch register.

Notice that the immediate version of CMPNE reduces to a load immediate operation for branch registers when x is zero.

```
$b0.bd = $r0.x != [$r0.y|imm];
```

### 2.2.7.7 ALU selection instructions

The  $\rho$ -VEX ALU has single-cycle instructions for conditional moves and computation of the minimum and maximum of two integer values.

**slct \$r0.d = \$b0.bs, \$r0.x, \$r0.y**

**slct \$r0.d = \$b0.bs, \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	1	1		bs		0	d						x					y									S		
0	0	1	1	1		bs		1	d						x					imm										S	

Conditional move.

```
$r0.d = $b0.bs ? $r0.x : [$r0.y|imm];
```

**slctf \$r0.d = \$b0.bs, \$r0.x, \$r0.y**

**slctf \$r0.d = \$b0.bs, \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	1	0	bs		0	d				x				y								S							
0	0	1	1	0	bs		1	d				x				imm								S							

Conditional move, with operands swapped with respect to SLCT.

Notice that the immediate version of SLCTF reduces to a move from a branch register to an integer register when x is 0 and y is 1.

```
$r0.d = $b0.bs ? [$r0.y|imm] : $r0.x;
```

**max \$r0.d = \$r0.x, \$r0.y**

**max \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	1	0	0	1	0	1	0	d				x				y								S						
0	1	1	0	0	1	0	1	1	d				x				imm								S						

Computes maximum of the input operands using signed arithmetic.

```
$r0.d = ($r0.x >= [$r0.y|imm]) : $r0.x ? [$r0.y|imm];
```

```
maxu $r0.d = $r0.x, $r0.y
```

```
maxu $r0.d = $r0.x, imm
```

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0	1	1	0	0	1	1	0	0	d						x						y										S	
0	1	1	0	0	1	1	0	1	d						x						imm										S	

Computes maximum of the input operands using unsigned arithmetic.

```
$r0.d = ((unsigned int)$r0.x >= (unsigned int)[$r0.y|imm]) : $r0.x ? [$r0.y|imm];
```

```
min $r0.d = $r0.x, $r0.y
```

```
min $r0.d = $r0.x, imm
```

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0	1	1	0	0	1	1	1	0	d						x						y										S	
0	1	1	0	0	1	1	1	1	d						x						imm										S	

Computes minimum of the input operands using signed arithmetic.

```
$r0.d = ($r0.x <= [$r0.y|imm]) : $r0.x ? [$r0.y|imm];
```

```
minu $r0.d = $r0.x, $r0.y
```

```
minu $r0.d = $r0.x, imm
```

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	1	0	1	0	0	0	0	d						x					y									S		
0	1	1	0	1	0	0	0	1	d						x					imm									S		

Computes minimum of the input operands using unsigned arithmetic.

```
$r0.d = ((unsigned int)$r0.x <= (unsigned int)[$r0.y|imm]) : $r0.x ? [$r0.y|imm];
```

## 2.2.7.8 ALU type conversion instructions

The  $\rho$ -VEX ALU is capable of supporting typecasts from 32-bit integers to 16-bit and 8-bit integers in a single cycle.

```
sxtb $r0.d = $r0.x
```

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	1	0	1	1	0	d						x												S				

Performs sign extension for an 8-bit value.

```
$r0.d = (char)$r0.x;
```

**sxth \$r0.d = \$r0.x**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	1	1	0	0	0	d							x														S	

Performs sign extension for a 16-bit value.

```
$r0.d = (short)$r0.x;
```

**zxtb \$r0.d = \$r0.x**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	1	1	0	1	0	d							x														S	

Performs zero extension for an 8-bit value.

```
$r0.d = (unsigned char)$r0.x;
```

**zxth \$r0.d = \$r0.x**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	1	1	1	0	0	d							x														S	

Performs zero extension for a 16-bit value.

```
$r0.d = (unsigned short)$r0.x;
```

## 2.2.7.9 ALU miscellaneous instructions

**nop**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	1	0	0	0	0	0																			S					

Performs no operation.

**clz \$r0.d = \$r0.x**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	1	0	0	0	1	0	d							x														S	

This operations counts the number of leading zeros in the operand. That is, the value 0x80000000 returns 0 and the value 0 returns 32.

```
unsigned int in = $r0.x;
int out = 32;
while (in) {
    in >>= 1;
    out--;
}
$r0.d = out;
```

**movtl \$l0.0 = \$r0.y**

**movtl \$l0.0 = imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0	0	0	0	1	0	1	1	0													y										S	
0	0	0	0	1	0	1	1	1													imm										S	

Copies a general purpose register or immediate to the link register.

```
$l0.0 = [$r0.y|imm];
```

**movfl \$r0.d = \$l0.0**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	0	1	1	0	0	0	d																				S	

Copies the link register to a general purpose register.

```
$r0.d = $l0.0;
```

**trap \$r0.x, \$r0.y**

**trap \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	1	0	0	0	0	0								x					y									S	
1	0	0	1	0	0	0	0	1								x					imm									S	

Software trap. The first parameter is the trap argument, while the second parameter is the trap cause byte.

## 2.2.7.10 Multiply instructions

$\rho$ -VEX pipelines may be design-time configured to contain a multiplication unit. This unit supports 16x16 and 16x32 multiplications.

In the default pipeline configuration, these instructions are pipelined by two cycles. That is, the result of a multiply instruction is not available yet in the subsequent instruction.

Properly document the multiply instructions. This is a bit of a pain due to the fact that they make no sense to me at all.

**mpyll \$r0.d = \$r0.x, \$r0.y**

**mpyll \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	0	0	0	0	0	d						x					y								S			
0	0	0	0	0	0	0	0	1	d						x					imm								S			

Multiply signed low 16 x low 16 bits.

**mpyllu \$r0.d = \$r0.x, \$r0.y**

**mpyllu \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	0	0	0	1	0																							
0	0	0	0	0	0	0	1	1																							

Multiply unsigned low 16 x low 16 bits.

**mpylh \$r0.d = \$r0.x, \$r0.y**

**mpylh \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	0	0	0	1	0																							
0	0	0	0	0	0	0	1	0	1																						

Multiply signed low 16 (s1) x high 16 (s2) bits.

**mpylhu \$r0.d = \$r0.x, \$r0.y**

**mpylhu \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	0	0	0	1	1	0																						
0	0	0	0	0	0	0	1	1	1																						

Multiply unsigned low 16 (s1) x high 16 (s2) bits.

**mpyhh \$r0.d = \$r0.x, \$r0.y**

**mpyhh \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	0	0	1	0	0	0																						
0	0	0	0	0	0	1	0	0	1																						

Multiply signed high 16 x high 16 bits.

**mpyhu \$r0.d = \$r0.x, \$r0.y**

**mpyhu \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	0	0	1	0	1	0																						
0	0	0	0	0	0	1	0	1	1																						

Multiply unsigned high 16 x high 16 bits.

**mpyl \$r0.d = \$r0.x, \$r0.y**

**mpyl \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	0	0	1	1	0	0																						
0	0	0	0	0	0	1	1	0	1																						

Multiply signed low 16 (s2) x 32 (s1) bits.



**mpylu \$r0.d = \$r0.x, \$r0.y**

**mpylu \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	0	1	1	1	0																							
0	0	0	0	0	1	1	1	1																							

Multiply unsigned low 16 (s2) x 32 (s1) bits.

**mpyh \$r0.d = \$r0.x, \$r0.y**

**mpyh \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	1	0	0	0	0																							
0	0	0	0	1	0	0	0	1																							

Multiply signed high 16 (s2) x 32 (s1) bits.

**mpyhu \$r0.d = \$r0.x, \$r0.y**

**mpyhu \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	1	0	0	1	0																							
0	0	0	0	1	0	0	1	1																							

Multiply unsigned high 16 (s2) x 32 (s1) bits.

**mpyhs \$r0.d = \$r0.x, \$r0.y**

**mpyhs \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	1	0	1	0	0																							
0	0	0	0	1	0	1	0	1																							

Multiply signed high 16 (s2) x 32 (s1) bits, shift left 16.

**mpylhus \$r0.d = \$r0.x, \$r0.y**

**mpylhus \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	1	0	0	1	1	0																							
1	0	0	1	0	0	1	1	1																							

Multiply unsigned low 16 (s2) x signed 32 (s1) bits, shift right 32.

**mpyhhs \$r0.d = \$r0.x, \$r0.y**

**mpyhhs \$r0.d = \$r0.x, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	1	0	0	1	1	0																							
1	0	0	1	0	0	1	1	1																							

Multiply signed high 16 (s2) x 32 (s1) bits, shift right 16.

### 2.2.7.11 Memory instructions

Some  $\rho$ -VEX pipelines have a memory unit. The memory unit supports byte, halfword and word operations. Sign or zero extension is part of the byte and halfword load instructions.

The addressing mode is always register + immediate. Note that attempts to read misaligned memory locations will fail with a TRAP\_MISALIGNED\_ACCESS trap.

In the default pipeline configuration, these instructions are pipelined by two cycles. That is, the result of a memory load instruction is not available yet in the subsequent instruction. However, the current cache and core guarantee that a memory write to address  $x$  immediately followed by a memory read from address  $x$  returns the newly written value.

**ldw \$r0.d = imm[\$r0.x]**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	0	0	0	0	1	d						x						imm						S				

Loads a 32-bit word from memory.

```
$r0.d = *(int*)($r0.x + imm);
```

**ldh \$r0.d = imm[\$r0.x]**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	0	0	0	1	1	d						x						imm						S				

Loads a 16-bit halfword from memory and sign-extends it.

```
$r0.d = *(short*)($r0.x + imm);
```

**ldhu \$r0.d = imm[\$r0.x]**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	0	0	1	0	1	d						x						imm						S				

Loads a 16-bit halfword from memory and zero-extends it.

```
$r0.d = *(unsigned short*)($r0.x + imm);
```

**ldb \$r0.d = imm[\$r0.x]**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	0	0	1	1	1	d						x						imm						S				

Loads a byte from memory and sign-extends it.

```
$r0.d = *(char*)($r0.x + imm);
```

**ldbu \$r0.d = imm[\$r0.x]**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	0	1	0	0	1																							

Loads a byte from memory and zero-extends it.

```
$r0.d = *(unsigned char*)($r0.x + imm);
```

**ldw \$l0.0 = imm[\$r0.x]**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	1	1	0	1	1							x						imm						S				

Loads a word from memory. The result is written to the link register.

```
$l0.0 = *(int*)($r0.x + imm);
```

**ldbr imm[\$r0.x]**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	0	1	1	1	0	1							x						imm						S				

Loads a byte from memory. The result is written to the entire branch register file at once. This is intended to improve context switching performance somewhat.

```
char tmp = *(char*)($r0.x + imm);
$b0.0 = tmp & 1;
$b0.1 = tmp & 2;
$b0.2 = tmp & 4;
$b0.3 = tmp & 8;
$b0.4 = tmp & 16;
$b0.5 = tmp & 32;
$b0.6 = tmp & 64;
$b0.7 = tmp & 128;
```

**stw imm[\$r0.x] = \$r0.d**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0	0	0	1	0	1	0	1	1	d						x						imm										S	

Stores a 32-bit word into memory.

```
*(int*)($r0.x + imm) = $r0.d;
```

**sth imm[\$r0.x] = \$r0.d**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	0	1	1	0	1	d						x						imm						S				

Stores a 16-bit halfword into memory.

```
*(short*)($r0.x + imm) = $r0.d;
```

**stb imm[\$r0.x] = \$r0.d**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	0	1	1	1	1	d							x							imm							S	

Stores a byte into memory.

```
*(char*)($r0.x + imm) = $r0.d;
```

**stw imm[\$r0.x] = \$l0.0**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	1	1	1	0	1								x							imm							S	

Store word in memory, from link register.

```
*(int*)($r0.x + imm) = $l0.0;
```

**stbr imm[\$r0.x]**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	0	1	1	1	1	1								x							imm							S	

Store byte in memory, from branch register file.

```
char tmp = $b0.0;
tmp |= $b0.1 << 1
tmp |= $b0.2 << 2
tmp |= $b0.3 << 3
tmp |= $b0.4 << 4
tmp |= $b0.5 << 5
tmp |= $b0.6 << 6
tmp |= $b0.7 << 7
*(char*)($r0.x + imm) = tmp
```

### 2.2.7.12 Branch instructions

The highest-indexed pipeline in every  $\rho$ -VEX system (i.e., the pipeline that the last syllable in a bundle maps to) contains a branch unit. This unit supports the flow control operations outlined below.

Branch offsets are signed immediates relative to the next program counter (PC+1). Because there are certain alignment requirements to program counters, the lower two or three bits of the offset are not actually included in the bitfield. Whether this value is two or three depends on the value of the `BRANCH_OFFSETS_SHIFT` constant defined in `core_intIface_pkg.vhd`; it is three by default. It must be set to two to support branching to the start of any bundle when stop bits are fully enabled. This must then also be updated in the assembler.

Note that branch offsets and the stack adjust immediate are not eligible for long immediate instructions.

### goto offs

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	0	0	0	0	0	offs																						S	

Branches to PC+1 + offs unconditionally.

```
PCP1 += offs;
```

### igoto \$l0.0

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	0	0	0	0	1																							S	

Branches to the address in \$l0.0 unconditionally. This is used for branches to code that cannot be reached using the branch offset immediate.

```
PCP1 = $l0.0;
```

### call \$l0.0 = offs

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	0	0	0	1	0	offs																						S	

Branches to PC+1 + offs unconditionally, while storing PC+1 in the link register. This is used for function calls.

```
$l0.0 = PCP1;  
PCP1 += offs;
```

### icall \$l0.0 = \$l0.0

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	0	0	0	1	1																							S	

Branches to the address in \$l0.0 unconditionally, while storing PC+1 in the link register. In other words, it essentially swaps PC+1 and \$l0.0. This is used for dynamic function calls or calls to functions that cannot be reached using the branch offset immediate method.

```
unsigned int tmp = $l0.0;  
$l0.0 = PCP1;  
PCP1 = tmp;
```

### br \$b0.bs, offs

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	0	0	1	0	0	offs																bs				S			

Branches to PC+1 + offs only if \$b0.bs is true. This instruction performs no operation if \$b0.bs is false.

```
PCP1 += $b0.bs ? offs : 0;
```

**brf \$b0.bs, offs**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	0	0	1	0	1	offs																		bs				S	

Branches to PC+1 + offs only if \$b0.bs is false. This instruction performs no operation if \$b0.bs is true.

```
PCP1 += $b0.bs ? 0 : offs;
```

**return \$r0.1 = \$r0.1, stackadj, \$l0.0**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	0	0	1	1	0	stackadj																						S	

Returns from a function by branching to \$l0.0 unconditionally, while adding stackadj to \$r0.1. stackadj is interpreted as a signed immediate. This allows final stack pointer adjustment and returning to be done with a single syllable.

Notice that this instruction is identical to IG0T0, except for the fact that IG0T0 does not access \$r0.1.

```
$r0.1 += stackadj;
PCP1 = $l0.0;
```

**rfi \$r0.1 = \$r0.1, stackadj**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	0	0	1	1	1	stackadj																						S	

Returns from a trap service routine by branching to CR\_TP unconditionally and restoring CR\_SCCR to CR\_CCR, while adding stackadj to \$r0.1. stackadj is interpreted as a signed immediate. This allows final stack pointer adjustment and returning to be done with a single syllable.

```
$r0.1 += stackadj;
CR_CCR = CR_SCCR;
PCP1 = CR_TP;
```

**stop**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	0	1	0	0	0																							S	

Causes a TRAP\_STOP trap to occur during execution of the next instruction. The TRAP\_STOP trap will cause the B flag in CR\_DCR to be set, which will stop execution. Thus, the processor will be stopped after the bundle in which the STOP instruction resides is executed.

### 2.2.7.13 Long immediate instructions

**lmmh tgt, imm**

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	0	tgt				imm																						S	

This special instruction forwards `imm` to lane `tgt`. Actually, only the least significant bit of `tgt` is used by the processor, to distinguish between the two possible long immediate forwarding paths. Refer to Section 2.2.4.5 for more information.

## 2.3 Control registers

The  $\rho$ -VEX processor has two control register files. These are the global control register file (gbreg) and the context control register file (cxreg).

The gbreg file contains mostly status information, such as a general purpose cycle counter, the current configuration vector and design-time configuration information. While the debug bus has read/write access to gbreg, the core can only read from it.

For more information, refer to Section 2.2.2.4.

### 2.3.1 Global control registers

The following table lists the global control registers of the  $\rho$ -VEX processor. The offsets listed are with respect to the control register base address. If you are viewing this manual digitally, you can click the register mnemonics on the right to jump to their documentation.

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0					
0x000	R																E	B	RID													CR_GSR					
0x004	BCRR																																				CR_BCRR
0x008	CC																																				CR_CC
0x00C	AF																																				CR_AFF
0x010	CNT																																				CR_CNT
0x014	CNTH																																				CR_CNTH
...	Unused																																				
0x0A0	BORROW15															BORROW14																CR_LIMC7					
0x0A4	BORROW13															BORROW12																CR_LIMC6					
0x0A8	BORROW11															BORROW10																CR_LIMC5					
0x0AC	BORROW9															BORROW8																CR_LIMC4					
0x0B0	BORROW7															BORROW6																CR_LIMC3					
0x0B4	BORROW5															BORROW4																CR_LIMC2					
0x0B8	BORROW3															BORROW2																CR_LIMC1					
0x0BC	BORROW1															BORROW0																CR_LIMC0					
0x0C0	SYL15CAP							SYL14CAP							SYL13CAP							SYL12CAP							CR_SIC3								
0x0C4	SYL11CAP							SYL10CAP							SYL9CAP							SYL8CAP							CR_SIC2								
0x0C8	SYL7CAP							SYL6CAP							SYL5CAP							SYL4CAP							CR_SIC1								
0x0CC	SYL3CAP							SYL2CAP							SYL1CAP							SYL0CAP							CR_SIC0								
0x0D0																																		CR_GPS1			
0x0D4					MEMAR				MEMDC				MEMDR				MULC				MULR				ALUC				ALUR				CR_GPS0				
0x0D8																																		CR_SPS1			
0x0DC	MEMMC				MEMMR				MEMDC				MEMDR				BRC				BRR				ALUC				ALUR				CR_SPS0				
0x0E0																																		CR_EXT2			
0x0E4																																		CR_EXT1			
0x0E8					T	BRK								C	I	P											O	L	F	CR_EXT0							
0x0EC																BA				NC				NG				NL				CR_DCFG					
0x0F0	VER							CTAG0							CTAG1							CTAG2							CR_CVER1								
0x0F4	CTAG3							CTAG4							CTAG5							CTAG6							CR_CVER0								
0x0F8	COID							PTAG0							PTAG1							PTAG2							CR_PVER1								
0x0FC	PTAG3							PTAG4							PTAG5							PTAG6							CR_PVER0								



### 2.3.1.1 CR\_GSR - Global status register

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0x000	R																		E	B													CR_GSR
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Core																																	
Debug																																	

This register contains miscellaneous status information.

**R flag, bit 31** Reset flag. The entire  $\rho$ -VEX processor will be reset when the debug bus writes a one to this flag. Writing a zero has no effect.

**E flag, bit 13** Reconfiguration error flag. This flag is set by hardware when an invalid configuration was requested. It is cleared once a valid configuration is requested.

**B flag, bit 12** Reconfiguration busy flag. While high, reconfiguration requests are ignored.

**RID field, bits 11..8** Reconfiguration requester ID. When a configuration is requested, this field is set to the context ID of the context that requested the configuration, or to 0xF if the request was from the debug bus. This may be used by the reconfiguration sources to see if they have won arbitration. Refer to Section 2.5.2 for more information.

### 2.3.1.2 CR\_BCRR - Bus reconfiguration request register

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0x004																																	CR_BCRR
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Core																																	
Debug																																	

This register may be written to by the debug bus only. When it is written, a reconfiguration is requested. Refer to Sections 2.5.1 and 2.5.2 for more information.

### 2.3.1.3 CR\_CC - Current configuration register

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0x008																																	CR_CC
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Core																																	
Debug																																	

This register is hardwired to the current configuration vector. Refer to Section 2.5.1 for more information.

### 2.3.1.4 CR\_AFF - Cache affinity register

Offset	31 30 29 28 27 26 25 24   23 22 21 20 19 18 17 16   15 14 13 12 11 10 9 8   7 6 5 4 3 2 1 0	
0x00C	AF	
Reset	0 0	
Core		
Debug		

This register stores the cache block index (akin to a lane group) that most recently serviced an instruction fetch for a given context. This may be used for achieving the maximum possible instruction cache locality when reconfiguring.

Each nibble represents a lane group. The nibble value is the context index.

### 2.3.1.5 CR\_CNT - Cycle counter register, low word

Offset	31 30 29 28 27 26 25 24   23 22 21 20 19 18 17 16   15 14 13 12 11 10 9 8   7 6 5 4 3 2 1 0	
0x010	CNT	
Reset	0 0	
Core		
Debug		

Cycle counter. This register is simply always incremented by one in hardware. Simply overflows when it reaches 0xFFFFFFFF. Its intended use is performance monitoring.

### 2.3.1.6 CR\_CNTH - Cycle counter register, high word

Offset	31 30 29 28 27 26 25 24   23 22 21 20 19 18 17 16   15 14 13 12 11 10 9 8   7 6 5 4 3 2 1 0	
0x014	CNTH	
Reset	0 0	
Core		
Debug		

Extension to the CR\_CNT register. The order is illogical for a big endian system for compatibility with older code that assumes that this counter is only 32 bits wide. The high word of the counter value is latched whenever CR\_CNT is read to avoid needing an atomic 64-bit read operation. Thus, CR\_CNT must always be read before CR\_CNTH is read.

The CNTH register doesn't exist yet.

### 2.3.1.7 CR\_LIMCn - Long immediate capability register *n*

Offset	31 30 29 28 27 26 25 24   23 22 21 20 19 18 17 16   15 14 13 12 11 10 9 8   7 6 5 4 3 2 1 0	
0x0A0	BORROW15	
0x0A4	BORROW13	
0x0A8	BORROW11	
0x0AC	BORROW9	
0x0B0	BORROW7	
0x0B4	BORROW5	
0x0B8	BORROW3	
0x0BC	BORROW1	
Reset	* * * * *	
Core		
Debug		

This group of hardwired values represent the supported LIMMH forwarding routes.

The LIMCn registers don't exist yet.

**BORROW $2n + 1$  field, bits 31..16, a.k.a. CR\_BORROW $i$**

**BORROW $2n$  field, bits 15..0, a.k.a. CR\_BORROW $i$**  Each bit in these fields represents a possible LIMMH forwarding route. The bit index within the field specifies the source syllable index, i.e. the LIMMH syllable;  $i = (2n, 2n + 1)$  is the index of the syllable that uses the immediate.

As an example, if bit 2 in CR\_BORROW4 (CR\_LIMC2) is set, it means that the third syllable in a bundle (index 2) can be a LIMMH instruction that forwards to the fifth syllable in a bundle (index 4).

For the purpose of generic binaries, the configuration is repeated beyond the number of physically available lanes.

### 2.3.1.8 CR\_SIC $n$ - Syllable index capability register $n$

Offset	31 30 29 28 27 26 25 24	23 22 21 20 19 18 17 16	15 14 13 12 11 10 9 8	7 6 5 4 3 2 1 0	
0x0C0	SYL15CAP	SYL14CAP	SYL13CAP	SYL12CAP	CR_SIC3
0x0C4	SYL11CAP	SYL10CAP	SYL9CAP	SYL8CAP	CR_SIC2
0x0C8	SYL7CAP	SYL6CAP	SYL5CAP	SYL4CAP	CR_SIC1
0x0CC	SYL3CAP	SYL2CAP	SYL1CAP	SYL0CAP	CR_SIC0
Reset	0 0 0 0 * * * 1	0 0 0 0 * * * 1	0 0 0 0 * * * 1	0 0 0 0 * * * 1	
Core					
Debug					

The SIC $n$  registers don't exist yet.

This group of hardwired values represent the capabilities of each syllable within a bundle.

**SYL $4n + 3$ CAP field, bits 31..24, a.k.a. CR\_SYL $i$ CAP**

**SYL $4n + 2$ CAP field, bits 23..16, a.k.a. CR\_SYL $i$ CAP**

**SYL $4n + 1$ CAP field, bits 15..8, a.k.a. CR\_SYL $i$ CAP**

**SYL $4n$ CAP field, bits 7..0, a.k.a. CR\_SYL $i$ CAP** Each bit within the field represents a functional unit or resource that is available to syllable index  $i$  within a bundle. The following encoding is used.

Bit index	Function
0	Always set, indicated that ALU class syllables are supported.
1	If set, multiplier class syllables are supported.
2	If set, memory class syllables are supported.
3	If set, branch class syllables and syllables with stop bits are supported.
4..7	Always zero, reserved for future expansion.

For the purpose of generic binaries, the configuration is repeated beyond the number of physically available lanes.

### 2.3.1.9 CR\_GPS1 - General purpose register delay register B

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0x0D0																																	CR_GPS1
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Core																																	
Debug																																	

This register is reserved for future expansion.

### 2.3.1.10 CR\_GPS0 - General purpose register delay register A

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0x0D4																																	CR_GPS0
Reset	0	0	0	0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Core																																	
Debug																																	

This register lists the key pipeline stages in which the core appears to read from and write to the general purpose register file. Forwarding is taken into consideration, so the core may not actually write to the register file in the listed stages, but from the perspective of the software it seems to.

From these values, the required number of bundles between an instruction that writes to a general purpose register and an instruction that reads from one can be determined, being  $stage_{commit} - stage_{read} - 1$ .

The GPS<sub>n</sub> registers don't exist yet.

**MEMAR field, bits 27..24** Hardwired to the stage in which the memory unit reads its address operands from the general purpose registers.

**MEMDC field, bits 23..20** Hardwired to the stage in which the memory unit appears to commit the data loaded from memory to the general purpose registers.

**MEMDR field, bits 19..16** Hardwired to the stage in which the memory unit appears to read the data to be stored to memory from the general purpose registers.

**MULC field, bits 15..12** Hardwired to the stage in which the multiplier appears to commit its result to the general purpose registers.

**MULR field, bits 11..8** Hardwired to the stage in which the multiplier appears to read its operands from the general purpose registers.

**ALUC field, bits 7..4** Hardwired to the stage in which the ALU appears to commit its result to the general purpose registers.

**ALUR field, bits 3..0** Hardwired to the stage in which the ALU appears to read its operands from the general purpose registers.

### 2.3.1.11 CR\_SPS1 - Special delay register B

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	CR_SPS1
0x0D8																																	
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
Core																																	
Debug																																	

This register is reserved for future expansion.

### 2.3.1.12 CR\_SPS0 - Special delay register A

Offset	31 30 29 28 27 26 25 24	23 22 21 20 19 18 17 16	15 14 13 12 11 10 9 8	7 6 5 4 3 2 1 0	CR_SPS0													
0x0DC	MEMMC	MEMMR	MEMDC	MEMDR		BRC	BRR	ALUC	ALUR									
Reset	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	*	*
Core																		
Debug																		

The SPS<sub>n</sub> registers don't exist yet.

This register serves a similar purpose as CR\_GPS0, but instead of being only for the general purpose registers, these values represents the delay for branch registers, the link register and memory.

**MEMMC field, bits 31..28** Hardwired to the stage in which the memory unit actually commits the data from a store instruction to memory.

**MEMMR field, bits 27..24** Hardwired to the stage in which the memory unit actually reads the data for a load operation from memory.

**MEMDC field, bits 23..20** Hardwired to the stage in which the memory unit appears to commit the data loaded from memory to the link and branch registers.

**MEMDR field, bits 19..16** Hardwired to the stage in which the memory unit appears to read the data to be stored to memory from the link and branch registers.

**BRC field, bits 15..12** Hardwired to the stage in which the branch unit appears to commit the new program counter. This thus represents the number of branch delay slots. The next instruction is requested in stage 1 and its PC is forwarded combinatorially, thus the number of branch delay slots is  $BRC - 2$ . Note that the  $\rho$ -VEX processor does not actually execute its branch delay slots; it is invalidated when a branch is taken.

**BRR field, bits 11..8** Hardwired to the stage in which the branch unit appears to read its operands from the branch and link registers.

**ALUC field, bits 7..4** Hardwired to the stage in which the ALU appears to commit its result to the branch and link registers.

**ALUR field, bits 3..0** Hardwired to the stage in which the ALU appears to read its operands from the branch and link registers.

### 2.3.1.13 CR\_EXT2 - Extension register 2

Offset	31 30 29 28 27 26 25 24	23 22 21 20 19 18 17 16	15 14 13 12 11 10 9 8	7 6 5 4 3 2 1 0	CR_EXT2												
0x0E0																	
Reset	0 0																
Core																	
Debug																	

This register is reserved for future expansion.

### 2.3.1.14 CR\_EXT1 - Extension register 1

Offset	31 30 29 28 27 26 25 24	23 22 21 20 19 18 17 16	15 14 13 12 11 10 9 8	7 6 5 4 3 2 1 0	CR_EXT1												
0x0E4																	
Reset	0 0 0 0 0 0 0 0	0 0 0 0 0 0 0 0	0 0 0 0 0 0 0 0	0 0 0 0 0 0 0 0													
Core																	
Debug																	

This register is reserved for future expansion.

### 2.3.1.15 CR\_EXT0 - Extension register 0

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0				
0x0E8									T	BRK										C	I	P											O	L	F	CR_EXT0
Reset	0	0	0	0	*	*	*	*	0	0	0	0	0	0	*	*	*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	*	*	*		
Core																																				
Debug																																				

This register contains flags that specify the supported extensions and quirks of the processor as per its design-time configuration.

**T flag, bit 27** Defines whether the trace unit is available. The trace unit has its own capability flags in CR\_DCR2.

**BRK field, bits 26..24** Defines the number of available hardware breakpoints.

**C flag, bit 18** If set, cache-related performance counters exist.

**I flag, bit 17** If set, ILP-related performance counters CR\_C\_BUN, CR\_C\_SYL and CR\_C\_NOP exist.

**P flag, bit 16** If set, performance counters CR\_C\_CYC and CR\_C\_STALL exist.

**O flag, bit 2** This flag determines the unit in which the branch offset field is encoded. When this flag is cleared, the branch offset is encoded in 8-byte units. When it is set, the branch offset is encoded in 4-byte units.

The EXT<sub>n</sub> registers don't exist yet.

**L flag, bit 1** This flag is set when register `$r0.63` is mapped to `$l0.0`, to allow arithmetic to be performed on the link register directly. If it is cleared, these registers are independent.

**F flag, bit 0** This flag is set when forwarding is enabled.

### 2.3.1.16 CR\_DCFG - Design-time configuration register

Offset	31 30 29 28 27 26 25 24	23 22 21 20 19 18 17 16	15 14 13 12 11 10 9 8	7 6 5 4 3 2 1 0	CR_DCFG		
0x0EC			BA	NC		NG	NL
Reset	0 0 0 0 0 0 0 0		* * * * *			* * * * *	
Core	0 0 0 0 0 0 0 0		* * * * *		* * * * *		
Debug							

The DCFG register doesn't exist yet.

This register is hardwired to the key parameters that define the size of the processor, such as the number of pipelanes and the number of contexts.

**BA field, bits 15..12** Specifies the minimum bundle alignment necessary. Specified as the alignment size in 32-bit words minus 1. For example, if this value is 7, each bundle must start on a 128-byte boundary, as  $(7 + 1) \cdot 32 = 128$ .

**NC field, bits 11..8** Number of hardware contexts supported, minus one.

**NG field, bits 7..4** Number of pipeline groups supported, minus one. This determines the degree of reconfigurability. Together with NC, it fully specifies the number of valid configuration words.

**NL field, bits 3..0** Number of pipelanes in the design, minus one.

### 2.3.1.17 CR\_CVER1 - Core version register 1

Offset	31 30 29 28 27 26 25 24	23 22 21 20 19 18 17 16	15 14 13 12 11 10 9 8	7 6 5 4 3 2 1 0	CR_CVER1
0x0F0	VER	CTAG0	CTAG1	CTAG2	
Reset	0 0 1 1 0 0 1 1	0 * * * * * * *	0 * * * * * * *	0 * * * * * * *	
Core					
Debug					

The CVER<sub>n</sub> registers don't exist yet.

This register specifies the major version of the processor and, together with CR\_CVER0, a 7-byte ASCII core version identification tag.

**VER field, bits 31..24, a.k.a. CR\_CVER** Specifies the major version number of the  $\rho$ -VEX processor in ASCII. This will most likely always be '3'.

**CTAG0 field, bits 23..16, a.k.a. CR\_CTAG** First ASCII character in a string of seven characters, which together identify the core version, similar to how a license plate identifies a car. It is intended that a database will be set up which maps each tag to an immutable archive containing the source code for the core and a mutable errata/notes file.

### 2.3.1.18 CR\_CVER0 - Core version register 0

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	CR_CVER0
0x0F4	CTAG3								CTAG4								CTAG5								CTAG6								
Reset	0	*	*	*	*	*	*	*	0	*	*	*	*	*	*	*	0	*	*	*	*	*	*	*	0	*	*	*	*	*	*	*	
Core																																	
Debug																																	

Refer to CR\_CVER1 for more information.

### 2.3.1.19 CR\_PVER1 - Platform version register 1

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	CR_PVER1
0x0F8	COID								PTAG0								PTAG1								PTAG2								
Reset	*	*	*	*	*	*	*	*	0	*	*	*	*	*	*	*	0	*	*	*	*	*	*	*	0	*	*	*	*	*	*	*	
Core																																	
Debug																																	

This register specifies the processor index within a platform and, together with CR\_PVER0, uniquely identifies the platform using a 7-byte ASCII identification tag.

The PVER<sub>n</sub> registers don't exist yet.

**COID field, bits 31..24, a.k.a. CR\_COID** Unique processor identifier within a multi-core platform.

**PTAG0 field, bits 23..16, a.k.a. CR\_PTAG** First ASCII character in a string of seven characters, which together identify the platform and bit file, similar to how a license plate identifies a car. It is intended that a database will be set up which maps each tag to an immutable archive containing the source code for the platform, synthesis logs and a bit file, as well as mutable memory.map, rvex.h and errata/notes files.

### 2.3.1.20 CR\_PVER0 - Platform version register 0

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	CR_PVER0
0x0FC	PTAG3								PTAG4								PTAG5								PTAG6								
Reset	0	*	*	*	*	*	*	*	0	*	*	*	*	*	*	*	0	*	*	*	*	*	*	*	0	*	*	*	*	*	*	*	
Core																																	
Debug																																	

Refer to CR\_PVER1 for more information.



### 2.3.2 Context control registers

The following table lists the context control registers of the  $\rho$ -VEX processor. The offsets listed are with respect to the control register base address. If you are viewing this manual digitally, you can click the register mnemonics on the right to jump to their documentation.

Offset	31 30 29 28 27 26 25 24								23 22 21 20 19 18 17 16								15 14 13 12 11 10 9 8								7 6 5 4 3 2 1 0									
0x200	CAUSE								BRANCH																K	C	B	R	I	CR_CCR				
0x204	ID																								K	C	B	R	I	CR_SCCR				
0x208	LR																																CR_LR	
0x20C	PC																																CR_PC	
0x210	TH																																CR_TH	
0x214	PH																																CR_PH	
0x218	TP																																CR_TP	
0x21C	TA																																CR_TA	
0x220	BR0																																CR_BR0	
0x224	BR1																																CR_BR1	
0x228	BR2																																CR_BR2	
0x22C	BR3																																CR_BR3	
0x230	D	J			I	E	R	S	B	CAUSE										BR3			BR2			BR1				BR0	CR_DCR			
0x234	RESULT																TRCAP								T	M	R	C	I				E	CR_DCR2
...	Unused																																	
0x240	CRR																																CR_CRR	
0x244	Unused																																	
0x248	WCFG																																CR_WCFG	
0x24C																									RUN								S	CR_SAWC
0x250	SCR1																																CR_SCR1	
0x254	SCR2																																CR_SCR2	
0x258	SCR3																																CR_SCR3	
0x25C	SCR4																																CR_SCR4	
0x260	RSC																																CR_RSC	
0x264	CSC																																CR_CSC	
0x268	RSC1																																CR_RSC1	
0x26C	CSC1																																CR_CSC1	
0x270	RSC2																																CR_RSC2	
0x274	CSC2																																CR_CSC2	
0x278	RSC3																																CR_RSC3	
0x27C	CSC3																																CR_CSC3	
0x280	RSC4																																CR_RSC4	
0x284	CSC4																																CR_CSC4	
0x288	RSC5																																CR_RSC5	
0x28C	CSC5																																CR_CSC5	
0x290	RSC6																																CR_RSC6	
0x294	CSC6																																CR_CSC6	
0x298	RSC7																																CR_RSC7	
0x29C	CSC7																																CR_CSC7	
...	Unused																																	
0x300	CYC																																CR_CYC	
0x304	STALL																																CR_STALL	
0x308	Unused																																	
0x30C	BUN																																CR_BUN	

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0x314	Unused																															
0x318	SYL																															
0x31C	Unused																															
0x320	NOP																															
0x324	Unused																															
0x328	IACC																															
0x32C	Unused																															
0x330	IMISS																															
0x334	Unused																															
0x338	DRACC																															
0x33C	Unused																															
0x340	DRMISS																															
0x344	Unused																															
0x348	DWACC																															
0x34C	Unused																															
0x350	DWMISS																															
0x354	Unused																															
0x358	DBYPASS																															
0x35C	Unused																															
0x360	DWBUFF																															

### 2.3.2.1 CR\_CCR - Main context control register

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	CR_CCR
0x200	CAUSE								BRANCH												K	C	B	R	I								
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	1	0	1	0		
Core																										✓	✓	✓	✓	✓	✓	✓	
Debug	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓										✓	✓	✓	✓	✓	✓	✓	

The primary purpose of the context control register is to store the primary control flags of the processor, for example whether interrupts are enabled. In addition, it also stores the trap cause and exposes the branch register file to the debug bus.

**CAUSE field, bits 31..24, a.k.a. CR\_TC** Trap cause. Set to the trap cause by hardware when the trap handler is called. Reset to 0 by hardware when an RFI instruction is encountered. Read-write by the debug bus, but the processor cannot write to this register.

**BRANCH field, bits 23..16, a.k.a. CR\_BR** Branch register file. Contains the current state of the branch registers. Only intended for use by the debug bus to see and modify the state of the branch register file. While the core is running, accessing this register is undefined due to it being dependent on the pipeline and forwarding state.

**K field, bits 9..8** This register selects between kernel mode and user mode. Currently, this flag only controls whether the MMU is enabled; the  $\rho$ -VEX processor does not have any security features yet. In kernel mode, the MMU is bypassed; in user mode, it is

The kernel mode/MMU enable flag exists, but the MMU is not in the design yet.

activated. Kernel mode is activated when the core is reset and when entering the trap or panic handlers. These must thus always point to code in hardware memory space. When RFI is executed, the state is restored from CR\_SCCR.

In kernel mode, the register reads as 01, while in user mode, it reads as 10. The only way to enter user mode is by writing the user mode command to CR\_SCCR and subsequently executing RFI. Neither the core nor the debug bus can write to this field directly.

**C field, bits 7..6** This register controls whether the context switch trap is enabled. It does not exist on hardware context 0. When the core is reset or the trap service routine is entered, the context switch trap is disabled. When RFI is executed, the state is restored from CR\_SCCR.

When the context switch trap is enabled, this register reads as 01. When it is disabled, it reads as 10. Both the core and the debug bus can write to this register. Writing 00 has no effect, writing 01 enables the context switching trap, writing 10 disables it and writing 11 toggles the state. This prevents the need for read-modify-write operations.

Refer to CR\_RSC for more information.

**B field, bits 5..4** This register controls whether breakpoints are enabled in self-hosted debug mode. Its value is ignored in external debug mode. When the core is reset or the trap service routine is entered due to a debug trap in self-hosted debug mode, breakpoints are disabled. When RFI is executed, the state is restored from CR\_SCCR.

When breakpoints are enabled, this register reads as 01. When they are disabled, it reads as 10. Both the core and the debug bus can write to this register. Writing 00 has no effect, writing 01 enables debug traps, writing 10 disables them and writing 11 toggles the state. This prevents the need for read-modify-write operations.

**R field, bits 3..2** This register, named ready-for-trap, tentatively specifies if the processor is currently capable of servicing traps. However, since traps cannot be masked, any trap that occurs while ready-for-trap is cleared will cause a panic. Therefore, the only thing this register does in hardware is switch between the trap handler and panic handler address. When the core is reset or the trap service routine is entered, ready-for-trap is cleared. When RFI is executed, the state is restored from CR\_SCCR.

When ready-for-trap is set (trap handler selected), this register reads as 01. When it is cleared (panic handler selected), it reads as 10. Both the core and the debug bus can write to this register. Writing 00 has no effect, writing 01 sets ready-for-trap, writing 10 clears it and writing 11 toggles the state. This prevents the need for read-modify-write operations.

**I field, bits 1..0** This register selects whether external interrupts are enabled or not. When the core is reset or the trap service routine is entered, external interrupts are disabled. When RFI is executed, the state is restored from CR\_SCCR.

When interrupts are enabled, this register reads as 01. When they are disabled, it reads as 10. Both the core and the debug bus can write to this register. Writing 00 has

no effect, writing 01 enables external interrupts, writing 10 disables them and writing 11 toggles the state. This prevents the need for read-modify-write operations.

### 2.3.2.2 CR\_SCCR - Saved context control register

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	CR_SCCR	
0x204	ID																		K		C		B		R		I							
Reset	*	*	*	*	*	*	*	*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	1	0	1		0
Core																								✓	✓	✓	✓	✓	✓	✓	✓	✓		
Debug																								✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	

This register saves the state of the primary control flags of the processor when entering the trap service routine. When RFI is executed, the state is restored from this register. In addition, this register contains the context ID, which contexts may read to identify themselves.

**ID field, bits 31..24, a.k.a. CR\_CID** This field is hardwired to the context index plus the core ID generic. Programs running on the  $\rho$ -VEX processor may use this field to determine which hardware context they are running on.

**K field, bits 9..8** When the trap service routine is entered, this register stores whether kernel the processor was in kernel mode or user mode. When RFI is executed, the state is set to this value.

Unlike the kernal mode field in CR\_CCR, this field can be written. Writing 00 has no effect, writing 01 enables external interrupts, writing 10 disables them and writing 11 toggles the state. This prevents the need for read-modify-write operations. Read behavior is identical to the K field in CR\_CCR.

**C field, bits 7..6** When the trap service routine is entered, this register stores whether the context switching trap was enabled. When RFI is executed, the state is set to this value.

Core and debug bus access behavior is identical to the C field in CR\_CCR.

**B field, bits 5..4** When the trap service routine is entered, this register stores whether self-hosted debug breakpoints were enabled. When RFI is executed, the state is set to this value.

Core and debug bus access behavior is identical to the B field in CR\_CCR.

**R field, bits 3..2** When the trap service routine is entered, this register stores whether ready-for-trap was set. When RFI is executed, the state is set to this value.

Core and debug bus access behavior is identical to the R field in CR\_CCR.

**I field, bits 1..0** When the trap service routine is entered, this register stores whether interrupts were enabled. When RFI is executed, the state is set to this value.

Core and debug bus access behavior is identical to the I field in CR\_CCR.

### 2.3.2.3 CR\_LR - Link register

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0		
0x208	LR																																CR_LR	
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Core																																		
Debug	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Contains the current link register (\$10.0) value. Only intended for use by the debug bus. While the core is running, accessing this register is undefined due to it being dependent on the pipeline and forwarding state.

### 2.3.2.4 CR\_PC - Program counter

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	CR_PC
0x20C	PC																																
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Core																																	
Debug	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Contains the current program counter. Only intended for use by the debug bus. When the register is written by the debug bus, the jump flag in CR\_DCR is set, to ensure that the branch unit properly jumps to the new PC. This works even if the processor is running.

### 2.3.2.5 CR\_TH - Trap handler

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	CR_TH
0x210	TH																																
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Core	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Debug	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Contains the address of the trap service routine. This is where the processor will jump to if a trap occurs while ready-for-trap in CR\_CCR is set. Even if the design contains an MMU, this should be a hardware address, as the MMU is disabled when a trap occurs.

### 2.3.2.6 CR\_PH - Panic handler

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	CR_PH
0x214	PH																																
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Core	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Debug	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	

Contains the address of the panic service routine. This is where the processor will jump to if a trap occurs while ready-for-trap in CR\_CCR is NOT set. Even if the design contains an MMU, this should be a hardware address, as the MMU is disabled when a trap occurs.

The difference between the trap and panic service routines, is that the trap service routine has all state information of the processor at its disposal. That is, if the trap is recoverable, the program can continue after the trap service routine completes. The

panic service routine, however, should assume that the state information of the processor is incomplete. Refer to Section 2.4 for more information.

### 2.3.2.7 CR\_TP - Trap point

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0x218	TP																																CR_TP
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Core																																	
Debug	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	

When a trap occurs, this register is set to the address of the start of the offending bundle. The address is in user space if the MMU was enabled when the trap occurred. In addition, when RFI is executed, the processor will jump back to this address to resume execution. This is the correct behavior for both external interrupts and traps that, after servicing, should return to the previously offending instruction, such as a page fault.

To support software context switching, the processor may write to this register to change the resumption address. RFI will then cause execution to be resumed in the new software context, assuming the rest of the processor state has been swapped in as well.

### 2.3.2.8 CR\_TA - Trap argument

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0x21C	TA																																CR_TA
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Core																																	
Debug	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	

When a trap occurs, this register is set to the trap argument. The significance of this value depends on the trap, which can be identified from the trap cause field in CR\_CCR. Refer to Section 2.4 for more information.

### 2.3.2.9 CR\_BR<sub>n</sub> - Breakpoint *n*

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0x220	BR0																																CR_BR0
0x224	BR1																																CR_BR1
0x228	BR2																																CR_BR2
0x22C	BR3																																CR_BR3
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Core	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Debug	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	

These registers hold the addresses for the hardware breakpoints and/or watchpoints. These registers only exist up to how many break-/watchpoints are design-time configured to be supported by the processor. The functionality of the breakpoints is configured in CR\_DCR. These registers are always writable by the debug bus, but they are only writable by the core when the E flag is cleared, i.e. when self-hosted debug mode is selected.

### 2.3.2.10 CR\_DCR - Debug control register 1

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	CR_DCR
0x230	D	J		I	E	R	S	B	CAUSE										BR3			BR2					BR1				BR0		
Reset	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Core							✓												✓	✓			✓	✓			✓	✓		✓	✓		
Debug	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓			✓	✓			✓	✓		✓	✓		

This register controls the debugging system of the  $\rho$ -VEX processor.

**D flag, bit 31** Done/reset flag. This bit is set by hardware when a STOP instruction is encountered. It is cleared when a one is written to the R or S flags.

In addition, when a one is written to this flag, the control register file for this context is completely reset, as if the external context reset signal was asserted. Writing a zero has no effect. When combined with writing a one to the external debug flag, the core starts in external debug mode, and when combined with writing a one to B or the S flag, the core will stop execution before any instruction is executed, allowing the user to single-step from the start of the program. This works because I, E, S and B are not affected by a context reset.

Note that breakpoint information will have to be reloaded when the context is reset using this method.

**J flag, bit 30** This bit is set by hardware when the debug bus writes to the PC register and is cleared when the processor jumps to it. It can thus be used as an acknowledgement flag for jumping. The flag is read only.

**I flag, bit 28** Internal debug flag. Complement of the external debug flag. When the debug bus writes a one to this flag, the external debug flag is cleared, giving the processor control over debugging. Writing a zero has no effect. This flag is not affected by a context reset; it is only reset when the entire core is reset.

**E flag, bit 27** External debug flag. Complement of the internal debug flag. When the debug bus writes a one to this flag, the external debug flag is set, enabling external debug mode. Writing a zero has no effect. This flag is not affected by a context reset; it is only reset when the entire core is reset.

While in external debug mode, debug traps cause the B flag to be set and the trap cause to be recorded in CR\_DCR instead of the normal registers. This thus allows an external debugger to handle the debug traps instead, even if the processor is in the middle of a trap service routine and is not even ready for a trap. Writing a one to the R or the S flag is the equivalent of RFI for the external debugging system.

**R flag, bit 26** Resume flag. When the debug bus writes a one to this flag, the B flag is cleared, causing the processor to resume execution if it was halted. Writing a zero has no effect; this flag is cleared by hardware when the first instruction is successfully fetched. It can thus be used as an acknowledgement flag for resuming execution.

In addition, debug traps are disabled for instructions that were fetched while this flag was set. This behavior allows the processor to step beyond the breakpoint that caused the processor to break, so there is no need to disable the triggered breakpoint in order to resume. This behavior is also used for single stepping; see below.

**S flag, bit 25** Step flag. This flag may be set by the debug bus by writing a one to it. Doing so will also cause the R flag to be set and the B flag to be cleared, causing the processor to resume execution if it was halted. Writing a zero has no effect. The processor can also set this flag, but only if the E flag is cleared, i.e., if the processor is in self-hosted debug mode. This flag is not affected by a context reset; it is only reset when the entire core is reset.

While set, any instruction will cause a step debug trap. However, as noted above, all debug traps are disabled for the first instruction fetched after execution resumes. They should also be disabled while in the trap service routine through the breakpoint enable field in CR\_CCR. This allows both an external debugger and the self-hosted debug system to single-step.

**B flag, bit 24** Break flag. When this flag is set, the context stops fetching instructions and flushes the pipeline, as it would if the external run signal is low or if a reconfiguration is pending. It effectively halts execution. This flag is not affected by a context reset; it is only reset when the entire core is reset.

This flag may be set by the debug bus by writing a one to it, in order to pause execution. Writing a zero has no effect. In addition, the flag is set by hardware when a debug trap occurs while the E flag is set and when a STOP instruction is executed.

**CAUSE field, bits 23..16** Trap cause for debug traps that should be handled by the external debug system. This is set to the debug trap cause by hardware when the B flag is set due to a debug trap.

**BR3 field, bits 13..12** Breakpoint 3 control field. This field only exists if the core is design-time configured to support all four hardware breakpoints. See also BR0.

**BR2 field, bits 9..8** Breakpoint 2 control field. This field only exists if the core is design-time configured to support at least three hardware breakpoints. See also BR0.

**BR1 field, bits 5..4** Breakpoint 1 control field. This field only exists if the core is design-time configured to support at least two hardware breakpoints. See also BR0.

**BR0 field, bits 1..0** Breakpoint 0 control field. This field only exists if the core is design-time configured to support at least one hardware breakpoint.

The core can only write to BR $n$  fields when the E flag is cleared, i.e. when self-hosted debug mode is selected. The encoding for the fields is as follows.



BRn = 00: breakpoint/watchpoint disabled.  
 BRn = 01: breakpoint enabled.  
 BRn = 10: data write watchpoint enabled.  
 BRn = 11: data read/write watchpoint enabled.

### 2.3.2.11 CR\_DCR2 - Debug control register 2

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0x234	RESULT																TRCAP								T	M	R	C	I			E	CR_DCR2
Reset	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	*	*	*	*	*	0	0	*	0	0	0	0	0	0	0	0	
Core	✓	✓	✓	✓	✓	✓	✓	✓																		✓	✓	✓	✓	✓		✓	
Debug	✓	✓	✓	✓	✓	✓	✓	✓																		✓	✓	✓	✓	✓		✓	

This register controls the trace unit, if the core is design-time configured to support tracing. It also contains an 8-bit scratchpad register for communicating an execution result to the debug system.

**RESULT field, bits 31..24, a.k.a. CR\_RET** This field does not have a hardwired function. It is intended to be used to communicate the reason for executing a STOP instruction to the debug system. The default `_start.s` file will write the `main()` return value to this register before stopping.

**TRCAP field, bits 15..8** This field lists the tracing capabilities of the core. The bit indices in this byte correspond to the bit indices in the control byte (the least significant byte of CR\_DCR2). If a bit is high, the feature is available.

**T flag, bit 7** Setting this bit enables trap tracing if the E flag is set and the core is design-time configured to support it.

**M flag, bit 6** Setting this bit enables memory/control register tracing if the E flag is set and the core is design-time configured to support it.

**R flag, bit 5** Setting this bit enables register write tracing if the E flag is set and the core is design-time configured to support it.

**C flag, bit 4** Setting this bit enables cache performance tracing if the E flag is set and the core is design-time configured to support it.

**I flag, bit 3** Setting this bit causes all fetched instructions to be traced if the E flag is set and the core is design-time configured to support it.

**E flag, bit 0** Setting this bit enables tracing if the core is design-time configured to support it. If no other bits are set, only branch origins and destinations are traced.

### 2.3.2.12 CR\_CRR - Context reconfiguration request register

Offset	31 30 29 28 27 26 25 24	23 22 21 20 19 18 17 16	15 14 13 12 11 10 9 8	7 6 5 4 3 2 1 0					
0x240	CRR								CR_CRR
Reset	0 0								
Core									
Debug									

This register may be written to by the core only. When it is written, a reconfiguration is requested. Refer to Section 2.5 for more information.

### 2.3.2.13 CR\_WCFG - Wakeup configuration

Offset	31 30 29 28 27 26 25 24	23 22 21 20 19 18 17 16	15 14 13 12 11 10 9 8	7 6 5 4 3 2 1 0	
0x248	WCFG				CR_WCFG
Reset	0 0				
Core					
Debug					

This register only exists on context 0. This configuration register is used in conjunction with the S flag in CR\_SAWC. Refer to Section 2.5.3 for more information.

### 2.3.2.14 CR\_SAWC - Sleep and wake-up control register

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	CR_SAWC
0x24C																									RUN				S				
Reset	0 0																																
Core																																	
Debug																																	

This register only exists on context 0. This register contains special control features for sleeping (reconfiguring to a configuration with all lane groups disabled) and waking up other hardware contexts.

**RUN field, bits 7..1** This field contains a bit for every other context, i.e., not all of these bits will be available if the core is not configured to support all eight hardware contexts. When reading this register, each bit represents the ones complement of the B flag in CR\_DCR for each other context. Writing a one to a bit is equivalent to writing a one to the R flag in CR\_DCR for each other context.

A scheduler running on context 0 may use this feature, combined with an interrupt controller that triggers an interrupt when the done output for any other context has a rising edge, to support task yielding for cooperative scheduling. A yield will then be equivalent to a STOP instruction, which will thus trigger an interrupt for the scheduler. The scheduler may then switch out the software context and subsequently restart the hardware context using these flags.

**S flag, bit 0** Sleep flag. This enables or disables the sleep and wake-up system. Refer to Section 2.5.3 for more information.

The WCFG and SAWC.S flag don't do anything yet.

### 2.3.2.15 CR\_SCRPn - Scratchpad register *n*

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0x250	SCR1																																CR_SCRP1
0x254	SCR2																																CR_SCRP2
0x258	SCR3																																CR_SCRP3
0x25C	SCR4																																CR_SCRP4
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Core																																	
Debug																																	

Scratch pad registers. May be used at the discretion of the application and/or debug system.

### 2.3.2.16 CR\_RSC - Requested software context

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0x260	RSC																																CR_RSC
Reset	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Core																																	
Debug																																	

The RSC register doesn't exist yet.

*This register does not exist on context 0.* It is hardwired to RSC<sub>n</sub> in hardware context 0, and represents the software context that should be loaded into our hardware context, if it is not already loaded. The encoding of the register is at the user's discretion, but it is intended that this points to a memory region that contains the to be loaded context.

The contents of this register are controlled by hardware context 0, which is expected to run the scheduler. When this value does not equal the value in CSC and context switching is enabled in CR\_CCR, the TRAP\_CONTEXT\_SWITCH trap is caused. Refer to its documentation in Section 2.4 for more information.

### 2.3.2.17 CR\_CSC - Current software context

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0x264	CSC																																CR_CSC
Reset	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Core																																	
Debug																																	

The CSC register doesn't exist yet.

*This register does not exist on context 0.* It is hardwired to CSC<sub>n</sub> in hardware context 0. The value in this register should be set to the value in CR\_RSC by the TRAP\_CONTEXT\_SWITCH trap.

### 2.3.2.18 CR\_RSCn - Requested swctxt on hwctxt $n$

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0x268	RSC1																CR_RSC1																
0x270	RSC2																CR_RSC2																
0x278	RSC3																CR_RSC3																
0x280	RSC4																CR_RSC4																
0x288	RSC5																CR_RSC5																
0x290	RSC6																CR_RSC6																
0x298	RSC7																CR_RSC7																
Reset	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Core																																	
Debug																																	

*This register only exists on context 0, and only if the core is design-time configured to support hardware context  $n$ . This register is hardwired to CR\_RSC in hardware context  $n$ . Refer to CR\_RSC for more information.*

The RSC $n$  registers don't exist yet.

### 2.3.2.19 CR\_CSCn - Current swctxt on hwctxt $n$

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0x26C	CSC1																CR_CSC1																
0x274	CSC2																CR_CSC2																
0x27C	CSC3																CR_CSC3																
0x284	CSC4																CR_CSC4																
0x28C	CSC5																CR_CSC5																
0x294	CSC6																CR_CSC6																
0x29C	CSC7																CR_CSC7																
Reset	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Core																																	
Debug																																	

*This register only exists on context 0, and only if the core is design-time configured to support hardware context  $n$ . This register is hardwired to CR\_CSC in hardware context  $n$ . Refer to CR\_CSC for more information.*

The CSC $n$  registers don't exist yet.

### 2.3.2.20 CR\_CYC - Cycle counter

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	CR_CYC
0x300	CYC																																
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Core																																	
Debug																																	

This register will automatically increment every cycle while an instruction from this context is in the pipeline, even when the context is stalled.

When the debug bus writes to this register, the register is cleared. When it writes 1 to it, CR\_STALL, CR\_BUN, CR\_SYL and CR\_NOP will also be cleared, simultaneously.

### 2.3.2.21 CR\_STALL - Stall cycle counter

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0x308	STALL																																CR_STALL
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Core																																	
Debug																																	

This register will automatically increment every cycle while an instruction from this context is in the pipeline and the context is stalled. When the debug bus writes to this register, the register is cleared. It will also be cleared if the debug bus writes a 1 to CR\_CYC.

As long as neither CR\_CYC nor CR\_STALL have overflowed, CR\_CYC - CR\_STALL represents the number of active cycles.

### 2.3.2.22 CR\_BUN - Committed bundle counter

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0x310	BUN																																CR_BUN
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Core																																	
Debug																																	

This register will automatically increment whenever the results of executing a bundle are committed. When the debug bus writes to this register, the register is cleared. It will also be cleared if the debug bus writes a 1 to CR\_CYC.

As long as neither CR\_CYC, CR\_STALL nor CR\_BUN have overflowed, CR\_CYC - CR\_STALL - CR\_BUN represents the number of cycles spent doing pipeline flushes, for example due to traps or the branch delay slot.

### 2.3.2.23 CR\_SYL - Committed syllable counter

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0x318	SYL																																CR_SYL
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Core																																	
Debug																																	

This register will automatically increment whenever the results of executing a non-NOP syllable are committed. When the debug bus writes to this register, the register is cleared. It will also be cleared if the debug bus writes a 1 to CR\_CYC.

As long as neither CR\_BUN nor CR\_SYL have overflowed, CR\_SYL / CR\_BUN represents average instruction-level parallelism since the registers were cleared.

### 2.3.2.24 CR\_NOP - Committed NOP counter

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0x320	NOP																																CR_NOP
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Core																																	
Debug																																	

This register will automatically increment whenever a NOP syllable is committed. When the debug bus writes to this register, the register is cleared. It will also be cleared if the debug bus writes a 1 to CR\_CYC.

As long as neither CR\_SYL nor CR\_NOP have overflowed,  $CR\_SYL / (CR\_SYL + CR\_NOP)$  represents average fraction of syllables that are NOP, i.e. the compression efficiency of the binary.

### 2.3.2.25 CR\_IACC - Instruction cache access counter

Offset	31 30 29 28 27 26 25 24	23 22 21 20 19 18 17 16	15 14 13 12 11 10 9 8	7 6 5 4 3 2 1 0	
0x328	IACC				CR_IACC
Reset	0 0				
Core					
Debug					

This register increments for every instruction cache access.

### 2.3.2.26 CR\_IMISS - Instruction cache miss counter

Offset	31 30 29 28 27 26 25 24	23 22 21 20 19 18 17 16	15 14 13 12 11 10 9 8	7 6 5 4 3 2 1 0	
0x330	IMISS				CR_IMISS
Reset	0 0				
Core					
Debug					

This register increments every time there is a miss in the instruction cache.

### 2.3.2.27 CR\_DRACC - Data cache read access counter

Offset	31 30 29 28 27 26 25 24	23 22 21 20 19 18 17 16	15 14 13 12 11 10 9 8	7 6 5 4 3 2 1 0	
0x338	DRACC				CR_DRACC
Reset	0 0				
Core					
Debug					

This register increments every time there is a read access to the data cache.

### 2.3.2.28 CR\_DRMISS - Data cache read miss counter

Offset	31 30 29 28 27 26 25 24	23 22 21 20 19 18 17 16	15 14 13 12 11 10 9 8	7 6 5 4 3 2 1 0	
0x340	DRMISS				CR_DRMISS
Reset	0 0				
Core					
Debug					

This register increments every time there is a read miss in the data cache.

### 2.3.2.29 CR\_DWACC - Data cache write access counter

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0x348	DWACC																																CR_DWACC
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Core																																	
Debug																																	

This register increments every time there is a write access to the data cache.

### 2.3.2.30 CR\_DWMISS - Data cache write miss counter

Offset	31 30 29 28 27 26 25 24	23 22 21 20 19 18 17 16	15 14 13 12 11 10 9 8	7 6 5 4 3 2 1 0	CR_DWMISS												
0x350	DWMISS																
Reset	0 0																
Core																	
Debug																	

This register increments every time there is a write miss in the data cache.

### 2.3.2.31 CR\_DBYPASS - Data cache bypass counter

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0x358	DBYPASS																																CR_DBYPASS
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Core																																	
Debug																																	

This register increments every time there is a bypassed access to the data cache.

### 2.3.2.32 CR\_DWBUF - Data cache write buffer counter

Offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
0x360	DWBUF																																CR_DWBUF
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Core																																	
Debug																																	

This register increments every time there is a write to the data cache while the write buffer is full.

## 2.4 Traps and interrupts

There are many systems in a processor that need to be able to interrupt normal program flow. For instance, an external interrupt may be requested, or a problem occurred while trying to load a word from memory, such as a page fault. The naming conventions for such interruptions varies from processor to processor; in the  $\rho$ -VEX processor all such interruptions are called traps. The word ‘interrupt’ is reserved for the special trap that deals with external interrupts, i.e. asynchronous signals from outside the core. The word ‘fault’ is used to refer to traps that signal that an instruction could not be executed.

### 2.4.1 Trap sources

There are roughly six sources of traps in the  $\rho$ -VEX processor, which are handled in slightly different ways.

- **Faults.** A fault signals that an instruction could not be executed for some reason. They are always handled by the processor by jumping to the trap or panic handler. With the exception of page faults, these traps are usually non-recoverable, leading to abnormal termination of the executing task in an operating system environment, or the STOP instruction to be called in a bare-metal environment.
- **Interrupts.** The  $\rho$ -VEX processor core has an interface for an interrupt controller. When an interrupt is requested and interrupts are enabled through the I flag in CR\_CCR, a TRAP\_EXT\_INTERRUPT trap will be generated. This trap causes the processor to jump to the trap or panic handler.
- **Context switch request.** When the values in CR\_RSC and CR\_CSC do not match and the context switching system is enabled by means of the the C flag in CR\_CCR, a TRAP\_CONTEXT\_SWITCH trap will be generated. This trap causes the processor to jump to the trap or panic handler.
- **Breakpoints/debug traps.** When a hardware or software breakpoint is hit while breakpoints are enabled through the B flag in CR\_CCR, the processor will generate a debug trap. Debug traps can be handled in two ways, depending on the E and I flags in CR\_DCR. When the I flag is set (this is the default), the traps will be handled as any other trap, i.e. by jumping to the trap or panic handler. However, when the E flag is set, the context will simply halt, and write the trap cause to the cause field in CR\_DCR. This allows an external debugging system to handle the breakpoints instead of the processor itself. In addition, debug traps are disabled for every first instruction executed after returning from a trap handler or restarting the context, allowing either to jump over breakpoints.
- **TRAP instructions.** The TRAP instruction can be used to emulate any trap. If the cause maps to a debug trap, it is handled exactly as a debug trap, allowing it to be used as a software breakpoint. Otherwise, it is handled like a fault.



- STOP instructions. A STOP instruction halts the core by generating a TRAP\_STOP trap during execution of the subsequent instruction. The TRAP\_STOP trap is always handled by stopping the hardware context. In addition, the D flag in CR\_DCR is set and the done output signal for the stopped hardware context is asserted.

### 2.4.2 Trap and panic handlers

As stated above, most traps are handled by jumping to the so-called trap or panic handler. These handlers are simply subroutines that typically end with either a RFI or STOP instruction. They should be pointed to by the CR\_TH and CR\_PH control registers; it is up to the initialization code to set up these links.

The hardware switches between the trap and panic handlers based on the R flag in CR\_CCR. The only hardware difference between them is that this flag always switches to the panic handler upon servicing a trap, such that a trap that immediately follows another trap will always be handled by the panic handler.

The tentative difference between the two trap handlers is that one should attempt to jump back to the application (or alternatively, in the case of an operating system, kill the current process with the appropriate signal and context switch to another thread), and the other should not. The necessity of such a difference can be best illustrated with a simple example.

Consider a program that has just been trapped due to an interrupt. The first course of action in handling a trap must always be to save the state of the running program, so the trap cause and argument registers can be examined. Now consider that it is possible for these context-saving memory accesses to cause, say, a misaligned memory access, due to a programming error. A regular trap handler may in theory try to recover from the fault by emulating the faulting instruction and then jumping over it. However, if it would do so, the trap point, cause and argument control registers of the original interrupt trap will have been overwritten with the misaligned memory access. This data was simply lost when the second trap occurred; there is no way around this. Thus, the program cannot continue.

Through the dual handler system as implemented in the  $\rho$ -VEX processor, the first trap will be handled by the regular trap handler. Upon jumping to this trap handler, the processor will automatically clear the ready-for-trap flag, such that the second trap will be handled by the panic handler.

What it comes down to, is that the trap handler may try to recover from a fault, handle an interrupt or breakpoint, etc., while the panic handler should simply display or log an error message if it can, and then stop execution or reset. The regular trap handler may also want to jump to the panic handler if it is posed with a fault trap that it cannot recover from.

### 2.4.3 Trap identification

In the  $\rho$ -VEX processor, traps are identified not by the address that the processor branches to (as there are only two of these addresses, as described in the previous sec-

tion), but by the trap cause (CR\_TC) and trap argument (CR\_TA) control registers. The former stores an 8-bit value that identifies the cause of the trap. The latter is a 32-bit register whose significance depends on the trap cause.

The list below documents the trap causes as currently defined in the processor, and the significance of the trap argument. Note, however, that a TRAP instruction may emulate any of these traps with any argument.

- TRAP\_NONE = 0x00

Trap cause 0 is reserved to indicate normal operation. When an RFI instruction is executed, the trap cause register (cause field in CR\_CCR) will be reset to 0, so an external debug system can always determine what a program is doing, unless nested traps are utilized.

- TRAP\_INVALID\_OP = 0x01

This trap is generated by hardware in the following conditions.

- An unknown opcode is encountered.
- The stop bit was set such that the next bundle would start on an address violating the minimum design-time configured bundle alignment.
- A branch opcode is encountered in a pipeline that does not have an active branch unit.
- A memory opcode is encountered in a pipeline that is not design-time configured to include a memory unit.
- A multiplier opcode is encountered in a pipeline that is not design-time configured to include a multiplier.

The trap argument is set to the lane index that caused the trap.

- TRAP\_MISALIGNED\_BRANCH = 0x02

This trap is generated by hardware when a branch to a misaligned address is requested. The trap argument is set to the branch target.

- TRAP\_FETCH\_FAULT = 0x03

This trap is generated by hardware when an instruction fetch resulted in a bus fault. The trap argument is unused; the program counter can be determined from the trap point.

- TRAP\_MISALIGNED\_ACCESS = 0x04

This trap is generated by hardware when a misaligned memory access was requested. That is, a 32-bit word access was attempted with an address that is not divisible by four, or a 16-bit word access was attempted with an odd address. The trap argument is set to the requested memory address.

- TRAP\_DMEM\_FAULT = 0x05

This trap is generated by hardware when a data memory access resulted in a bus fault. The trap argument is set to the requested memory address.

- TRAP\_LIMMH\_FAULT = 0x06

This trap is generated by hardware under the following conditions.

- A LIMMH instruction is trying to forward to a lane for which no route is available in the core. Note that only the least significant bit of the target lane is actually checked, though. In this case, the trap argument is the index of the lane with the LIMMH instruction.
- Two LIMMH instructions are trying to forward to the same lane. In this case, the trap argument is the index of the target lane.
- A LIMMH instruction is attempting to forward to a syllable that is not using an immediate. In this case, the trap argument is also the index of the target lane.

- TRAP\_EXT\_INTERRUPT = 0x07

This trap is generated by hardware when the external interrupt request line is asserted while interrupts are enabled by means of the I flag in CR\_CCR. When the trap service routine is entered, the state of the external interrupt ID signal is saved as the trap argument in CR\_TA, and in the same cycle, the interrupt is acknowledged. This ensures that the interrupt ID presented to the trap service routine always matches the acknowledged interrupt.

There is a delay between the core registering that the external interrupt request line is asserted and generating the trap, and the actual entering of the trap service routine. This delay is due to the pipeline flush required to do this, and is in the order of a couple cycles; compared to actually servicing a trap this delay is negligible. However, if it is ever possible that an active interrupt is disabled before it is acknowledged by the core, it is possible that the core will enter the trap service routine due to an interrupt that was disabled before it could be handled. In this case, the interrupt controller should provide the core with an otherwise reserved interrupt ID indicating that there was no interrupt. The trap service routine should handle this special interrupt ID as no-operation.

- TRAP\_STOP = 0x08

This trap is generated by hardware in the instruction immediately following a STOP instruction. It is handled in a completely different way than the other traps are; the hardware will not jump to CR\_TH or CR\_PH. Instead, the D and B flags in CR\_DCR are set, thus stopping execution, and the program counter is set to the trap point. This allows an external debugging or control system to resume processing after the stop trap by simply writing a one to the R flag in CR\_DCR.

- `TRAP_CONTEXT_SWITCH = 0x09`

This trap is generated by hardware when the contents of `CR_RSC` differ from `CR_CSC` while this trap is enabled using the `C` flag in `CR_CCR`. The intended use of this trap is to allow hardware context 0 to control software context switching on the other hardware contexts. When used in this way, the trap service routine for this trap should perform the following tasks.

- If `CR_CSC`  $\neq$  -1, save the current context to the memory identified by `CR_CSC`.
- Set `CR_CSC` to `CR_RSC`.
- Restore the software context identified by `CR_RSC` from memory.

The way in which `CR_RSC` and `CR_CSC` identify the software context to be exchanged is up to the operating system code.

- `TRAP_SOFT_DEBUG_0 = 0xF8`
- `TRAP_SOFT_DEBUG_1 = 0xF9`
- `TRAP_SOFT_DEBUG_2 = 0xFA`

These traps are never generated by hardware, but are intended to be used as soft breakpoints using the `TRAP` instruction. That is, the debug system may override one of the syllables in a any bundle where a breakpoint is desired with a `TRAP` syllable. It may return control to the application by reverting the `TRAP` syllable back into the original syllable. If it is not the intention of the debugger to disable the breakpoint, it may single step over the instruction at the breakpoint, and then replace the `TRAP` syllable.

Unlike the other undefined traps (which may be used as arbitrary software traps), these traps behave like hardware debug traps. That is, they will be handled by halting the core if the core is in external debug mode (i.e. the `E` flag in `CR_DCR` is set). This means that an external debugger can also use this system to support an arbitrary number of breakpoints.

Likewise, disabling breakpoints using the `B` flag in `CR_CCR` will prevent even the `TRAP` instruction from actually generating a trap.

- `TRAP_STEP_COMPLETE = 0xFB`

This trap is generated by hardware whenever the `S` flag in `CR_DCR` is set while debug traps are enabled. This allows the debug system to single-step. Refer to the documentation of `CR_DCR` for more information.

- `TRAP_HW_BREAKPOINT_0 = 0xFC`
- `TRAP_HW_BREAKPOINT_1 = 0xFD`
- `TRAP_HW_BREAKPOINT_2 = 0xFE`

- `TRAP_HW_BREAKPOINT_3 = 0xFF`

These traps are generated by hardware when the corresponding hardware breakpoint or watchpoint is hit while debug traps are enabled.

#### 2.4.4 State saving and restoration

Upon entering a trap, it is mostly up to the software to save and restore the processor state. Specifically, the software must ensure that the state of the general purpose registers, branch registers and the link register is as it was when the trap handler was entered when the RFI instruction is executed. The hardware will handle saving and restoration of the context control flags in `CR_CCR` and the program counter, as both of these are modified immediately when entering the trap handler. `CR_CCR` is saved in and restored from `CR_SCCR`, the program counter is saved in and restored from `CR_TP`.

Aside from restoring the state of the currently running task, an operating system environment may also wish to restore the state of a different task. In this case, the complete state of a task is defined by the contents of the general purpose register file, the branch register file, the link register, the program counter (to be accessed using `CR_TP`) and the context control register (to be accessed using `CR_SCCR`).

## 2.5 Reconfiguration and sleeping

The process in which the  $\rho$ -VEX processor switches between one large core and more smaller cores is called reconfiguration. Reconfigurations may be requested by the software running on the processor or the debugging interface by writing the requested configuration to a control register. The reconfiguration controller will then temporarily stop all contexts that will be affected by the reconfiguration, commit the new configuration, and (re)start any contexts that are part of the new configuration but are currently stopped.

### 2.5.1 Configuration word encoding

A configuration is described by means of a single register at most 32-bits in size. The actual size depends on the design-time configuration of the core; in particular, the number of lane groups and the number of contexts.

In the configuration word, each nibble (group of 4 bits, represented by a single hexadecimal digit) maps to a lane group. The nibble signifies the context that is to be run on that lane group. Disabling a lane group to save power is also possible, by selecting ‘context’ eight. This will never map to an actual context, as the maximum amount of hardware contexts supported by the design-time configuration system is also eight, and numbering starts at zero.

Obviously, not all 4.2 billion 32-bit values represent valid configurations. Configuration words must adhere to the following rules.

- The nibbles for existing pipeline groups may be set to either zero through the number of hardware contexts minus one to select a context, or eight to disable the pipeline group. For instance, the configuration word 0x7777 is illegal on an  $\rho$ -VEX processor that does not support eight hardware contexts. Configuration words like 0x9999 are reserved for future configurations, such as fault tolerant duplicate and triplicate modes.
- The nibbles for non-existent pipeline groups must be set to zero. For instance, the configuration word 0x88880000 is illegal for an  $\rho$ -VEX processor that is design-time configured to only support 4 lane groups, even though it may make more sense than the configuration word that was probably the intention here, which is simply zero.
- Any context may only be mapped to a power-of-two of contiguous pipeline groups. For instance, configuration words 0x1118 and 0x1231 are illegal, because the mapping for context 1 violates these rules.
- A set of pipeline groups mapped to a single context must be aligned. Mathematically, the index of the first pipeline group in the set must be divisible by the cardinality of the set. For instance, the configuration word 0x0112 is illegal, because the mapping for context 1 is improperly aligned.

The reconfiguration controller will ensure that a configuration word is valid before committing it to the processor. If an invalid configuration is requested, the E flag in CR\_GSR is set and the request is otherwise ignored.

### 2.5.2 Requesting a reconfiguration

There are three ways in which a reconfiguration can be requested.

- Writing to the CR\_CRR context control register from a program running on the core. This section primarily deals with this mechanism.
- Writing to the CR\_BCRR global control register from the debug bus. This mechanism is equivalent to the first, except it is triggered from outside the core.
- Using the sleep and wake-up system, as described in Section sec:core-ug-reconf-saw.

Usually, when a reconfiguration is requested, the new configuration will be committed within something in the order of tens of cycles, depending on how long it takes the reconfiguration controller to pause the affected contexts. However, a reconfiguration may also be rejected, either another context or the bus is requesting a new configuration simultaneously and arbitration is lost, or because the requested configuration is invalid. The following C function correctly deals with arbitration, and performs a best-effort attempt at detecting errors without using locks implemented in software.

```
/**
 * Requests a reconfiguration. Returns 1 if reconfiguration was successful,
 * -1 if the requested configuration is invalid or 0 if it is not known
 * whether the configuration was valid or not.
 */
int reconfigure(unsigned int newConfiguration) {

    // Extract our own context ID from the register file, which we will use
    // to check if we won arbitration or not.
    int ourselves = CR_CID;

    // Used to store the ID of the winning context after the request.
    int winner;

    // Retry requesting the new configuration until we win arbitration.
    do {

        // Request the new configuration.
        CR_CRR = newConfiguration;

        // Load the GSR register for state information.
        gsr = CR_GSR;

        // Extract the reconfiguration requester ID field from GSR.
        int winner = (gsr & CR_GSR_RID_MASK) >> CR_GSR_RID_BIT;
```

```

} while (winner != ourselves);

// Busy-wait for reconfiguration to complete.
while (gsr & CR_GSR_B_MASK) {
    gsr = CR_GSR;
}

// If our context is still the one that was the last to request a
// reconfiguration, the error flag in GSR is also meant for us. If not,
// there is no way to tell if the configuration we requested was valid
// or not.
if (((gsr & CR_GSR_RID_MASK) >> CR_GSR_RID_BIT) != ourselves) {
    return 0;
}

// If the error flag is set, return -1.
if (gsr & CR_GSR_E_MASK) {
    return -1;
}

// Reconfiguration was successful.
return 1;
}

```

### 2.5.3 Sleep and wake-up system

The sleep and wake-up system refers to two context control registers that only exist on context zero, through which the processor can be set up to automatically request a reconfiguration when the interrupt request input of context zero is asserted. More specifically, the wakeup system will activate when all of the following conditions are met.

- The S flag in CR\_SAWC is set.
- An interrupt is pending on context 0.
- Context 0 is not already active in the current configuration.
- There is no reconfiguration in progress.

When activated, the following actions are performed.

- A reconfiguration to the configuration stored in CR\_WCFG is requested.
- CR\_WCFG is set to the old configuration.
- The S flag in CR\_SAWC is cleared.

This system may be used to save power that is otherwise wasted in an idle loop, or to improve interrupt latency by dedicating hardware context zero to only handling interrupts. These use cases are described below.



### 2.5.3.1 Power saving

To conserve power, the user may want to switch to a configuration where all pipeline groups are idle until an interrupt occurs. This is called sleeping. On an FPGA this is merely a proof of concept, but in an ASIC the amount of power that might be saved by clock gating or powering down the computational resources may be very significant. To go to sleep, the program should take the following steps.

1. If other hardware contexts were running other tasks in parallel to context zero, which may be in a state in which the processor should not sleep, first request these tasks to pause gracefully. If necessary, request a reconfiguration to configuration zero, as described in Section 2.5.2. to disable all contexts except for context zero.
2. Disable interrupts using the I field in CR\_CCR.
3. If necessary, ensure that no interrupt occurred before interrupts were disabled that should cause the processor to stay awake. If this did happen, take the appropriate actions, such as re-enabling interrupts, before attempting to sleep again.
4. Copy CR\_CC, the current configuration, to CR\_WCFG, the wake-up configuration. This is an easy way to ensure that CR\_WCFG will not contain an invalid configuration.
5. Set the S flag in CR\_SAWC to enable the wake-up system.
6. Request a reconfiguration to the configuration where all pipeline groups are disabled, for instance 0x8888 on a core that is design-time configured to have four pipeline groups, as described in Section 2.5.2.
7. Busy-loop until the S flag in CR\_SAWC is cleared. This ensures that the program will not continue until after the processor has finished sleeping.
8. Enable interrupts using the I field in CR\_CCR to service the interrupt. The fact that this is not done automatically also allows the interrupt request input to simply be used as a wake-up input in a simple system where no interrupts exist.

### 2.5.3.2 Decreasing interrupt latency

To decrease interrupt latency, context zero may be used as a dedicated context for servicing interrupts. This prevents the context zero trap handler from having to save and restore the state of the processor as it was before the interrupt trap, as this information is not relevant. The other hardware contexts may be used to run the main program; the reconfiguration system is then used for hardware context switching.

To initialize this system, the program should do the following in context zero.

1. Set up links to the trap and panic handlers for context 0 in CR\_TH and CR\_PH.
2. Copy CR\_CC, the current configuration, to CR\_WCFG, the wake-up configuration. This is an easy way to ensure that CR\_WCFG will not contain an invalid configuration.

3. Set the S flag in CR\_SAWC to enable the wake-up system.
4. Request a reconfiguration as described in Section 2.5.2, to, for instance, 0x1111, if the main program is to run in hardware context 1.
5. Busy-loop until the S flag in CR\_SAWC is cleared. This ensures that the program will not continue until after the first interrupt is requested.
6. Set ready-for-trap and enable interrupts using the R and I fields in CR\_CCR to service the interrupt.
7. Busy-loop forever to wait for the interrupt to be serviced.

The other contexts can initialize in the usual manner. The context 0 trap handler should do the following.

1. Perform body of the regular trap handling tasks, i.e., everything except for saving and restoring the context and executing RFI.
2. Set ready-for-trap and enable interrupts using the R and I fields in CR\_CCR to quickly service the next interrupt if one is already pending. Clear ready-for-trap and disable interrupts in the next cycle again; one cycle is enough for an interrupt to be handled.
3. Store the contents of CR\_WCFG in a temporary register.
4. Copy CR\_CC, the current configuration, to CR\_WCFG, the wake-up configuration. This is an easy way to ensure that CR\_WCFG will not contain an invalid configuration.
5. Set the S flag in CR\_SAWC to enable the wake-up system.
6. Request a reconfiguration to the configuration as stored in the temporary register, as described in Section 2.5.2.
7. Busy-loop until the S flag in CR\_SAWC is cleared. This ensures that the program will not continue until after the first interrupt is requested.
8. Set ready-for-trap and enable interrupts using the R and I fields in CR\_CCR to service the interrupt.
9. Busy-loop forever to wait for the interrupt to be serviced.

Write more about the sleep and wake-up system

## 2.6 Configuration and instantiation

This section describes how the core should be instantiated, what the function of all the external signals are, and how the core may be design-time configured. It is intended for HDL designers who wish to incorporate the bare-metal core into their design.

Refer to some place that designers can turn to if they want to instantiate higher-level  $\rho$ -VEX core blocks, such as the cached core.

### 2.6.1 Data types

The following basic VHDL data types are used for the ports and generics. They are defined in `common_pkg`.

```
subtype rvex_address_type is std_logic_vector(31 downto 0);
subtype rvex_data_type is std_logic_vector(31 downto 0);
subtype rvex_mask_type is std_logic_vector( 3 downto 0);
subtype rvex_syllable_type is std_logic_vector(31 downto 0);
subtype rvex_byte_type is std_logic_vector( 7 downto 0);

type rvex_address_array is array (natural range <>) of rvex_address_type;
type rvex_data_array is array (natural range <>) of rvex_data_type;
type rvex_mask_array is array (natural range <>) of rvex_mask_type;
type rvex_syllable_array is array (natural range <>) of rvex_syllable_type;
type rvex_byte_array is array (natural range <>) of rvex_byte_type;
```

The address, data and syllable types all represent 32-bit words. The distinction is made only for clarity; one can not simply give the  $\rho$ -VEX processor 64-bit address map by widening the address type.

The mask type is used for byte-masking the data vectors for bus operations. As all memory operations operate on 32-bit words, the mask type has four bits to mask each byte. The most significant bit of these masks maps to the most significant byte of the 32-bit word, and thus to the lowest byte address, as the  $\rho$ -VEX system is big endian.

The byte type should be self-explanatory.

### 2.6.2 Instantiation template

The following listing serves as an instantiation template for the core. The code is documented in the following sections.

If you get errors when instantiating the core with this template, the documentation might be out of date. Fear not, for the signals are also documented in the entity description in `core.vhdl`.

Make sure the instantiation template is at least up-to-date at the time of writing; this was copied from the manual from a year ago.

```
library rvex;
use rvex.common_pkg.all;
use rvex.core_pkg.all;

-- ...

rvex_inst: entity rvex.core
  generic map (
    -- Core configuration.
    CFG => rvex_cfg(
      numLanesLog2 => 3,
```

```

        numLaneGroupsLog2      => 2,
        numContextsLog2       => 2
    )
)
port map (
    -- System control.
    reset      => reset,
    resetOut   => resetOut,
    clk        => clk,
    clkEn      => clkEn,

    -- Run control interface.
    rctrl2rv_irq      => rctrl2rv_irq,
    rctrl2rv_irqID    => rctrl2rv_irqID,
    rv2rctrl_irqAck   => rv2rctrl_irqAck,
    rctrl2rv_run      => rctrl2rv_run,
    rv2rctrl_idle     => rv2rctrl_idle,
    rctrl2rv_reset    => rctrl2rv_reset,
    rctrl2rv_resetVect => rctrl2rv_resetVect,
    rv2rctrl_done     => rv2rctrl_done,

    -- Common memory interface.
    rv2mem_decouple   => rv2mem_decouple,
    mem2rv_blockReconfig => mem2rv_blockReconfig,
    mem2rv_stallIn    => mem2rv_stallIn,
    rv2mem_stallOut   => rv2mem_stallOut,
    mem2rv_cacheStatus => mem2rv_cacheStatus,

    -- Instruction memory interface.
    rv2imem_PCs       => rv2imem_PCs,
    rv2imem_fetch     => rv2imem_fetch,
    rv2imem_cancel    => rv2imem_cancel,
    imem2rv_instr     => imem2rv_instr,
    imem2rv_affinity  => imem2rv_affinity,
    imem2rv_busFault  => imem2rv_busFault,

    -- Data memory interface.
    rv2dmem_addr      => rv2dmem_addr,
    rv2dmem_readEnable => rv2dmem_readEnable,
    rv2dmem_writeData  => rv2dmem_writeData,
    rv2dmem_writeMask  => rv2dmem_writeMask,
    rv2dmem_writeEnable => rv2dmem_writeEnable,
    dmem2rv_readData   => dmem2rv_readData,
    dmem2rv_ifaceFault => dmem2rv_ifaceFault,
    dmem2rv_busFault   => dmem2rv_busFault,

    -- Control/debug bus interface.
    dbg2rv_addr       => dbg2rv_addr,
    dbg2rv_readEnable  => dbg2rv_readEnable,
    dbg2rv_writeEnable => dbg2rv_writeEnable,
    dbg2rv_writeMask   => dbg2rv_writeMask,
    dbg2rv_writeData   => dbg2rv_writeData,
    rv2dbg_readData    => rv2dbg_readData,

    -- Trace interface.
    rv2trsink_push     => rv2trsink_push,
    rv2trsink_data     => rv2trsink_data,
    rv2trsink_end      => rv2trsink_end,
    trsink2rv_busy     => trsink2rv_busy
);

```

## 2.6.3 Port description

As you can see in the template, signals are grouped by their function. The following subsections will document each group of signals.

### 2.6.3.1 System control

The system control signals include the clock source for the core, a synchronous reset signal and a global clock enable signal. `clk` and `reset` are required `std_logic` input

signals. `clkEn` is an optional `std_logic` input signal.

The core is clocked on the rising edge of `clk` while `clkEn` is high. When a rising edge on `clk` occurs while `reset` is high, most components of the core will be reset, regardless of the state of `clkEn`. The only component of the core that is not reset by this is the general purpose register file. This is because this register file is implemented using block RAMs, which have no physical reset input in Xilinx FPGAs.

The `resetOut` signal is asserted high for one cycle when the debug bus writes a one to the `reset` bit in `CR_GSR`. This signal may be used to reset support systems as well as the core, or it may be ignored.

### 2.6.3.2 Run control

The run control signals provide an interface between the core and an interrupt controller or a master processor if the  $\rho$ -VEX is used as a coprocessor. All signals are optional. All signals are arrays of some sort, indexed by hardware context IDs in descending order.

- `rctrl2rv_irq` : in `std_logic_vector(number of contexts - 1 downto 0)`
- `rctrl2rv_irqID` : in `rvex_address_array(number of contexts - 1 downto 0)`
- `rv2rctrl_irqAck` : out `std_logic_vector(number of contexts - 1 downto 0)`

When `rctrl2rv_irq` is high, an interrupt trap will be generated within the indexed context as soon as possible, if the interrupt enable flag in the context control register is set. Interrupt entry is acknowledged by `rv2rctrl_irqAck` being asserted high for one `clkEnabled` cycle. `rctrl2rv_irqID` is sampled in exactly that cycle and is made available to the trap handler through the trap argument register. When not specified, `rctrl2rv_irq` is tied to '0' and `rctrl2rv_irqID` is tied to `X"00000000"`.

When `rv2rctrl_irqAck` is high, an interrupt controller would typically release `rctrl2rv_irq` and set `rctrl2rv_irqID` to a value signalling that no interrupt is active on the subsequent clock edge. Alternatively, if more interrupts are pending, `rctrl2rv_irq` may remain high and `rctrl2rv_irqID` may be set to the code identifying the next interrupt.

Releasing `rctrl2rv_irq` before an interrupt is acknowledged may still cause an interrupt trap to be caused. This is due to the fact that traps take time to propagate through the pipeline. The core will still assert `rv2rctrl_irqAck` upon entry of the trap service routine in this case. In order to properly account for this behavior, interrupt controllers should ignore `rv2rctrl_irqAck` if no interrupt is active, and there should be a special `rctrl2rv_irqID` value that signals 'no interrupt'. The trap service routine should return to application code as soon as possible in this case.

- `rctrl2rv_run` : in `std_logic_vector(number of contexts - 1 downto 0)`

- `rv2rctrl_idle` : out std\_logic\_vector(*number of contexts* - 1 downto 0)

When `rctrl2rv_run` is asserted low, the indexed context will stop executing instructions as soon as possible. It will finish instructions that were already in the pipeline and have already committed data, and set the program counter to point to the next instruction that should be issued for the program to resume correctly later. As soon as `rctrl2rv_run` is asserted high again, the context will resume, assuming there is nothing else preventing it from running. When `rctrl2rv_run` is not specified, it is tied to '1'.

Only when the context has completely stopped, i.e., there are no instructions in the pipeline, will `rv2rctrl_idle` be asserted high. This may also happen while `rctrl2rv_run` is high, when the core is being halted for a different reason. Such reasons include preparing for reconfiguration, the context not having lane groups assigned to it, and the B flag in `CR_DCR`. `rv2rctrl_idle` remains high until the next instruction is fetched.

- `rctrl2rv_reset` : in std\_logic\_vector(*number of contexts* - 1 downto 0)
- `rctrl2rv_resetVect` : in rvex\_address\_array(*number of contexts* - 1 downto 0)
- `rv2rctrl_done` : out std\_logic\_vector(*number of contexts* - 1 downto 0)

When `rctrl2rv_reset` is asserted high, the context control registers for the indexed context are synchronously reset in the next `clkEnabled` cycle. Note that this behavior is different from the master reset signal, which ignores `clkEn`. When it is not specified, it is tied to '0'.

`rctrl2rv_resetVect` determines the reset vector for each context, i.e. the initial program counter. When it is not specified, it is tied to the reset vector specified by the CFG generic.

`rv2rctrl_done` is connected to the D flag in `CR_DCR`, which is set when the processor executes a `STOP` instruction. The only way to clear this signal without debug bus accesses is to assert `reset` or `rctrl2rv_reset`.

When the  $\rho$ -VEX is running as a co-processor, `rctrl2rv_reset` could be used as an active low flag indicating that the currently loaded kernel needs to be executed, in which case `rv2rctrl_done` signals completion. `rctrl2rv_resetVect` marks the entry point for the kernel.

### 2.6.3.3 Common memory interface

These control signals are common to both the data and instruction memory interface.

- `rv2mem_decouple` : out std\_logic\_vector(*number of lane groups* - 1 downto 0)

This vector represents the current runtime configuration of the core. In particular, it specifies which lane groups are working together to execute code within a single

context. When a bit in this vector is high, the indexed lane group is ‘decoupled’ from the next lane group, i.e., is operating within a different context. When a bit is low, the indexed lane group is working as a slave to the next higher indexed lane group for which the bit is set.

Due to constraints in the core, the indices of pipeline groups working together are always aligned to the number of pipeline groups in the group. As an example, if pipeline groups 0 and 1 are working together, group 2 cannot join them without group 3 also joining them. This allows binary tree structures to be used in the coupling logic. This means that, in the default core configuration, only the following decouple vectors are legal: "1111", "1110", "1011", "1010" and "1000".

The state of the `rv2mem_decouple` signal has several implications on the behavior of the memory ports on the  $\rho$ -VEX.

- The PCs presented by the instruction memory ports will always be contiguous and aligned for groups that are working together. The fetch and cancel signals will always be equal.
- The  $\rho$ -VEX assumes that the `mem2rv_blockReconfig` and `mem2rv_stallIn` signals are equal for coupled pipeline groups. Behavior is completely undefined if these assumptions are violated.

- `mem2rv_blockReconfig` : in `std_logic_vector(number of lane groups - 1 downto 0)`

This signal can be used by the memories to block reconfiguration due to ongoing operations. When a bit in this vector is high, the context associated with the indexed group is guaranteed to not reconfigure. The  $\rho$ -VEX will assume that the associated bits in the `mem2rv_blockReconfig` signal will always be released eventually when no operations are requested by those pipeline groups, otherwise the system may deadlock. When pipeline groups are coupled, their respective `mem2rv_blockReconfig` signals must be equal. When this signal is not specified, it is tied to all zeros.

- `mem2rv_stallIn` : in `std_logic_vector(number of lane groups - 1 downto 0)`

Stall input signals for each pipeline group. When the stall signal for a pipeline group is high, the next rising edge of the clock signal will be ignored. When pipeline groups are coupled, their respective `mem2rv_stallIn` signals must be equal. When this signal is not specified, it is tied to all zeros.

- `rv2mem_stallOut` : out `std_logic_vector(number of lane groups - 1 downto 0)`

Stall output signals for each pipeline group. This serves as a combined stall signal from all stall sources, indicating whether a pipeline group is actually stalled or not. When `rv2mem_stallOut` is high, all memory request signals from the associated

pipeline group should be considered to be undefined. Memory access requests should thus be initiated (and registered) only at the rising edge of the `clk` signal when `clkEn` is high and the associated `rv2mem_stallOut` signal is low. In addition, the result of a previously requested memory operation should remain valid until the next `clkEnabled` cycle where the `rv2mem_stallOut` signal is low, as this is when the core will sample the signal.

When pipeline groups are coupled, their respective `rv2mem_stallOut` signals will be equal. In addition, the `unifiedStall` configuration parameter in the CFG record may be set to `true` to enforce equal stall signals for all pipeline groups at all times, should this be desirable for the memory implementation.

- `mem2rv_cacheStatus` : in `rvex_cacheStatus_array(number of lane groups - 1 downto 0)`

This signal may be driven with cache status information. This is used by the trace unit only. The data type is a record defined in `core_pkg` as follows.

```
type rvex_cacheStatus_type is record
    instr_access      : std_logic;
    instr_miss       : std_logic;
    data_accessType   : std_logic_vector(1 downto 0);
    data_bypass       : std_logic;
    data_miss         : std_logic;
    data_writePending : std_logic;
end record;
```

All signals must be externally gated by the stall signals of the core for compatibility with performance counters in the future. Otherwise, the `instr_` prefixed signals share the timing of the instruction fetch result, and `data_` prefixed signals share the timing of the data memory access result.

`instr_access` should be high when an instruction fetch was performed. In this case, `instr_miss` may also be high to signal that the fetch caused a cache miss.

`data_access` should be set to `01` if a read access was performed, to `10` if a 32-bit write access was performed and to `11` if a partial write was performed. `00` logically means no operation. If an access was performed that bypassed the cache, `data_bypass` should be set. If an access was performed that caused a cache miss, `data_miss` should be set. If an access was performed by a cache block that had a nonempty write buffer when the request was made, `data_writePending` should be set.

Note that these signals are very cache implementation dependent. They were designed to work with the reconfigurable cache described in Section 4 specifically. It may, of course, be abused by other cache implementations, as long as the people working with the resulting traces are adequately informed.



### 2.6.3.4 Instruction memory interface

These signals interface between the  $\rho$ -VEX and the instruction memory or cache. All signals in this section are clock gated by not only `clkEn`, but also by the respective signal in `rv2mem_stallOut`. They should be considered to be invalid when the respective `rv2mem_stallOut` signal is high. The number of enabled clock cycles without stalls after which the reply for a request is assumed to be valid is defined by `L_IF`, which is defined in `core_pipeline_pkg`. `L_IF` defaults to 1.

- `rv2imem_PCs` : out `rvex_address_array(number of lane groups - 1 downto 0)`

Program counter outputs for each lane group. These will always be aligned to the size of an instruction for a full lane group. When lane groups are coupled, the PC for the first lane group will always be aligned to the size of the instruction to be executed on the set of lane groups, and the PCs for those lane groups will be contiguous.

- `rv2imem_fetch` : out `std_logic_vector(number of lane groups - 1 downto 0)`

Read enable output. When high, the instruction memory should supply the instructions pointed to by `rv2imem_PCs` on `imem2rv_instr` after `L_IF` processor cycles.

- `rv2imem_cancel` : out `std_logic_vector(number of lane groups - 1 downto 0)`

Cancel signal. This signal will go high combinatorially (regardless of the stall input from the memory) when it has been determined that the result of the most recently requested instruction fetch will not be used. In this case, the memory may cancel the request in order to be able to release the stall signal earlier. This signal can safely be ignored for correct operation.

- `imem2rv_instr` : in `rvex_syllable_array(number of lanes - 1 downto 0)`

Syllable input for each lane. Expected to be valid `L_IF` processor cycles after `rv2imem_fetch` is asserted if `rv2imem_cancel` and `imem2rv_fault` are low.

- `imem2rv_affinity` : in `std_logic_vector(n log(n) - 1 downto 0)`

Where  $n = \text{number of lane groups}$

Optional block affinity input signal for reconfigurable caches. If used, it is expected to have the same timing as the `imem2rv_instr` signal. Each lane group has  $\log(\text{number of lane groups})$  bits in this signal, forming an unsigned integer that indexes the lane group that serviced the instruction read. When the processor wants to reconfigure, it may use this signal as a hint to determine which program should be placed on which lane group next, assuming that there will be fewer cache misses if the currently running application is mapped to the lane group indexed by the affinity signal. Its value is made available to the program using the `CR_AFF` register.

- `imem2rv_busFault` : in `std_logic_vector(number of lane groups - 1 downto 0)`

Instruction fetch bus fault input signal. Expected to have the same timing as the `imem2rv_instr` signal. When high, a `TRAP_FETCH_FAULT` trap is generated and the instruction defined by `imem2rv_instr` will not be executed.

### 2.6.3.5 Data memory interface

These signals interface between the  $\rho$ -VEX and the data memory or cache. All signals in this section are clock gated by not only `clkEn`, but also by the respective signal in `rv2mem_stallOut`. They should be considered to be invalid when the respective `rv2mem_stallOut` signal is high. The number of enabled clock cycles after which the reply for a request is assumed to be valid is defined by `L_MEM`, which is defined in `core_pipeline_pkg`. `L_MEM` defaults to 1.

- `rv2dmem_addr` : out `rvex_address_array(number of lane groups - 1 downto 0)`

Memory address that is to be accessed if `rv2dmem_readEnable` or `rv2dmem_writeEnable` is high. The two least significant bits of the address will always be "00" and may be ignored. Note that a configurable 1 kiB block within this 4 GiB memory space is inaccessible, because it is replaced by the core control registers. This is configurable through the `cregStartAddress` entry in `CFG`, which defaults to `0xFFFFFC00`, meaning that addresses `0xFFFFFC00` through `0xFFFFFFFF` are inaccessible.

- `rv2dmem_readEnable` : out `std_logic_vector(number of lane groups - 1 downto 0)`

Active high read enable signal from the core for each memory unit. When high during an enabled rising clock edge, the  $\rho$ -VEX expects the access result to be valid `L_MEM` enabled cycles later.

- `rv2dmem_writeData` : out `rvex_data_array(number of lane groups - 1 downto 0)`

- `rv2dmem_writeMask` : out `rvex_mask_array(number of lane groups - 1 downto 0)`

These signals define the write operation to be performed when `rv2dmem_writeEnable` is high. `rv2dmem_writeMask` contains a bit for each byte in `rv2dmem_writeData`, which determines whether the byte should be written or not: when high, the respective byte should be written; when low, the byte should not be affected. Mask bit  $i$  governs data bits  $i * 8 + 7$  downto  $i * 8$ . This corresponds to byte address  $a + 3 - i$ , where  $a$  is the word address specified by `rv2dmem_addr`, because the  $\rho$ -VEX is big endian.

- `rv2dmem_writeEnable` : out `std_logic_vector(number of lane groups - 1 downto 0)`

Active high write enable signal from the core for each memory unit. When high during an enabled rising clock edge, the  $\rho$ -VEX expects either that the write request defined by `rv2dmem_addr`, `rv2dmem_writeData` and `rv2dmem_writeMask` will be performed, or that `dmem2rv_ifaceFault` or `dmem2rv_busFault` is asserted high `L_MEM` cycles later.

- `dmem2rv_readData` : in `rvex_data_array(number of lane groups - 1 downto 0)`

This is expected to contain the read data for read requested by `rv2dmem_readEnable` and `rv2dmem_addr` `L_MEM` enabled cycles earlier, unless `dmem2rv_ifaceFault` or `dmem2rv_busFault` are high.

- `dmem2rv_ifaceFault` : in `std_logic_vector(number of lane groups - 1 downto 0)`

These signals are expected to be valid `L_MEM` enabled cycles after a read or write request. `dmem2rv_ifaceFault` being high indicates that the read or write could not be performed because the memory system is incapable of servicing the specific type of memory access. For instance, the reconfigurable cache asserts this signal if more than one request is made at a time by coupled lane groups. `dmem2rv_busFault` being high indicates that some kind of bus fault occurred, for example if a memory access was made to unmapped memory.

In either case, a `DMEM_FAULT` trap will be issued. The trap argument will be set to the address that was requested.

There is currently no way to distinguish between a data memory interface fault and a bus fault. A new trap should probably be added to the core for this sometime.

### 2.6.3.6 Debug bus interface

The debug bus provides an optional slave bus interface capable of accessing most of the registers within the core.

- `dbg2rv_addr` : in `rvex_address_type`
- `dbg2rv_readEnable` : in `std_logic`
- `dbg2rv_writeEnable` : in `std_logic`
- `dbg2rv_writeMask` : in `rvex_mask_type`
- `dbg2rv_writeData` : in `rvex_data_type`
- `rv2dbg_readData` : out `rvex_data_type`

Debug interface bus. `dbg2rv_readEnable` and `dbg2rv_writeEnable` are active high and should not be active at the same time. `rv2dbg_readData` is valid

one `clkEnabled` cycle after `dbg2rv_readEnable` is asserted and contains the data read from `dbg2rv_addr` as it was while `dbg2rv_readEnable` was asserted. `dbg2rv_writeMask`, `dbg2rv_writeData` and `dbg2rv_addr` define the write request when `dbg2rv_writeEnable` is asserted. All input signals are tied to '0' when not specified.

### 2.6.3.7 Trace interface

The trace interface provides an optional write-only bus to some memory system or peripheral, which the core may send trace information to. The trace system is disabled by default and must be enabled in the `CR_DCR2` control register. In addition, the trace unit hardware is only instantiated when `traceEnable` is set in the CFG vector.

- `rv2trsink_push` : out std\_logic

When high, `rv2trsink_data` and `rv2trsink_end` are valid and should be registered in the next cycle where `clkEn` is high.

- `rv2trsink_data` : out rvex\_byte\_type

Trace data signal. Valid when `rv2trsink_push` is high.

- `rv2trsink_end` : out std\_logic

When high, this is the last byte of this trace packet. May be used to flush buffers downstream, or may be ignored.

- `trsink2rv_busy` : in std\_logic

When high while `rv2trsink_push` is high, the trace unit is stalled. While stalled, `rv2trsink_push` will stay high and `rv2trsink_data` and `rv2trsink_end` will remain stable.

### 2.6.4 Generic configuration

Write about the CFG generic.

### 2.6.5 Package configuration

The  $\rho$ -VEX processor has more configuration options than those described by the CFG generic. These configuration options are instead



This chapter documents how the  $\rho$ -VEX processor core works internally. Refer to Chapter 2 instead if you are only interested in using the core as is.

The first section of this chapter gives an architectural overview of the core, lists the VHDL files that represent the core and deals with code style. The second and third sections together describe how instructions are executed; the former documents the datapath (tentatively, the lifespan of an instruction) while the latter documents how the next instruction is chosen. The fourth section deals with the reconfiguration system of the core, and what the interconnect between the lane groups and the contexts looks like. Finally, the fifth section documents the external debug and trace interfaces.

## 3.1 Overview

This section gives an overview of the structural hierarchy of the core, as well as a VHDL entity and package file listing. The last section documents the coding style employed within all  $\rho$ -VEX core files.

### 3.1.1 Architecture

A block diagram of the rvex core is shown in Figure 3.1. The abbreviations used are described in the next section. The same abbreviations are used in the code to mark the source and/or destination of a signal, as described in Section 3.1.3.

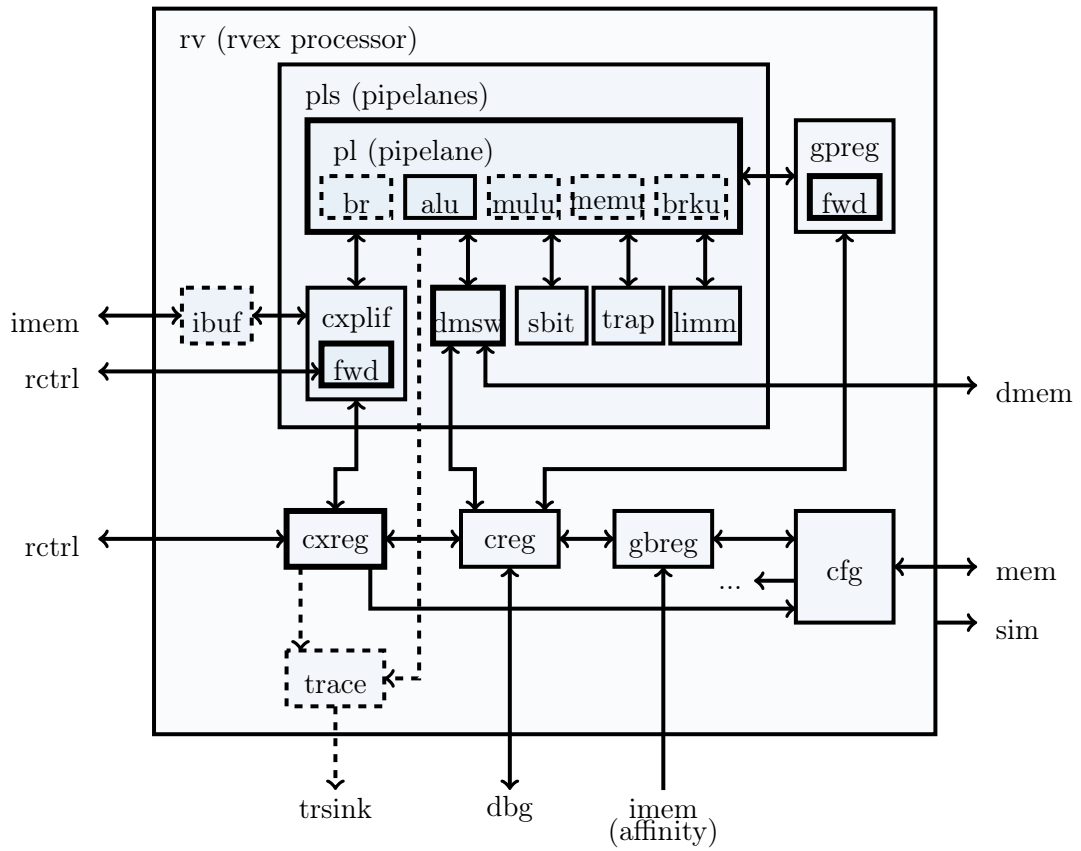


Figure 3.1: Block diagram of the  $\rho$ -VEX core.

### 3.1.2 File and abbreviation list

This section lists all the core files and their functions. Files describing entities also have their entity abbreviation listed. Abbreviations without a corresponding file are also listed, at the bottom of the list.

This is a year old; at least the stop bit system is missing.

**$\rho$ -VEX processor**                      **rv**                      core.vhd

This is the toplevel file for the  $\rho$ -VEX processor.

**External  $\rho$ -VEX package**                      -                      core\_pkg.vhd

This package contains type definitions and constants relevant both in the core internally and for the external interface of the core. In particular, it contains the type specification for the CFG generic, and the rvex\_cfg subprogram that should be used to construct or modify it.

**Internal  $\rho$ -VEX package**                      -                      core\_intf\_pkg.vhd

This package contains all type specifications, constants and subprograms that are relevant only to the core files and do not belong in a specific file. This file does not contain configuration constants, aside from the following constants related to simulation performance: GEN\_VHDL\_SIM\_INFO, SIM\_FULL\_GPREG\_FILE and RVEX\_UNDEF. These constants are documented extensively in the code.

**Pipelanes**                                      **pIs**                      core\_pipelines.vhd

This entity contains the datapaths for the processor. It also contains the reconfigurable routing logic used to couple or decouple lane groups.

**Pipeline**                                      **pI**                      core\_pipeline.vhd

This entity contains the datapath for a single pipeline, capable of executing a single syllable. It instantiates the necessary functional units based on configuration and its index. The pipeline is described in a single behavioral process, in such a way that the timing can be modified by just changing constants. These constants may be found in core\_pipeline\_pkg.vhd. Assert statements are in place to check the configuration specified by core\_pipeline\_pkg.vhd.

**Pipeline configuration**                      -                      core\_pipeline\_pkg.vhd

This contains constants that define the timing and the number of stages of the pipeline. All stage definitions and latencies may be changed without breaking functionality, as long as the requirements for each constant are complied with. Assert statements in core\_pipeline.vhd verify that the pipeline configuration is valid during static elaboration.

**Branch unit**                                      **br**                      core\_branch.vhd

This entity determines the program counter for the next cycle and provides its pipeline with the capability of executing branch class syllables. There must be exactly one branch unit in each pipeline group, and only the branch unit in the highest indexed pipeline group is active when groups are coupled.



**Arithmetic logic unit**                      **alu**                      `core_alu.vhd`

This entity contains the arithmetic unit for the  $\rho$ -VEX. The ALU takes up to two 32-bit integer operands and one boolean operand as input, and outputs a 32-bit integer and/or a boolean. Registers may be inserted in two places in the datapath, affecting the timing of the ALU. Insertion is controlled by `L_ALU1` and `L_ALU2`, defined in `core_pipeline_pkg.vhd`.

**Memory unit**                                      **memu**                      `core_memu.vhd`

This entity interfaces with the data memory port and control registers of the  $\rho$ -VEX. When present, it provides its pipeline with the capability of executing memory class syllables. There must be exactly one memory unit in each pipeline group, and only the memory unit in the highest indexed pipeline group is active when groups are coupled.

**Multiply unit**                                      **mulu**                      `core_mulu.vhd`

This entity contains a 32x16 multiplier. When present, it provides its pipeline with the capability of executing multiply class syllables. The latency is configurable using the `L_MUL` constant in `core_pipeline_pkg.vhd`. Directives for the Xilinx synthesis tools are in place to have the tools automatically insert the pipeline registers in the appropriate places within the DSP core.

**Breakpoint unit**                                      **brku**                      `core_brku.vhd`

This entity matches the PC and memory access command against the up to four enabled hardware breakpoint registers, and generates debug traps if there is a match. It should only be instantiated in pipelines that also have a memory unit.

**Opcode package**                                      -                      `core_opcode_pkg.vhd`

This package defines the `OPCODE_TABLE` constant array, which maps the 8-bit opcode portion of a syllable to its control signals and (dis)assembly information. Operations can be added, removed and modified without breaking the processor. In addition, if the (dis)assembly formatting strings are maintained properly, the core unit test runner will generate correct machine code regardless of the opcode configuration when the `load` command is used, but externally compiled code loaded with the `srec` command will of course need to be recompiled.

**Datapath ctrl. signal package**                      -                      `core_opcodeDatapath_pkg.vhd`

This package defines sets of control signals defining how the functional units are to be connected to the register files and each other, for use in `core_opcode_pkg.vhd`.

**ALU ctrl. signal package**                      -                      `core_opcodeAlu_pkg.vhd`

This package defines sets of control signals defining valid ALU functions for use in `core_opcode_pkg.vhd`.

**Mult. ctrl. signal package**            -            `core_opcodeMultiplier_pkg.vhd`

This package defines sets of control signals defining valid multiplier functions for use in `core_opcode_pkg.vhd`.

**Mem. ctrl. signal package**            -            `core_opcodeMemory_pkg.vhd`

This package defines sets of control signals defining valid memory unit functions for use in `core_opcode_pkg.vhd`.

**Branch ctrl. signal package**        -            `core_opcodeBranch_pkg.vhd`

This package defines sets of control signals defining valid branch unit functions for use in `core_opcode_pkg.vhd`.

**(Dis)assembler package**            -            `core_asDisas_pkg.vhd`

This package defines simulation/elaboration only subprograms that can perform basic assembly and disassembly, used for the core unit test runner and the simulation-only core state output signal.

**General purpose registers**           **gpreg**            `core_gpRegs.vhd`

This entity instantiates the general purpose register file and associated forwarding logic. Two register file implementations are available, specified in `core_gpRegs_sim.vhd` and `core_gpRegs_mem.vhd`.

**BRAM-based gpreg spec.**            -            `core_gpRegs_mem.vhd`

This entity specifies the general purpose register file in such a way that block RAMs are inferred for the register contents. In order to provide simultaneous access to all read and write ports, the contents of the register file are duplicated for each read and write port pair. Fabric based registers are used to store which write port last wrote to each register. Because of the duplication, it is hard to trace the contents of the register file in simulation. Therefore, `core_gpRegs_sim.vhd` will be used for simulation instead, unless `SIM_FULL_GPREG_FILE` in `core_intIface_pkg.vhd` is set to true.

**Behavioral gpreg spec.**            -            `core_gpRegs_sim.vhd`

This entity specifies the general purpose register file behaviorally, in such a way that the register contents can be easily traced in simulation. However, it is not decently synthesizable.

**Forwarding logic**                    **fwd**            `core_forward.vhd`

This entity infers the priority encoder and muxes needed for forwarding. It is highly generic and customizable, allowing it to be used for both the general purpose register file as well as the branch register file and link register.

**Context-pipeline interface**      **cxplif**      `core_contextPipelineIFace.vhd`

This entity serves as a central reconfigurable routing matrix between all pipelines, pipeline groups and contexts.

**Data memory switch**      **dmsw**      `core_dmemSwitch.vhd`

This entity switches between forwarding data memory access requests to the external data memory port and the core control registers. It adds additional latency stages to the core control register read data signal when the memory latency (`L_MEM` in `core_pipeline_pkg.vhd`) is specified to be greater than one.

**Long immediate routing**      **limm**      `core_limmRouting.vhd`

This entity contains the inter-pipeline routing needed to support long immediate (LIMMH) instructions. It can be configured to support routing long immediate data between aligned pipeline pairs and/or from the previous pair by means of the `limmhFromNeighbor` and `limmhFromPreviousPair` members of the CFG generic. When `limmhFromNeighbor` is set, a LIMMH instruction in lane 0 can forward to lane 1, lane 1 can forward to lane 0, lane 2 to 3, 3 to 2 and so on. When `limmhFromPreviousPair` is set, lane 0 can forward to lane 2, lane 1 to 3, 3 to 4 and so on. Registers are instantiated in this case when the generic binary bundle size (`genBundleSizeLog2` in CFG) is set to be larger than the size of a lane group to store the LIMMH data from the previous instruction when necessary.

**Trap routing**      **trap**      `core_trapRouting.vhd`

This entity merges trap information from pipelines together when they are coupled, and broadcasts the merged information back to the lanes for the invalidation logic.

**Trap code package**      **-**      `core_trap_pkg.vhd`

This package defines the `TRAP_TABLE` constant array, which maps an 8-bit trap cause code to its friendly name and control signals. Constants are also available for each trap cause, prefixed by `RVEX_TRAP_`. In general, the definitions in this package can be changed without breaking functionality, as long as existing traps are not removed.

**Control registers**      **creg**      `core_ctrlRegs.vhd`

This entity contains the generic parts of the core control registers and the bus logic needed to access them. Functionality of the registers is defined by `core_contextRegLogic.vhd` and `core_globalRegLogic.vhd`, and the word addresses of the registers are defined in `core_ctrlRegs_pkg.vhd`.

**Ctrl. reg. map package** - core\_ctrlRegs\_pkg.vhd

This package defines the constants that determine the memory map of the core control registers and several boilerplate subprograms used to generate certain types of control registers with. All control register memory map related constants prefixed with CR\_ can be changed without breaking code, as long as the overall map remains consistent. Note that the constant specifying at which word the global registers stop and the context-specific registers start, CTRL\_REG\_GLOB\_WORDS, is defined in core\_intIface\_pkg.vhd.

**Ctrl. reg. bank** - core\_ctrlRegs\_bank.vhd

This entity instantiates a group of generic control registers. Used by core\_ctrlRegs.vhd to instantiate the global control registers and the context control registers for each context.

**Ctrl. reg. read port** - core\_ctrlRegs\_readPort.vhd

This entity instantiates an additional read port for a control register bank instantiated with core\_ctrlRegs\_bank.vhd.

**Ctrl. reg. bus switch** - core\_ctrlRegs\_busSwitch.vhd

This entity connects a single control register bus master to several slaves, switching based on the request address.

**Ctrl. reg. context switch** - core\_ctrlRegs\_contextLaneSwitch.vhd

This entity connects the control register busses from the memory units to the appropriate context-specific register bank, based on the current runtime configuration.

**Context register logic** cxreg core\_contextRegLogic.vhd

This entity defines the functionality of the context-specific control registers. Extensive documentation is provided in the code, and the registers are defined using the subprograms defined in core\_ctrlRegs\_pkg.vhd. This should make it easy to define new control registers and understand the current ones.

**Global register logic** gbreg core\_globalRegLogic.vhd

Similar to core\_contextRegLogic.vhd, this entity defines the functionality of the global core control registers. Be aware that these registers are only writable from the external debug bus interface.

**Configuration control** cfg core\_cfgCtrl.vhd

This entity provides the runtime configuration control signals to the rest of the core and controls the timing for runtime reconfiguration.

**Configuration decoder** - core\_cfgCtrl\_decode.vhd

This entity error-checks and decodes the configuration words as presented by the core or the debug bus when they request reconfiguration.

<b>Trace unit</b>	<b>trace</b>	core_trace.vhd
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This optional unit (enabled through CFG.traceEnable) configurably selects and compresses trace information into a byte stream. While the byte stream is being written to the memory system or peripheral connected to the trace interface of the core, this unit ensures that the core is properly stalled.

<b>Memory</b>	<b>mem</b>	-
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Abbreviation for the memory or cache connected to the  $\rho$ -VEX.

<b>Instruction memory</b>	<b>imem</b>	-
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Abbreviation for the instruction memory or cache connected to the  $\rho$ -VEX.

<b>Data memory</b>	<b>dmem</b>	-
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Abbreviation for the data memory or cache connected to the  $\rho$ -VEX.

<b>Debug bus</b>	<b>dbg</b>	-
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Abbreviation for the debug bus connected to the  $\rho$ -VEX.

<b>Run control</b>	<b>rctrl</b>	-
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Abbreviation for the entity or group of entities connected to the  $\rho$ -VEX run control interface.

<b>Simulation</b>	<b>sim</b>	-
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Abbreviation for the behavioral VHDL simulator, used as destination for simulation-only debug output signals.

<b>Trace data sink</b>	<b>trsink</b>	-
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Abbreviation for the external system that the trace output data is sent to.

### 3.1.3 Coding style

All code within the  $\rho$ -VEX packages is wrote using a consistent code style. Special attention was paid to naming conventions, as VHDL easily becomes confusing due to the large amount of signals and variables everywhere.

- All signals, entity names, package names and types use a combination of camel-Case and underscores. Typically, underscores are used as a form of hierarchy separation, where the VHDL language does not otherwise allow it, and camelCase is used to indicate word boundaries within one level of hierarchy. For example, core\_ctrlRegs\_bank refers to a (register) bank for the control registers for the  $\rho$ -VEX core.

- Most signal names start with an underscore-terminated abbreviation, which indicates the source and destination entity. This identifier contains two entity abbreviation codes separated by a 2. The entity abbreviation codes are defined at the top of `core.vhd` and are also listed in the previous section. Sometimes other abbreviations are used for signals local to one entity, which should be clear from context.
- All constant names are uppercase with underscores.
- Labels typically use underscores only, to prevent conflicts between similarly named entities and signals.
- Types use one of the following suffixes to indicate what kind of type they represent.
  - `_type`: scalar type.
  - `_array`: array type.
  - `_ptr`: access type for a scalar.
  - `_array_ptr`: access type for an array.
- Entities and packages have the same name as their filename; exactly one entity or package is defined per VHDL file. Package names end in `_pkg`. All  $\rho$ -VEX core files start with `core_` to keep their names unique within the `rvex` package, which contains a number of supporting packages as well.
- Entity descriptions must clearly document the function of every port and generic that passes it by, *especially* when the entity generates or uses the signal (as opposed to just routing it). All hope of future generations comprehending the code is lost when interfaces are not clear.
- Ports should be grouped by function or route. The groups should be made apparent in the entity descriptions using blocks so they're easy to spot.
- Entity instantiation code should include the port group names.
- If words cannot describe how the code works, ASCII art diagrams might. This may seem a bit silly, but the only way to maintain up-to-date documentation is by having the documentation right in the developer's face. A picture somewhere in some documentation folder simply will not do. This manual is already a stretch.
- Indentation is accomplished using two spaces, tabs are not used.
- The `:` symbol in declarations, and the `=>` symbol in case statements, port maps and generic maps, is generally aligned to column 33 using spaces for aesthetically pleasing code.
- Comments must wrap at column 80 for easy readability. Code should also not be too wide, although the column 80 limit is not strictly adhered to.

## 3.2 Datapath

Write about how the datapath works, and how `pipeline_pkg` can be used to configure it.

### 3.3 Flow control

Write about flow control. A lot of this has already been done, refer to the notes folder.



## 3.4 Reconfiguration

Write about how reconfiguration works and how contexts and lane groups are interconnected.

### 3.5 External debug and trace interface

Write about how the external debug and trace systems work.



Cache

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## External debug support unit

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